Review Article

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Promoting the sustainable construction: A scientometric review on the utilization of waste glass in concrete

https://doi.org/10.1515/rams-2024-0036
received March 25, 2024; accepted June 03, 2024

Abstract: Concrete is the second-most used material globally and significantly impacts the environment by emitting a large amount of carbon dioxide (CO_2). This scientometric review investigates the sustainable use of waste glass (WG) in concrete. Our study examines the impact of waste glass powder (WGP) on the mechanical and fresh characteristics of concrete and its environmental implications, enhanced by a machine learning prediction model. We observed a progressive increase in research activity on WGP-based concrete since 2000, indicating the growing interest in this area. The primary focus areas are engineering and material science, reflecting the application potential, structural performance, and material properties of WGP-based concrete. Our discussions highlight the significant benefits of WGP in concrete, including its potential to reduce landfill usage, environmental pollution, and enhance properties such as strength, sulfate resistance, alkali–silica reaction resistance, and freeze–thaw resistance. The review also explores the microstructure of glass powder (GP)-based concrete, illuminating the complex interactions between glass particles and the concrete matrix, which influence the material's overall performance. Environmental impact assessments underscore the necessity for sustainable construction practices and waste reduction. Utilizing machine learning prediction models helps optimize the composition of GP-based concrete, thus enhancing material performance and durability. This review provides a comprehensive analysis of using WG in concrete, contributing to the field's understanding and informing future research and innovations to optimize WG use in concrete applications.

Keywords: waste glass, concrete, scientometric review, sustainable construction, cement replacement, utilization of glass powder

1 Introduction

Everything in the world is becoming more environmentally friendly and sustainable in recent years. Concrete is the second-most useful material in the world, right behind water [1,2]. Concrete continues to be the substance that is utilized in construction most frequently. Previous researchers [3–5] carried out a study and calculated that 11.5 billion tons of concrete are consumed worldwide, or roughly 1.7 tons for every person on the planet. Concrete is one of the largest hurdles to a more friendly environment since it releases the majority of carbon dioxide (CO_2) into the atmosphere. Torres-Carrasco *et al.* [6] have done research, finding a conclusion that 1.7 tons of raw materials are needed to produce 1 ton of cement, and the burning of those raw materials and fuel releases 0.8 tons of CO_2 back into the atmosphere. Because there are no concrete eco-friendly alternatives available now in our industry, the usage of concrete is constantly growing. Due to its high compressive strength, the concrete utilization is increasing day by day. China alone has used more concrete than US in the twentieth century. According to Li [7], the results indicated that the amount of waste concrete reached 239 million tonnes in 2010 and is projected to reach 638 million tonnes in 2020, showing an average annual growth rate of 8%. In spite of this, the use of concrete is not

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slowing down. The usage of concrete in our society is one of the main causes of the extreme rise in the planet's temperature that the globe is currently experiencing. The generation of greenhouse gases and subsequent climate change are both considerably increased by the construction industry [8]. As mentioned in the study by Ma *et al.* [9], high temperatures have been recognized as a significant factor in causing severe damage to the micro- and meso-structure of concrete. This results in a decrease in overall mechanical properties and may harm the concrete's ability to maintain structural integrity, including spalling and exposure of reinforcement bars, particularly in fire situations. Spalling can expose the reinforcement bars to corrosion, which may degrade the bond strength and decrease the concrete structure's ability to bear weight [10,11]. The concrete absorbs most of the heat coming from the sun and the water absorption of the paved surface also decreases due to this. Water level of the ground also decreases by the paved surfaces like street pathways and other concrete surfaces. The two countries that create the most CO_2 globally are the United States and China due to the presence of large industries in these countries. About 60% of the cement produced and consumed globally is in China [12,13], while the USA produces about 86 million metric tons per year [14,15]. Concrete is the main cause for most of the CO_2 emission into the atmosphere. While preparing concrete, when its reaction takes place, around 0.93 pound of CO_2 is release while preparing 1 pound of concrete which is very high and dangerous for the environment. Concrete emits roughly 8% of world CO_2 into the atmosphere. Recycling rate of glass is improving day by day. Some of the countries has up to 90% recycling rate of glass.

Recognizing the urgent need to address these environmental concerns, our scientometric review focuses on the utilization of glass powder (GP) as a sustainable alternative in concrete production. The use of recycled glass has been considered in the construction sector's circular economy, focusing on its benefits for concrete and addressing challenges and opportunities for sustainable construction [16]. By incorporating waste glass (WG) into concrete mixtures, we can reduce the demand for traditional raw materials, such as sand and gravel, while simultaneously diverting glass waste from landfills and minimizing its harmful impact on the environment. According to Liu *et al.* [17], due to their non-biodegradable nature, these glass wastes cover vast areas of open space and seriously harm the ecosystem through air, water, and land pollution. Nearly 10 million tons of glass is produced every month for different purposes and the recycle rate of glass is very low. Ruth and DellAnno [18] conducted a study, in which they have concluded that 1.2 tons of nonrenewable raw materials are used to produce one ton of container glass. Glass is mostly recycled by burning in the kiln to mold it for the future use, when the glass is burned, it requires high amount of energy and it pollutes environment as well. In previous research [10,19,20], it is discussed how recycling glass could reduce the energy use and environmental impact of glass production and disposal. Glass is composed of different chemicals and when it is burned, different kinds of chemical smokes are released into the atmosphere which is very dangerous for most of the living things in the world. EID [19] discussed that glass is brittle and can break easily, causing injury or waste. According to Sundaram *et al.* [21], most glass waste could be periodically recycled without losing any of its chemical or physical characteristics, but the key challenge is the variety in color and quality of the glass collected. There is no completely safe method to recycle glass. In advanced kilns, water is used to clean the smoke, but chemicals from the process mix with the water, which then seeps into the ground and contaminates groundwater, negatively impacting both the land and water quality. Only 60% of the glass is recyclable, due to different colors and chemicals used in glass, it cannot be recycled by only burning the glass. The non-recyclable glass is dumped into landfill and in the ocean. By using GP in concrete, it will not affect environment as much as when glass is burned, which emits most of the CO_2 in the atmosphere. According to Jani and Hogland [22], incorporating WG in cement and concrete production offers several benefits such as conservation of natural resources, energy and cost savings, and reduction in CO_2 emissions and other greenhouse gases. According to Guo *et al.* [23], every year, more glass is produced as a result of the rising standard of living and the increasing speed of industrialization, which results in more glass waste ending up in landfills. The natural resources can be preserved, and the glass can be recycled without emitting hazardous chemical smoke into the atmosphere, when the glass replaces in part the cement and fine and coarse aggregates.

Waste glass powder (WGP) concrete has a number of beneficial qualities, as shown in Figure 1. First, it presents an effective cost-saving solution as the GP is a byproduct of glass manufacturing, readily available at a lower cost compared to conventional cementitious materials [24]. Additionally, the inclusion of WGP enhances the hydration process in concrete, leading to improved strength and durability concluded by previous studies [25–27]. Acting as a pozzolanic material, it reacts with calcium hydroxide when mixed with water, forming additional cementitious compounds. Another notable benefit is the increased resistance of WGP concrete against chemical attacks. Structures made with this type of concrete exhibit enhanced durability, as they are less susceptible to corrosion caused by chemicals or aggressive substances. By using WGP in concrete,

Figure 1: Benefit of WGP concrete.

pollution can be reduced as glass waste is diverted from landfills, effectively minimizing the environmental impact associated with glass disposal. Furthermore, WGP concrete is considered environmentally friendly. By partially substituting cement with WGP, the reliance on fresh raw resources is decreased. As a result, the carbon emissions associated with concrete production are lowered, contributing to a reduction in CO_2 emissions. This method encourages sustainability and helps in the preservation of natural resources, including clay and limestone, which are commonly utilized in the manufacture of cement. Finally, WGP concrete exhibits improved resistance to freeze and thaw (FT) cycles, making it suitable for colder climates. The incorporation of GP helps minimize the risk of cracking and deterioration caused by repeated FT cycles. Overall, the multiple benefits of WGP concrete, including cost savings [28], improved hydration [29], chemical resistance [30], pollution reduction [31], eco-friendliness [32], CO_2 reduction [33], conservation of natural resources [34], and resistance against FT [35], make it a desirable choice for environmentally friendly building techniques.

The scientometric review for this study is to examine the impacts of incorporating GP into concrete, emphasis on how it affects the environment and how the concrete's mechanical and fresh properties are affected. GP, when recycled or disposed improperly in water or land, can have detrimental effects on the environment. Burning glass releases harmful chemicals into the atmosphere [8]. However, there are significant environmental advantages of using glass waste in the production of geopolymer concrete. These include conserving natural resources, conversion of landfill waste into useful products, reduction in CO_2 and greenhouse gas emissions, promotion of sustainable building practices, and significant energy and cost savings. Traditionally, concrete production relies heavily on cement, fine aggregate, and coarse aggregate, which are obtained by crushing natural resources from the earth. This leads to a rapid depletion of valuable natural resources [36]. By incorporating GP into concrete, the need for burning is eliminated, making it an environmentally friendly alternative. Utilizing WG in concrete not only avoids disposal in landfills but also contributes to resource conservation [37]. In addition, testing the effects of GP on newly formed characteristics is another goal of its use in concrete [38], such as workability [39] and setting time [40], as well as the mechanical properties [39], including compressive [41], tensile [42], and flexural strengths [43]. Understanding how GP affects these properties is crucial for sustainable construction practices. The primary focus is to reduce the reliance on natural aggregates and maximize waste recycling. GP can be used as a cementitious material, substituting both fine and coarse cement in specific applications [44] and coarse aggregates [45] in others. Due to its widespread household usage and disposal in landfills [46], GP is readily available and cost-effective to procure. To use glass in concrete, it is crushed into a fine powder form, ensuring its suitability for concrete applications. The objective of the scientometric review is to assess the environmental effects of utilizing GP in concrete, considering its effects on recycling and incorrect disposal. In order to maximize sustainable construction techniques, the fresh and mechanical qualities of the final concrete are also prioritized. This is done by minimizing the use of natural aggregate and maximizing waste recycling [47]. The availability and cost-effectiveness of GP make it a viable option for incorporating recycled materials into concrete production.

The utilization of WG in concrete represents a pivotal area of research within sustainable construction practices. This review holds substantial importance as it systematically synthesizes and analyzes the application of WGP, a largely underutilized by-product, in concrete, contributing to environmental sustainability and innovation in construction materials. By investigating the integration of WG into concrete, this study addresses a significant gap in current construction practices that often overlook the potential of recycled materials in reducing carbon footprints and enhancing material properties. The primary contribution of this review to the existing body of knowledge lies in its comprehensive analysis of how WGP influences the mechanical and fresh properties of concrete. Through a detailed scientometric analysis, this review highlights emerging trends, evaluates the effectiveness of past and current methodologies, and provides a new perspective on the potential scalability of such practices. This not only aids in advancing academic understanding but also serves as a crucial resource for industry practitioners seeking to implement more sustainable and cost-effective materials. Furthermore, this review tackles the problem of industrial waste, specifically the underutilization of glass waste, which has been a longstanding environmental issue. By mapping out the benefits and challenges associated with using WG in concrete, the review sets a foundation for future research and development in this area. The objectives of this review are to delineate the current state of research on WG in concrete, to identify and fill gaps in the knowledge, and to suggest directions for future research that could lead to wider adoption of this sustainable practice in the construction industry. By achieving these goals, this review intends to foster a deeper understanding of the material's capabilities and encourage its incorporation into mainstream construction practices, thus promoting greater environmental responsibility and innovation in building materials.

2 Methods

The methodology for reviewing WGP-based concrete, as represented in Figure 2, involves a series of systematic steps. First, a thorough search is conducted in a reputable literature database, such as Scopus, to gather relevant scholarly articles and research papers. The information extracted from the literature database is then stored and organized in a Microsoft Excel comma-separated value file for efficient data management. Subsequently, scientometric analysis is performed using Scopus and VOSviewer, enabling the visualization and examination of publication trends, subject areas, sources, articles, organizations, funding sponsors, and countries associated with WGP-based concrete research. Finally, the obtained results are presented, encompassing various aspects such as publication trends over time, distribution of research across subject areas, prominent literature sources, article counts, contributing organizations, funding sources, and active countries in the field of WGP-based concrete research. The review seeks to provide a thorough knowledge of the research landscape through this rigorous technique, identify key contributors, and shed light on the development and impact of WGP-based concrete.

3 Results

The findings of the scientometric review on the use of recycled glass in concrete for green building, as part of the aim, encompass a comprehensive analysis of various key aspects. First, publication trends over time are examined, providing insights on the development and evolution of this field's research. The distribution of research across subject areas helps identify the diverse areas of focus within the domain of WGP-based concrete. The review also highlights prominent literature sources, showcasing the key references and resources that have contributed significantly to the body of knowledge. Additionally, article counts offer a quantitative measure of the research output and productivity in the field. The analysis also encompasses identifying the contributing organizations, shedding light on the institutions and entities actively involved in WGP-based concrete research. Moreover, the review explores funding sources, providing an understanding of the financial support that drives research in this area. Finally, the examination of

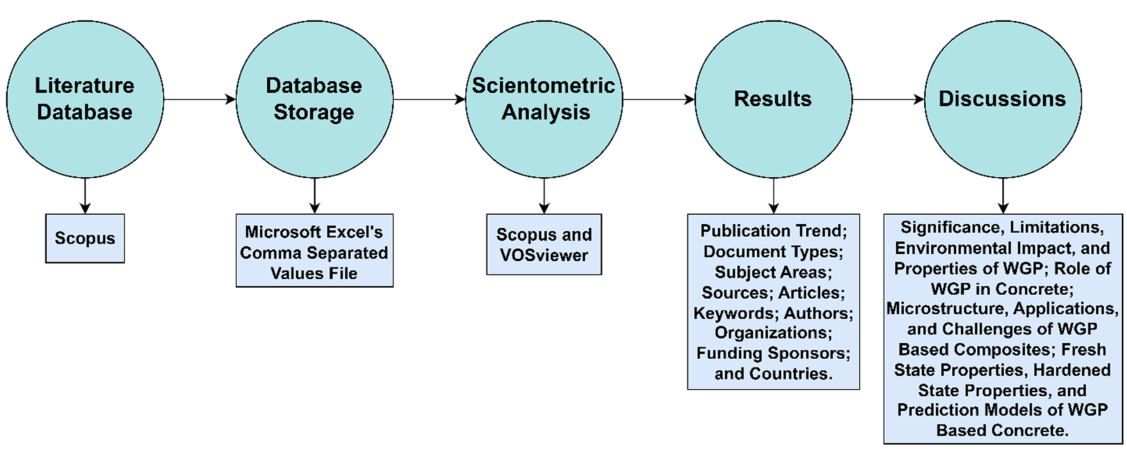

Figure 2: Review methodology of WGP-based concrete.

active countries in WGP-based concrete research highlights the global distribution and participation, offering insights into the geographical spread of research endeavors. These findings add to our understanding of sustainable building techniques in this area by offering a thorough analysis of the use of WG in concrete.

3.1 Publication trend

According to Chadegani *et al.* [48], a thorough comparison of databases such as Web of Science and Scopus, which classify journals based on output and total citations, reveals the latest research on the use of discarded glass in concrete. According to Markoulli *et al.* [49], science visualization is used in scientometric reviews, a method developed by researchers for analyzing bibliometric data with diverse objectives. The trend of annual publication patterns related to WGP-based concrete, as illustrated in Figure 3, exhibits a remarkable and progressive increase in research activity over time. Upon analyzing the data from 1960 to 2000, it becomes evident that the number of publications per year during this period was relatively low, averaging less than 10. However, a significant shift occurred starting from 2000 to 2008, as the number of publications experienced a notable surge, reaching nearly 30 per year. Subsequently, from 2008 to 2016, there was a substantial improvement in research output, with the number of published documents skyrocketing to approximately 80 per year. This upward trajectory persisted, with a remarkable growth observed from 2016 to 2024, as exemplified by the consistently increasing number of publications each year. The year 2017 witnessed a count of 80 publications, followed by a substantial jump to 120 in 2018, 140 in 2019, 170 in 2020, 290 in 2021, and 300 in 2022. Up until May 2023, approximately 150 additional publications have already been recorded, indicating a continued surge in research activity. It is predicted that this year's total number of publications will exceed 300 based on current patterns, further reinforcing the escalating interest and engagement in research related to WGP-based concrete. This trend underscores the increasing importance of this innovative material in the field of sustainable construction and highlights its potential for driving positive change.

3.2 Document types

According to Qin *et al.* [50], the scientific mapping review included analysis of document sources, keyword co-occurrence, citation networks, co-authorship, publications, bibliometric overlap, and country contributions. The distribution of WGP-based concrete records among various categories is shown in Figure 4. The analysis reveals that articles constitute the majority, accounting for 60% of the documents. Conference papers comprise 24.5% of the total, indicating a significant contribution from conference proceedings in disseminating research in this area. Conference review papers make up 5.8% of the documents, reflecting the importance of critical assessments and evaluations within conference settings. Review papers, which provide comprehensive summaries and analyses of existing literature, represent 5.6% of the documents, indicating their role in synthesizing knowledge and highlighting key findings in WGP-based concrete research. Additionally, there are book chapters, comprising 2.9% of the documents, suggesting the inclusion of this topic within book compilations. Books and

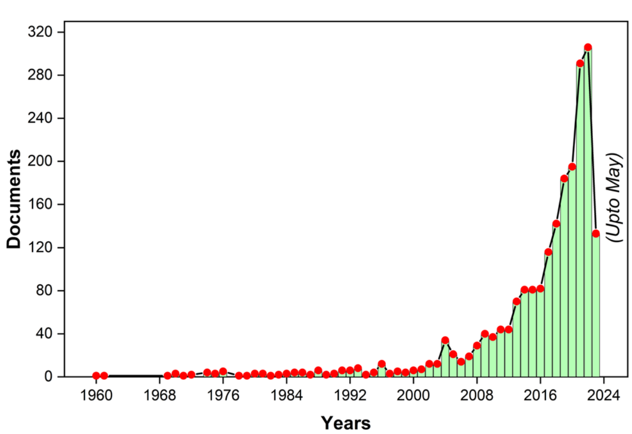

Figure 3: Annual publication pattern of WGP-based concrete documents.

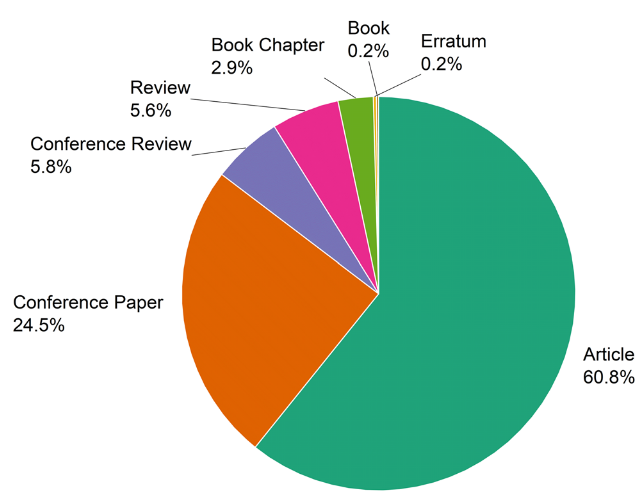

Figure 4: Types of WGP-based concrete documents.

erratum make up a small fraction, each accounting for 0.2% of the total. This distribution across different document types signifies the diverse range of scholarly outputs, including original research articles, conference contributions, reviews, book chapters, and books, contributing to the knowledge base on WGP-based concrete.

3.3 Subject areas

In order to identify the most important study fields, the Scopus database was examined using the Scopus analyzer. Figure 5 presents a pie chart illustrating the distribution of subject areas in WGP-based concrete research. The analysis reveals that engineering represents the largest portion, comprising 36.7% of the chart. This highlights the close relationship between WGP-based concrete and engineering disciplines, emphasizing the engineering-driven approach in exploring its applications, structural performance, and construction techniques. Material science follows closely, accounting for 24.8% of the distribution, indicating the significance of understanding the material properties, durability, and structural behavior of WGP-based concrete. This field of study is essential for maximizing the material's composition, characteristics, and performance and assuring its compatibility for various construction applications. The presence of environmental science at 10.7% underscores the increasing focus on sustainable construction practices. WGP-based concrete provides advantages for the environment by lowering waste production, conserving natural resources, and minimizing carbon emissions associated with traditional concrete production. The inclusion of physics and astronomy at 6.8% highlights the scientific principles applied to study the physical properties, interactions, and behavior of WGP-based concrete.

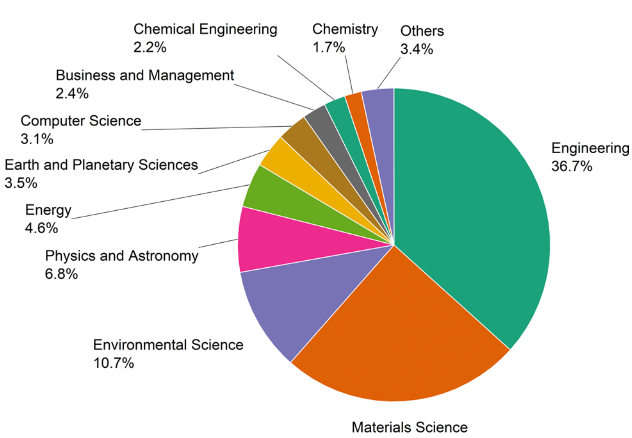

Figure 5: Subject areas of WGP-based concrete documents.

Energy-related research at 4.6% reflects the growing emphasis on energy efficiency in the construction sector, with WGP-based concrete offering potential benefits in reducing energy consumption and carbon footprint. The presence of earth and planetary science, computer science, business and management, chemical engineering, and chemistry in the chart signifies the interdisciplinary nature of WGP-based concrete research. These subject areas contribute expertise in areas such as geotechnical aspects, computational modeling, sustainability assessment, industrial processes, and chemical interactions, enriching the understanding and development of WGP-based concrete. The diverse subject areas represented in the chart highlight the collaborative and interdisciplinary efforts required for advancing WGP-based concrete as a sustainable construction material.

3.4 Sources

The investigation of growth and innovation may be visualized, thanks to source mapping. These sources provide data within the bounds of particular, predetermined limits. Table 1 presents the sources of literature on WGP-based concrete, along with the corresponding document counts, citation counts, and total link strength. The sources are ranked according to the quantity of papers they contribute to the field. At the top of the list is "Construction and Building Materials," which accounts for 176 documents. It has received a significant number of citations (7,870) and has a high total link strength (4,825), indicating its influence and impact within the research community. Following closely is the "Journal of Cleaner Production" with 77 documents. It has received a substantial number of citations (3,992) and has a total link strength of 2,710. Other sources, such as "Materials Today: Proceedings," "IOP Conference Series: Materials Science and Engineering," "Materials Science Forum," and "Materials," also contribute a significant number of documents to the field, with varying citation counts and total link strengths. IOP Conference Series: Materials Science and Engineering, known for publishing conference proceedings, has contributed 62 documents to the field. It has received 232 citations and has a total link strength of 319, indicating its role in disseminating conference-based research on WGP-based concrete. As per Materials Science Forum with 53 published documents, this source has received 179 citations. It has a total link strength of 176, reflecting its contributions to the knowledge base on WGP-based concrete from a materials science perspective. The source "Materials" has contributed 52 documents on WGP-based concrete. It has received

Table 1: Sources of WGP-based concrete documents

S. no.	Source	Documents	Citations	Total link strength
1	Construction and Building Materials	176	7,870	4,825
2	Journal of Cleaner Production	77	3,992	2,710
3	Materials Today: Proceedings	70	363	1,176
4	IOP Conference Series: Materials Science and Engineering	62	232	319
5	Materials Science Forum	53	179	176
6	Materials	52	761	1,455
7	Journal of Building Engineering	40	1,128	2,006
8	IOP Conference Series: Earth and Environmental Science	37	54	108
9	Advanced Materials Research	35	38	4
10	Case Studies in Construction Materials	33	379	1,563
11	Resources, Conservation, and Recycling	31	3,514	1,237
12	Key Engineering Materials	30	117	129
13	International Journal of Civil Engineering and Technology	25	131	63
14	Sustainability (Switzerland)	24	266	1,008
15	Cement and Concrete Composites	23	1,937	1,106
16	Waste Management	21	2,756	432
17	AIP Conference Proceedings	20	18	31
18	American Concrete Institute, ACI Special Publication	19	24	157
19	Applied Sciences (Switzerland)	19	172	668
20	Cement and Concrete Research	19	3,420	212

761 citations and demonstrates a total link strength of 1,455, indicating its impact and connectivity within the research field. The "Journal of Building Engineering" has contributed 40 documents on WGP-based concrete, receiving 1,128 citations. With a total link strength of 2,006, it demonstrates strong connections and references within the field of building engineering. The "IOP Conference Series: Earth and Environmental Science" has contributed 37 documents on WGP-based concrete. These publications have received 54 citations, indicating their impact and recognition within the field. With a total link strength of 108, this source demonstrates connections and references to other studies in the realm of earth and environmental science. The source "Advanced Materials Research" has provided 35 documents on WGP-based concrete. These documents have received 38 citations, suggesting a moderate level of recognition. With a total link strength of 4, this source may have fewer connections to other studies in the field. However, it still holds value for exploring specific aspects of WGP-based concrete. The source "Case Studies in Construction Materials" has 33 documents on WGP-based concrete, with 379 citations and a total link strength of 1,563. It offers valuable case studies and practical applications of this material in construction projects. The journal "Resources, Conservation and Recycling" has 31 documents, with 3,514 citations and a total link strength of 1,237, focusing on the sustainable aspects of utilizing waste materials. "Key Engineering Materials" offers 30 documents with 117 citations and a link strength of 129, providing insights into the engineering properties and materials science aspects. "International Journal of Civil Engineering and Technology" features 25 documents, 131 citations, and a link strength of 63, presenting research on civil engineering applications. "Sustainability (Switzerland)" publishes 24 documents, with 266 citations and a link strength of 1,008, emphasizing sustainable practices in WGP-based concrete. "Cement and Concrete Composites" presents 23 documents, with 1,937 citations and a link strength of 1,106, focusing on the composites' performance and properties. "Waste Management" explores waste management strategies with 21 documents, 2,756 citations, and a link strength of 432. "AIP Conference Proceedings" contains 20 documents, 18 citations, and a link strength of 31, providing conference contributions on the topic. "American Concrete Institute, ACI Special Publication" and "Applied Sciences (Switzerland)" both offer 19 documents, with 24 citations and a link strength of 157, and 172 citations and a link strength of 668, respectively. Finally, "Cement and Concrete Research" presents 19 documents, 3,420 citations, and a link strength of 212, focusing on research in cement and concrete materials. The table presents a diverse range of sources contributing to the literature on WGP-based concrete. These sources address a variety of topics related to the topic, such as engineering, environmental science, materials science, construction and building materials, and cleaner production. The findings suggest a strong emphasis on sustainability, engineering properties, civil engineering applications, and composites' performance. The high citation counts and total link strengths of certain sources indicate their significant impact and influence within

the research community. Overall, these sources collectively contribute to the growing knowledge and understanding of WGP-based concrete, supporting advancements in its applications, properties, and sustainable utilization.

Figure 6 depicts a graphical representation of the sources of WGP-based concrete study. The graph showcases the range of documents contributed by each source, indicating their significance in the field. The source with the minimum number of documents is “Case Studies in Construction Materials,” which accounts for 33 documents. On the other hand, the source with the maximum number of documents is “Construction and Building Materials,” which contributes 176 documents. Other notable sources include “Advanced Materials Research” with 35 documents, “IOP Conference Series: Earth and Environmental Science” with 47 documents, “Journal of Building Engineering” with 40 documents, “Materials” with 52 documents, “Materials Science Forum” with 53 documents, “IOP Conference Series: Materials Science and Engineering” with 62 documents, “Materials Today: Proceedings” with 70 documents, “Journal of Cleaner Production” with 77 documents, and “Construction and Building Materials” with the highest number of 176 documents. The distribution of research efforts among different sources is represented graphically in the graph, which sheds light on the academic contributions made in the area of WGP-based concrete.

Figure 7 illustrates the publication pattern of sources in WGP-based concrete research over the years. The graph provides insights into the number of publications by each source across different time periods. The source “Construction and Building Materials” shows significant progress, starting with an average of five publications per year from 2005 to 2010. The number of publications increases

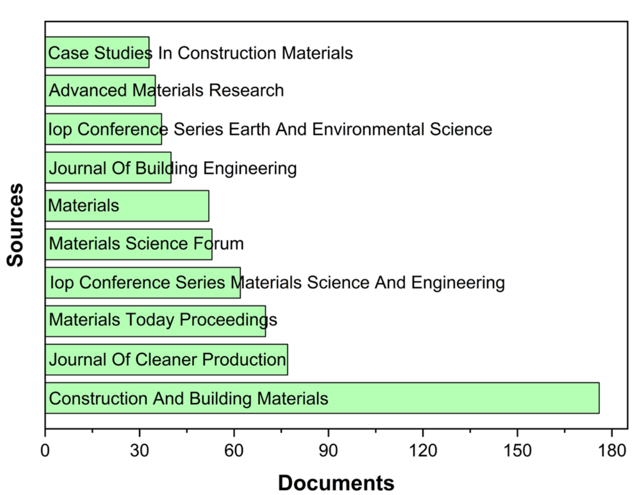

Figure 6: Sources of WGP-based concrete documents.

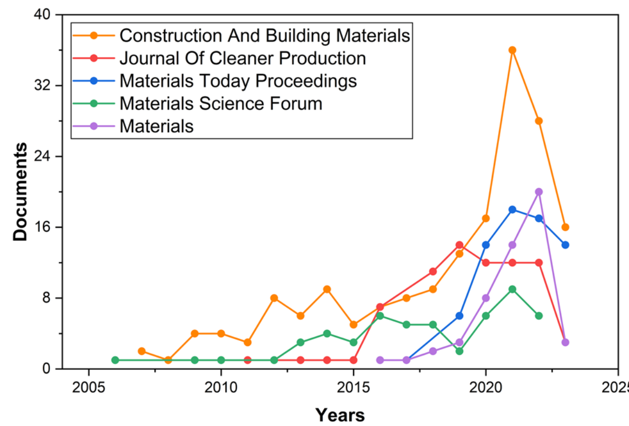

Figure 7: Publication pattern of the sources of WGP-based concrete documents.

to around seven per year from 2010 to 2015 and further rises to an average of ten publications per year from 2015 to 2020. Notably, from 2020 to 2023, the average publication rate reaches 26 papers per year, with a peak in 2021 with 36 publications. In contrast, the “Journal of Cleaner Production” initially had around one publication per year from 2005 to 2015, but the average publication rate increases to eight papers per year from 2015 to 2023, with the highest number of publications in 2019. “Materials Today: Proceedings” started its publication in 2017, averaging around 12 papers per year. “Materials Science Forum” began publishing in 2006, with an average of one paper per year from 2006 to 2012, and then increased to around five papers per year from 2012 to 2023. “Materials” published its first paper in 2016, with an average of approximately eight papers per year. The publication pattern graph provides valuable information about the research output and trends of these sources in the field of WGP-based concrete over time.

Figures 8 and 9 provide a comprehensive analysis of the network and density mapping of leading sources in WGP-based concrete literature. A network of interconnected dots representing different sources, with the largest dot indicating the highest density observed for the source Construction and Building Materials. This source exhibits extensive connections and collaborations with other sources in the network. Notable sources in the network, represented by dots in different colors, include Journal of Cleaner Production, Materials Today: Proceedings, IOP Conference Series: Materials Science and Engineering, and more, each with distinct roles and characteristics within the network. The analysis of the network and density provides insights into the interconnections and collaborations among these leading sources in the field. A density mapping is provided, with colors representing different levels of density. Red indicates

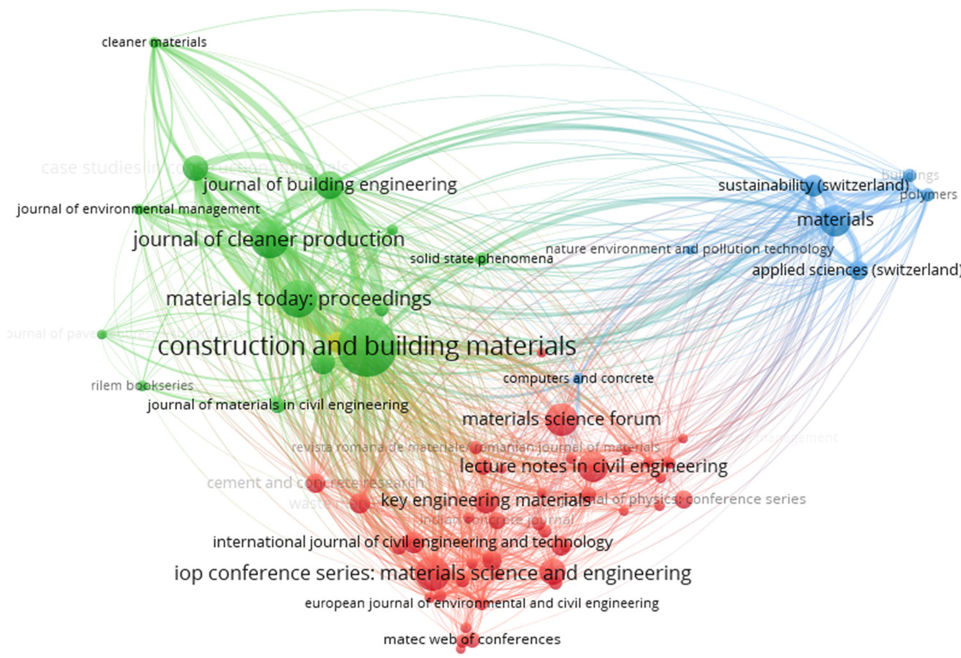

Figure 8: Network mapping of the sources of WGP-based concrete documents.

the highest density, yellow represents the intermediate density, and blue represents the lowest density. The mapping reveals that "Construction and Building Materials" is the most densely connected source, demonstrating a high level of collaboration, citations, and interactions within the research community. On the other hand, "Cement and Concrete Research" is the least dense source, indicating a lower level of connectivity and collaboration compared to others. The density mapping helps visualize the varying levels of interconnectedness among the sources, with red indicating

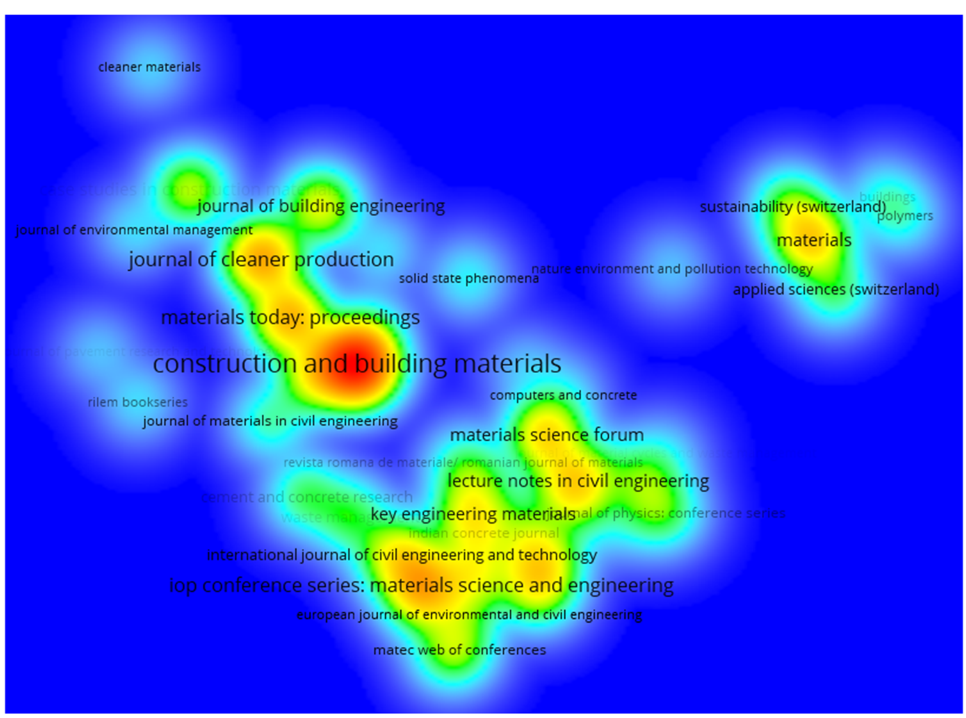

Figure 9: Density mapping of the sources of WGP-based concrete documents.

strong connectivity and blue indicating weaker connectivity. Figures 8 and 9 offer a comprehensive overview of the network of leading sources in WGP-based concrete literature. Figure 8 highlights the network's structure and the prominent sources within it, while Figure 9 provides a density mapping that visually represents the levels of interconnectedness among the sources. This combined analysis provides valuable insights into the collaborations and interconnections among these leading sources in the field.

3.5 Articles

The scientometric method was used to analyze these articles in order to show the clarity of the overall literature sample, research keywords, publication source, most productive and influential scholars, most-cited articles, nations, and institutions actively involved in the concrete WGP research. Table 2 presents a collection of articles on WGP-based concrete, showcasing their document titles, total link strengths, and citation counts. Among the articles listed, the one titled "The Greening of the Concrete Industry" by Neyer C. in 2009 stands out with the highest number of citations, reaching 986. This article has garnered significant attention and recognition within the research community. On the other hand, the article titled "Microstructural Characterisation" by Torres-Carrasco M. and Puertas F. in 2015 has the lowest number of citations, with a count of 232. In terms of total link strength, the article titled "Waste Materials and By-Products in Concrete" by Siddique R. in 2008 holds the highest value at 25. This suggests a strong interconnection and referencing of this particular article within the field. Conversely, the lowest total link strength is associated with multiple papers, one of which is titled "Studies on Concrete Containing Ground Waste Glass" by Shao *et al.* in 2000. This indicates a relatively lower level of interconnection and referencing for this group of papers compared to others in the table. The citation counts mentioned in Table 2 for the articles on WGP-based concrete play a crucial role in advancing research in this field. Citations serve as an indicator of the impact and significance of a particular article within the academic community. A higher number of citations suggests that the article has been widely recognized and referenced by other researchers, indicating its influence and contribution to the existing body of knowledge. The information presented in Table 2 provides insights into the citation counts and link strengths of various articles in the field of WGP-based concrete, highlighting the articles that have garnered significant attention and influence within the research community.

Figures 10 and 11 provide valuable insights into WGP-based concrete research. A network mapping that visually

Table 2: Articles of WGP-based concrete

S. no.	Document	Ref.	Citations	Total link strength
1	The greening of the concrete industry	[51]	986	1
2	Studies on concrete containing ground waste glass	[52]	525	0
3	Use of selected waste materials in concrete mixes	[53]	492	0
4	Value-added utilization of waste glass in concrete	[54]	461	6
5	Properties of concrete containing waste glass	[55]	442	2
6	A review on the use of waste glasses in the production of cement and concrete	[56]	362	14
7	Studies on mechanical properties of concrete containing waste glass aggregate	[57]	343	0
8	Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs	[58]	324	6
9	A review on the viable technology for construction waste recycling	[59]	320	1
10	Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications	[60]	315	3
11	Recycling of waste glass as a partial replacement for fine aggregate in concrete	[61]	305	5
12	A review of waste products utilized as supplements to Portland cement in concrete	[62]	293	7
13	Waste glass powder as partial replacement of cement for sustainable concrete practice	[63]	279	4
14	Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement	[64]	266	11
15	Use of glass waste as an activator in the preparation of alkali-activated slag. Mechanical strength and paste characterization	[65]	259	5
16	Utilization of waste glass powder in the production of cement and concrete	[3]	257	0
17	Waste glass in the production of cement and concrete – A review	[22]	248	14
18	Waste materials and by-products in concrete	[66]	247	25
19	Durability of mortar using waste glass powder as cement replacement	[67]	244	12
20	Waste glass in the geopolymer preparation. Mechanical and microstructural characterization	[68]	232	5

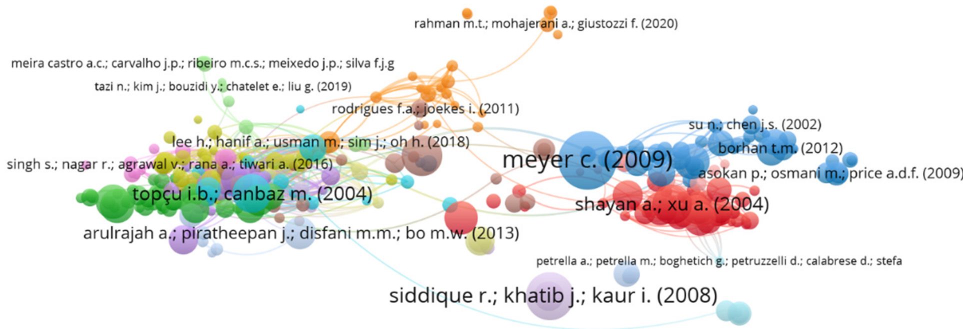

Figure 10: Network mapping of the WGP-based concrete documents.

represents the connections and relationships between articles and authors. Each article is represented by a colored dot, indicating specific authors or groups of authors with common research focuses. The size of each dot corresponds to the number of citations received, reflecting the influence and impact of the articles within the research community. On the other hand, a density mapping showcases the citation impact of different authors in the field. The figure utilizes color coding to represent varying levels of citations, with red indicating high impact, yellow indicating moderate impact, and light blue representing lower impact. This visualization allows researchers to identify influential authors and understand the varying levels of impact associated with different articles. Figures 10 and 11 provide a comprehensive understanding of the network mapping and citation impact in WGP-based concrete research, enabling researchers to navigate the research landscape, identify key contributors, and gain insights into the field's trends and connections.

3.6 Keywords

The search term used to find relevant publications and data in the Scopus database was WGP concrete. Table 3 provides a comprehensive overview of the keywords associated with WGP-based concrete. The table includes columns such as occurrences, keywords, and total link power. The keywords listed in the table highlight the important concepts and aspects related to this field of research. The keyword "Glass" appears most frequently, with 971 occurrences and overall link strength of 5,847, indicating its significance in WGP-based concrete studies. Other prominent keywords include "Compressive Strength" with 689 occurrences and a total link strength of 4,288, "Recycling" with 524 occurrences and a total link strength of 3,058, and "Concretes" with 494 occurrences and a total link strength of 3,026. These keywords reflect the key focus areas within the research, covering aspects such as glass being used as a material, the strength properties of the concrete, recycling practices, and the overall durability and

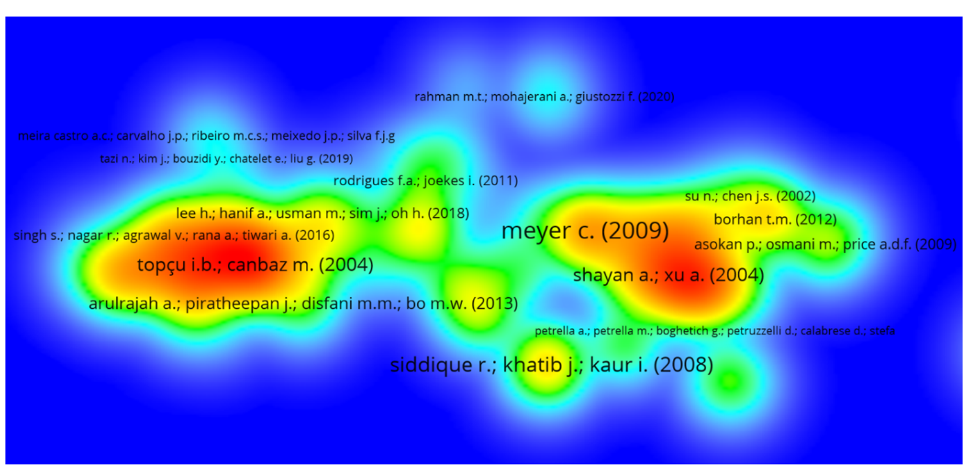

Figure 11: Density mapping of the WGP-based concrete documents.

Table 3: Keywords of WGP-based concrete documents

S. no.	Keyword	Occurrences	Total link strength
1	Glass	971	5,847
2	Compressive strength	689	4,288
3	Recycling	524	3,058
4	Concretes	494	3,026
5	Concrete aggregates	448	2,918
6	Aggregates	347	2,304
7	Concrete	334	1,844
8	Waste glass	322	2,031
9	Cements	312	2,108
10	Fly ash	284	1,796
11	Durability	211	1,478
12	Silica	208	1,509
13	Sustainable development	203	1,418
14	Slags	201	1,410
15	Mechanical properties	195	1,176
16	Tensile strength	195	1,398
17	Concrete mixtures	179	1,284
18	Portland cement	178	1,263
19	Glass powder	177	1,103
20	Mortar	174	1,223

sustainability of concrete made using leftover GP. The table provides the list of researchers with valuable insights into the prevalent themes and areas of interest in this field, allowing us to identify relevant keywords and explore specific aspects of WGP-based concrete more effectively.

Figures 12 and 13 offer comprehensive insights into WGP-based concrete research. Figure 12 presents a network mapping of keywords associated with the field, representing them as dots with varying sizes. The size of each dot reflects the frequency of occurrence and the strength of links associated with the keyword. Different colors categorize specific groups of keywords, such as yellow for materials like glass and WG, red for properties like compressive strength and durability, green for supplementary cementitious materials, and blue for keywords related to concrete and sustainability. This mapping visually illustrates the interconnections and relationships between keywords, aiding researchers in identifying significant keywords and their associations for further exploration and analysis.

In Figure 13, a density mapping focuses on the impact of different keywords in WGP-based concrete research. Colors indicate the frequency of occurrence for each keyword, with red representing high occurrence, yellow indicating moderate occurrence, and light blue representing minimum occurrence. The mapping allows researchers to understand the distribution and prominence of keywords within the research literature. It helps identify frequently

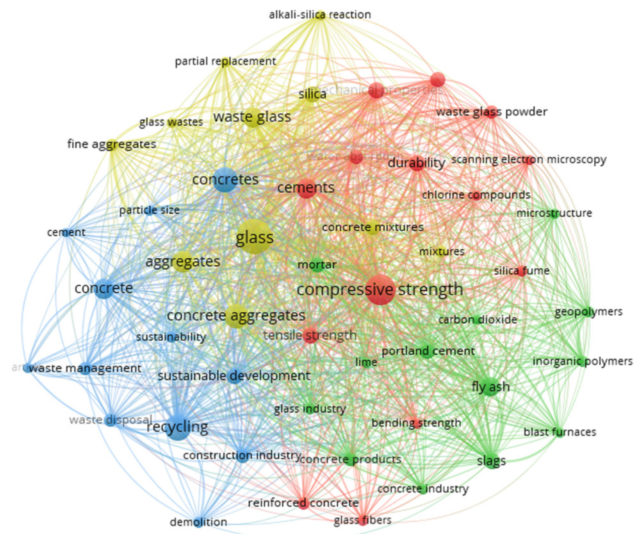

Figure 12: Network mapping of the keywords of WGP-based concrete documents.

studied and influential keywords, highlighting key areas of focus and enabling researchers to explore the relationships and connections between these keywords. Overall, Figures 12 and 13 provide researchers with a comprehensive visual representation of the network mapping and density of keywords in WGP-based concrete research, facilitating deeper understanding and analysis of the subject matter.

3.7 Authors

In scientometric reviews, the authors play a crucial role in conducting comprehensive analyses and providing valuable

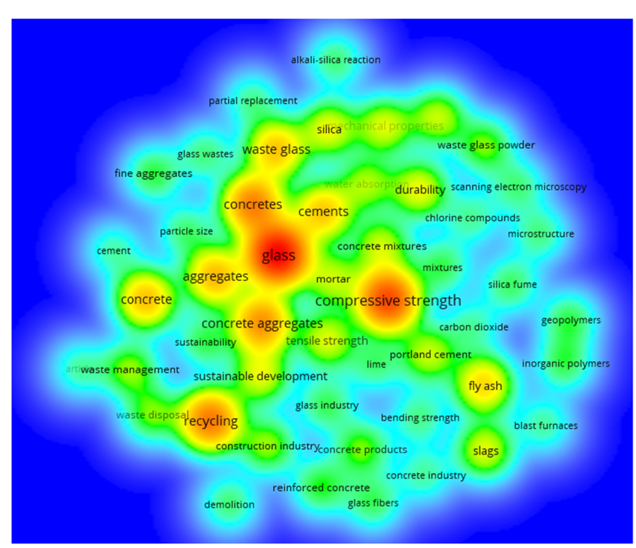

Figure 13: Density mapping of the keywords of WGP-based concrete documents.

Table 4: Authors of WGP-based concrete documents

S. no.	Author	Citations	Total link strength
1	Poon C. S.	1,285	40,199
2	De Brito J.	704	17,981
3	Tagnit-Hamou A.	605	22,129
4	Shi C.	592	19,630
5	Ling T. C.	487	16,362
6	Du H.	434	16,871
7	Tan K. H.	434	17,010
8	Meyer C.	413	9,880
9	Arulrajah A.	395	11,990
10	Shayan A.	343	10,171
11	Xu A.	309	9,478
12	Siddique R.	306	7,097
13	Tayeh B. A.	305	8,147
14	Wang Y.	302	8,308
15	Dhir R. K.	299	11,112
16	Provis J. L.	292	8,695
17	Topcu I. B.	281	8,468
18	Wang H.	279	8,732
19	Li J.	268	6,310
20	Cyr M.	263	10,362

insights. Table 4 provides information on the researchers that developed WGP-based concrete, presenting data in columns such as author, citations, and total link strength. According to the most citations they have earned, the authors are presented in descending order. The table offers valuable insights into the prominent authors in this field and their research impact. Topping the list is author Poon C.S. with 1,285 citations and a total link strength of 40,199. Following closely is De Brito J. with 704 citations and 17,981 total link strength, and Tagnit-Hamou A. with 605 citations and 22,129 total link strength. Other notable authors include Shi C. with 592 citations and 19,630 total link strength, Ling T.C. with 487 citations and 16,362 total link strength, and Du H. and Tan K.H., both with 434 citations and total link strengths of 16,871 and 17,010, respectively. These data provide researchers with an overview of the leading contributors in the field of WGP-based concrete and allows for a deeper understanding of the research landscape and the authors who have made significant contributions to this area of study.

Figure 14 presents a vertical bar graph illustrating the distribution of authors and the number of documents related to WGP-based concrete. The accompanying table displays the authors in descending order, with Poon C.S. having the highest number of papers, exceeding 30 publications. On the other hand, Choudhary J. has the lowest number of papers, with approximately nine publications. This bar graph provides a visual representation of the distribution of research contributions among different authors

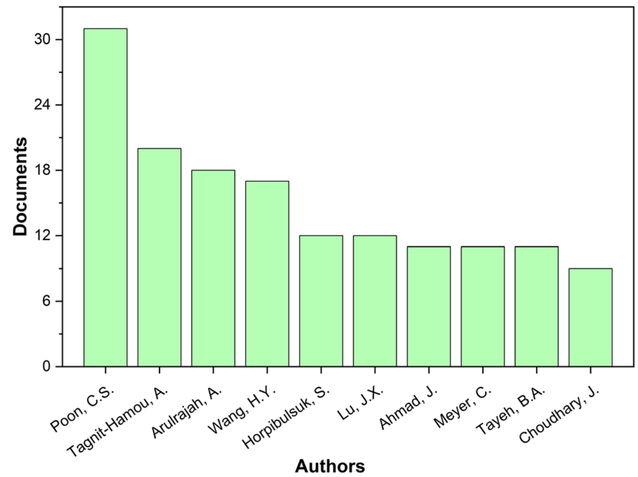

Figure 14: Authors of WGP-based concrete documents.

in the use of concrete made using WGP. It highlights the varying levels of involvement and productivity among researchers, showcasing the extensive body of work produced by authors such as Poon C.S. while indicating the relatively lower number of publications by Choudhary J. This information can be useful in understanding the research landscape and identifying key contributors and their research output in this particular field.

Figures 15 and 16 provide complete insights into the WGP-based concrete research landscape. Figure 15 presents a network mapping of authors involved in this research, with the size of each author's dot representing their citation count. Larger dots indicate higher citation counts, showcasing the influence and impact of authors within the field. The mapping also illustrates the collaborative relationships and co-authorships among researchers. Additionally, the dot colors correspond to each author's research focus, enabling viewers to identify authors with similar objectives based on their dot colors. This network mapping visually represents citation impact, collaborations, and research aims, facilitating a better understanding of influential authors and their areas of expertise. In Figure 16, a density mapping of authors in the area of WGP-based concrete research is shown. The mapping utilizes different colors to indicate the level of citation impact for each author. The authors with the most citations are shown in red, those with a moderate number of citations in yellow, and authors with the minimum number of citations in light blue. This density mapping allows for a quick visual assessment of citation distribution among authors, highlighting those who have made significant contributions to the research field and distinguishing them from those with fewer citations. By examining the density of colors across the mapping, viewers can easily identify authors who have garnered substantial

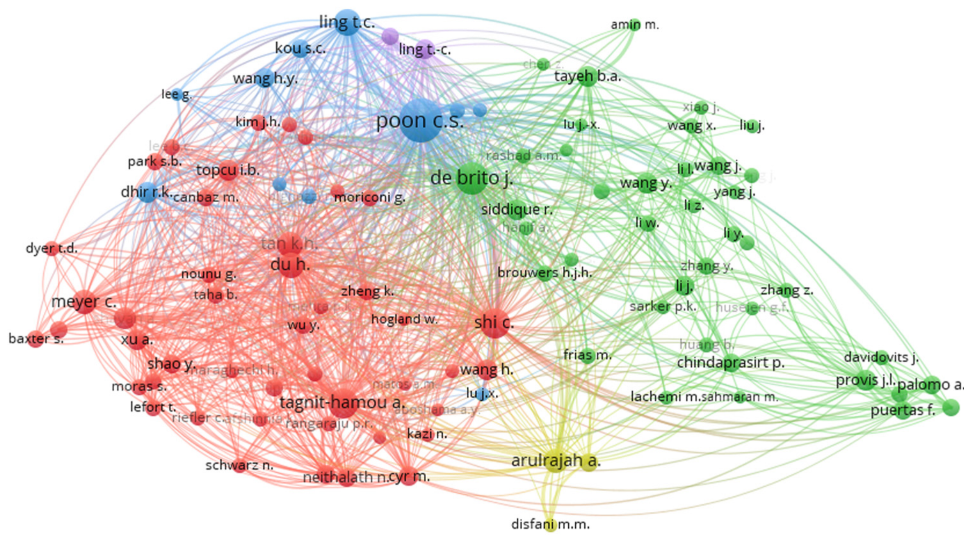

Figure 15: Network mapping of the authors of WGP-based concrete documents.

attention and recognition for their work in WGP-based concrete research.

Together, Figures 15 and 16 provide a comprehensive visual representation of the network mapping, collaborative relationships, citation impact, and research focuses within the field of WGP-based concrete. These figures offer valuable insights into influential authors, their contributions, and the overall research landscape, aiding researchers in identifying key contributors, understanding research trends, and fostering further exploration and collaboration.

3.8 Organizations

The organization provides the necessary resources and infrastructure to carry out the analysis of bibliometric data effectively. It may include academic institutions, research centers, or scientific organizations that have expertise in scientometrics and bibliometrics. Figure 17 presents a horizontal bar graph that depicts the connection between various organizations and their involvement in research on WGP-based concrete. The chart highlights several institutions, including Hong Kong Polytechnic University, Czech Technical University

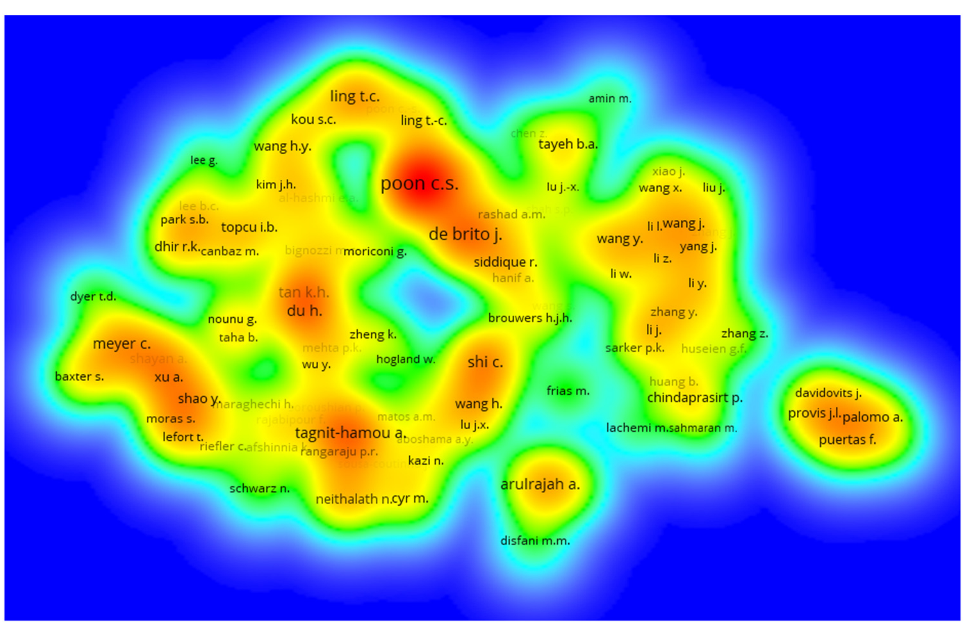

Figure 16: Density mapping of the authors of WGP-based concrete documents.

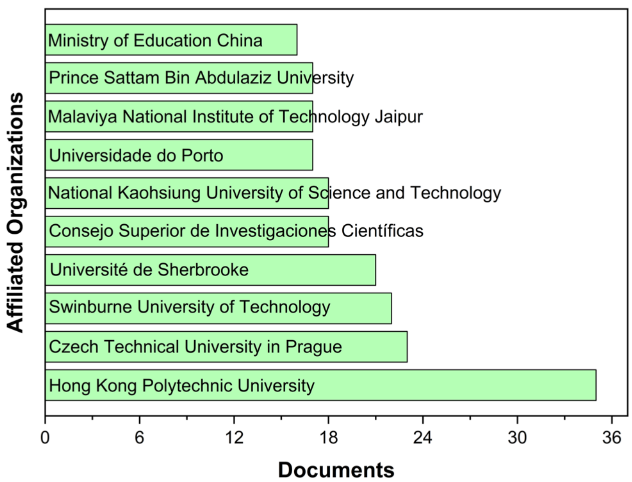

Figure 17: Organizations linked with WGP-based concrete documents.

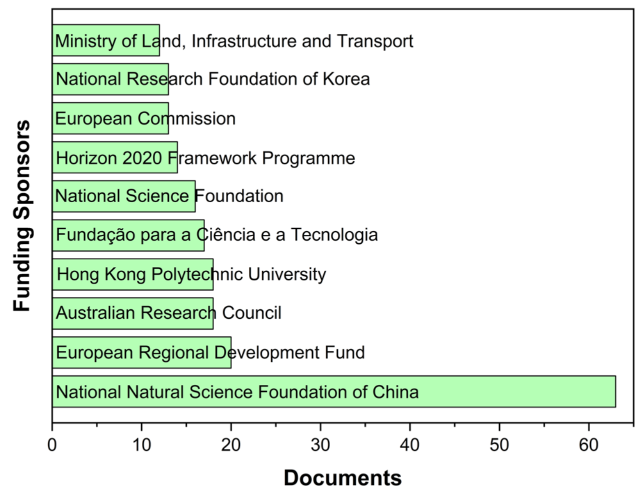

Figure 18: Funding sponsors of WGP-based concrete documents.

of Prague, University de Sherbrooke, Consejo Superior de Investigaciones Científicas, National Kaohsiung University of Science and Technology, Universidade do Porto, Malaviya National Institute of Technology Jaipur, Prince Sattam Bin Abdulaziz University, and the Ministry of Education China. Each organization is represented by a node within the bar graph, indicating their presence in this research field.

Each node's size indicates how many papers have been published by that organization, according to the nodes' sizes, reflecting their research contributions. Hong Kong Polytechnic University holds the largest node with 35 papers, demonstrating their significant involvement in WGP-based concrete research. Czech Technical University of Prague follows with 23 papers, while University de Sherbrooke, Consejo Superior de Investigaciones Científicas, and National Kaohsiung University of Science and Technology have 22, 21, and 18 papers, respectively. Other institutions, including Universidade do Porto, Malaviya National Institute of Technology Jaipur, Prince Sattam Bin Abdulaziz University, and the Ministry of Education China, also show their presence in the field with varying numbers of published papers. Overall, this bar graph provides valuable insights into the collaboration and research output among different organizations engaged in studying WGP-based concrete.

3.9 Funding sponsors

The sponsors can be governmental or non-governmental organizations, research foundations, or private entities that recognize the importance of scientometric analysis and its potential impact on scientific knowledge. Figure 18 presents a horizontal bar graph depicting the funding and sponsorship sources for research on concrete made with WGP. The majority of research funding is contributed by corporations through their research and development departments, as well as by government entities. Among the funding sources, the National Natural Science Foundation of China stands out with the highest number of papers supported, totaling approximately 63. On the other hand, the Ministry of Land, Infrastructure, and Transport has the lowest number of papers, with around 12. Other notable funding sponsors include the European Regional Development Fund, the Australian Research Council, the Hong Kong Polytechnic University, and the National Science Foundation, among others. These organizations play a crucial role in supporting research and development in the field of WGP-based concrete.

3.10 Countries

Countries play a significant role in scientometric reviews as they provide a geographical context for analyzing scientific output and collaboration patterns. Understanding the contribution of different countries to scientific research is essential for identifying global research trends, assessing scientific productivity, and promoting international collaborations. Table 5 provides information about the countries that are actively involved in research on WGP-based concrete. The table consists of five columns, including serial number, country, number of documents, citations, and total link strength. The data reveal the research output and impact of each country in this field. India occupies the top position with 315 documents, 5,036 citations, and a total link strength of 13,989. China follows closely with 192 documents, 4,101 citations, and a total link strength of 14,214.

Table 5: Countries linked with WGP-based concrete documents

S. no.	Country	Documents	Citations	Total link strength
1	India	315	5,036	13,989
2	China	192	4,101	14,214
3	United States	166	6,332	13,661
4	Australia	118	4,613	14,026
5	United Kingdom	93	3,371	9,036
6	Iraq	83	1,339	11,966
7	Turkey	70	1,593	10,549
8	Malaysia	69	1,364	9,931
9	Canada	63	2,691	6,153
10	Russian Federation	62	292	6,350
11	Egypt	61	1,634	5,096
12	Italy	58	1,403	5,072
13	Iran	55	1,410	6,068
14	South Korea	55	1,297	4,296
15	Saudi Arabia	52	715	11,254
16	Spain	52	2,518	7,067
17	Pakistan	51	809	9,002
18	Poland	46	519	2,610
19	Hong Kong	44	2,830	4,464
20	Portugal	43	1,954	6,053

The United States ranks third with 166 documents, 6,332 citations, and a total link strength of 13,661. Australia, United Kingdom, Iraq, Turkey, Malaysia, Canada, and the Russian Federation also contribute significantly to the research on WGP-based concrete. Each country's research output is measured by the number of documents, citations, and total link strength, providing valuable insights into their contributions to this field of study. The table highlights the global nature of research on WGP-based concrete, with diverse countries actively participating and making significant contributions. This international collaboration and knowledge exchange facilitate advancements in this area, leading to a more comprehensive understanding of WGP-based concrete applications and technologies.

Figure 19 presents a vertical bar graph illustrating the countries that are actively engaged in research on WGP-based concrete. The graph provides a visual representation of the number of documents that each country has provided, enabling us to understand the level of research activity in different regions. According to the graph, India stands out as the leading country with the highest number of documents, recording a significant count of 315. On the other end of the spectrum, the Russian Federation has the lowest number of documents, with 62. Notable countries that contribute significantly to the research on WGP-based concrete include China, the United States, Australia, the United Kingdom, Iraq, Turkey, Malaysia, and Canada. The vertical bar graph offers a quick overview of the research landscape, allowing us to identify the countries with a substantial research presence in this field. By understanding which countries are actively researching WGP-based concrete, researchers, policymakers, and industry professionals can identify potential collaborators, gain insights into regional expertise, and foster international cooperation for further advancements in this area of study.

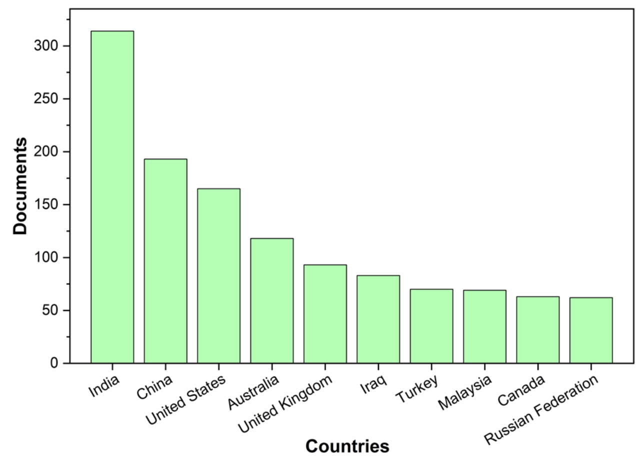

Figure 19: Countries linked with WGP-based concrete documents.

Figures 20 and 21 offer valuable insights into WGP-based concrete research at the global level. Figure 20 presents a network mapping of countries connected to this research, with dots representing individual countries and links indicating their interconnections and collaborations. The colors assigned to the dots signify regional associations and research interests. This network mapping visually depicts the relationships and connections among different countries, enabling researchers to identify clusters or groups with similar interests and collaborations. The visual representation emphasizes the global reach of research efforts in this field and facilitates the identification of potential opportunities for international cooperation and knowledge exchange. In Figure 21, a density mapping of countries linked to WGP-based concrete research is presented. The mapping illustrates the level of research contributions from different countries. The density of each country's research output is represented by the color of the corresponding spot on the map. Red spots indicate countries with a higher number of research papers and substantial involvement in the field, while yellow spots represent countries with a moderate level of research activity. Light yellow spots signify countries with a relatively smaller research output in this area. This density mapping provides an overview of the distribution and intensity of research efforts across countries, allowing researchers, policymakers, and stakeholders to identify active contributors

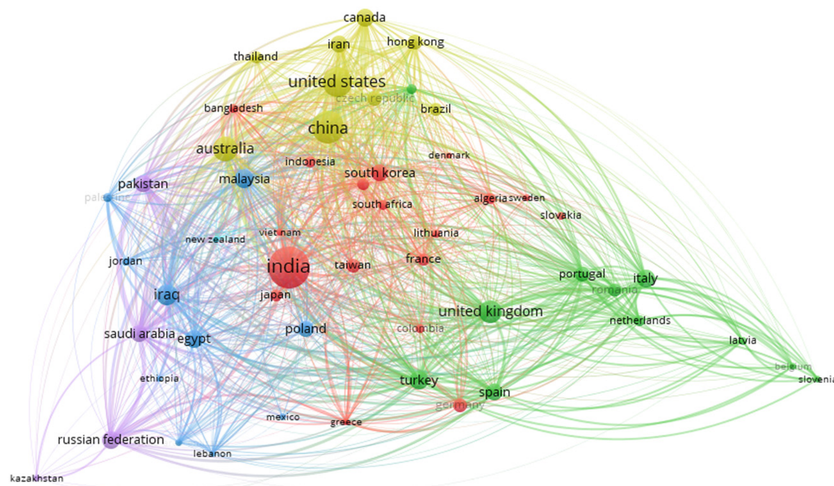

Figure 20: Network mapping of the countries linked with WGP-based concrete documents.

and those making significant contributions to the field. The visualization helps in understanding the global research landscape of WGP-based concrete, supporting collaboration, knowledge sharing, and targeted initiatives to further advance research and development.

Figures 20 and 21 provide a comprehensive visual representation of the network mapping, interconnections, collaborations, and research contributions at the country level in the field of WGP-based concrete. These figures facilitate a better understanding of the global landscape, foster international cooperation, and support strategic efforts to drive research and innovation in this domain.

4 Discussion

This research section delves into various parameters concerning WGP-based concrete. These parameters include the significance of WGP, limitations of WGP, environmental impact assessment of WGP, properties of WGP, role of WGP in concrete, fresh state properties of WGP-based concrete, and hardened state WGP-based concrete's properties. The significance of WGP explores the importance and potential benefits associated with its usage in concrete applications. The limitations of WGP shed light on the challenges or constraints that may arise when

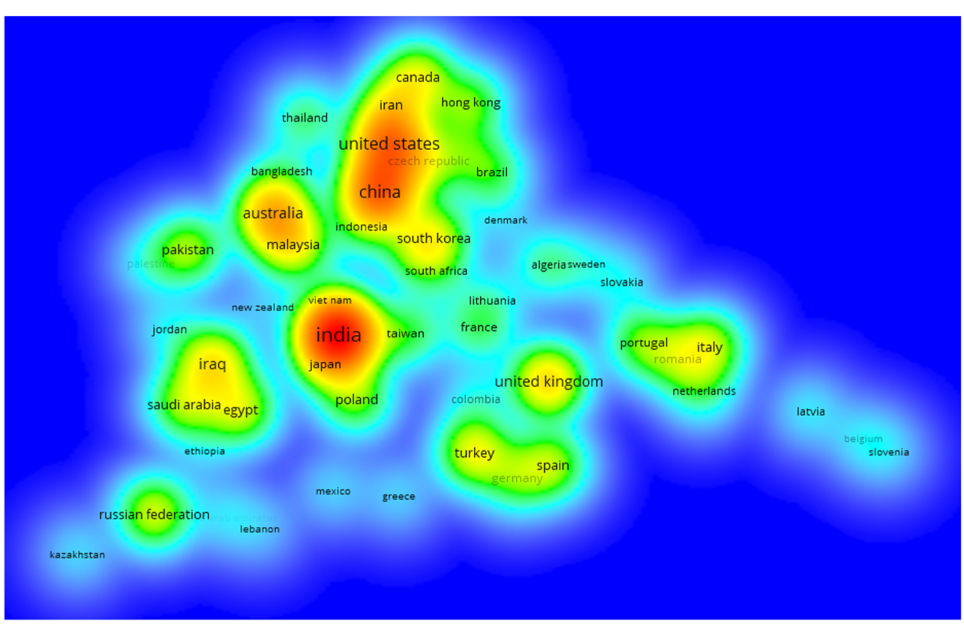

Figure 21: Density mapping of the countries linked with WGP-based concrete documents.

incorporating WGP into concrete mixtures. The environmental impact assessment of WGP evaluates the ecological implications and sustainability aspects associated with its use. The properties of WGP focus on its physical and chemical characteristics, including particle size distribution, chemical composition, and pozzolanic reactivity. The role of WGP in concrete investigates impact on the strength and other qualities of concrete, durability, and workability. The fresh state properties of WGP-based concrete examine its behavior during mixing, placing, and early curing stages. Finally, the hardened state properties of WGP-based concrete assess its long-term performance, including mechanical strength, durability, and resistance to environmental factors. By addressing these parameters, the research aims to provide comprehensive insights into the utilization and potential using WGP in improving the sustainability and properties of concrete.

4.1 Significance of WGP

Concrete is a widely used construction material, but it presents various challenges related to both cement and aggregates. The usage of natural aggregates is one of the main issues, it harms the ecosystem and results in the depletion of natural resources. This poses a significant problem for future generations. According to Aliabdo *et al.* [3], an analysis of concrete that used WGP as a cement component revealed increased strength with 10% cement replacement and enhanced properties with up to 15% replacement or 15% addition. However, in this section, we will discuss several significant advantages of using WGP to make concrete. First, it helps reduce the volume of waste dumped in landfills, promoting waste management and sustainability. Second, the incorporation of WGP in concrete leads to a reduction in environmental pollution, as it provides an alternative use for glass waste that would otherwise contribute to pollution. Additionally, it offers improvements in concrete properties, increasing its durability and strength. Concrete made using WGP displays increased resistance against various deleterious effects, including sulfate attack [69], alkali–silica reaction (ASR) [70], and FT cycles [71]. Federico and Chidiac [72] conducted a study in which they concluded that cost-effective collection of WG in mixed colors is possible. Moreover, the utilization of WGP promotes better hydration, leading to improved concrete performance. By highlighting these significant benefits, this study area aims to highlight the benefits and potential of waste GP-based concrete as an environmentally responsible and long-lasting substitute for conventional concrete production techniques.

4.1.1 Reduction in landfills

One of the main waste sources in the globe is glass. Glass is a common substance in the world's largest landfills and in the oceans, where it affects not just people but also marine life. Egypt produces over 3.45 million tons of glass waste per year, with 84% of it ending up in landfills [69]. Glass has a tremendous potential for use in concrete as a partial replacement for cement because of its pozzolanic qualities.

4.1.2 Reduction in environmental pollution

The large portion of the waste produced worldwide is made of glass. Basically, burning and melting glass to shape it into various jars and bottles will produce more pollution. According to Shekhawat and Aggarwal [73], environmental legislation is driving the increased availability supplementary aggregates for concrete made of WG. This is due to the impact of regulations governing containers, end-of-life vehicles, and waste electrical goods. When concrete contains GP in place of some of the cement, glass acts as pozzolan. In addition to increasing glass utilization, using glass in concrete will reduce pollution by preventing glass burning, which is good for the environment.

4.1.3 Improvement in basic properties of concrete

The WGP has a particle size that is smaller than cement. In comparison to regular cement concrete, smaller particles will help the concrete have less porosity, which will help the concrete have fewer cracks. Concrete's mechanical strength will increase with the addition of GP with smaller particles. Khatib *et al.* [74] reported an increase in the compressive strength of concrete with a maximum observed enhancement of up to 10.0% while utilizing GP in place of cement. Concrete's workability is also influenced by particle size; smaller particles will be more workable than typical cement concrete.

4.1.4 Resistance against sulfate attack

Concrete is significantly affected by sulfate attack. The sulfate attack can result in spalling, expansion, delayed ettringite formation, and cracking. According to Rashad [75], long-term chloride permeability performance was increased by the durability of concrete containing WG. However, concerns were raised regarding ASR. Over the course of the concrete's existence, noxious chemical components like sulfides, sulfates, and alkalis provide a higher danger of ASR. It was noted that a suitable pozzolan can effectively mitigate ASR and consume lime, thereby significantly reducing efflorescence. GP can help concrete be more sulfate resistant than regular concrete by being used in the concrete-making process. The glass will withstand the sulfate attack because it is less permeable than cement and does not react with salt.

4.1.5 Resistance against ASR

When the mixture contains silica material that is reactive, an ASR occurs. ASR damages the structure and generates significant cracks. GP does not react with silica; hence it can help to keep the silica material from reacting with other substances. In a study by Du and Tan [76], a unique behavior of concrete was observed upon the addition of GP. When 60% of the cement was replaced with GP, the researcher discovered that the resistance to the ASR and water absorption dramatically increased.

4.1.6 Resistance against FT effect

When water is present in small voids in the concrete, a cycle of freezing and thawing causes the concrete to crack. Concrete cracks as a result of freezing and thawing's expansion and contraction of the material. GP is very fine particle, which will absorb less water than cement. Concrete will be less vulnerable to the effects of freezing and thawing because of the smaller size of GP will lead to less voids. Furthermore, the study found that adding more WGP to concrete increases the FT resilience of plain concrete [77].

4.1.7 Improvement in hydration process

Concrete's mechanical properties are crucial. The majority of researchers investigate a variety of approaches to enhance the concrete's mechanical properties. Because it is smaller and absorbs less water than cement, the improved strength of the concrete will be aided by the use of GP in its manufacturing. As a result, there will be enough water available for the reaction to fully hydrate and develop its maximum strength. Based on hydration studies, investigations were made on the WGP's pozzolanic reactivity through experimental analysis at different cement replacement levels (0, 15, 30, 45, and 60% by weight). The results demonstrated that up to 30% cement substitution, due to the pozzolanic reaction between glass particles and cement hydration products, the compressive strength of concrete was unchanged after 28 days [78].

4.2 Limitations of WGP

WGP-based concrete has a few limitations. The color of the glass used can affect not only the visual appearance but also the chemical properties of the concrete. Certain glass colors, such as amber or green, may contain additives or impurities that can react with the cementitious matrix and impact the concrete's performance. According to the findings by Vandhiyan *et al.* [79], using GP in concrete adversely affected the workability. The GP, with an angular shape and passing through a 90 µm sieve, resulted in 50% retention on a 75 µm sieve [80]. Additionally, other factors like glass sources, availability, and the challenges associated with working with glass must be considered to maximize the benefits and minimize the limitations of WGP-based concrete. Ongoing research and innovation are crucial in addressing these limitations and optimizing the utilization of used glass in practical applications.

4.2.1 Glass color

Glass is available in a wide range of forms and originates from numerous sources. Glass comes in a variety of colors as well. It can often be very difficult to remove its color without the help of chemicals. Different chemicals are used to remove the color of glass, but they are also costly and dangerous [81]. The properties of glass are also changed by its color. It is quite hard to use colored glass in concrete since it also reacts with some materials when a reaction occurs. Jiang *et al.* [82] have discussed how the color of the glass affects pozzolanic and ASR reactivity [83], durability of alkali-activated materials (AAMs) with GP [84], performance of glass fume in ultra-high-performance concrete (UHPC) [85], and use of GP in phase change materials and sintering products [86].

4.2.2 Glass sources

Many different household and other products are made from glass. Glass is not obtained from a single source in landfills or other locations. The majority of WGP is sourced from landfills as the non-recyclable fraction, because it is difficult to achieve the standards for quality in remanufacturing glass. Consequently, usually, this portion is abandoned and dumped in landfills [87]. Glass is gathered from a variety of places. When glass from various sources is used in the preparation of concrete, the concrete's strength will be impacted. In certain areas, the concrete's strength will be higher, while in others, it will be lower, which is risky for important structures [88].

4.2.3 Difficulty to work with glass

Glass is a very sharp material that easily cuts through anything. When glass is used in concrete, it is done so in the form of powder. Due to the high percentage of amorphous silica (50–70%) in large particle size glass aggregates, the ASR poses a serious concern [89] and sodium (8–15%) [90] in soda-lime glass [91]. Glass is crushed down to a fine powder to use it in concrete. When someone comes into contact with the smaller glass, it can hurt both humans and animals since it is so sharp. The GP behaves sharply like crystal, and working with it can be challenging [92].

4.3 Environmental impact assessment of WGP

Almost all household items, including drinking glasses, plates, cups, tables, bottles, jars, mirrors, building partitions, windows, facades, TV, computer, and smartphone screens, are made of glass. Almost everyone comes in contact with glass more than once every day, and tones of glass waste are produced daily, increasing the amount of waste pollution from garbage and the amount of waste in landfills. Recycling WG reduces quantity of glass that have been dumped in landfills; however, using traditional recycling techniques causes more pollution in the air and water, whether the glass is recycled or new glass is manufactured, both causes increase in pollution. WGP needs to be recycled quickly and effectively because of its growing accumulation, which is taking up more space, pollutes the environment, and wastes valuable resources for its management [93]. The large amount of waste in landfills across the world is glass. Natural materials including sand, soda ash, cullet, and limestone are used to make glass. High heat energy is needed to melt and shape glass during manufacturing [94], for 1 kg glass, over 0.6 kWh is used. Glass can be recycled such that it uses less energy during recycling compared to manufacturing of new glass. Other advantages of recycling include reduced air and water pollution as well as a decrease in disposal in landfills. Given the final applications and volume of production, recycling WG in the production of cement and concrete can have a positive impact on the environment and the economy [56]. The recycling rate of glass waste remains considerably low worldwide, as depicted in Figure 22, which illustrates the percentage of recycled glass through a horizontal bar graph. The Netherlands stands out with the highest recycling rate of approximately 90%, while Iran demonstrates the lowest rate of recycling WG. This highlights the significant impact of WG on our environment and the urgent need for effective recycling practices. Furthermore, these findings indicate a vast potential to utilize WG in concrete production, providing a sustainable solution that improves the environmental performance of the building sector while also reducing waste. By harnessing the opportunities presented by WG, we can help promote a circular economy and lessen the environmental harm caused by the disposal of glass waste. According to Heriyanto and Pahlevani [95], with a recycling rate of 42%, Australia produced roughly 800,000 tons of glass garbage in 2015.

Glass is made of silica, a naturally occurring material similar to sand. Nearly every year, 28 billion glass bottles are added to landfills. Despite growing public awareness of municipal garbage separate collection, less than 10% of used glass beverage bottles are recycled [96]. Glass pollutes the environment because of the chemicals it contains. When glass decomposes, sulfate is formed, and when it burns, nitrogen is created. Ocean acidification, land toxicity, and freshwater toxicity are all caused by glass waste. The effects of glass waste on people, animals, and plants extend to all other living things in the planet. Glass takes approximately 1 million years to break down. There are various phases for recycling of glass. The glass is initially collected from various landfills. After that, the glass is thoroughly cleaned by having all of the impurities removed

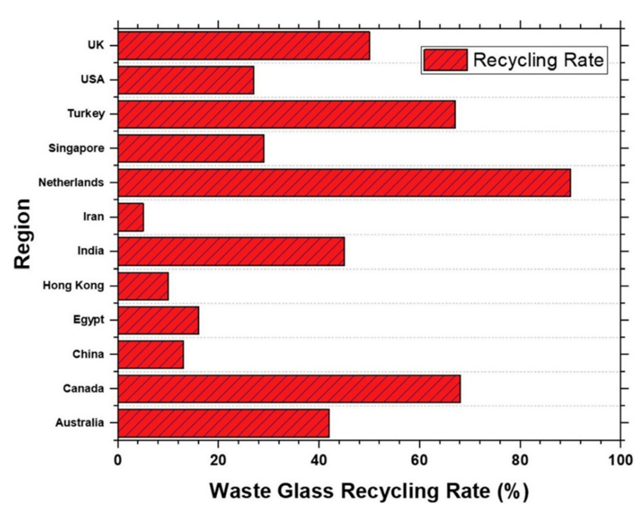

Figure 22: Percentage of WG in different countries.

from it, which requires a lot of water. The glass aggregate used in the study was sourced from building and car window panels, which were carefully washed and treated in a dedicated facility [91]. To remove the glass's color, various chemicals are added, and water is then used to wash the glasses once more. Glass is placed in a big kiln in the last phase, and when it melts, it is then shaped into bottles, jars, and other objects. Recycling uses less energy than producing new glass, yet it still pollutes the air and water.

Glass has a significant amount of silica, which is what causes the pozzolanic reaction while concrete is being mixed. The creation of items for extra hydration, such as magnesium silicate hydrate (MSH) [97] and magnesium calcium silicate hydrate (MCSH) [98], can occur through the reaction between a magnesium source (such as MgO nanoparticles [99], Mg $(OH)_2$, and $MgCO_3$ hydrated phases) and an amorphous silica source (such as rice husk ash, silica fume [SF], and pulverized fuel ash). These recently developed phases (MSH and MCSH) improve the mechanical properties of composite cement matrices [100]. Glass recycling using the conventional approach uses a lot of energy and water. When glass is reduced to powder, it develops into a natural pozzolan that gives concrete its hardening and fresh properties. It will not consume a lot of energy or other processing to employ glass in concrete when it is ground into powder form. Glass can be used to make concrete more economically and since it does not need to be melted, there will be less water and air pollution. Due to rising population levels and the need for new homes and buildings, glass has a significant market [101]. GP is the most acceptable replacement for cement in the production of concrete due to its low cost of WG and pozzolanic activity.

4.4 Properties of WGP

In Table 6, the chemical composition of GP and cement is compared. The amount of Al_2O_3 in GP is about 0.4%, compared to 6.97% in cement, and it acts as the cement's nuclei, accelerating the hydration reaction until the concrete's initial setting time has passed. Al_2O_3 also improves the strength of concrete while reducing its porosity. The hydration reaction will be slowed down, there will be an increase in porosity, and the strength will also be compromised if GP is used to replace cement. This is so because GP has a lower Al_2O_3 content than cement does. Around 2–5% of cement contains magnesium oxide, which is essential for the reaction that creates concrete. The production of C3S and C4A3S is facilitated by MgO, which also helps in the absorption of additional lime. While MgO is present in GP in amounts between 2 and 5% of what is needed, it also helps concrete gain strength and speed up the setting time. When a reaction occurs, calcium oxide helps the concrete in expanding and overcoming past contraction. When there is more CaO in concrete, there are less cracks. GP contains less calcium oxide (9.7%) than cement (62.72%), which will result in more microscopic cracks in concrete. A slight decrease in compressive strength will occur, and Fe_2O_3 helps the concrete obtain additional flexure strength. GP contains 0.2% Fe_2O_3, which is less than cement, which has 3.34% Fe_2O_3. There will be no changes in compressive strength when GP is used; however, there will be a small increase in flexure strength. Due to SiO_2's pozzolanic nature, there will be an increase in shrinkage but a decrease in permeability when there is more SiO_2 in concrete. SiO_2 content in GP is higher than in cement, resulting in greater shrinkage but decreased permeability. Na_2O should not exceed more than 0.6% while making concrete. When the amount of sodium oxide increases, it will damage the concrete. In GP, the amount is very high compared to cement which will cause damage. The alkaline metal found in cement is potassium oxide. When there is more K_2O in concrete, the concrete will weaken. Less K_2O is present in GP, which makes it more workable and aesthetically pleasing.

Table 7 compares the physical properties of cement and GP from several papers. Ordinary Portland cement (OPC) has a specific gravity between 3.1 and 3.16, which shows how much heavier cement is. Compared to cement,

Table 6: Comparison of chemical property of GP with cement

Chemical composition	Al_2O_3	MgO	CaO	Fe_2O_3	SiO_2	Na_2O	K_2O
Percentage in GP	0.40	3.30	9.70	0.20	72.50	13.7	0.10
Percentage in cement	6.97	2.36	62.72	3.34	21.24	0.13	0.81

Table 7: Physical properties of GP

Physical properties	Specific gravity	Specific density ($kg{\cdot}m^{-3}$)	Mean particle size (μm)	Maximum particle size (μm)
Ref.				
[104]	2.53	—	11.72	80
[105]	2.40	—	17	—
[106]	2.55	2,174	5.07	—
[107]	2.60	2,510	10.97	—

GP has a lower specific gravity, which is between 2.4 and 2.6, indicating that the GP will absorb less water than the cement. GP will absorb less water, allowing concrete to form more quickly and with more strength. Density is important in cement. Density has a direct impact on the concrete's mechanical properties. The mechanical properties of concrete will increase as cement density increases. GP has a density of 2,000–2,600 $kg \cdot m^{-3}$, which is higher than cement, although cement has a density of 1,440 $kg \cdot m^{-3}$ [102]. GP concrete will have more mechanical strength than conventional cement concrete. The mean particle size affects the porosity of the concrete; as the particle size increases, the porosity of the concrete also increases [103]. Cement has a mean particle size of 10–20 μm compared to GP, which has a mean particle size of 5–18 μm. Concrete will be less permeable when GP is used. GP has a maximum particle size of 80 m, whereas cement has a maximum particle size of 200 m.

4.5 Role of WGP in concrete

A crucial component of concrete is WGP, affecting various parameters that influence its performance. Table 8 provides an overview of some of these parameters. First, the heat of hydration is influenced by the finer GP's ability to absorb more water compared to cement. This results in reduced thermal cracking in the concrete. Second, WGP contributes to volume stability by decreasing early-age shrinkage [104], micro cracks [108], and drying shrinkage cracks [109]. The experimental findings demonstrated that the composite incorporating 10% WGP and 0.5% nanomaterial filler in OPC exhibited the highest thermal stability [98]. This increases the concrete structure's overall durability. The presence of GP in concrete results in the production of a compact matrix, according to microstructural studies, thereby enhancing the durability characteristics of the material [54]. Additionally, the water–cement ratio is positively impacted as the remaining cement can utilize more water, increasing workability. Finally, WGP contains silica, which enhances the pozzolanic reaction and improves the characteristics of the concrete [83]. Finer GP particles also increase the pozzolanic reaction, leading to improved performance in concrete applications. These effects highlight the significance of WGP in optimizing concrete properties and promoting sustainable construction practices.

4.5.1 Heat of hydration

The increase in initial temperature, which occurs when cement reacts with water, is known as the "heat of hydration." The cementitious characteristics of the material, curing temperature, water-to-cement ratio, and material fineness all have an impact on the heat of hydration. The mechanical properties of normal concrete with WG varies at high temperatures. Despite this, little is known about how reactive glass (RG) affects the high-temperature performance of geopolymer UHPC, especially in light of the glass's heat stability and lack of a defined melting point [117]. When GP is finer, it will absorb more water, changing the concrete's water-to-cement ratio as a result. In this condition, concrete will have enough water for hydration because cement absorbs more water than GP. Due to GP's chemical makeup and resistance to sulfates, making concrete with it will require less heat of hydration [118]. Thermal cracking in the concrete will be less likely to take place with less heat of hydration, and it will not affect the volume.

4.5.2 Volume stability

The volume of new concrete varies when it is settling up initially. The volume of the concrete increases during mixing, when more heat is produced, and it will shrink

Table 8: Different factors affecting GP

S. no.	Parameter	Effect of WGP
1	Heat of hydration	• Finer GP will absorb more water [110] • GP absorbs less water than cement [111] • Thermal cracking in concrete will be less [112]
2	Volume stability	• Decrease in early age shrinkage micro cracks [113] • Decrease in drying shrinkage cracks [30]
3	Water–cement ratio	• Workability increases due to remaining cement will have more water [114]
4	Pozzolanic reaction of WGP	• Presence of silica improves pozzolanic reaction [115] • Finer GP will increase pozzolanic reaction [116]

after 24 h due to heat loss. Early age shrinkage and drying shrinkage will increase the number of cracks and damage the concrete. In order to mitigate drying shrinkage, WG cullet was utilized as a substitute for natural aggregates [119]. There will be less volume change in concrete because GP does not produce as much heat as cement. By adding more GP to concrete, early age shrinkage and drying shrinkage cracks will be reduced.

4.5.3 Water–cement ratio

The term “water–cement ratio” refers to the mass ratio of cement and water used to build concrete. As the water–cement ratio is raised, the strength of the concrete will drop. However, as the water–cement ratio rises, the concrete becomes more workable. GP does not absorb much water; therefore, making concrete with less water results in stronger concrete. Due to its angular shape and decreased water–cement ratio, GP slightly decreases workability. Meena *et al.* [120] have written a research paper about partial replacement of cement. GP content in M30 concrete was 0, 2.5, and 7%. The water–cement ratio was 0.43 on each occasion. The highest compressive strength was 43.1 $N \cdot mm^{-2}$.

4.5.4 Pozzolanic reaction of WGP

Due to the material’s inclusion of silica and alumina, a pozzolanic reaction occurs when moisture is added to a material that already has certain cementitious properties. Due to their pozzolanic behavior, concrete can be made partially without cement by using a variety of ingredients. According to the study, if the glass particle size is less than 38 μm, it exhibits favorable pozzolanic behavior, whereas between 38 and 75 μm, its pozzolanic activity decreases or becomes negligible. Furthermore, it was observed that finer glass particles result in higher concrete strength, particularly at later stages [121]. Fly ash (FA), SF, and granulate blast furnace slag are a few of these materials, all of which have demonstrated great performance when employed as cementitious materials. High levels of silica in GP indicate that it shows pozzolanic behavior. A high silica content will facilitate the initiation of the pozzolanic reaction when mixing GP. According to Parghi and Alam [122], due to the potential for the pozzolanic reaction to increase the density of the microstructure, the hardened mixture’s water absorption was observed to be decreased and its density increased with the addition of GP. Smaller GP will give better results because of the increase in pozzolanic reaction as the size of the GP decrease. The pozzolanic reactivity of GP is also affected by color. Due to its chemical composition and glass structure, the green color has a higher pozzolanic reaction. According to Li *et al.* [123], because of its pozzolanic feature and low thermal conductivity, GP was said to have had a key influence in improving the strength development and lowering thermal conductivity. This was possible because blocks physio-mechanical characteristics could be easily met.

4.6 Fresh state properties of WGP-based concrete

The fresh state properties of WGP-based concrete, including setting time and workability, are important factors to consider. To ensure correct handling and finishing, it is essential to accurately calculate the setting time. Setting time is the period it takes for the concrete to harden. The size of the WGP’s particles and its chemical make-up can both affect how long things take to set. Workability determines how easily it can be handled and placed. The research findings demonstrate a significant decrease in workability upon the addition of WGP-0.5 h to the mortar [87]. It directly affects the construction process and the final product’s quality.

4.6.1 Setting time

Concrete’s initial and final settings both take a certain amount of time to complete. The qualities of the concrete are still fresh during the initial setting phase, and they harden during the final setting time. The initial setting time takes around 45 min to mold the concrete in shape, and the final setting time takes about 10 h for the concrete to harden. Similar findings have been reported by Samarakoon *et al.* [124] where the addition of GP as a precursor in place of up to 30% FA led to an increase in the initial and final setting times. The water–cement ratio will increase when GP is added to concrete as a partial replacement for cement since glass needs less water to hydrate while other components in the concrete mix need more water. The initial setting time of concrete will be impacted by this. Both the initial and final setting times of concrete are increased by GP. Guo *et al.* [125] conducted a study, in which they concluded that when GP is used in the concrete, the reaction rate experienced reduction in polycondensation rate due to which the formation of activation products is slower. According to Lu *et al.* [126], the increase in setting time that resulted from the addition of GP, which increased the water content in the fresh AAM, was caused by the physical characteristics of the GP (Figure 23).

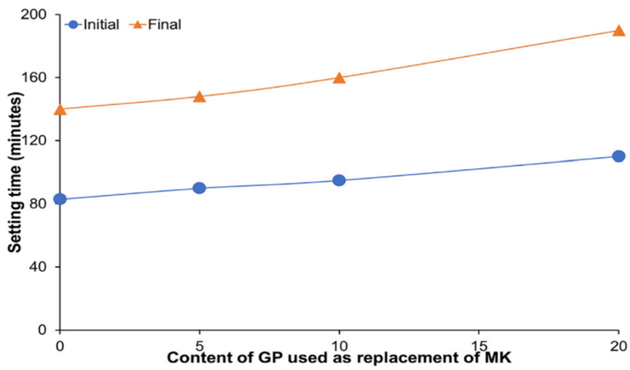

Figure 23: Influence of GP on setting time [127].

4.6.2 Workability

For usage in concrete, glass is ground into a fine powder. The fundamentally angular shape of the GP creates a link with other concrete components. GP makes concrete less workable because of its angular shape, but because it did not absorb as much water, there is more water in the mixture, making the concrete more workable. Si *et al.* [128] conducted a study, in which he evaluated the mini-slump test's ability to assess the workability of AAMs created by substituting GP for metakaolin (MK) by 20%. As one property increases and one property drops, the workability of the concrete practically remains the same. Therefore, adding GP to concrete will not significantly change the workability of concrete. These results agree with that in the study by Samarakoon *et al.* [124] where using GP as the precursor instead of up to 30% FA led to an improvement in the workability of the AAMs of up to 80%. According to the study's findings, fresh concrete became more workable with a higher GP content, as can be seen in Figure 24.

As shown in Figure 25 and reported by Liao *et al.* [129], GP has been used up to 40% in the concrete flow of concrete. The flow has increased by 11, 22, 28, and 33%, respectively, when 10, 20, 30, and 40% GP has been used in concrete. These studies have concluded that when GP is used in concrete, the workability of the concrete improves as the GP quantity increases. In another study, Jiang *et al.* [130] utilized GP as a replacement for FA in AAMs by up to 30%. The study's findings also point to an improvement in the workability of fresh AAMs with more GP. When compared to AAM made with only FA as the precursor, the flow increased by 3, 11, and 14%, respectively, when GP was used as 10, 20, and 30% replacement of the FA.

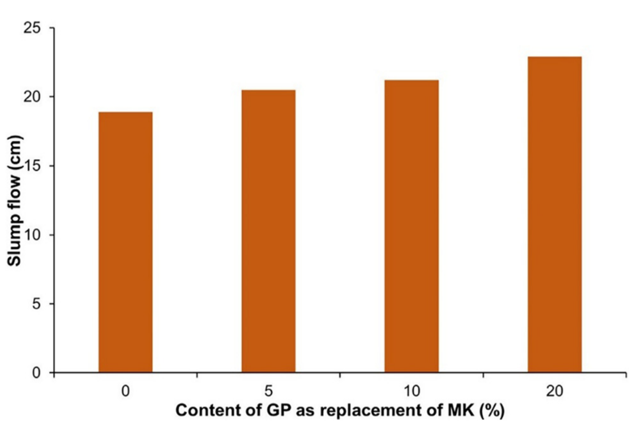

Figure 24: Influence of GP on slump flow [127].

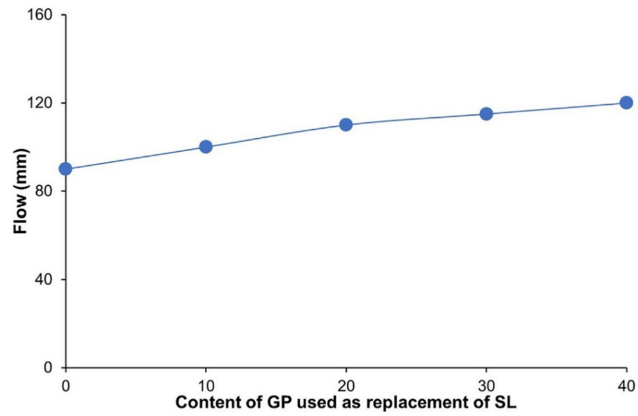

Figure 25: Influence of GP on workability [127].

4.7 Hardened state properties of WGP-based concrete

When evaluating the effectiveness and durability of a material, the qualities of the material's hardened state are crucial. These characteristics describe how the concrete will behave once it has fully dried and hardened. Evaluating these properties helps determine the structural integrity, strength, and long-term behavior of the concrete. In a study conducted by de Castro and de Brito [91], the largest glass particle size that would not result in the ASR was explored by the researchers. Glass particles were used to replace between 30 and 70% of the sand mass. Interestingly, glass particles smaller than 100 µm had no deleterious effects [131]. In contrast, despite the rise in water content, the concrete's compressive and flexural strength increased. Factors such as compressive strength, split tensile strength, and flexural strength against various environmental conditions are considered in the assessment. WGP can influence these properties, and optimizing its content in the concrete mixture is crucial. Tests like compressive strength tests [132], split tensile test [39], and flexural strength tests [39] are conducted to measure and analyze these hardened state properties. By understanding and enhancing these properties, engineers can ensure that WGP-based concrete meets the required structural standards and exhibits the desired durability for its intended applications.

4.7.1 Compressive strength

The force used to compress an object against it is known as its compressive strength. Because of the inclusion of coarse aggregate and the adherence of the constituent materials, concrete has a good compressive strength. Table 9 demonstrates the results of concrete samples using different amounts of GP in terms of compressive strength. The samples are labeled as "Sample," and the table displays the compressive strength values in $N{\cdot}mm^{-2}$ for each GP percentage. The results reveal the compressive strength values achieved when using 0, 5, 10, 15, 20, and 40% GP content. Notably, the data show that as the GP percentage increases, the compressive strength generally follows an increasing trend, with a few exceptions. The highest compressive strength is observed at 55.1 $N{\cdot}mm^{-2}$ for a 15% GP content, while the lowest value is 24.22 $N{\cdot}mm^{-2}$ for a 0% GP content. It is worth mentioning that some entries lack compressive strength values, indicated by dashes in the table. This table provides valuable insights into the effect of GP on the compressive strength of concrete, allowing researchers and practitioners to assess the performance of concrete mixes incorporating various amounts of GP. According to Sethi *et al.* [133], WGP can be added to the geopolymer matrix together with other source materials to strengthen the bonding between aggregates and binder in the transition zone. GP also helps in filling small voids present in the concrete. As the amount of GP in the sample grows, so does its compressive strength. In another research, Chen *et al.* [104] conducted the compressive test on the FA-type geopolymer binder by substituting WGP at various concentrations (10–40%). According to Liao *et al.* [129], increasing the WGP content by 30% boosts the compressive strength of the ground granulated blast-furnace slag (GGBS)-based geopolymer binder.

As shown in Figure 26, the graph shows how the amount of GP used in concrete and its effect on compressive strength are related to one another. The *x*-axis represents the various levels of GP replacement, ranging from 0 to 40%, the concrete's compressive strength, measured in $N{\cdot}mm^{-2}$, is shown on the *y*-axis. The graph clearly shows that adding GP to the concrete mixture results in a general boost in compressive strength. Compressive strength consistently and noticeably improves as the fraction of GP replacement rises from 0 to 15%. This indicates that incorporating GP in concrete positively influences its ability to withstand compressive forces. However, beyond the 15% threshold, the graph shows a decline in compressive strength with higher percentages of GP replacement. This decline suggests that there may be limitations or adverse effects associated with using higher amounts of GP in the concrete mix. It can be inferred from the graph's tendencies that 15% of GP is the ideal amount to use in order to achieve the highest compressive strength. At this level, the concrete exhibits significant improvements in strength without experiencing a decline in performance. Utilizing a 15% GP replacement in concrete is thus recommended to maximize the compressive strength and ensure optimal performance.

4.7.2 Split tensile strength

Concrete's split tensile strength is crucial for the concrete. The split tensile force is applied on the cylinder to split the cylinder into two parts. Split tensile force extends the size of the cracks in the structure. Basically, the concrete is weak in tensile strength and good in compressive strength. Sethi *et al.* [133] have shown an improvement in the split tensile characteristics of the geopolymer matrix when WGP was employed as a ternary source material as opposed to reference concrete made with FA and GGBS. Table 10

Table 9: Compressive strength of concrete containing GP

Ref.	0% GP ($N{\cdot}mm^{-2}$)	5% GP ($N{\cdot}mm^{-2}$)	10% GP ($N{\cdot}mm^{-2}$)	15% GP ($N{\cdot}mm^{-2}$)	20% GP ($N{\cdot}mm^{-2}$)	40% GP ($N{\cdot}mm^{-2}$)
[120]	44.1	46.13	50.56	55.1	47.11	41.70
[134]	36.5	38.7	40.2	41.6	39.8	32.4
[135]	24.22	33.19	36.88	35.55	34.44	—
[136]	32.3	34.8	36.9	35.7	33.6	—
[137]	28.6	30.4	31.8	30.6	—	—
[134]	25.9	27.8	29.7	28.6	—	—
[138]	26.7	28.9	30.8	29.7	—	—

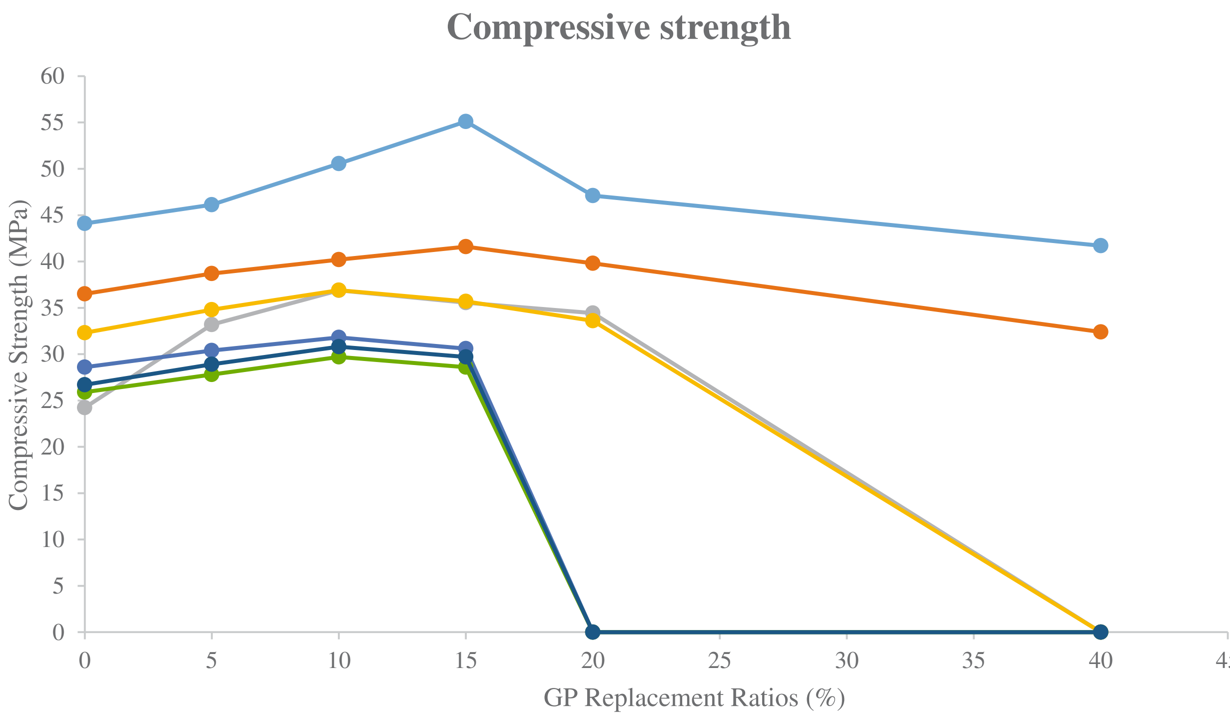

Figure 26: Effect of GP on compressive strength.

illustrates the concrete samples' split tensile strength when GP was added in various amounts. The table includes different samples labeled as "Sample" and presents the split tensile strength values in N·mm^{-2} for each GP percentage. The data demonstrate the split tensile strength values achieved at 0, 5, 10, 15, 20, and 40% GP content. The highest split tensile strength value recorded is 5 N·mm^{-2} at a 15% GP content, while the lowest value is 2.32 N·mm^{-2} for the 0% GP content. Some entries in the table are marked with dashes, indicating missing values. This table provides valuable insights into how the inclusion of GP influences the split tensile strength of concrete, aiding researchers and practitioners in assessing the performance of concrete mixes incorporating different amounts of GP. Hemanth *et al.* [139] have done a study from which they concluded that adding different WGP replacement percentages had an impact on the matrix of the FA-type geopolymer. The experimental investigations' findings indicated that an improvement in split tensile strength of 3.3 MPa is produced by a 10% increase in WGP.

According to Figure 27, it is evident that adding GP to concrete results in a rise in split tensile strength. The graph shows the effect of the proportion of GP used in the concrete mix on the split tensile strength, which ranges from 0 to 40%. The graph shows that, compared to conventional concrete without GP, split tensile strength consistently and significantly improves up to a 15% replacement of GP. This indicates that the inclusion of GP positively affects the concrete's ability to resist tensile forces. The graph, however,

Table 10: Split tensile strength of concrete containing GP

Ref.	0% GP (N·mm^{-2})	5% GP (N·mm^{-2})	10% GP (N·mm^{-2})	15% GP (N·mm^{-2})	20% GP (N·mm^{-2})	40% GP (N·mm^{-2})
[120]	4.41	4.53	4.83	5	4.32	3.91
[140]	2.32	2.42	2.51	2.38	2.43	—
[141]	3.12	3.28	3.42	3.36	3.24	—
[142]	2.86	3.04	3.18	3.06	—	—
[120]	2.59	2.78	2.97	2.86	—	—
[143]	2.67	2.89	3.08	2.97	—	—

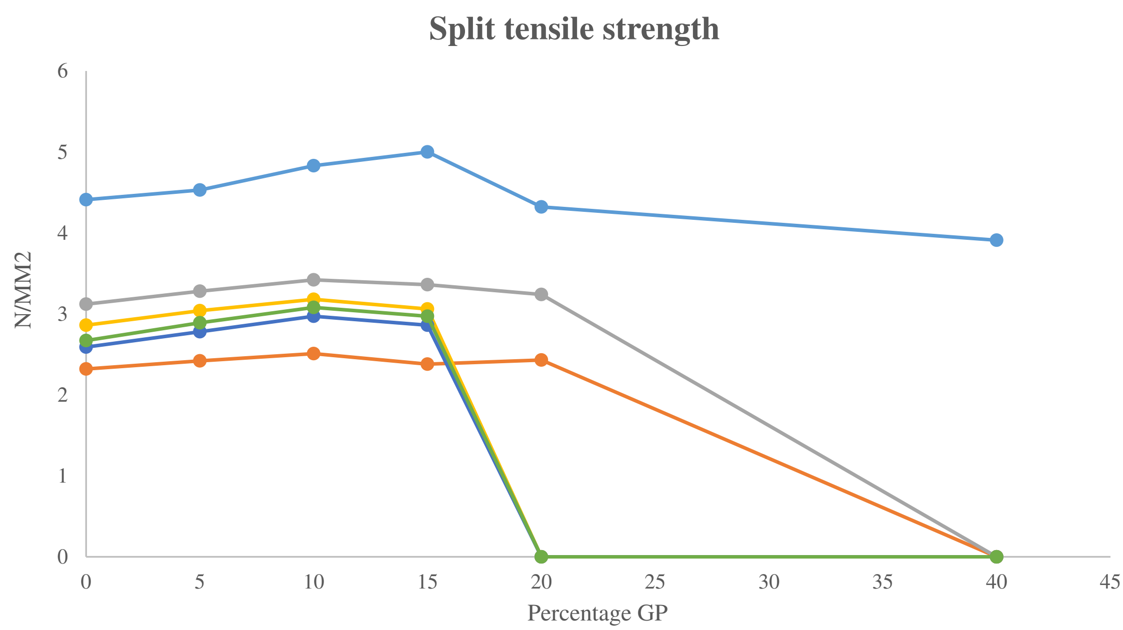

Figure 27: Effect of GP on split tensile strength.

reveals a decrease in split tensile strength when the proportion of GP replacement rises above the 15% limit point. This decline suggests that there may be limitations or adverse effects associated with higher percentages of GP in the concrete mix. Comparing the GP-containing samples to the normal concrete, it is notable that the GP-containing samples generally exhibit higher split tensile strength. This finding suggests that adding GP to concrete can improve the concrete's tensile strength, which is a good result for using GP in concrete applications. Overall, the data from Figure 27 demonstrate that incorporating GP in concrete can result in increased split tensile strength. It has been discovered that 15% of GP is the ideal amount for generating the highest split tensile strength. However, further investigations and considerations may be required to understand the potential limitations and effects associated with higher percentages of GP in concrete.

4.7.3 Flexure strength

The flexure strength of the concrete is obtained by applying load on the beam sample. The tensile strength of unreinforced concrete is measured by the flexure strength of the concrete. The flexure strength is the beam resistance against bending. Sethi *et al.* [133] conducted a study in which they concluded that the flexural strength of a geopolymer matrix, made with ternary blends of WGP and GGBS as partial replacements for FA, demonstrated significant improvements. Table 11 displays the flexure strength of concrete samples containing varying percentages of GP. The table includes different samples labeled as "Sample" and presents the flexure strength values in N·mm^{-2} for each GP content. The data represent the flexure strength achieved at 0, 5, 10, 15, 20, and 40% GP content. The highest flexure strength recorded is 5.76 N·mm^{-2} at a 10% GP content, while the

Table 11: Flexure strength of concrete containing GP

Ref.	0% GP (N·mm^{-2})	5% GP (N·mm^{-2})	10% GP (N·mm^{-2})	15% GP (N·mm^{-2})	20% GP (N·mm^{-2})	40% GP (N·mm^{-2})
[120]	4.03	4.1	4.3	4.8	4.04	3.88
[145]	4.12	5.09	5.67	5.32	5.11	—
[142]	4.86	5.28	5.76	5.54	5.18	—
[136]	4.56	4.98	5.36	5.14	—	—
[146]	4.29	4.68	5.09	4.86	—	—

lowest value is 4.03 $N\cdot mm^{-2}$ at the 0% GP content. Some entries in the table contain dashes, indicating missing values. This table provides insights into the influence of GP content on the flexure strength of concrete, offering researchers and practitioners valuable information for evaluating concrete performance when incorporating different levels of GP. Chen *et al.* [144], studied the impact of different WGP concentrations (10%–30%) on the flexural strength of FA-type geopolymers. According to them, adding more than 10% WGP negatively affected the mixture's flexural strength.

Figure 28 shows that the flexural strength of concrete increases with the addition of GP. The graph shows how the amount of GP, which can range from 0 to 40% in the concrete mix, affects the flexural strength. The graph shows that, compared to conventional concrete without GP, there is a continuous and significant gain in flexural strength up to a 10% GP replacement. This indicates that the inclusion of GP positively affects the concrete's ability to withstand bending or flexural stresses. However, beyond the 10% threshold, the graph shows a decline in flexural strength as the percentage of GP replacement increases. Similar to what was seen in earlier data for split tensile strength and compressive strength, this decline raises the possibility that increasing percentages of GP in the concrete mix may have restrictions or unfavorable impacts. Upon comparing the GP-containing samples to the normal concrete, it is evident that the GP-containing samples generally exhibit higher flexural strength. This finding indicates that incorporating GP in concrete is beneficial for enhancing the concrete's ability to withstand bending forces, which is a positive outcome for the use of GP in concrete applications. Overall, the data from Figure 28 demonstrate that incorporating GP in concrete can result in increased flexural strength. The optimal percentage of GP for achieving the highest flexural strength is observed to be around 10%. However, it is important to consider the potential limitations and effects associated with higher percentages of GP in concrete to ensure optimal performance and durability.

4.7.4 Durability

Millions of tons of glass are being dumped in landfills, and the amount is rising extremely fast. Because glass has extremely slow rate of degradation and the millions of years it takes to decompose, disposal is one of the primary issues with glass. Glass can be recycled in concrete, which makes it a great option for use in concrete. The concrete industry has shown its ability to use glass in concrete, which will start to decrease the amount of waste going to landfills. By adding glass to concrete, the construction will become less dependent on natural aggregate and move closer to being sustainable. There are certain issues with replacing aggregate with GP, since the concrete's durability will be reduced by the ASR. According to Maraghechi *et al.* [147], with 30% GP present, the compressive strength of up to 55 and 78 MPa, respectively, could be achieved after 3 and 28 days, although no overt ASR susceptibility was

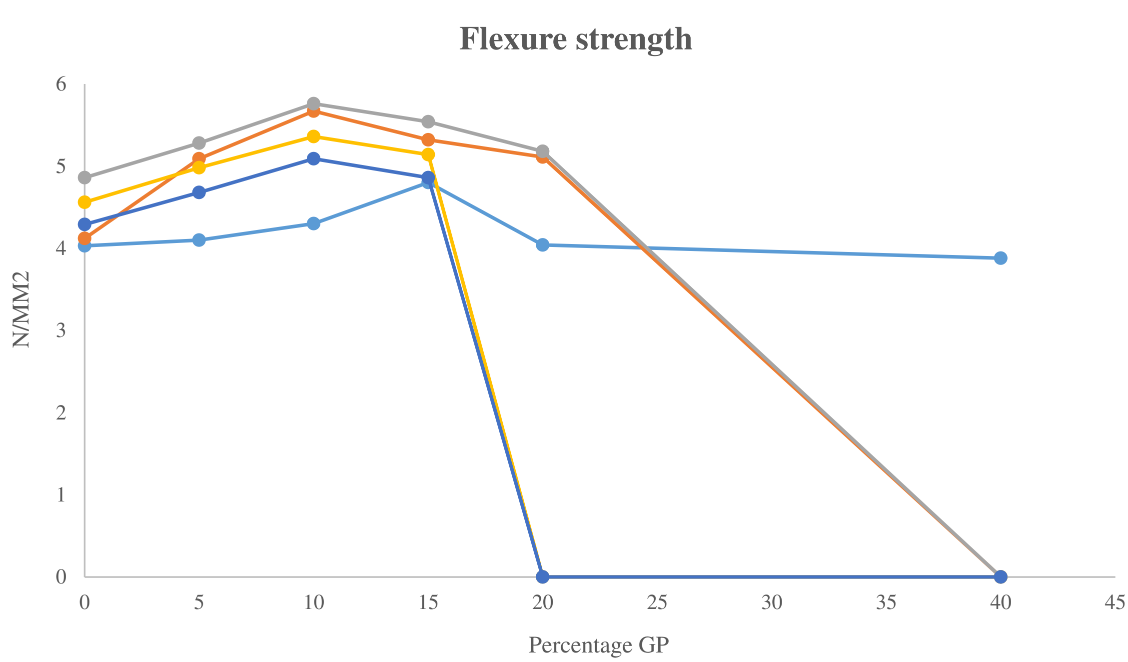

Figure 28: Effect of GP on flexure strength.

found. These results relate to mechanical and durability aspects. GP shows pozzolanic behavior, making it suitable for use as a cementitious material and a partial replacement for cement to some extent. Concrete having up to 15% GP has a substantially positive effect on compressive, split tensile, and flexure strength because of the pozzolanic characteristics of the GP and its ability to fill voids. According to various studies, in terms of durability, adding GP as an additional cementitious component works well.

Table 12 summarizes a number of studies looking into the impact of WG incorporation on concrete's durability performance. The references cited in the table investigate various percentages of cement replacements with WG and analyze a number of effects, including oxygen permeability, porosity, electrical resistivity, chloride diffusivity, drying shrinkage, compressive strength, flexural strength, split tensile strength, modulus of elasticity, transport properties, chemical attack, ASR, FT, water absorption, chloride penetration, and sulfate attack. The main findings suggest that incorporating WG into concrete can lead to improved durability characteristics, including reduced permeability, enhanced resistance to chemical attack, ASR, FT cycles, and reduced water absorption. GP displays pozzolanic properties, especially with smaller particle sizes (<75 μm), which prevent the development of ASR gel and enhance durability and strength performance. Particle size, shape, color, and type are just a few variables that affect how much WG is to be replaced at any one time. Overall, the studies indicate that WG can contribute positively to the durability of concrete, forming denser microstructures, enhancing hydration, reducing permeability, and increasing strength.

The water absorption tendencies of ultra-high performance self-compacting concrete (UHPSCC) that incorporates different proportions of GP and lime powder (LP) replacements for cement are shown in Figure 29, and we see a strong tendency. As the content of GP and LP increases within the mix, a noticeable reduction in water absorption becomes evident when compared to the control mix. The conventional sample exhibits a water absorption rate of 1.151%, while the UHPC 4 mix (30% GP) and UHPC 8 mix (30% LP) remarkably show substantially lower water absorption percentages of 1.05 and 0.98%, respectively. This marks a significant decrease of 8.77 and 14.8% for UHPSCC 4 and 8 mixes when contrasted with the control mix [151]. The increased adhesion of the aggregate paste matrix and the density gain brought on by the addition of glass and lime powder are credited with this decrease in water absorption. It is important to highlight that the nanoparticle size of the lime powder contributes to its role as a filler, effectively densifying the concrete and, in turn, reducing water absorption. In contrast, Kanellopoulos *et al.* [152] reported opposing results concerning recycled LP's

Table 12: Effect of WG on the durability performance of concrete

Ref.	Percentage replacement	Effects	Main findings
[148]	20–40%	Oxygen permeability, porosity, electrical resistivity, chloride diffusivity, and drying shrinkage	In comparison to glass powder (GP) and FA mixes at a similar cement replacement level, the durability characteristics of the glass-incorporated self-compacting concrete (SCC) mixes were comparable to or better. Beyond 90 days, a notable improvement in the glass SCC mixtures' transport characteristics was seen
[136]	5–30%	Compressive strength, flexural strength, split tensile strength, modulus of elasticity	GP with a particle size of less than 75 μm can have pozzolanic properties that prevent the formation of ASR gel, increasing the performance in terms of toughness and durability. This study has demonstrated that when GP replacement levels for cement vary between 10 and 15%, concrete performs adequately overall
[70]	5–100%	Transport properties, chemical attack, ASR, and FT	The incorporation of RG in concrete applications can improve the durability performance by reducing the permeability and enhancing the resistance to chemical attack, ASR, and FT cycles. However, the optimum replacement level depends on several factors such as particle size, shape, color, and type of RG.
[58]	0–30%	Reduced water absorption, chloride penetration, and ASR expansion	GP can improve the durability of concrete by acting as a pozzolanic material and filling the pores
[149]	0–30%	Reduced water absorption, chloride penetration, sulfate attack, and ASR expansion	GP can enhance the hydration of cement and form a denser and more stable microstructure
[150]	0–40%	Reduced water absorption, chloride penetration, and ASR expansion	GP can reduce the permeability and increase the strength of concrete by forming calcium silicate hydrate gel

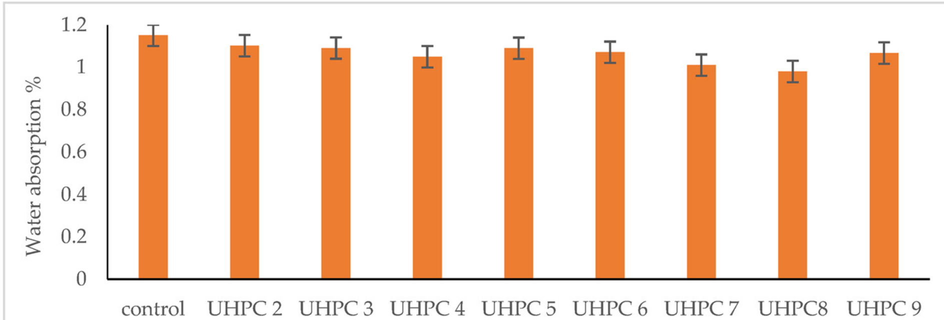

Figure 29: Impact of water absorption on the durability of GP-based concrete after 90 days [151].

impact on water absorption. However, LP's potential as a replacement filler in cement remains promising and calls for additional investigation.

The assessment of sorptivity, a key indicator of concrete's long-term durability, involves a technique where UHPSCC samples are partially submerged in bottles filled with distilled water. This evaluation revolves around capillary suction, influenced by the presence of capillary pores and their continuity within the concrete [151]. Sorptivity results for all UHPSCC combinations are shown in Figure 30, with values ranging from 6.5 to 4.1 $g{\cdot}cm^{-2}{\cdot}s^{-0.5}$. Notably, when compared to the control, all UHPC combinations had much reduced sorptivity values. This observation is consistent with the findings of Dou *et al.* [153], underscoring the impact of nano glass on UHPC durability. The lowest sorptivity values among the mixtures are displayed by UHPSCC 4 (30% GP) and UHPSCC 9 (20% GP + 20% LP), which have sorptivity values of 4.1 and 4.2 $g{\cdot}cm^{-2}\ s^{-0.5}$, respectively. These numbers indicate a considerable decline of 36.9 and 35.3% from the control mix. The significant pozzolanic reaction caused by the presence of GP and SF, which effectively shrinks pores, is blamed for the decrease in sorptivity. Additionally, pore plugging, which increases the concrete's resistance to water penetration, is greatly aided by the tiny LP particles, which act as fillers and nanoparticles.

4.8 Microstructure of glass-based cementitious composites

Glass-based cementitious composites' performance and characteristics are greatly influenced by their microstructure. Concrete mixtures known as "glass-based cementitious composites" use recycled glass in place of some of the aggregates or cement that is typically used. The organization and distribution of individual components, such as cementitious particles, aggregates, and WG, at the microscopic level within the composite material are referred to as its microstructure. The presence of tiny WG particles is one of the primary characteristics of the microstructure in cementitious composites based on glass. When added to the mixture, these glass particles combine with the cementitious matrix and other ingredients to produce a special composite structure. The very small size of the glass particles allows for better contact with the cement matrix and results in a more precise microstructure when compared to ordinary concrete. Glass-based

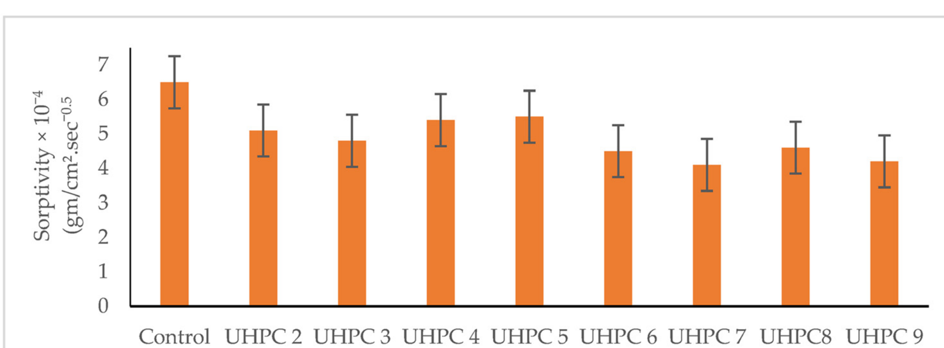

Figure 30: Sorptivity's influence on durability with GP and LP replacement ratios at 90 days [151].

cementitious composites' microstructure shows a number of characteristics that boost the material's performance. By reacting with the cementitious materials in the presence of water, glass particles combine with WG to produce additional binding substances like calcium silicate hydrates (C–S–H) gel. These aspects are subject to considerable debate among researchers; nevertheless, the precise influence of glass, with its significant alkali content, on concrete microstructure remains uncertain. While many scientists attribute the ASR to three key factors – adequate alkali content, reactive aggregates, and ample water – disagreements persist [154–156]. This process is known as pozzolanic reactions and can be facilitated by the integration of WG. The composite is made stronger and more durable, thanks to this formation. Furthermore, the microstructure of glass-based cementitious composites frequently displays reduced porosity due to the pozzolanic reaction and filling effect of the glass particles. The reduced permeability of the denser microstructure makes the material more impervious to the penetration of hostile substances such as water, chlorides, and other chemicals. These composites thus exhibit improved resistance to sulfate attack, chloride penetration, ASR, and other chemical degradation processes. The microstructure of glass-based cementitious composites affects their mechanical properties as well. Increased compressive, flexural [157], and tensile strengths [158] are the result of better load transfer mechanisms and increased glass-cement matrix interfacial bonding [159]. Additionally, the inclusion of glass particles can have a bridging effect that increases the material's overall toughness by assisting in the prevention of crack propagation.

These properties include an extensive variety of microstructural study and characterization techniques used to investigate the performance of glass-based cementitious composites. They discuss electrical impedance spectra (EIS) [160], pore size distribution [159], X-ray diffraction (XRD) studies [161], rapid chloride permeability (RCP) values [160], non-steady-state migration coefficients (NSSMC) [162], and the composites improved microstructure [163]. They also explore the interactions and binding mechanisms between the components' porosity and permeability characteristics, and microstructure optimization for sustainable building.

4.8.1 EIS

An effective and non-destructive method for examining the electrical characteristics of materials, particularly cementitious composites made of glass, is electrical impedance spectroscopy (EIS). In the context of studying the microstructure of these composites, EIS provides valuable insights into their internal electrochemical behavior and can offer a deeper understanding of their durability and performance [164]. During EIS analysis, an alternating current is applied to the material at different frequencies, and the resulting impedance (resistance and reactance) is measured [165]. This impedance response is then plotted on a Nyquist plot [166] or a Bode plot [167], providing a clear representation of the material's electrical behavior. In the case of glass-based cementitious composites, EIS can offer valuable information on several aspects of the microstructure. For instance, it can help assess the presence and extent of porosity, as different pore structures and sizes can affect the electrical conductivity of the material. A denser microstructure with fewer pores is expected to exhibit lower electrical conductivity compared to a more porous one [160]. Furthermore, EIS can provide insights into the electrochemical reactions occurring within the composite. It can be used to research the interactions between glass particles, cementitious matrix, and other elements as well as the hydration products' production and characteristics, such as the calcium silicate hydrate (C–S–H) gel [168]. The durability and overall performance of the glass-based cementitious composites are greatly influenced by these parameters. Additionally, EIS is a helpful tool for tracking the long-term performance and stability of these composites in practical applications since it may assist detect any changes in electrical behavior over time. Overall, EIS is a valuable technique for characterizing the microstructure of glass-based cementitious composites. Its non-destructive nature and ability to probe the internal electrochemical behavior make it an essential tool for researchers and engineers seeking to optimize the microstructural design and enhance the performance and durability of these sustainable construction materials [110].

4.8.2 Pore size distribution

Pore size distribution is a critical aspect of the microstructure analysis for various materials, including glass-based cementitious composites. It refers to the characterization of pores in terms of their size [169], shape [104], and distribution within the material. Understanding the pore size distribution is essential because it directly influences several key properties and performance aspects of the composites. In the context of glass-based cementitious composites, pore size distribution plays a vital role in determining their mechanical strength [163], durability [169], permeability, and other important characteristics. A well-optimized pore size distribution can lead to enhanced properties, while an undesirable distribution may result in reduced performance. The mechanical properties of the composite, such as compressive strength and flexural strength, are often improved by a denser microstructure with a smaller average pore size. Smaller pores provide more efficient load transfer mechanisms, resulting in increased overall strength and resistance to mechanical forces. Additionally, the relationship between pore size distribution and material permeability is simple to understand [157]. A lower porosity and a narrow range of pore sizes can lead to reduced permeability, making the composite less susceptible to water ingress and chemical attack. This improved durability is especially crucial in structures exposed to harsh environmental conditions. Analyzing the pore size distribution can also help in understanding the potential for pore connectivity within the material. If larger pores are prevalent and interconnected, it may create pathways for the ingress of harmful agents, such as chlorides and sulfates, leading to possible deterioration of the composite over time. Researchers and engineers use various techniques to determine the pore size distribution in glass-based cementitious composites. Mercury intrusion porosimetry [159], gas adsorption methods [170], and image analysis [171] using scanning electron microscopy are some common techniques employed to characterize the pore structure. In summary, pore size distribution is a critical microstructural characteristic in glass-based cementitious composites. A crucial consideration in the design and development of high-performance and sustainable building materials is that the distribution of pores may considerably enhance the material's mechanical strength, durability, and permeability features.

Figure 31 presents the pore size distribution of various components, including GP, lime stone (LS), SF, and MK. Notably, the particle size of SF is the smallest among these materials, followed by LS and MK, which have similar particle sizes. In comparison, GP exhibits a larger pore size distribution, a characteristic attributed to its particle size. This variation in pore size can significantly influence concrete properties and durability. The benefit of GP's larger particle size lies in its potential to enhance interparticle packing, leading to improved overall density. Reduced pore connectivity in concrete mixtures also highlights the intriguing observation that the pore size of GP's performance is comparable to that of OPC, highlighting its potential as an additional cementitious ingredient.

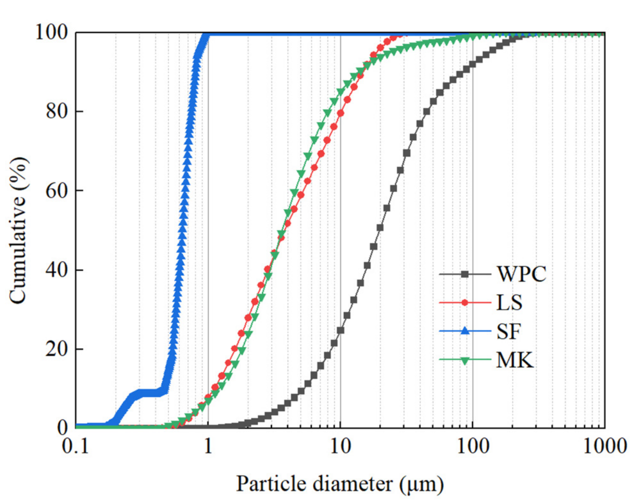

Figure 31: Comparison of particle size distribution with GP [172].

4.8.3 XRD analysis

An effective approach for examining the crystallographic structure and mineralogical makeup of materials, particularly glass-based cementitious composites, is the XRD analysis [173,161]. XRD is a non-destructive method that provides valuable information about the arrangement of atoms within the material and helps identify the phases present in the sample. In the context of studying the microstructure of glass-based cementitious composites, XRD analysis is particularly useful for understanding the cement hydration products and the interactions between cementitious materials and WG particles. Multiple crystalline phases and amorphous components may be identified in the composites using the diffraction patterns produced from the XRD examination [110]. XRD can detect various mineral phases in the cementitious matrix, including C–S–H [174], calcium hydroxide (CH) [175], and calcium aluminate hydrates (C–A–H) [176]. Additionally, it can detect the crystalline phases of WG, such as silica (SiO_2) [168] or other glass-forming oxides, which can undergo reactions with cementitious materials. XRD analysis is also useful in evaluating the degree of pozzolanic reaction in the composite. The appearance of new phases or shifts in diffraction peaks can indicate the formation of pozzolanic compounds, such as C–S–H gel or calcium–aluminum–silicate–hydrates (C–A–S–H), resulting from the interaction between the WG particles and cement hydration products. Moreover, XRD can provide information about the amorphous content in the material, which can significantly impact its performance. Amorphous components, such as glassy phases, may have an impact on the composite's mechanical and durability qualities by adding to its pozzolanic activity. Researchers often utilize XRD analysis to assess the changes in the microstructure of glass-based cementitious composites over time, such as during the curing process or in response to environmental exposure. This helps in comprehending the material's stability and long-term behavior in practical applications. In summary, XRD analysis is a useful method for describing the microstructure of cementitious composites made of glass. It provides critical information about the crystallographic structure, mineralogical composition, and pozzolanic reactions within the material [76]. By understanding the XRD patterns, researchers and engineers can optimize the microstructural design, tailor the composite's properties, and develop high-performance and sustainable construction materials.

Figure 32 presents a comparative analysis of the properties of SF (a) and GP (b) through XRD analysis. The XRD spectra for both materials, designated as spectrum 8, spectrum 9, spectrum 23, and spectrum 24, provide insights into the composition of oxygen, calcium, carbon, silicon, aluminum, and magnesium. Specifically, spectra 8 and 9 correspond to SF, while spectra 23 and 24 correspond to GP. In spectrum 8, the composition percentages are 42.5% oxygen (O), 36.3% calcium (Ca), 9.7% carbon (C), 9.1% silicon (Si), 1.4% aluminum (Al), and 1% magnesium (Mg). Spectrum 9 exhibits composition percentages of 51.5% O, 22.5% Ca, 14.7% C, 8.1% Si, 1.4% Al, 1.1% Mg, and 0.6% carbon (C). Spectrum 23 showcases composition percentages of 45.4% O, 28.9% Ca, 9.6% C, 3.6% Si, 2.3% Al, and 1.4% Mg. In contrast, spectrum 24 illustrates composition percentages of 50.4% O, 21.1% Ca, 15.4% C, 11.3% Si, 1% Al, and 0.7% Mg. The data from this analysis highlight the elemental makeup

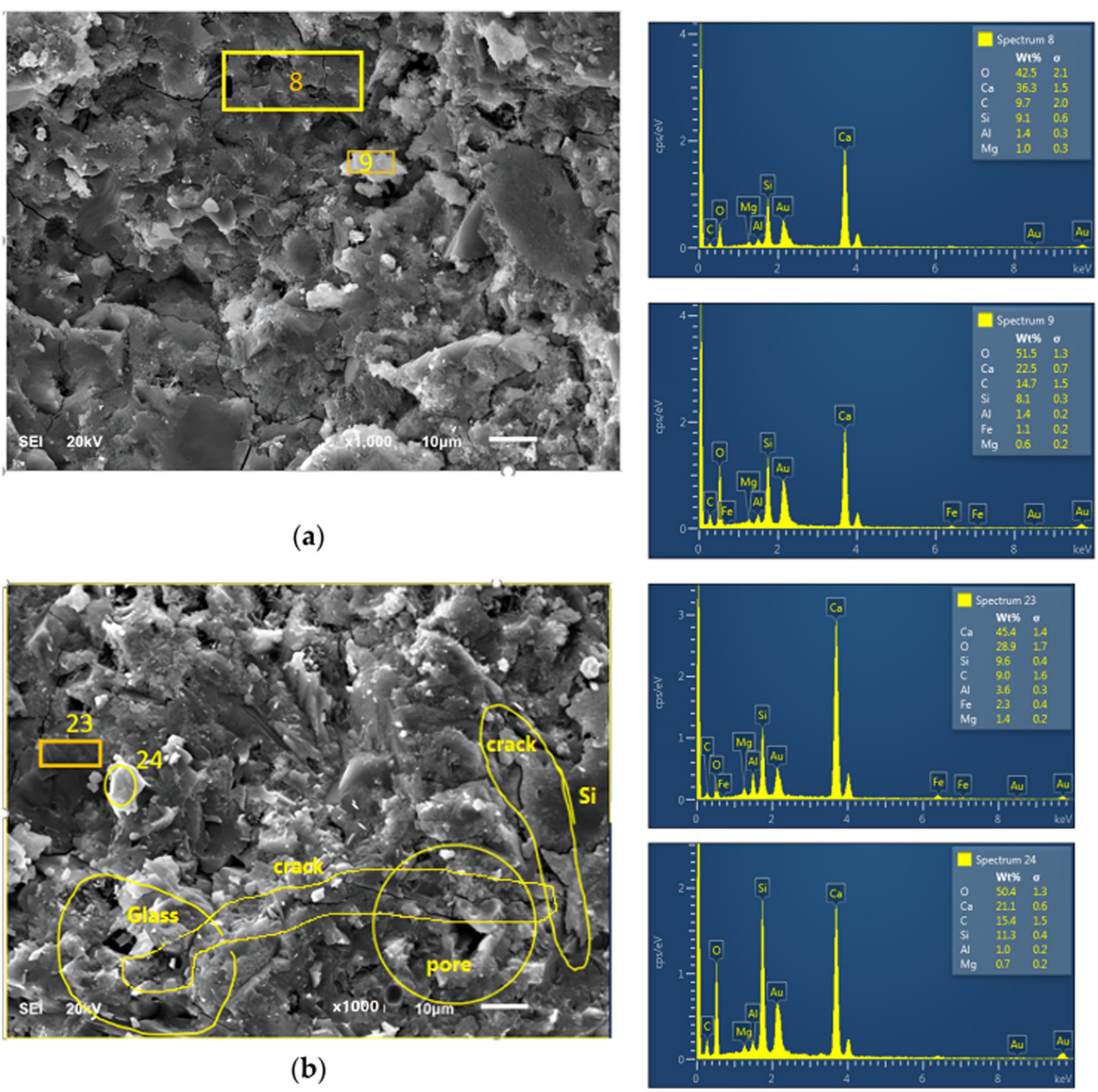

Figure 32: X-ray diffraction analysis of (a) SF and (b) GP. The graphs characterize the chemical composition and structural properties of SF and GP [177].

of SF and GP, shedding light on their chemical composition and potential benefits for concrete performance.

4.8.4 RCP

RCP values, or rapid chloride permeability values, are a measure of the resistance of concrete, including glass-based cementitious composites, to the penetration of chloride ions [160]. Chloride ions can be particularly harmful to concrete structures as they can initiate and accelerate corrosion of embedded reinforcement, leading to structural deterioration and reduced service life. In chloride-rich settings, such as coastal locations or places exposed to deicing salts, RCP testing is a frequently used technique to evaluate the resilience and long-term performance of concrete [178]. The test involves subjecting the concrete specimen to an electrical potential, which drives chloride ions into the material [179]. By monitoring the rate of chloride ion penetration over a specified duration, the RCP value can be determined. In the context of glass-based cementitious composites, RCP values can provide valuable information about the material's permeability to chloride ions [160]. A composite is less vulnerable to chloride-induced corrosion if it has a lower RCP value, which implies a stronger resistance to chloride penetration. This is particularly important in marine or harsh environments where chloride ingress can be a major concern for the durability of concrete structures. The incorporation of WG in the cementitious composite can influence the RCP values due to the effects on the microstructure. As glass particles contribute to a denser and less porous microstructure, the pathways for chloride ions to migrate through the composite are reduced, resulting in lower permeability and lower RCP values. Lower RCP values indicate that glass-based cementitious composites are less prone to chloride-induced corrosion, making them suitable for use in structures exposed to chloride-rich environments. By extending the service life of concrete buildings and decreasing maintenance expenses, this improved resistance to chloride penetration can increase sustainability. In conclusion, RCP values play a crucial role in assessing the durability of glass-based cementitious composites by evaluating their resistance to chloride ion penetration. The incorporation of WG can contribute to lower RCP values due to the positive effects on the material's microstructure, making these composites promising candidates for sustainable and long-lasting concrete applications in challenging environments.

The RCP values of three distinct kinds of concrete – plain concrete, GP concrete, and FA concrete – are shown in Figure 33. These measurements were collected after 28, 56, and 90 days with varied curing times. Notably, plain

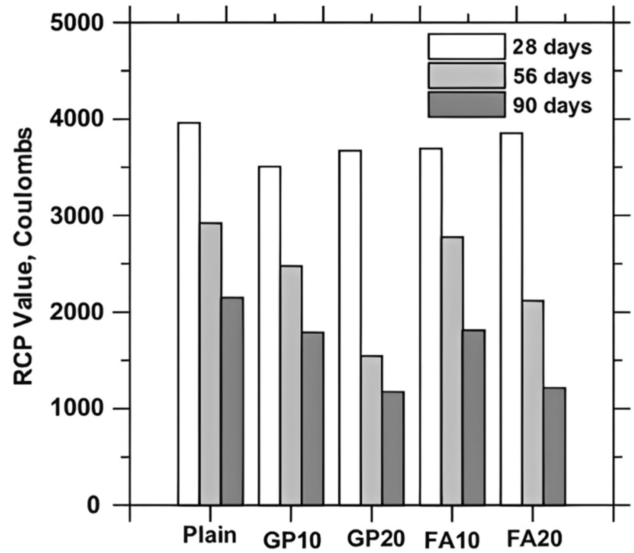

Figure 33: Comparison of RCP values among plain concrete, GP-based concrete, and FA-based concrete [160].

concrete exhibits the highest RCP value among the three types, indicating its relatively lower permeability to chloride ions. The inclusion of GP in concrete brings forth a notable observation from these data. Despite plain concrete showcasing the highest RCP value, the RCP values of GP concrete demonstrate its potential to achieve chloride permeability levels comparable to or even better than that of FA concrete. This demonstrates how well GP works to reduce chloride ion penetration inside the concrete matrix, improving the concrete's durability and resistance to chloride-induced corrosion. This suggests that GP, as an additional cementitious material, can efficiently contribute to the improvement of concrete's resistance to chloride ingress, making it an important component for enhancing the long-term durability and performance of concrete structures, especially in corrosive environments.

4.8.5 NSSMCs

NSSMC is a parameter used to characterize the transport properties of ions [180], particularly chloride ions, within concrete materials, including glass-based cementitious composites. It is a valuable measure to assess the material's resistance to chloride ingress and its overall durability performance in chloride-rich environments. In the NSSMC test, a concrete specimen is electrically potentiated, and the rate at which chloride ions diffuse through the material over time is observed. This test differs from the RCP test in that it examines the transport behavior of ions under non-steady-state conditions, representing more realistic conditions that occur in real-world scenarios. The NSSMC values provide insights into the effectiveness of the composite's microstructure in mitigating chloride ion penetration. Lower NSSMC values indicate a higher resistance to chloride migration, signifying a denser and less porous microstructure that restricts the movement of chloride ions. The durability and service life of concrete buildings can be greatly impacted by chloride-induced corrosion, which can be prevented by this feature. The incorporation of WG in the cementitious composite can influence NSSMC values due to its impact on the microstructure [181]. Glass particles can enhance the material's overall density, reduce porosity, and create a more tortuous path for chloride ions, leading to lower NSSMC values and improved chloride resistance. Researchers and engineers can better understand the transport characteristics of glass-based cementitious composites and how well they might function in chloride-contaminated settings by analyzing NSSMC values. Lower NSSMC values are indicative of a material's enhanced durability and resistance to chloride ingress, making these composites suitable for use in infrastructure exposed to aggressive chloride-rich conditions. In conclusion, NSSMC is a crucial parameter for assessing the chloride resistance and durability performance of glass-based cementitious composites [160]. The integration of WG can positively influence NSSMC values by enhancing the microstructure and reducing chloride ion penetration, making these composites promising candidates for sustainable and resilient construction materials in challenging environments.

Three different forms of concrete – plain concrete, GP concrete, and FA concrete – have different NSSMC values, which are shown in Figure 34. These measurements were taken at various curing intervals of 28, 56, and 90 days. Notably, the NSSMC values reflect the rate at which chloride ions migrate through the concrete matrix, offering insights into the materials' resistance to chloride penetration. Examining the information in this image reveals a huge advantage of using GP in concrete. Favorably, 20% GP concrete had the highest NSSMC value of all the concrete combinations, demonstrating that it has a higher level of resistance to chloride ion migration than other mixtures like plain concrete and 20% FA concrete. This shows that adding GP to concrete enhances the material's capacity to obstruct the flow of chloride ions, increasing its longevity and lowering the likelihood of chloride-induced corrosion within concrete buildings. GP concrete has excellent performance in terms of NSSMC values, indicating that it has the potential to be a useful additive for extending the lifespan and service life of concrete in chloride-exposed situations, resulting in more robust and durable concrete buildings.

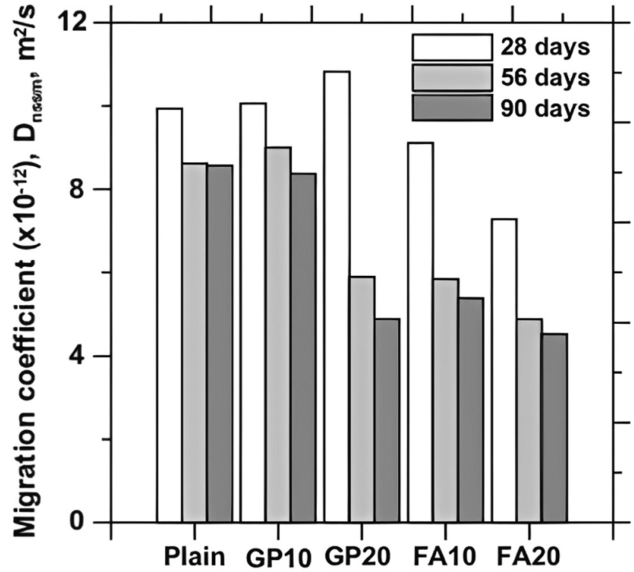

Figure 34: Comparison of NSSMC values among plain concrete, GP-based concrete, and FA-based concrete [160].

4.8.6 Enhanced microstructure

Enhanced microstructure refers to the improved arrangement and distribution of components within a material, such as glass-based cementitious composites, which leads to superior properties and performance compared to conventional materials. The concept of enhancing the microstructure involves optimizing the interaction and bonding between various constituents, resulting in a more refined and tailored composite with desirable characteristics [182]. Enhancing the microstructure of glass-based cementitious composites often involves utilizing WG in place of some of the cement or aggregates. The cementitious matrix may benefit from the inclusion of finely ground glass particles to achieve a more uniform distribution of elements and a denser, less porous structure. When WG is added, pozzolanic reactions may occur. In these reactions, glass particles combine with cement hydration products and water to generate new binding substances such as C–S–H gel. The interfacial transition zone between the glass particles and the cementitious matrix is strengthened and made more robust as a result of these processes, which improves the composite's load-transfer mechanisms and overall mechanical performance [183]. Furthermore, the inclusion of WG in the microstructure can aid to boost packing density and minimize pore diameters, which improves resistance to the entry of hazardous substances like chlorides and sulfates and lowers permeability. This enhanced durability makes glass-based cementitious composites more suitable for applications in aggressive environments or structures exposed to harsh weather conditions. The optimized microstructure also influences the long-term performance of glass-based cementitious composites. It can reduce the potential for early-age cracking and enhance the material's resistance to thermal stresses and environmental factors, ensuring the structural integrity and service life of the composite over time [184]. By carefully changing the amount and properties of WG and other cementitious materials, researchers and engineers hope to build glass-based cementitious composites with improved microstructure. By understanding the relationships between the composition, microstructure, and properties, they can develop high-performance and sustainable construction materials tailored to specific applications. In summary, enhancing the microstructure of glass-based cementitious composites involves improving the arrangement and interaction of components to create a denser, more durable, and better-performing material. The incorporation of WG plays a vital role in achieving these improvements, making glass-based cementitious composites promising candidates for sustainable construction solutions with enhanced properties and longer service life.

Figure 35a illustrates the effects of replacing sand with untreated GP, where the presence of silica initiates a reaction with hydrated cement, causing microcracks of approximately 3 μm width to develop. This reaction creates silica gel, which is highly attracted to water and causes swelling

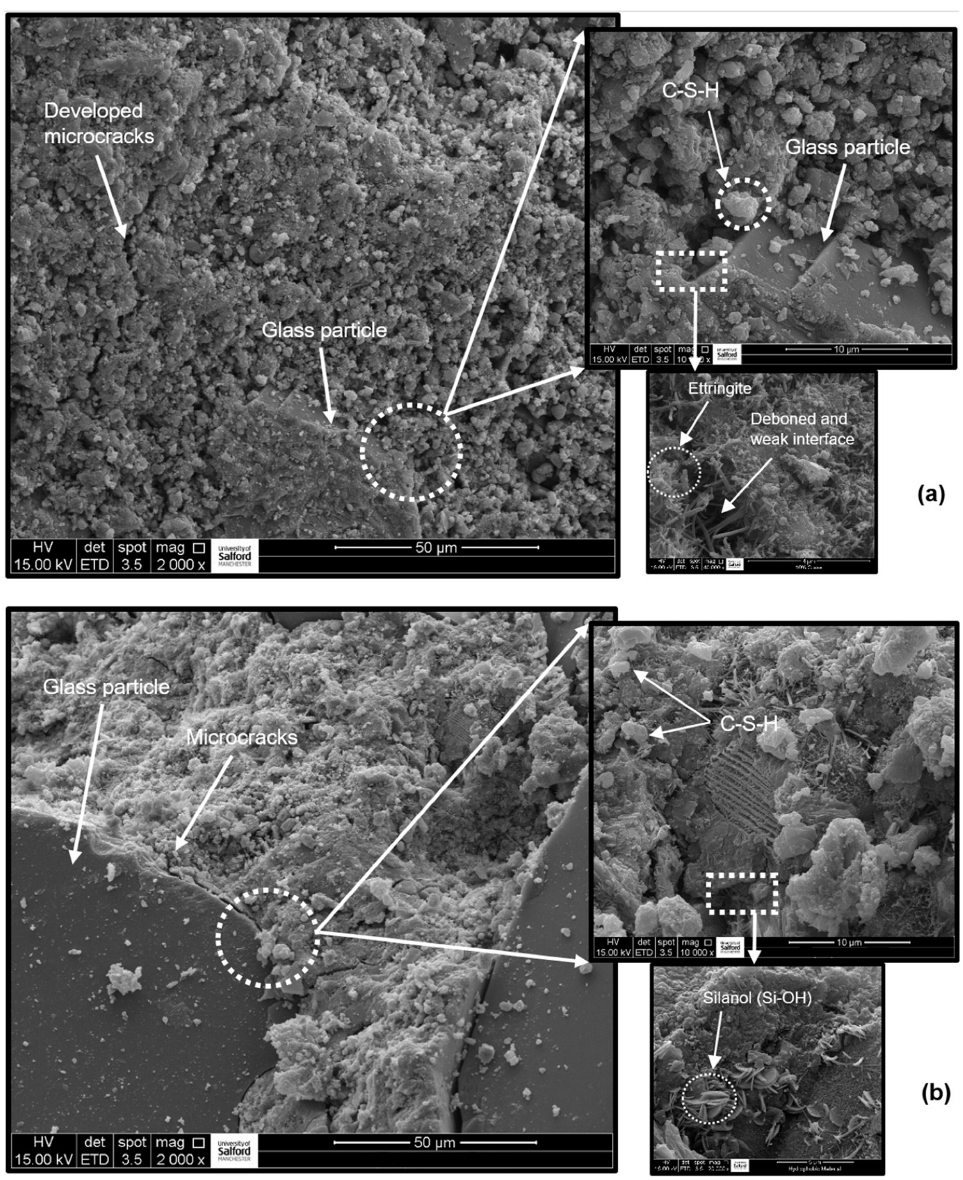

Figure 35: Microstructural examination of (a) untreated GP concrete and (b) silane-treated GP concrete [185].

and pressure at the glass-cementitious matrix contact. The structure develops cracks as a result of this pressure. The problem is made worse by the rough surface roughness of the GP, which prevents effective pore-filling and reduces the strength of the concrete matrix. Additionally, the addition of GP causes a delay in the synthesis of C–S–H, potentially as a result of a slowed cement hydration process. The link between cement paste and glass particles becomes much weaker when considerable ettringite production starts to show after adding GP. On the other hand, Figure 35b shows that using GP that has been silane-treated improves the concrete's resistance to fracture propagation. The increased adhesion between glass particles and cement paste made possible by the presence of silane is responsible for the decreased frequency of detected fractures. Through the formation of silanol groups, the smoother surface of glass particles treated with silane improves pore-filling and boosts bonding with all constituents of concrete. The internal toughness of the concrete is greatly increased as a result of this treatment, which creates a denser structure rich in C–S–H, particularly where the cementitious matrix and glass meet. Additionally, reducing ettringite forms, which increases the overall strength of the concrete, is another benefit of using GP that has been silane-treated. While using silane-treated GP increases adhesion, pore-filling, and strength, resulting in a denser structure rich in C–S–H and improved crack resistance, using untreated GP instead of sand causes the development of micro-cracks because of chemical reactions and reduced pore-filling.

4.8.7 Interactions and binding mechanisms

The term "Interactions and Binding Mechanisms" in the context of glass-based cementitious composites refers to the intricate chemical and physical interactions that take place between the various components of the composite [186]. This includes the interactions between cementitious materials, WG particles, and other supplementary materials used in the mixture. Understanding the interactions and binding mechanisms is crucial as they directly influence the microstructure and overall performance of the composite material. These interactions can occur at both the macroscopic and microscopic levels, affecting properties such as mechanical strength, durability, and long-term stability. One of the key interactions is between the cementitious matrix and WG particles. Glass can experience pozzolanic interactions with the calcium hydroxide (CH) found in the cement when it is included in the cementitious composite. As a result, new binding substances are created, such as C–S–H gel, which adds to the material's overall toughness and durability. Additionally, WG particles can act as nucleation sites for the cement hydration products, enhancing the development of the microstructure and improving the overall packing density of the composite [187]. The interactions between the glass particles and the cementitious matrix strengthen the bond and improve the material's capacity for load transmission. The binding mechanisms within the composite can also influence the resistance to various forms of degradation, such as chemical attack and ASR [188]. Proper interactions between the glass particles and cementitious materials can lead to the formation of stable and less reactive compounds, reducing the potential for harmful chemical reactions and enhancing the material's long-term performance. Moreover, the interactions between supplementary materials, like pozzolans or mineral admixtures, and the cementitious matrix can further contribute to the optimization of the microstructure. These substances can make it easier for cement hydration products and glass particles to stick together, which will increase performance and allow for more effective usage of cementitious substances. To achieve desirable interactions and binding mechanisms, researchers and engineers carefully control the composition, proportion, and characteristics of the components in the composite. By understanding the complex interactions between the constituents, they can design glass-based cementitious composites with enhanced properties and tailor them for specific applications, such as sustainable construction, infrastructure development, and building materials. In conclusion, the study of "Interactions and Binding Mechanisms" in glass-based cementitious composites is essential for understanding the chemical and physical relationships between the various components. These interactions play a key role in the creation of high-performance and environmentally friendly building materials because they have a considerable impact on the microstructure, mechanical characteristics, and durability of the composite.

4.8.8 Porosity and permeability characteristics

Porosity and permeability characteristics are vital parameters in the study of glass-based cementitious composites, as they directly influence the material's durability, resistance to environmental factors, and overall performance [173]. Porosity refers to the volume fraction of voids or pores within the composite, while permeability refers to the ease with which fluids or gases can penetrate the material. Reducing porosity is essential for improving the mechanical characteristics of glass-based cementitious composites, such as compressive strength and tensile strength [189]. A lower porosity implies a more compact and denser microstructure, which enhances load transfer mechanisms and results in improved overall mechanical performance. The incorporation of WG particles can contribute to a reduction in porosity by promoting a more efficient packing of cementitious materials and filling up voids within the composite. On the other hand, permeability is a crucial factor in determining how well the composite resists the entry of hazardous elements like chloride ions or dangerous chemicals. Lower permeability indicates a reduced ability for these agents to penetrate the material, thereby enhancing its durability and resistance to degradation. By creating a denser microstructure with smaller pore sizes, WG particles can significantly lower the permeability of the cementitious composite. In addition to the macroscopic porosity, the pore size distribution within the composite is also essential [163]. A well-optimized pore size distribution can further enhance the material's durability and mechanical properties. Smaller and more uniform pores contribute to improved resistance against chloride ingress and other forms of chemical attack, ensuring a longer service life for concrete structures. Researchers and engineers use various techniques, such as mercury intrusion porosimetry and image analysis, to evaluate the porosity and permeability characteristics of glass-based cementitious composites. These studies aid in the creation of high-performance composites for use in sustainable building applications and offer insightful information on the microstructure of the material. In summary, porosity and permeability characteristics are crucial factors in determining the performance and durability of glass-based cementitious composites. The incorporation of WG particles can lead to a reduction in porosity, creating a denser microstructure that enhances mechanical properties. Additionally, the reduced permeability contributes to improved resistance against harmful agents, making glass-based cementitious composites promising materials for sustainable and long-lasting infrastructure development.

4.8.9 Microstructure optimization for sustainable construction

Microstructure optimization for sustainable construction is a crucial approach aimed at creating high-performance materials with enhanced properties while minimizing their impact on the environment [85]. The aim of this optimization method is to increase the mechanical strength, durability, and eco-friendliness of the material, such as glass-based cementitious composites, by fine-tuning the arrangement, distribution, and interactions of components inside the material. In the context of glass-based cementitious composites, microstructure optimization involves several key aspects. The use of WG, a sustainable and environmentally beneficial element that can improve the composite's overall performance, is one crucial component. Additional binding compounds are created as a result of pozzolanic interactions between the WG particles and the cement hydration products. As a result, the interfacial transition zone between the glass and cementitious matrix becomes denser and more robust, eventually enhancing the load transmission mechanisms. Another essential consideration in microstructure optimization is the reduction in porosity within the composite [190]. By promoting a more efficient packing of cementitious materials and filling up voids within the matrix, a lower porosity can be achieved. This leads to enhanced mechanical strength and resistance to degradation, making the composite more robust in various applications. Moreover, controlling the permeability of the composite is crucial to prevent the penetration of harmful substances, such as chloride ions or aggressive chemicals. A denser microstructure with smaller pore sizes can significantly lower the permeability, ensuring the composite's long-term durability and service life. To further enhance microstructure optimization, supplementary materials like pozzolans or mineral admixtures can be added. These materials improve the interaction between the glass particles and cementitious matrix, leading to a more efficient use of cementitious materials and improved overall performance. Comprehensive performance testing is a fundamental part of microstructure optimization [159]. Through thorough evaluations of mechanical properties, durability characteristics, and resistance to environmental factors, engineers and researchers ensure that the composite meets the required performance standards for sustainable construction. By optimizing the microstructure of glass-based cementitious composites, we can create materials that offer superior mechanical strength, enhanced durability, and reduced environmental impact. By increasing the service life of infrastructure, lowering maintenance requirements, and encouraging the effective use of waste materials in construction, these composites have the potential to make a substantial contribution to sustainable building methods.

4.9 Prediction models for glass-based cementitious composites

The development of accurate prediction models (*i.e.*, artificial intelligence based [191–194] or pure mathematical ones [195–198]) is a crucial aspect in the field of glass-based cementitious composites research. These models seek to create connections between the composition, microstructure, and characteristics of the composites so that scientists and engineers can predict how well they will function in certain scenarios. By leveraging prediction models, valuable insights can be gained to optimize the design, production, and application of glass-based cementitious composites for sustainable construction. Prediction models can concentrate on a wide range of attributes in the context of glass-based cementitious composites, including mechanical strength, durability, permeability, and resistance to environmental conditions. These models may incorporate various parameters, including the content and type of WG, cementitious material proportions, curing conditions, and other supplementary materials. Machine learning techniques, statistical analyses, and computational simulations are commonly employed to develop prediction models. The authors used a dataset of 200 concrete samples to train three different machine learning models: support vector machines (SVMs) [199], random forests (RF) [200], and artificial neural networks (ANN) [201]. The outcomes demonstrated that all three models had a decent ability to predict the strength of recycled aggregate concrete (RAC). The SVM model had the highest accuracy, followed by the RF model and the ANN model [202]. These methods leverage data obtained from experimental testing and observations to build robust and accurate models. As more data become available and the understanding of glass-based cementitious composites deepens, these prediction models can be continually refined and improved. The application of prediction models for glass-based cementitious composites extends beyond laboratory settings. In order to ensure that the chosen composites fulfill precise performance requirements and sustainability objectives, engineers may utilize these models to make educated decisions throughout the design phase of building projects. Moreover, prediction models facilitate the identification of optimal mix designs, reducing the need for trial-and-error approaches and expediting the development of new and improved materials.

4.9.1 Linear regression (LR) model

LR model applied to GP in concrete predicts how changes in GP percentage influence concrete properties like strength and durability. It establishes a linear relationship between these variables using experimental data. This model provides insights into the optimal GP range for desired concrete performance, aiding in sustainable mix design. However, it assumes a linear correlation and should be used alongside other methods for a comprehensive understanding of GP's effects on concrete.

Eq. (1) represents the thorough examination of the variables affecting the compressive strength of typical concrete mixes containing WG dust. This complex inquiry was carried out using optimization strategies, including the use of least squares and sum of error squares procedures. Utilizing the Solver tool in an Excel software speed up the procedure. Each of the parameters in the equation is important: "w/b" stands for the water-to-binder ratio, "C.C." represents the cement content, "G.P." stands for glass powder content, "F.A." stands for fine aggregate content, "C.A." stands for coarse aggregate content, and "T" stands for time or a related time-dependent variable. The equation effectively captures the interplay of these parameters and their collective impact on the compressive strength of concrete, offering valuable insights for the optimization of WG-incorporated concrete mixtures. This optimization was conducted in a designated cell termed the "objective cell," bounded by values from other relevant equations. The connection between anticipated and actual compressive strengths of regular concrete mixes incorporating WG particles is shown graphically in Figure 36, both for training and testing datasets. Statistical methods were used to do a thorough evaluation of the model, which resulted in R^2 values of 0.918 for training data and 0.923 for testing data. While the mean absolute error (MAE) was computed as 2.41 MPa (training) and 2.58 MPa (testing), the root mean square error (RMSE) was 3.07 MPa (training) and 3.28 MPa (testing). The structural index (SI) value indicated good efficiency within the range of 0.1–0.2, and the objective (OBJ) value was equal to 6.039. Furthermore, the model's application is uncomplicated; however, it does exhibit a limitation, displaying slightly reduced predictive capability for compressive strength with higher error percentages compared to alternative models. Both the training and testing datasets in the study have an error margin of about ±25%. The compressive strength of low-strength normal concrete mixes

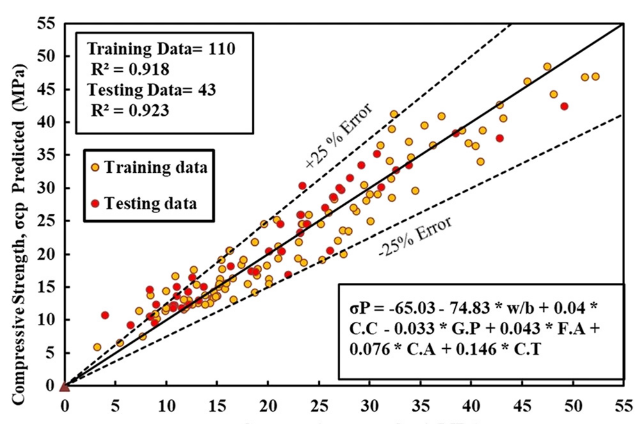

Figure 36: LR model [203].

tended to be somewhat overestimated by the model under development, whereas samples of high-strength normal concrete were found to have compressive strengths that were slightly underestimated.

$$\sigma P = -65.03 - 74.83 \times \frac{w}{b} + 0.04 \times \text{C.C.} - 0.033 \times \text{G.P.} + 0.043 \times \text{F.A.} + 0.076 \times \text{C.A.} + 0.146 \times \text{T.} \quad (1)$$

4.9.2 Nonlinear regression (NLR) model

NLR model applied to GP in concrete predicts concrete properties considering the complex, nonlinear relationship between GP percentage and outcomes. Unlike linear models, it captures intricate effects and offers accurate insights into real-world behavior. This model is particularly useful for materials like GP, where effects on concrete may not follow a linear trend. However, it requires careful parameter estimation and validation to prevent overfitting. It is a valuable tool for optimizing concrete mix designs, providing deeper understanding of how GP levels impact properties and aiding sustainable construction practices.

For both the training and testing datasets, connections between predicted compressive strength and experimentally acquired compressive strength data from typical concrete combinations are highlighted. The suggested equation for the NLR model combining several variable factors is shown in Figure 37. Eq. (2), generated through thorough analysis, produced outstanding results using 110 data points for training and 43 for testing, with an amazing R^2 of 0.921 for training data and 0.929 for testing data. While the MAE data showed accuracy with 2.34 MPa (training) and 2.43 MPa (testing), the RMSE values showed precision with 3.022 MPa (training) and 3.159 MPa (testing). Notably, the equation's parameters hold distinct importance: "w/b" represents the water-to-binder ratio, "C.C." symbolizes the cement content, "G.P." represents the GP content, "F.A." represents the fine aggregate content, "C.A." denotes the coarse aggregate content, and "T" represents time or a relevant time-dependent variable. The resultant OBJ value of 5.1 underlined the model's efficacy, while the SI value, which fell between 0.1 and 0.2, underlined successful performance. Importantly, the assessed datasets showed error margins of −15 and +20% for both testing and validation datasets, and a ±20% error line for training data. Analogous to the LR model, the NLR model exhibited a slight underestimation for high-strength normal concrete mixes, accompanied by a moderate overestimation for low-strength normal concrete samples. The equation's multifaceted parameters collectively contribute to a comprehensive understanding of their impact on predicting the compressive strength of concrete infused with WGPs.

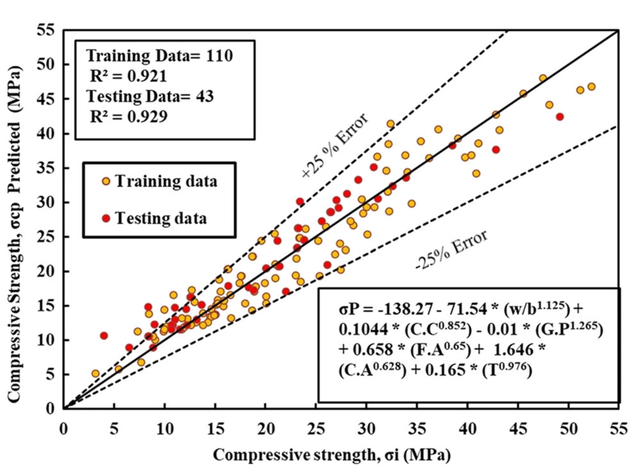

Figure 37: NLR model [203].

$$\sigma P = -138.27 - 71.54 \times \left(\frac{w}{b1.125}\right) + 0.1044 \times (\text{C.C.}\ 0.852) - 0.01 \times (\text{G.P.}\ 1.265) + 0.658 \times (\text{F.A.}\ 0.65) + 1.646 \times (\text{C.A.}\ 0.628) + 0.165 \times (T0.976). \quad (2)$$

4.9.3 ANN

ANN mirrors the human brain's neural structure and are pivotal in deciphering intricate material behaviors within glass-based cementitious composites. By amassing extensive experimental data encompassing glass content, curing conditions, and mechanical and durability traits, researchers train the ANN to grasp the nuanced links between input factors and material properties. Comprising interconnected neurons organized in layers, the ANN processes input data through mathematical transformations, learning from patterns and refining connection weights to boost predictive accuracy. Trained ANNs exhibit potent predictive capabilities, projecting the mechanical strength, durability, permeability, and more of novel glass-based compositions. They unveil complex interactions between factors, elucidating how composition adjustments impact performance. This nonlinear aptitude enables ANNs to capture intricate relationships often evading traditional linear models. ANNs continually enhance predictions as they learn from fresh data, ensuring ongoing refinement. Nonetheless, their efficacy hinges on substantial data and careful parameter tuning to avert overfitting. Armed with adaptability and computational prowess, ANN stands as a potent asset for predicting and optimizing material properties in glass-based cementitious composites, significantly advancing sustainable and high-performance construction materials.

In order to maximize the effectiveness of the ANN, several combinations of neurons, momentum rates, learning rates, and iterations were investigated. The results showed that the configuration of a single hidden layer with 9 neurons, 0.2 momentum, 0.1 learning rate, and 50,000 iterations produced the best precise predictions for the compressive strength of regular concrete mixes incorporating WG granules. The ANN model was calibrated using training datasets and subsequently validated against independent testing datasets to forecast compressive strength values based on appropriate input parameters. Comparing projected and experimentally determined compressive strength values for regular concrete mixes containing WG particles was part of the assessment, which took into account both training and testing datasets. Depicted in Figure 38 is a graphical representation that showcases the outcome of data analysis. Specifically, this analysis pertains to the accuracy of predictions made by the ANN model in comparison to other models. The data points in the graph are indicative of the extent to which the predicted values align with the actual values. Importantly, for both the training and testing datasets, it is noted that the error line, which reflects the difference between projected and actual values, is considerably less than ±25%. According to this observation, the forecasts of the ANN model are noticeably closer to the actual values than the predictions of the other produced models. It means that, practically speaking, the ANN model is more accurate in predicting the compressive strength of regular concrete mixes that contain WG particles. Following this study, more assessments are made in order to fully gauge the effectiveness of the ANN model. These evaluations are guided by specific metrics that are widely utilized in predictive modeling. The MAE, which measures the average magnitude of absolute errors, the RMSE, which measures the average magnitude of prediction errors, and the coefficient of determination (R^2), which measures the percentage of the variance in the dependent variable that can be explained by the independent variables are some examples of these metrics. In essence, the graphical representation in Figure 38 provides an initial visual insight into the relative accuracy of the ANN model's predictions, emphasizing its favorable performance in comparison to other models. Subsequent quantitative assessments through metrics such as RMSE, MAE, and R^2 offer a more detailed and precise understanding of the model's predictive capabilities and its overall fit to the observed data.

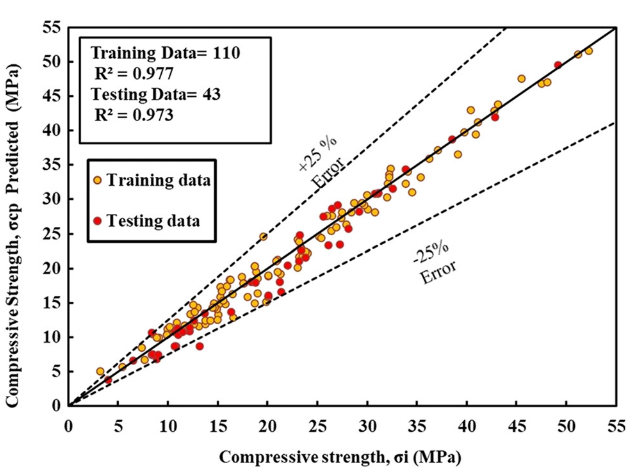

Figure 38: ANN model [203].

The efficacy of the ANN model in predicting the attributes of GP-based concrete is intricately analyzed in Table 13. The table systematically explores various configurations of hidden layers and neurons within those layers, detailing the resulting performance metrics. The first column indicates how many hidden layers there are in the ANN architecture, and the next two columns show how many neurons are located on the left and right sides of each hidden layer. The quantitative metrics of the model's prediction precision are shown in the following columns. The coefficient of determination, denoted by the "R^2" column, measures how well the model's forecasts match the data. Higher R^2 values signify a stronger correlation between predictions and actual values. The "MAE" column represents the MAE, which quantifies the average magnitude of prediction errors, as opposed to this, the "RMSE" column displays the root mean square error, which calculates the average magnitude of prediction mistakes and gives larger errors more weight. As we analyze the table, we observe trends in the performance metrics

Table 13: ANN model for GP-based concrete [203]

No. of hidden layers	No. of neurons in left side	No. of neurons in right side	R^2	MAE (MPa)	RMSE (MPa)
1	5	0	0.9846	1.6313	2.0347
1	6	0	0.9851	1.6326	2.028
1	7	0	0.9848	1.6772	2.0664
1	8	0	0.9869	1.4545	1.8039
1	**9**	**0**	**0.9892**	**1.2531**	**1.6056**
1	10	0	0.9824	1.7112	2.1077
1	11	0	0.9876	1.425	1.7442
1	12	0	0.9871	1.4324	1.7398
2	4	4	0.9733	2.1615	2.6982
2	5	5	0.9737	2.1551	2.6906
2	6	6	0.9745	2.1046	2.6346
2	7	7	0.9696	2.2522	2.8383
2	8	8	0.9765	2.0766	2.5582

Bold value shows the best performing ANN model out of all others.

based on the different configurations. For instance, the R^2 values range from approximately 0.9696 to 0.9892, indicating a relatively high degree of correlation between predictions and actual values across various settings. Similarly, the MAE and RMSE values provide insights into the average error magnitudes, with lower values indicating better predictive accuracy. In summary, Table 13 serves as a comprehensive guide to understanding how different combinations of hidden layers and neurons impact the ANN model's ability to predict properties of GP-based concrete. Researchers can use this table to select optimal configurations that yield the highest levels of accuracy and precision in predictions, enhancing the model's reliability and utility in practical applications.

4.9.4 SVMs

SVMs are robust machine learning models used to predict material behaviors in glass-based cementitious composites. Employing a classification algorithm, SVM determines an optimal hyperplane for segregating data points into distinct classes. In the realm of these composites, SVM proves valuable for forecasting whether a composite meets specific performance criteria based on its composition and microstructure. Researchers gather experimental data on diverse glass-based cementitious composites, encompassing attributes like glass content, cement type, curing conditions, and mechanical measurements. SVM endeavors to identify a hyperplane that maximizes separation between classes, ensuring robustness and precision. Trained SVMs classify new composites based on input features, estimating factors such as load-bearing strength and durability against environmental effects. SVM's adaptability accommodates various classification tasks, enabling exploration of different performance standards. Its capability to manage multiple features facilitates analysis of intricate variable-property relationships. Notably, SVM accuracy hinges on quality training data, necessitating continuous data collection and model refinement. With the ability to inform material design and enhance sustainable construction, SVMs and similar machine learning models are instrumental in propelling innovation and bolstering construction material efficiency and resilience.

The compressive strength of concrete cubes has been predicted using the SVM approach. Several statistical indicators, including the coefficient of correlation (CC) and RMSE, were used to evaluate the efficacy of this strategy. The coefficient of correlation is shown in Eq. (3) as CC. In a dataset of "n" paired observations, this statistical measure evaluates the magnitude and direction of the linear connection between two variables, denoted as "x" and "y," inside the dataset. The equation involves calculating the covariance between the deviations of the paired observations from their respective means, and then normalizing it by the product of the standard deviations of the two variables. With values ranging from −1 to +1, CC assesses how closely the different permutations of "x" and "y" align. Greater values of "x" correlate with greater values of "y," and vice versa. A positive number denotes a positive connection. Conversely, a negative value indicates an inverse correlation, while a value close to zero suggests a weak or no linear correlation between the variables.

RMSE, sometimes known as Eq. (4), is a statistical concept. It serves as a gauge for the average size of the discrepancies between observed ("x") and projected ("y") values. This metric provides insight into the overall accuracy of a predictive model or method. The equation involves squaring the differences between observed and predicted values, averaging these squared differences, and then taking the square root of the result. RMSE gives a sense of how well a predictive model's outcomes align with actual observations. Lower values of RMSE indicate a smaller average prediction error, reflecting a higher level of accuracy in the predictions. In the context of assessing predictive models for concrete properties, like compressive strength, RMSE provides a quantitative measure of the model's performance, enabling researchers to gauge how closely their predictions match the real-world data.

$$\mathrm{CC} = \frac{\sum_{i=1}^{n}(x_i - \bar{x}_i)(y_i - \bar{y}_i)}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x}_i)^2(y_i - \bar{y}_i)^2}}. \quad (3)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}. \quad (4)$$

In this case, x_i and y_i stand for the experimental and anticipated compressive strengths of the WGP concrete, respectively. n denotes the total number of data points included in the model, and $\bar{x}_i$ and $\bar{y}_i$ stands for the mean experimental and projected compressive strength, respectively.

4.9.5 Comparison of models

The comparison of different prediction models for glass-based cementitious composites highlights their diverse approaches for forecasting material properties. These models play a pivotal role in optimizing composite design, production, and application, ultimately contributing to sustainable construction practices. Machine learning models, statistical analyses, and computational simulations are commonly utilized to develop prediction models. The effectiveness of three well-known machine learning models, SVMs, RF, and ANN, in predicting the strength of RAC including WG particles was specifically examined in this study.

Linear regression model offers insights into the linear relationship between GP percentage and concrete properties. It employs optimization techniques to determine parameter influence on compressive strength, optimizing error squares *via* Solver in Excel. The relationship between expected and actual compressive strengths for typical concrete mixes with WG particles is shown graphically in Figure 36. R^2, RMSE, and MAE are evaluation measures that show how well the model performs. For both training and testing data, the LR model displays an error line of around ±25%, slightly underestimating high-strength concrete and overestimating low-strength concrete. NLR model captures the complex, nonlinear relationship between GP content and concrete properties. Figure 37 showcases the model's equation and its accuracy evaluation. The analysis reveals an error line within ±20% for training data and error margins of −15 to +20% for testing and validation datasets. This model provides accurate insights into real-world behavior. ANNs simulate the human brain's structure to predict material behaviors. Trained on extensive experimental data, ANN uncovers intricate links between input parameters and material properties. ANN's architecture, training process, and predictive power are detailed. Figure 38 illustrates a comparative analysis of ANN's predictive accuracy against other models. The error line is notably smaller than ±25%, indicating higher predictive accuracy. Table 13 further dissects ANN's predictive performance by exploring various configurations of hidden layers and neurons. The table provides a comprehensive view of R^2, MAE, and RMSE values for different setups, aiding researchers in selecting optimal configurations for accurate predictions. SVMs employ a classification algorithm to predict material behaviors. SVM determines an optimal hyperplane for classifying data points. Statistical indicators like the CC and RMSE are used in SVM's application for the prediction of compressive strength. Based on experimental and predicted results for WGP concrete compressive strength, these measures determine the prediction accuracy.

The ANN exhibits superior dependability in comparison to the other proposed models, according to the computed R^2, MAE, and RMSE values shown in Figures 39–42. Specifically, the R^2 value in the ANN model surpassed that of the regression model by 6% and exceeded the NLR by 5.7%. Compared to the regression model and the NLR, the RMSE value in the ANN model was significantly lower at 91.8 and 88.8%, respectively. Similar to how the MAE value in the ANN model significantly improved, being 87.2% lower than the NLR and 92.8% lower than the regression model. The ANN model's objective (OBJ) value was 95.8 and 89.6%, respectively, less than those of the LR and NLR models. Additionally, as shown in Figure 43, the SI value of the ANN model was within the desirable range of 0–0.1, suggesting outstanding performance.

In summary, these models offer distinct approaches for predicting material properties in glass-based cementitious composites, catering to different complexities and nuances of the relationship between input parameters

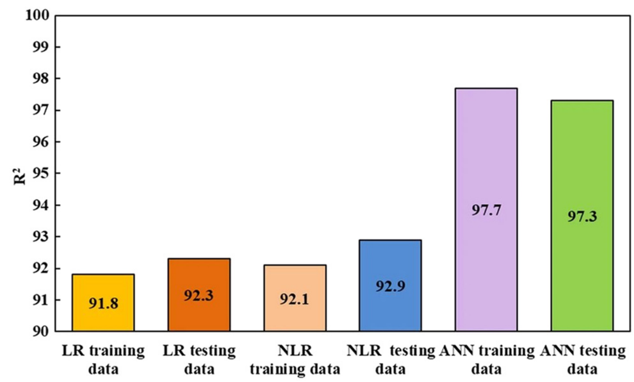

Figure 39: R^2 value for three proposed models [203].

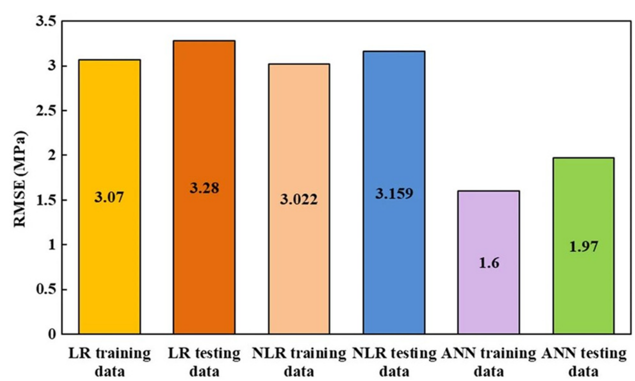

Figure 40: RMSE value for proposed models [203].

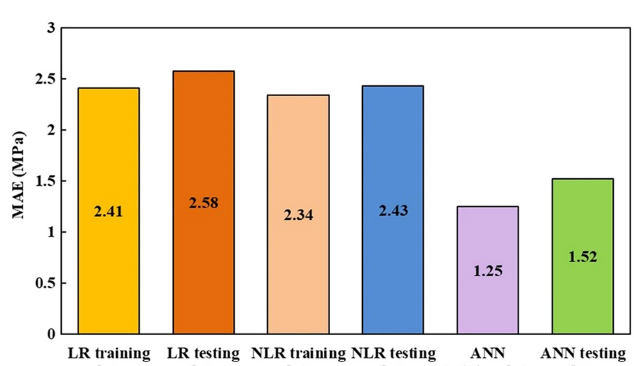

Figure 41: MAE value for proposed models [203].

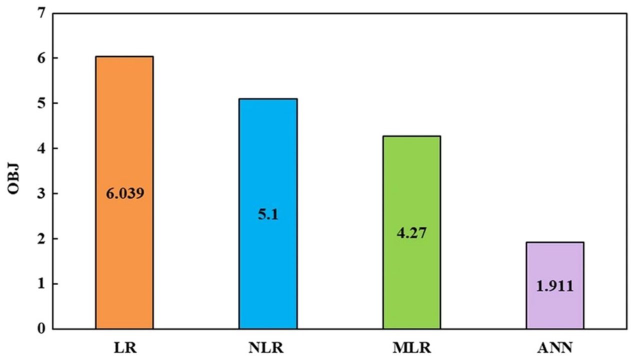

Figure 42: OBJ value for proposed models [203].

and material behavior. Researchers can leverage these models to make informed decisions during composite design, ensuring that the performance meets specific criteria while advancing sustainable construction practices.

4.10 Applications and challenges

Glass-based cementitious composites hold immense potential for various applications in sustainable construction. They have special qualities that can improve infrastructure's performance and lifetime while minimizing environmental effect. However, the adoption of these composites also comes with certain challenges that must be addressed to ensure their successful implementation.

4.10.1 Applications

Glass-based cementitious composites offer a wide range of applications in sustainable construction, showcasing their versatility and potential to revolutionize the industry. One of the main uses is the creation of high-performance concrete, where these composites improve the mechanical characteristics, such as compressive and flexural strength, which makes them perfect for load-bearing components in crucial infrastructure [204]. Additionally, their use as sustainable construction materials stands out, as they help alleviate the burden of glass waste disposal and reduce reliance on traditional cement, contributing to a greener environment. The enhanced durability of glass-based cementitious composites makes them suitable for aggressive environments like marine structures, where they resist chemical attack and ASR more effectively [108]. Moreover, incorporating these composites in the manufacturing of lightweight and insulating panels improves building energy efficiency and reduces carbon emissions. Their compatibility with prefabricated elements streamlines construction processes, reducing time and costs. As research and technology continue to advance, new applications are continually being explored, solidifying the position of glass-based cementitious composites as an innovative and sustainable solution in modern construction.

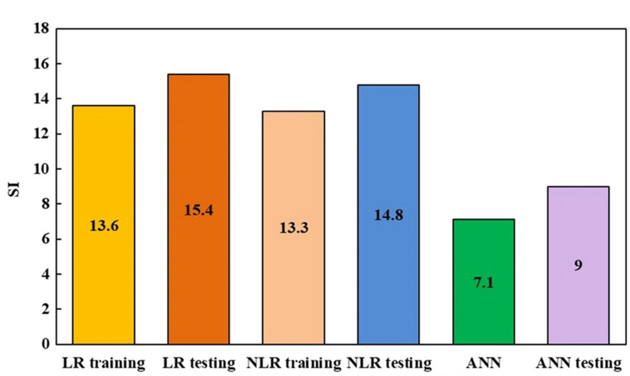

Figure 43: SI value for proposed models [203].

Table 14 provides an overview of the applications of glass-based cementitious composites in sustainable construction. Each application is described, along with its associated advantages and real-world projects where these composites have been used. High-performance concrete utilizes these composites to enhance mechanical properties in load-bearing structures like high-rise buildings and bridges, improving structural integrity. They are also employed as sustainable construction materials, utilizing WG to promote resource conservation and reduce environmental impact in projects such as green buildings and eco-friendly developments. Glass-based cementitious composites exhibit enhanced durability, making them ideal for use in coastal structures and wastewater facilities, where they resist chemical attack and environmental factors, prolonging the service life of these structures. Incorporating these composites in lightweight and insulating panels improves energy efficiency and reduces carbon emissions in buildings, while their application in prefabricated elements streamlines construction processes, leading to faster and cost-effective construction, particularly in modular construction projects. Overall, Table 13 showcases the versatility and potential of glass-based cementitious composites to address various construction needs, contributing to greener and more resilient infrastructure. The real-world projects mentioned demonstrate the practicality and success of using these composites in actual construction scenarios, emphasizing their growing importance in sustainable and high-performance building practices.

Table 14: Applications for glass-based cementitious composites

Application	Description	Advantages	Projects	Ref.
High-performance concrete	Enhances mechanical properties for load-bearing elements in critical structures like high-rise buildings and bridges, improving structural integrity	Increased structural integrity	High-rise buildings, bridges	[205]
Sustainable construction materials	Utilizes WG to promote sustainability and reduce environmental impact, contributing to resource conservation in projects such as green buildings and eco-friendly developments	Resource conservation	Green buildings, eco-friendly projects	[206]
Enhanced durability	Suitable for aggressive environments like coastal structures and wastewater facilities, where it resists chemical attack and environmental factors, prolonging the service life of these structures	Longer service life	Coastal structures, wastewater facilities	[207]
Lightweight and insulating panels	Improves energy efficiency and reduces carbon emissions in buildings	Reduced construction weight	Energy-efficient buildings, insulation panels	[208]
Prefabricated elements	Streamlines construction processes and reduces time and costs, particularly in modular construction projects	Faster construction	Modular construction projects	[209]

4.10.2 Challenges

The adoption of glass-based cementitious composites in sustainable construction presents several challenges that need careful consideration and innovative solutions [210]. It is crucial to ensure the performance and durability of these composites over the long term, which necessitates careful study and testing to determine how they respond to a range of loading situations and environmental factors. Standardization and the development of codes specific to these materials are crucial to ensure consistent quality and safety standards. Handling and processing WG during manufacturing can be complex, necessitating the development of efficient and cost-effective production processes. Maintaining quality control is essential to prevent variations in material properties [211]. The initial cost of glass-based cementitious composites may pose a barrier to their adoption, making it imperative to demonstrate their long-term benefits and cost-effectiveness. Integrating these composites into existing design practices may require adjustments, and promoting public perception and acceptance of new materials is essential. Additionally, establishing a robust recycling and circular economy infrastructure is vital to ensure a consistent supply of WG. Continued research and development efforts will further enhance their performance and sustainability. The integration of glass-based cementitious composites into mainstream construction will be speeded up by addressing these issues through cooperation between researchers, industry experts, and policymakers, leading to the development of future infrastructure that is more environmentally friendly and robust [212].

Table 15 provides a comprehensive overview of the challenges associated with the adoption of glass-based cementitious composites in sustainable construction. Every challenge is explained, stressing the most pressing issues that must be resolved to enable the broad application of these cutting-edge materials. As it influences the belief in the material's dependability over time, the first difficulty highlights the significance of assuring the long-term durability and performance of glass-based cementitious composites. Rigorous testing and real-world monitoring are essential to assess its behavior under various environmental conditions and loading scenarios. Another significant challenge lies in establishing standardized testing methods and codes specific to these composites, ensuring consistent quality and safety standards. Collaborating with regulatory authorities will aid in developing and implementing these standards effectively. The complexities involved in handling WG during the manufacturing process pose challenges to production efficiency. Developing

Table 15: Challenges for glass-based cementitious composites

Challenges	Description	Impact on adoption	Mitigation strategies	Ref.
Material performance and longevity	Ensuring long-term durability and performance of glass-based cementitious composites	Affects confidence in material reliability	Rigorous testing and real-world monitoring	[94]
Standardization and codes	Establishing standardized testing methods and codes for these composites	Ensures consistent quality and safety	Collaborate with regulatory authorities	[178]
Material handling and processing	Complexities in handling WG during production	Impacts production efficiency	Develop specialized equipment and processes	[213]
Quality control	Maintaining consistent quality during production	Varied material properties affect outcomes	Robust quality control measures	[214]
Initial cost	Higher initial cost compared to conventional materials	May hinder adoption in budget-constrained projects	Demonstrate long-term cost benefits	[26]
Design flexibility	Integrating these composites into existing design practices	Requires adjustments in construction methods	Collaboration between designers and engineers	[215]
Public perception and acceptance	Public perception and acceptance of new materials incorporating WG	May impact market demand and adoption	Educate stakeholders about benefits	[216]
Recycling and circular economy	Ensuring a consistent supply of WG for production	Reliability of glass waste availability	Promote recycling infrastructure development	[217]
Research and development	Continual research and development to improve performance and sustainability	Advances in material science and technology	Foster innovation and academic collaboration	[218]
Infrastructure and industry transition	Transitioning the construction industry to adopt new materials and practices	Requires significant investment and coordination	Infrastructure development and training	[219]

specialized equipment and processes will streamline the handling and processing of WG. Maintaining consistent quality during production is vital, as material properties may vary. Robust quality control measures are necessary to ensure that the final product meets desired performance standards. Additionally, the higher initial cost of glass-based cementitious composites compared to conventional materials may deter adoption, particularly in budget-constrained projects. Convincing stakeholders of the long-term cost benefits of these composites becomes crucial. Integrating these composites into existing design practices requires collaboration between designers and engineers to fully capitalize on their unique properties. Moreover, public perception and acceptance of new materials incorporating WG can significantly impact their market demand and adoption. Educating stakeholders about the benefits and sustainability aspects of these composites can help overcome resistance to change. Ensuring a consistent supply of WG for production is crucial for the continuous use of these composites, promoting recycling infrastructure development will help maintain a reliable source of WG. Continual research and development are essential to improve the performance and sustainability of glass-based cementitious composites, unlocking their full potential. Finally, transitioning the construction industry to adopt new materials and practices requires significant investment and coordination among stakeholders. Infrastructure development and training programs are vital for successful integration. The potential of glass-based cementitious composites for greener, more resilient, and sustainable infrastructure for the future will be unlocked by addressing these issues through cooperative efforts among researchers, industry experts, and policymakers.

5 Conclusion and future research direction

In this study, a thorough and in-depth debate was undertaken along with a scientometric evaluation of the use of WG in concrete for environmentally friendly construction. The research used a detailed scientometric analysis to evaluate a number of factors, including the most popular fields of study, article publishing patterns, the most important sources, keyword co-occurrence, highly cited papers, and well-known authors. We also looked at the countries that were actively involved in the field of WG usage in concrete for green building. We also carefully considered how adding WG to building materials might affect sustainability. We also carefully assessed how WG affected the performance of cement-based materials. We specifically gave attention to important factors including the composite material's workability, compressive strength, split-tensile strength, flexural strength, and durability. By going through into these aspects, the aim of our study was to provide valuable insights into the use of WG in concrete for sustainable construction, shedding light on its potential benefits and challenges for the construction industry.

The study presents a systematic scientometric review methodology for analyzing WGP-based concrete research. It involves a literature search, data organization, and scientometric analysis using Scopus and VOSviewer to understand the research landscape and identify key contributors in sustainable construction. The scientometric review on WG in concrete provides comprehensive insights into publication trends, subject areas, influential sources, key articles, and prominent keywords related to sustainable construction. The study highlights the increasing research activity, interdisciplinary nature, and significance of engineering and materials science in this field. Notably, "Construction and Building Materials" emerges as the most influential source, and "The Greening of the Concrete Industry" stands out as the most-cited article. Moreover, the review identifies top authors, organizations, and funding sponsors, reflecting global collaboration. As a valuable resource, it aids researchers and policymakers in advancing sustainable practices using WG in concrete. The importance of concrete based on WGP for sustainable construction. By reducing landfill waste and environmental pollution, it offers improved concrete properties and promotes eco-friendly practices. A feasible alternative to cement made of WGP has the potential to make the building sector more environmentally friendly. The limitations of WGP-based concrete, including issues related to glass color, glass sources, and challenges in working with glass. Different glass colors can impact the concrete's performance due to additives and reactions with the cementitious matrix. Glass from various sources affects concrete strength differently, and the sharpness of GP poses challenges in handling. Continuous research and innovation are required to maximize the usage of WG in concrete. A potential sustainable construction option is the use of WG in concrete. Recycling WGP can significantly reduce environmental impact, promote efficient resource use, and decrease landfill waste. By harnessing the pozzolanic properties of GP, concrete's performance can be improved, leading to enhanced durability and strength. In order to ensure correct construction and the caliber of the finished product, it is crucial to consider the fresh state characteristics of WGP-based concrete, including setting time and workability. The addition of GP can lead to increased setting times due to slower reactions and changes in water demand. However, adding more GP will increase the concrete's workability and make it easier to handle. Utilizing WG in concrete production for sustainable construction methods requires a comprehensive understanding and optimization of these qualities. For sustainable construction, using WGP in concrete can greatly improve the material's qualities in the hardened stage. Increased compressive, split tensile, and flexural strengths often come about by the use of GP, with 15% being the ideal replacement proportion. This addition also improves the concrete's durability by reducing permeability, enhancing resistance to chemical attack, ASR, and FT cycles, and decreasing water absorption. The performance of the concrete is further aided by the WGP's pozzolanic activity. For forecasting compressive strength in typical concrete containing WG, the ANN model performed better than other models across a range of statistical parameters.

In conclusion, this scientometric review on WGP-based concrete research provides valuable insights into sustainable construction. WGP has potential as an alternative to cement, offering improved properties and eco-friendly practices. Challenges include glass color impact and handling issues. Nevertheless, utilizing WG in concrete presents a sustainable solution, reducing environmental impact and promoting stronger structures. By optimizing properties and understanding pozzolanic behavior, we can advance sustainable construction practices effectively. Based on the outcomes of this study, the following practical recommendations are proposed to enhance the use of WG in concrete applications.

- Based on the findings of this study, construction and material science industries should consider the integration of WGP in concrete mix designs more aggressively. Regulatory bodies are also recommended to work toward standardizing the use of WG in construction materials, ensuring safety and performance standards are met.
- Further research should focus on the long-term durability of concrete structures incorporating WGP. Specific attention should be paid to the material's behavior under various climatic and environmental stressors over extended periods.
- It is recommended that further studies investigate the optimal particle size of GP for concrete reinforcement. This includes examining the balance between workability, strength, and durability of concrete with varying sizes of glass particles.
- Future projects should include detailed environmental impact assessments comparing traditional concrete and GP-enhanced concrete. This will help quantify the environmental benefits and identify any potential negative impacts.
- Conduct economic feasibility studies to assess the cost implications of using WG in concrete. Such studies should consider the entire lifecycle costs including material processing, transportation, and construction costs, as well as potential savings from longer lifespan and reduced maintenance.
- Encourage the development of specialized concrete mixes that use WG for specific applications such as decorative elements, pavement solutions, and precast structures, which can benefit aesthetically and functionally from the unique properties of glass.
- Increase public awareness and educational efforts about the benefits and practicalities of using WG in concrete. This can be achieved through workshops, seminars, and publications targeted at industry professionals, policymakers, and the general public.

These recommendations aim to propel the utilization of WG in concrete toward more sustainable and environmentally friendly construction practices, backed by research and economic validation. To further advance the field and address current limitations, the following future research directions are proposed.

- Investigate the compatibility of different types of WG with various cementitious materials, focusing on enhancing the mechanical properties and durability. This includes studying the interactions at the microscopic level and understanding how these interactions affect the macroscopic properties of the concrete.
- Conduct comprehensive life cycle assessments to quantify the environmental benefits and potential drawbacks of concrete mixtures that incorporate WG. These assessments should consider all stages from material extraction through manufacturing, use, and disposal to ensure a holistic evaluation of environmental impacts.
- Explore the pozzolanic reactions between WGPs and cement under different environmental conditions and curing processes. This research should aim to optimize the reaction conditions to maximize the strength and durability of the concrete, while minimizing negative environmental impacts.
- Assess the scalability of using WG in concrete production, including detailed cost-benefit analyses that consider the sourcing, processing, and transportation of WG. Economic feasibility studies should also explore potential market barriers and opportunities for commercial adoption.
- Examine the long-term performance of concrete incorporating WG, with a specific focus on its resistance to environmental conditions like FT cycles, sulfate attacks, and other deleterious effects. Studies should also look at the aging process to understand how the properties of concrete change over time with the inclusion of glass.

- Research innovative applications of WGP in concrete, aiming to enhance aesthetic qualities or develop specific functional properties such as improved reflectivity or insulation. This could include the use of colored glass for decorative purposes or the development of specialized concretes that offer better thermal or acoustic properties.
- Study the impact of regulatory frameworks on the adoption of WG in concrete. Work toward the development of standardized guidelines and best practices that facilitate broader acceptance and use in the construction industry. This should also involve collaboration with policy makers to ensure that the guidelines are practical and based on solid research findings.

By addressing these areas, researchers can contribute to the development of more sustainable, durable, and cost-effective concrete solutions, aligning with global sustainability goals.

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/11).

Funding information: This research work was funded by the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding through the project number (IF2/PSAU/2022/RV/11).

Author contributions: 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 analysed during the current study are available from the corresponding author on reasonable request.

References

[1] Asghar, R., M. A. Khan, R. Alyousef, M. F. Javed, and M. Ali. Promoting the green Construction: Scientometric review on the mechanical and structural performance of geopolymer concrete. *Construction and Building Materials*, Vol. 368, 2023, id. 130502.

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

[3] Aliabdo, A. A., A. E. M. Abd Elmoaty, and A. Y. Aboshama. Utilization of waste glass powder in the production of cement and concrete. *Construction and Building Materials*, Vol. 124, 2016, pp. 866–877.

[4] 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. *2nd Conference on Sustainability in Civil Engineering (CSCE'20), Department of Civil Engineering, Capital University of Science and Technology*, Islamabad, Pakistan, 2020, p. 8.

[5] Asghar, R., A. Shahzad, S. U. Amjad, and A. Akhtar. Experimental determination of the mechanical properties of brick masonry and low strength concrete block masonry. *2nd Conference on Sustainability in Civil Engineering CSCE20, Department of Civil Engineering, Capital University of Science and Technology*, Islamabad, Pakistan, 2020, p. 6.

[6] Torres-Carrasco, M., C. Rodríguez-Puertas, M. del Mar Alonso, and F. Puertas. Alkali activated slag cements using waste glass as alternative activators. *Rheological behaviour Boletín de la sociedad española de Ceramica y Vidrio*, Vol. 54, 2015, pp. 45–57.

[7] Li, X. Recycling and reuse of waste concrete in China: Part I. Material behaviour of recycled aggregate concrete. *Resources, Conservation and Recycling*, Vol. 53, 2008, pp. 36–44.

[8] Eštoková, A., M. Wolfová Fabiánová, and M. Ondová. Concrete structures and their impacts on climate change and water and raw material resource depletion. *International Journal of Civil Engineering*, Vol. 20, 2022, pp. 735–747.

[9] Ma, Q., R. Guo, Z. Zhao, Z. Lin, and K. He. Mechanical properties of concrete at high temperature – A review. *Construction and Building Materials*, Vol. 93, 2015, pp. 371–383.

[10] Zhang, H., Y. Zou, E. del Rey Castillo, and X. Yang. Detection of RC spalling damage and quantification of its key properties from 3D point cloud. *KSCE Journal of Civil Engineering*, Vol. 26, 2022, pp. 2023–2035.

[11] Yang, S., X. Gu, Q. Zhang, and X. Xia. Bond-associated non-ordinary state-based peridynamic model for multiple spalling simulation of concrete. *Acta Mechanica Sinica*, Vol. 37, 2021, pp. 1104–1135.

[12] Hawkins, A. The grey wall of China: Inside the world's concrete superpower. *The Guardian*, Vol. 28, 2019.

[13] Tian, F., Z. Liu, J. Zhou, L. Chen, and X.T. Feng. Quantifying Post-peak Behavior of Rocks with Type-I, Type-II, and Mixed Fractures by Developing a Quasi-State-Based Peridynamics. *Rock Mechanics and Rock Engineering*, Vol. 57, 2024, pp. 4835–4871.

[14] Bildirici, M. E. Cement production, environmental pollution, and economic growth: evidence from China and USA. *Clean Technologies and Environmental Policy*, Vol. 21, 2019, pp. 783–793.

[15] Akhtar, M. N., M. Jameel, Z. Ibrahim, and N. M. Bunnori. Incorporation of recycled aggregates and silica fume in concrete: an environmental savior-a systematic review. *Journal of Materials Research and Technology*, Vol. 20, 2022, pp. 4525–4544.

[16] Nodehi, M. and V. Mohamad Taghvaee. Sustainable concrete for circular economy: a review on use of waste glass. *Glass Structures & Engineering*, Vol. 7, 2022, pp. 3–22.

[17] Liu, G., M. V. A. Florea, and H. J. H. Brouwers. Characterization and performance of high volume recycled waste glass and ground granulated blast furnace slag or fly ash blended mortars. *Journal of Cleaner Production*, Vol. 235, 2019, pp. 461–472.

[18] Ruth, M. and P. Dell'Anno. An industrial ecology of the US glass industry. *Resources Policy*, Vol. 23, 1997, pp. 109–124.

[19] EID, J. Glass is the hidden gem in a carbon-neutral future. *Nature*, Vol. 599, 2021, id. 7.

[20] Alyousef, R., M. Fawad, F. Farooq, Y. Gamil, and T. Najeh. Predicting the properties of concrete incorporating graphene nano platelets by experimental and machine learning approaches. *Case Studies in Construction Materials*, Vol. 20, 2024, id. e03018.
[21] Sundaram, S. S., N. H. Basker, and L. Natrayan. Smart clothes with bio-sensors for ECG monitoring. *The International Journal of Innovative Technology and Exploring Engineering*, Vol. 8, 2019, pp. 298–301.
[22] Jani, Y. and W. Hogland. Waste glass in the production of cement and concrete – A review. *Journal of Environmental Chemical Engineering*, Vol. 2, 2014, pp. 1767–1775.
[23] Guo, P., W. Meng, H. Nassif, H. Gou, and Y. Bao. New perspectives on recycling waste glass in manufacturing concrete for sustainable civil infrastructure. *Construction and Building Materials*, Vol. 257, 2020, id. 119579.
[24] Bhat, V. V. and N. B. Rao. Influence of glass powder on the properties of concrete. *International Journal of Engineering Trends and Technology*, Vol. 16, 2014, pp. 196–199.
[25] Hoang, N.-D., T.-C. Huynh, and V.-D. Tran. Concrete spalling severity classification using image texture analysis and a novel jellyfish search optimized machine learning approach. *Advancements in Civil Engineering*, Vol. 2021, No. 1, 2021, id. 5551555.
[26] Najaf, E. and H. Abbasi. Using recycled concrete powder, waste glass powder, and plastic powder to improve the mechanical properties of compacted concrete: cement elimination approach. *Advancements in Civil Engineering*, Vol. 2022, No. 1, 2022, id. 9481466.
[27] Miraldo, S., S. Lopes, F. Pacheco-Torgal, and A. Lopes. Advantages and shortcomings of the utilization of recycled wastes as aggregates in structural concretes. *Construction and building materials*, Vol. 298, 2021, id. 123729.
[28] Nasier, S. Utilization of recycled form of concrete, E-wastes, glass, quarry rock dust and waste marble powder as reliable construction materials. *Materials Today: Proceedings*, Vol. 45, 2021, pp. 3231–3234.
[29] Lu, J.-X., X. Yan, P. He, and C. S. Poon. Sustainable design of pervious concrete using waste glass and recycled concrete aggregate. *Journal of Cleaner Production*, Vol. 234, 2019, pp. 1102–1112.
[30] Ahmad, J., Z. Zhou, and R. Martínez-García. A study on the microstructure and durability performance of rubberized concrete with waste glass as binding material. *Journal of Building Engineering*, Vol. 49, 2022, id. 104054.
[31] Ogundairo, T. O., D. D. Adegoke, I. I. Akinwumi, and O. M. Olofinnade. Sustainable use of recycled waste glass as an alternative material for building construction–A review. *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2019, p. 012073.
[32] Qaidi, S., H. M. Najm, S. M. Abed, Y. O. Özkılıç, H. Al Dughaishi, M. Alosta, et al. Concrete containing waste glass as an environmentally friendly aggregate: A review on fresh and mechanical characteristics. *Materials*, Vol. 15, 2022, id. 6222.
[33] Perez, O. F. A., D. R. Florez, L. M. Z. Vergara, and K. V. H. Benavides. Innovative use of agro-waste cane bagasse ash and waste glass as cement replacement for green concrete. Cost analysis and carbon dioxide emissions. *Journal of Cleaner Production*, Vol. 379, 2022, id. 134822.
[34] Ekop, I. E., C. J. Okeke, and E. V. Inyang. Comparative study on recycled iron filings and glass particles as a potential fine aggregate in concrete. *Resources, Conservation & Recycling Advances*, Vol. 15, 2022, id. 200093.
[35] Stefanidou, M., F. Kesikidou, S. Konopisi, and T. Vasiadis. Investigating the suitability of waste glass as a supplementary binder and aggregate for cement and concrete. *Sustainability*, Vol. 15, 2023, id. 3796.
[36] Gebremichael, N. N., K. Jadidi, and M. Karakouzian. Waste glass recycling: The combined effect of particle size and proportion in concrete manufactured with waste recycled glass. *Construction and Building Materials*, Vol. 392, 2023, id. 132044.
[37] Graziano, S. F., C. Zanelli, C. Molinari, B. De Gennaro, G. Giovinco, C. Correggia, et al. Use of screen glass and polishing sludge in waste-based expanded aggregates for resource-saving lightweight concrete. *Journal of Cleaner Production*, Vol. 332, 2022, id. 130089.
[38] Ahmad, J., R. Martínez-García, J. de-Prado-Gil, K. Irshad, M. A. El-Shorbagy, R. Fediuk, et al. Concrete with partial substitution of waste glass and recycled concrete aggregate. *Materials*, Vol. 15, 2022, id. 430.
[39] Zeybek, Ö., Y. O. Özkılıç, M. Karalar, A. İ. Çelik, S. Qaidi, J. Ahmad, et al. Influence of replacing cement with waste glass on mechanical properties of concrete. *Materials*, Vol. 15, 2022, id. 7513.
[40] Çelik, A. İ., U. Tunç, A. Bahrami, M. Karalar, M. A. O. Mydin, T. Alomayri, et al. Use of waste glass powder toward more sustainable geopolymer concrete. *Journal of Materials Research and Technology*, Vol. 24, 2023, pp. 8533–8546.
[41] Aslam, F., O. Zaid, F. Althoey, S. H. Alyami, S. M. Qaidi, J. de Prado Gil, et al. Evaluating the influence of fly ash and waste glass on the characteristics of coconut fibers reinforced concrete. *Structural Concrete*, Vol. 24, 2023, pp. 2440–2459.
[42] Najaf, E., M. Orouji, and S. M. Zahrai. Improving nonlinear behavior and tensile and compressive strengths of sustainable lightweight concrete using waste glass powder, nanosilica, and recycled polypropylene fiber. *Nonlinear Engineering*, Vol. 11, 2022, pp. 58–70.
[43] Muthukannan, M. and A. Kumar. Influence of incinerated biomedical waste ash and waste glass powder on the mechanical and flexural properties of reinforced geopolymer concrete. *Australian Journal of Structural Engineering*, 2022.
[44] Tahwia, A. M., A. M. Heniegal, M. Abdellatief, B. A. Tayeh, and M. Abd Elrahman. Properties of ultra-high performance geopolymer concrete incorporating recycled waste glass. *Case Studies in Construction Materials*, Vol. 17, 2022, id. e01393.
[45] Çelik, A. İ., Y. O. Özkılıç, Ö. Zeybek, M. Karalar, S. Qaidi, J. Ahmad, et al. Mechanical behavior of crushed waste glass as replacement of aggregates. *Materials*, Vol. 15, 2022, id. 8093.
[46] Hamada, H., A. Alattar, B. Tayeh, F. Yahaya, and B. Thomas. Effect of recycled waste glass on the properties of high-performance concrete: A critical review. *Case Studies in Construction Materials*, Vol. 17, 2022, id. e01149.
[47] Redondo-Mosquera, J. D., D. Sánchez-Angarita, M. Redondo-Pérez, J. C. Gómez-Espitia, and J. Abellan-Garcia. Development of high-volume recycled glass ultra-high-performance concrete with high C3A cement. *Case Studies in Construction Materials*, Vol. 18, 2023, id. e01906.
[48] Chadegani, A. A., H. Salehi, M. M. Yunus, H. Farhadi, M. Fooladi, M. Farhadi, et al. A comparison between two main academic

literature collections: web of science and scopus databases. *Asian Journal of Social Science*, Vol. 9, 2013, id. p18.

[49] Markoulli, M. P., C. I. S. G. Lee, E. Byington, and W. A. Felps. Mapping human resource management: reviewing the field and charting future directions. *The Human Resource Management Review*, Vol. 27, 2017, pp. 367–396.

[50] Qin, D., Y. Hu, and X. Li. Waste glass utilization in cement-based materials for sustainable construction: a review. *Crystals*, Vol. 11, 2021, id. 710.

[51] Meyer, C. The greening of the concrete industry. *Cement and Concrete Composites*, Vol. 31, 2009, pp. 601–605.

[52] Shao, Y., T. Lefort, S. Moras, and D. Rodriguez. Studies on concrete containing ground waste glass. *Cement and Concrete Research*, Vol. 30, 2000, pp. 91–100.

[53] Batayneh, M., I. Marie, and I. Asi. Use of selected waste materials in concrete mixes. *Waste management (New York, NY)*, Vol. 27, 2007, pp. 1870–1876.

[54] Shayan, A. and A. Xu. Value-added utilisation of waste glass in concrete. *Cement and Concrete Research*, Vol. 34, 2004, pp. 81–89.

[55] Topcu, I. B. and M. Canbaz. Properties of concrete containing waste glass. *Cement and Concrete Research*, Vol. 34, 2004, pp. 267–274.

[56] Shi, C. and K. Zheng. A review on the use of waste glasses in the production of cement and concrete. *Resources, Conservation and Recycling*, Vol. 52, 2007, pp. 234–247.

[57] Park, S. B., B. C. Lee, and J. H. Kim. Studies on mechanical properties of concrete containing waste glass aggregate. *Cement and Concrete Research*, Vol. 34, 2004, pp. 2181–2189.

[58] Shayan, A. and A. Xu. Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs. *Cement and Concrete Research*, Vol. 36, 2006, pp. 457–468.

[59] Tam, V. W. Y. and C. M. Tam. A review on the viable technology for construction waste recycling. *Resources, Conservation and Recycling*, Vol. 47, 2006, pp. 209–221.

[60] Arulrajah, A., J. Piratheepan, M. M. Disfani, and M. W. Bo. Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. *Journal of Materials in Civil Engineering*, Vol. 25, 2013, pp. 1077–1088.

[61] Ismail, Z. Z. and E. A. Al-Hashmi. Recycling of waste glass as a partial replacement for fine aggregate in concrete. *Waste Management (New York, NY)*, Vol. 29, 2009, pp. 655–659.

[62] Paris, J. M., J. G. Roessler, C. C. Ferraro, H. D. DeFord, and T. G. Townsend. A review of waste products utilized as supplements to Portland cement in concrete. *Journal of Cleaner Production*, Vol. 121, 2016, pp. 1–18.

[63] Islam, G. M. S., M. H. Rahman, and N. Kazi. Waste glass powder as partial replacement of cement for sustainable concrete practice. *International Journal of Sustainable Built Environment*, Vol. 6, 2017, pp. 37–44.

[64] Soroushian, P. Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement. *Construction and Building Materials*, Vol. 29, 2012, pp. 368–377.

[65] Puertas, F. and M. Torres-Carrasco. Use of glass waste as an activator in the preparation of alkali-activated slag. Mechanical strength and paste characterisation. *Cement and Concrete Research*, Vol. 57, 2014, pp. 95–104.

[66] 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.

[67] Matos, A. M. and J. Sousa-Coutinho. Durability of mortar using waste glass powder as cement replacement. *Construction and Building Materials*, Vol. 36, 2012, pp. 205–215.

[68] Torres-Carrasco, M. and F. Puertas. Waste glass in the geopolymer preparation. Mechanical and microstructural characterisation. *Journal of Cleaner Production*, Vol. 90, 2015, pp. 397–408.

[69] Bajad, M. N., C. D. Modhera, and A. K. Desai. Effect of glass on strength of concrete subjected to sulphate attack. *International Journal of Civil Engineering Research and Development*, Vol. 1, No. 2, 2011.

[70] Mansour, M. A., M. H. B. Ismail, Q. B. Alias Imran Latif, A. F. Alshalif, A. Milad, and W. A. A. Bargi. A systematic review of the concrete durability incorporating recycled glass. *Sustainability*, Vol. 15, 2023, id. 3568.

[71] Kim, J., J.-H. Moon, J. W. Shim, J. Sim, H.-G. Lee, and G. Zi. Durability properties of a concrete with waste glass sludge exposed to freeze-and-thaw condition and de-icing salt. *Construction and Building Materials*, Vol. 66, 2014, pp. 398–402.

[72] Federico, L. M. and S. E. Chidiac. Waste glass as a supplementary cementitious material in concrete – Critical review of treatment methods. *Cement and Concrete Composites*, Vol. 31, 2009, pp. 606–610.

[73] Shekhawat, B. S. and D. V. Aggarwal. Utilisation of waste glass powder in concrete–A literature review. *International Journal of Innovative Science Engineering and Technology*, Vol. 3, No. 7, 2014.

[74] Khatib, J. M., E. M. Negim, H. S. Sohl, and N. Chileshe. Glass powder utilisation in concrete production. *European Journal of Applied Sciences*, Vol. 4, 2012, pp. 173–176.

[75] Rashad, A. M. Recycled waste glass as fine aggregate replacement in cementitious materials based on Portland cement. *Construction and Building Materials*, Vol. 72, 2014, pp. 340–357.

[76] Du, H. and K. H. Tan. Waste glass powder as cement replacement in concrete. *Journal of Advanced Concrete Technology*, Vol. 12, 2014, pp. 468–477.

[77] Li, A., H. Qiao, Q. Li, T. Hakuzweyezu, and B. Chen. Study on the performance of pervious concrete mixed with waste glass powder. *Construction and Building Materials*, Vol. 300, 2021, id. 123997.

[78] Waste Glass Powder as Cement Replacement in Concrete, (n.d.). https://www.jstage.jst.go.jp/article/jact/12/11/12_468/_article (accessed June 12, 2023).

[79] Vandhiyan, R., K. Ramkumar, and R. Ramya. Experimental study on replacement of cement by glass powder. *International Journal of Engineering Research and Technology*, Vol. 2, 2013, pp. 234–238.

[80] Mahmoud, S. S., S. M. Hama, and A. S. Mahmoud. Predicting strength criteria of hardened concrete containing waste glass powder. *The 15th International Conference on the Developments in eSystems Engineering*, IEEE, 2023, pp. 417–421.

[81] Gokulakannan, S., P. Mukesh, M. Anitha, S. A. Sri, G. D. Kumar, and V. Vijayakumar. Experimentation on the impact of partial replacement of cement with glass powder in mortar mixture. *Materials Today: Proceedings*, Vol. 68, 2022, pp. 1628–1634.

[82] Jiang, Y., T.-C. Ling, K. H. Mo, and C. Shi. A critical review of waste glass powder – Multiple roles of utilization in cement-based materials and construction products. *Journal of Environmental Management*, Vol. 242, 2019, pp. 440–449.

[83] Mahmood, A. H., S. Afroz, A. Kashani, T. Kim, and S. J. Foster. The efficiency of recycled glass powder in mitigating the alkali-silica reaction induced by recycled glass aggregate in cementitious mortars. *Materials and Structures*, Vol. 55, 2022, id. 156.

[84] Xiao, R., B. Huang, H. Zhou, Y. Ma, and X. Jiang. A state-of-the-art review of crushed urban waste glass used in OPC and AAMs (geopolymer): Progress and challenges. *Cleaner Materials*, Vol. 4, 2022, id. 100083.

[85] Tahwia, A. M., A. Essam, B. A. Tayeh, and M. Abd Elrahman. Enhancing sustainability of ultra-high performance concrete utilizing high-volume waste glass powder. *Case Studies in Construction Materials*, Vol. 17, 2022, id. e01648.

[86] Asadi, I., M. H. Baghban, M. Hashemi, N. Izadyar, and B. Sajadi. Phase change materials incorporated into geopolymer concrete for enhancing energy efficiency and sustainability of buildings: a review. *Case Studies in Construction Materials*, Vol. 17, 2022, id. e01162.

[87] Lu, J., Z. Duan, and C. S. Poon. Combined use of waste glass powder and cullet in architectural mortar. *Cement and Concrete Composites*, Vol. 82, 2017, pp. 34–44.

[88] Najaf, E., H. Abbasi, and S. M. Zahrai. Effect of waste glass powder, microsilica and polypropylene fibers on ductility, flexural and impact strengths of lightweight concrete. *International Journal of Structural Integrity*, Vol. 13, 2022, pp. 511–533.

[89] Soliman, N. A. and A. Tagnit-Hamou. Partial substitution of silica fume with fine glass powder in UHPC: Filling the micro gap. *Construction and Building Materials*, Vol. 139, 2017, pp. 374–383.

[90] Vinai, R. and M. Soutsos. Production of sodium silicate powder from waste glass cullet for alkali activation of alternative binders. *Cement and Concrete Research*, Vol. 116, 2019, pp. 45–56.

[91] de Castro, S. and J. de Brito. Evaluation of the durability of concrete made with crushed glass aggregates. *Journal of Cleaner Production*, Vol. 41, 2013, pp. 7–14.

[92] Bilgen, G. and O. F. Altuntas. Sustainable re-use of waste glass, cement and lime treated dredged material as pavement material. *Case Studies in Construction Materials*, Vol. 18, 2023, id. e01815.

[93] Rakshvir, M. and S. V. Barai. Studies on recycled aggregates-based concrete. *Waste Management and Research*, Vol. 24, 2006, pp. 225–233.

[94] Jiang, X., R. Xiao, Y. Bai, B. Huang, and Y. Ma. Influence of waste glass powder as a supplementary cementitious material (SCM) on physical and mechanical properties of cement paste under high temperatures. *Journal of Cleaner Production*, Vol. 340, 2022, id. 130778.

[95] Heriyanto, F. and V. S. Pahlevani. From waste glass to building materials – An innovative sustainable solution for waste glass. *Journal of Cleaner Production*, Vol. 191, 2018, pp. 192–206.

[96] Ling, T.-C. and C.-S. Poon. Feasible use of recycled CRT funnel glass as heavyweight fine aggregate in barite concrete. *Journal of Cleaner Production*, Vol. 33, 2012, pp. 42–49.

[97] Liang, S., X. Zhou, S. Ruan, G. Kastiukas, and Y. Sun. Milled waste glass powder in magnesium-silicate-hydrate cement: technical and environmental assessment. *Journal of Materials in Civil Engineering*, Vol. 35, 2023, id. 04022379.

[98] Ramadan, M., S. M. A. El-Gamal, and F. A. Selim. Mechanical properties, radiation mitigation and fire resistance of OPC-recycled glass powder composites containing nanoparticles. *Construction and Building Materials*, Vol. 251, 2020, id. 118703.

[99] Soroushian, P. and M. Sufyan-Ud-Din. Long-term field performance of concrete produced with powder waste glass as partial replacement of cement. *Case Studies in Construction Materials*, Vol. 15, 2021, id. e00745.

[100] Sonat, C. and C. Unluer. Development of magnesium-silicate-hydrate (M-S-H) cement with rice husk ash. *Journal of Cleaner Production*, Vol. 211, 2019, pp. 787–803.

[101] Ahmad, J., R. Martinez-Garcia, S. Algarni, J. de-Prado-Gil, T. Alqahtani, and K. Irshad. Characteristics of sustainable concrete with partial substitutions of glass waste as a binder material. *The Eurasian Journal of Science and Engineering*, Vol. 16, 2022, id. 21.

[102] Mohammed, I. I., N. Abdul Nariman, K. Othman Ahmed, S. Ali, P. Mohammed, and S. Samad. Utilization of waste plastic and waste glass together as fine and coarse aggregate in concrete. *The Eurasian Journal of Science and Engineering*, Vol. 6, 2020, pp. 1–10.

[103] Belouadah, M., Z. E. A. Rahmouni, and N. Tebbal. Experimental characterization of ordinary concretes obtained by adding construction waste (glass, marble). *Procedia Computer Science*, Vol. 158, 2019, pp. 153–162.

[104] Chen, D. L., J. W. Zhao, and S. R. Qin. SVM strategy and analysis of a three-phase quasi-Z-source inverter with high voltage transmission ratio. *Science China: Technological Sciences*, Vol. 66, 2023, pp. 2996–3010.

[105] Rashidian-Dezfouli, H. and P. R. Rangaraju. A comparative study on the durability of geopolymers produced with ground glass fiber, fly ash, and glass-powder in sodium sulfate solution. *Construction and Building Materials*, Vol. 153, 2017, pp. 996–1009.

[106] Xie, G., B. Fu, H. Li, W. Du, Y. Zhong, L. Wang, et al. A gradient-enhanced physics-informed neural networks method for the wave equation. *Engineering Analysis with Boundary Elements*, Vol. 166, 2024.

[107] Liu, Y., C. Shi, Z. Zhang, and N. Li. An overview on the reuse of waste glasses in alkali-activated materials. *Resources, Conservation and Recycling*, Vol. 144, 2019, pp. 297–309.

[108] Cui, D., L. Wang, C. Zhang, H. Xue, D. Gao, and F. Chen. Dynamic splitting performance and energy dissipation of fiber-reinforced concrete under impact loading. *Materials (Basel)*, Vol. 17, 2024.

[109] Abellan-Garcia, J., M. I. Khan, Y. M. Abbas, V. Martínez-Lirón, and J. S. Carvajal-Muñoz. The drying shrinkage response of recycled-waste-glass-powder-and calcium-carbonate-based ultrahigh-performance concrete. *Construction and Building Materials*, Vol. 379, 2023, id. 131163.

[110] Jain, K. L., G. Sancheti, and L. K. Gupta. Durability performance of waste granite and glass powder added concrete. *Construction and Building Materials*, Vol. 252, 2020, id. 119075.

[111] Ibrahim, K. I. M. Recycled waste glass powder as a partial replacement of cement in concrete containing silica fume and fly ash. *Case Studies in Construction Materials*, Vol. 15, 2021, id. e00630.

[112] Xin, J., W. Xu, B. Cao, T. Wang, and S. Zhang. *A deep-learning-based MAC for integrating channel access, rate adaptation and channel switch*, 2024. http://arxiv.org/abs/2406.02291, accessed July 13, 2024.

[113] Gorospe, K., E. Booya, H. Ghaednia, and S. Das. Effect of various glass aggregates on the shrinkage and expansion of cement mortar. *Construction and Building Materials*, Vol. 210, 2019, pp. 301–311.

[114] Meng, S., F. Meng, H. Chi, H. Chen, and A. Pang. A robust observer based on the nonlinear descriptor systems application to estimate the state of charge of lithium-ion batteries. *Journal of the Franklin Institute*, Vol. 360, 2023, pp. 11397–11413.

[115] Mejdi, M., W. Wilson, M. Saillio, T. Chaussadent, L. Divet, and A. Tagnit-Hamou. Investigating the pozzolanic reaction of post-consumption glass powder and the role of portlandite in the formation of sodium-rich CSH. *Cement and Concrete Research*, Vol. 123, 2019, id. 105790.

[116] Tamanna, N., R. Tuladhar, and N. Sivakugan. Performance of recycled waste glass sand as partial replacement of sand in concrete. *Construction and Building Materials*, Vol. 239, 2020, id. 117804.
[117] 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.
[118] Serelis, E. and V. Vaitkevicius. Utilization of glass shards from municipal solid waste in aluminium-based ultra-lightweight concrete. *Construction and Building Materials*, Vol. 350, 2022, id. 128396.
[119] Zhu, C., X. Li, C. Wang, B. Zhang, and B. Li. Deep learning-based coseismic deformation estimation from InSAR interferograms. *IEEE Transactions on Geoscience and Remote Sensing : A Publication of the IEEE Geoscience and Remote Sensing Society*, Vol. 62, 2024, pp. 1–10.
[120] Meena, M. K., J. Gupta, and B. Nagar. Performance of concrete by using glass powder. *International Research Journal of Engineering and Technology*, Vol. 5, 2018, pp. 840–844.
[121] He, X., Z. Xiong, C. Lei, Z. Shen, A. Ni, Y. Xie, et al. Excellent microwave absorption performance of $LaFeO_3/Fe_3O_4/C$ perovskite composites with optimized structure and impedance matching. *Carbon*, Vol. 213, 2023, id. 118200.
[122] Parghi, A. and M. S. Alam. Physical and mechanical properties of cementitious composites containing recycled glass powder (RGP) and styrene butadiene rubber (SBR). *Construction and Building Materials*, Vol. 104, 2016, pp. 34–43.
[123] Li, J., H. Tang, X. Li, H. Dou, and R. Li. LEF-YOLO: a lightweight method for intelligent detection of four extreme wildfires based on the YOLO framework. *International Journal of Wildland Fire*, Vol. 33, No. 1, 2023.
[124] Samarakoon, M. H., P. G. Ranjith, and V. R. S. D.e Silva. Effect of soda-lime glass powder on alkali-activated binders: Rheology, strength and microstructure characterization. *Construction and Building Materials*, Vol. 241, 2020, id. 118013.
[125] Guo, J., Y. Liu, Q. Zou, L. Ye, S. Zhu, and H. Zhang. Study on optimization and combination strategy of multiple daily runoff prediction models coupled with physical mechanism and LSTM. *Journal of Hydrology*, Vol. 624, 2023, id. 129969.
[126] Lu, J., Z. Duan, and C. S. Poon. Fresh properties of cement pastes or mortars incorporating waste glass powder and cullet. *Construction and Building Materials*, Vol. 131, 2017, pp. 793–799.
[127] Chang, X., J. Guo, H. Qin, J. Huang, X. Wang, and P. Ren. Single-objective and multi-objective flood interval forecasting considering interval fitting coefficients. *Water Resources Management*, 2024, pp. 1–20.
[128] Si, R., S. Guo, Q. Dai, and J. Wang. Atomic-structure, microstructure and mechanical properties of glass powder modified metakaolin-based geopolymer. *Construction and Building Materials*, Vol. 254, 2020, id. 119303.
[129] Liao, L., Z. Guo, Q. Gao, Y. Wang, F. Yu, Q. Zhao, et al. Color image recovery using generalized matrix completion over higher-order finite dimensional algebra. *Axioms*, Vol. 12, 2023, id. 954.
[130] Jiang, X., R. Xiao, Y. Ma, M. Zhang, Y. Bai, and B. Huang. Influence of waste glass powder on the physico-mechanical properties and microstructures of fly ash-based geopolymer paste after exposure to high temperatures. *Construction and Building Materials*, Vol. 262, 2020, id. 120579.
[131] Wang, Y., Y. Cao, P. Zhang, and Y. Ma. Effective utilization of waste glass as cementitious powder and construction sand in mortar. *Materials*, Vol. 13, 2020, id. 707.
[132] Hong, J., L. Gui, and J. Cao. Analysis and experimental verification of the tangential force effect on electromagnetic vibration of PM motor. *IEEE Transactions on Energy Conversion*, Vol. 38, 2023, pp. 1893–1902.
[133] Sethi, H., P. P. Bansal, and R. Sharma. Effect of addition of GGBS and glass powder on the properties of geopolymer concrete. *Iranian Journal of Science and Technology-Transactions of Civil Engineering*, Vol. 43, 2019, pp. 607–617.
[134] de, E. J. P., M. Júnior, H. de, J. C. L. Bezerra, F. S. Politi, and A. E. M. Paiva. Increasing the compressive strength of Portland cement concrete using flat glass powder. *Materials Research*, Vol. 17, 2014, id. 45.
[135] Kang, L., B. Tang, J. Huang, and J. Li. 3D-MRI super-resolution reconstruction using multi-modality based on multi-resolution CNN. *Computer Methods and Programs in Biomedicine*, Vol. 248, 2024, id. 108110.
[136] Zhang, G., W. Li, M. Yu, H. Huang, Y. Wang, Z. Han, et al. Electric-field-driven printed 3D highly ordered microstructure with cell feature size promotes the maturation of engineered cardiac tissues. *Advancement of Science*, Vol. 10, No. 11, id. 2206264.
[137] Alfaiad, M. A., K. Khan, W. Ahmad, M. N. Amin, A. F. Deifalla, and N. A. Ghamry. Evaluating the compressive strength of glass powder-based cement mortar subjected to the acidic environment using testing and modeling approaches. *PLoS One*, Vol. 18, 2023, id. e0284761.
[138] Bao, X., H. Yuan, J. Shen, C. Liu, X. Chen, and H. Cui. Numerical analysis of seismic response of a circular tunnel-rectangular underpass system in liquefiable soil. *Computers and Geotechnics*, Vol. 174, 2024, id. 106642.
[139] Hemanth, R. D., M. S. Kumar, A. Gopinath, and L. Natrayan. Evaluation of mechanical properties of E-Glass and coconut fiber reinforced with polyester and epoxy resin matrices. *International Journal of Mechanical and Production Engineering Research and Development*, Vol. 7, 2017, pp. 13–20.
[140] Shah, A. A., M. Zakir, and S. Prakash. Detailed comparative study of concrete by partially replacement of cement with GGBS and glass powder, *Journal of Emerging Technologies and Innovative Research*, Vol. 5, No. 7, 2018, pp. 715–722.
[141] Fei, R., Y. Guo, J. Li, B. Hu, and L. Yang. An improved BPNN method based on probability density for indoor location. *The IEICE Transactions on Information and Systems*, Vol. 106, No. 5, 2023, pp. 773–785.
[142] Raza, S. S., L. A. Qureshi, and B. Ali. Residual mechanical strength of glass fiber reinforced reactive powder concrete exposed to elevated temperatures. *SN Applied Sciences*, Vol. 2, 2020, id. 1602.
[143] TeamCivil, Splitting Tensile Strength of Concrete. *Civil Engineering Forum*, 2017. https://www.civilengineeringforum.me/splitting-tensile-strength/accessed July 14, 2023.
[144] Chen, X., P. Yang, Y. Peng, M. Wang, F. Hu, and J. Xu. Output voltage drop and input current ripple suppression for the pulse load power supply using virtual multiple quasi-notch-filters impedance. *IEEE Transactions on Power Electronics*, Vol. 38, 2023, pp. 9552–9565.
[145] Dong, J. F., Z. W. Guan, H. K. Chai, and Q. Y. Wang. High temperature behaviour of basalt fibre-steel tube reinforced concrete columns with recycled aggregates under monotonous and fatigue loading. *Construction and Building Materials*, Vol. 389, 2023.
[146] Asteray, D. B., W. O. Oyawa, and S. M. Shitote. Compressive and flexural strength of recycled reactive powder concrete containing

finely dispersed local wastes. *The Open Civil Engineering Journal*, Vol. 8, 2018, pp. 12–26.
[147] Maraghechi, H., S. Salwocki, and F. Rajabipour. Utilisation of alkali activated glass powder in binary mixtures with Portland cement, slag, fly ash and hydrated lime. *Materials and Structures*, Vol. 50, 2016, id. 16.
[148] 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.
[149] Shi, C., Y. Wu, C. Riefler, and H. Wang. Characteristics and pozzolanic reactivity of glass powders. *Cement and Concrete Research*, Vol. 35, 2005, pp. 987–993.
[150] Taha, B. and G. Nounu. Using lithium nitrate and pozzolanic glass powder in concrete as ASR suppressors. *Cement and Concrete Composites*, Vol. 30, 2008, pp. 497–505.
[151] Ghareeb, K. S., H. E. Ahmed, T. H. El-Affandy, A. F. Deifalla, and T. A. El-Sayed. The novelty of using glass powder and lime powder for producing UHPSCC. *Buildings*, Vol. 12, 2022, id. 684.
[152] Kanellopoulos, A., D. Nicolaides, and M. F. Petrou. Mechanical and durability properties of concretes containing recycled lime powder and recycled aggregates. *Construction and Building Materials*, Vol. 53, 2014, pp. 253–259.
[153] Dou, J., J. Liu, Y. Wang, L. Zhi, J. Shen, and G. Wang. Surface activity, wetting, and aggregation of a perfluoropolyether quaternary ammonium salt surfactant with a hydroxyethyl group. *Molecules*, Vol. 28, 2023.
[154] Venkatanarayanan, H. K. and P. R. Rangaraju. Decoupling the effects of chemical composition and fineness of fly ash in mitigating alkali-silica reaction. *Cement and Concrete Composites*, Vol. 43, 2013, pp. 54–68.
[155] Han, D., H. X. Zhou, T. H. Weng, Z. Wu, B. Han, K. C. Li, et al. LMCA: a lightweight anomaly network traffic detection model integrating adjusted mobilenet and coordinate attention mechanism for IoT. *Telecommunication systems*, Vol. 84, 2023, pp. 549–564.
[156] Moon, J., S. Speziale, C. Meral, B. Kalkan, S. M. Clark, and P. J. Monteiro. Determination of the elastic properties of amorphous materials: case study of alkali–silica reaction gel. *Cement and Concrete Research*, Vol. 54, 2013, pp. 55–60.
[157] Wang, H.-Y. and W.-L. Huang. Durability of self-consolidating concrete using waste LCD glass. *Construction and Building Materials*, Vol. 24, 2010, pp. 1008–1013.
[158] Wang, H., D. Han, M. Cui, and C. Chen. NAS-YOLOX: a SAR ship detection using neural architecture search and multi-scale attention. *Connection Science*, Vol. 35, 2023, pp. 1–32.
[159] Li, Z., M. Gao, Z. Lei, L. Tong, J. Sun, Y. Wang, et al. Ternary cementless composite based on red mud, ultra-fine fly ash, and GGBS: Synergistic utilization and geopolymerization mechanism. *Case Studies in Construction Materials*, Vol. 19, 2023, id. e02410.
[160] Jain, J. A. and N. Neithalath. Chloride transport in fly ash and glass powder modified concretes–influence of test methods on microstructure. *Cement and Concrete Composites*, Vol. 32, 2010, pp. 148–156.
[161] Kamali, M. and A. Ghahremaninezhad. An investigation into the hydration and microstructure of cement pastes modified with glass powders. *Construction and Building Materials*, Vol. 112, 2016, pp. 915–924.
[162] Jain, J. and N. Neithalath. Electrical impedance analysis based quantification of microstructural changes in concretes due to non-steady state chloride migration. *Materials Chemistry and Physics*, Vol. 129, 2011, pp. 569–579.
[163] Shi, S., D. Han, and M. Cui. A multimodal hybrid parallel network intrusion detection model. *Connection Science*, Vol. 35, No. 1, 2023, id. 2227780.
[164] Schwarz, N., M. DuBois, and N. Neithalath. Electrical conductivity based characterization of plain and coarse glass powder modified cement pastes. *Cement and Concrete Composites*, Vol. 29, 2007, pp. 656–666.
[165] Christensen, B. J., T. Coverdale, R. A. Olson, S. J. Ford, E. J. Garboczi, H. M. Jennings, et al. Impedance spectroscopy of hydrating cement-based materials: measurement, interpretation, and application. *Journal of the American Ceramic Society*, Vol. 77, 1994, pp. 2789–2804.
[166] Chen, C., D. Han, and X. Shen. CLVIN: Complete language-vision interaction network for visual question answering. *Knowledge-Based System*, Vol. 275, 2023, id. 110706.
[167] Ortega, J. M., V. Letelier, C. Solas, M. Miró, G. Moriconi, M. Á. Climent, et al. Influence of waste glass powder addition on the pore structure and service properties of cement mortars. *Sustainability*, Vol. 10, No. 3, 2018, id. 842.
[168] Mejdi, M., W. Wilson, M. Saillio, T. Chaussadent, L. Divet, and A. Tagnit-Hamou. Hydration and microstructure of glass powder cement pastes–A multi-technique investigation. *Cement and Concrete Research*, Vol. 151, 2022, id. 106610.
[169] Chen, C., D. Han, and C. C. Chang. MPCCT: Multimodal vision-language learning paradigm with context-based compact transformer. *Pattern recognition*, Vol. 147, 2024.
[170] Korpa, A. and R. Trettin. The influence of different drying methods on cement paste microstructures as reflected by gas adsorption: Comparison between freeze-drying (F-drying), D-drying, P-drying and oven-drying methods. *Cement and Concrete Research*, Vol. 36, 2006, pp. 634–649.
[171] Wong, H. S., N. R. Buenfeld, and M. K. Head. Estimating transport properties of mortars using image analysis on backscattered electron images. *Cement and Concrete Research*, Vol. 36, 2006, pp. 1556–1566.
[172] Xiong, X.-R., J.-Y. Wang, A.-M. She, and J.-M. Lin. Characterization of Pore Size Distribution and Water Transport of UHPC Using Low-Field NMR and MIP. *Materials*, Vol. 16, 2023, id. 2781.
[173] Li, H., Y. Yang, X. Wang, and H. Tang. Effects of the position and chloride-induced corrosion of strand on bonding behavior between the steel strand and concrete. *Structures*, Vol. 58, 2023.
[174] Jawad, Z. F., R. J. Ghayyib, and A. J. Salman. Microstructural and compressive strength analysis for cement mortar with industrial waste materials. *Civil Engineering Journal*, Vol. 6, 2020, pp. 1007–1016.
[175] Liang, G., H. Li, H. Zhu, T. Liu, Q. Chen, and H. Guo. Reuse of waste glass powder in alkali-activated metakaolin/fly ash pastes: Physical properties, reaction kinetics and microstructure. *Resources, Conservation and Recycling*, Vol. 173, 2021, id. 105721.
[176] Liu, S., S. Wang, W. Zhou, L. Li, H. Xiao, J. Wei, et al. Strength and microstructure of mortar containing glass powder and/or glass aggregate. *Journal of Wuhan University of Technology-Materials Science Edition*, Vol. 31, 2016, pp. 1302–1310.
[177] Yusuf, M. O., K. A. A. Al-Sodani, A. H. AlAteah, M. M. H. Al-Tholaia, A. A. Adewumi, A. O. Bakare, et al. Performances of the synergy of silica fume and waste glass powder in ternary blended concrete. *Applied Sciences*, Vol. 12, 2022, id. 6637.

[178] Omran, A. and A. Tagnit-Hamou. Performance of glass-powder concrete in field applications. *Construction and Building Materials*, Vol. 109, 2016, pp. 84–95.
[179] Cam, H. T. and N. Neithalath. Moisture and ionic transport in concretes containing coarse limestone powder. *Cement and Concrete Composites*, Vol. 32, 2010, pp. 486–496.
[180] Almarshoud, M. Enhanced analysis tools and measurement methods to evaluate concrete transport properties. PhD Thesis, University of Florida, 2019.
[181] Du, H. and K. H. Tan. Properties of high volume glass powder concrete. *Cement and Concrete Composites*, Vol. 75, 2017, pp. 22–29.
[182] Baldovino, J. J., R. L. Izzo, J. L. Rose, and M. D. Domingos. Strength, durability, and microstructure of geopolymers based on recycled-glass powder waste and dolomitic lime for soil stabilization. *Construction and Building Materials*, Vol. 271, 2021, id. 121874.
[183] Lu, D., X. Zhou, X. Du, and G. Wang. 3D dynamic elastoplastic constitutive model of concrete within the framework of rate-dependent consistency condition. *Journal of Engineering Mechanics*, Vol. 146, No. 11, 2020, id. 04020124.
[184] Serelis, E., V. Vaitkevicius, H. Hilbig, L. Irbe, and Z. Rudzionis. Effect of ultra-sonic dispersion time on hydration process and microstructure development of ultra-high performance glass powder concrete. *Construction and Building Materials*, Vol. 298, 2021, id. 123856.
[185] Al-Kheetan, M. J., J. Byzyka, and S. H. Ghaffar. Sustainable valorisation of silane-treated waste glass powder in concrete pavement. *Sustainability*, Vol. 13, 2021, id. 4949.
[186] Huang, H., M. Huang, W. Zhang, S. Pospisil, and T. Wu. Experimental investigation on rehabilitation of corroded RC columns with BSP and HPFL under combined loadings. *Journal of Structural Engineering*, Vol. 146, No. 8, 2020, id. 04020157.
[187] Huang, H., M. Li, Y. Yuan, and H. Bai. Theoretical analysis on the lateral drift of precast concrete frame with replaceable artificial controllable plastic hinges. *Journal of Building Engineering*, Vol. 62, 2022.
[188] Lu, D., J. Liang, X. Du, C. Ma, and Z. Gao. Fractional elastoplastic constitutive model for soils based on a novel 3D fractional plastic flow rule. *Computers and Geotechnics*, Vol. 105, 2019, pp. 277–290.
[189] Lu, D., C. Ma, X. Du, L. Jin, and Q. Gong. Development of a new nonlinear unified strength theory for geomaterials based on the characteristic stress concept. *International Journal of Geomechanics*, Vol. 17, No. 2, 2017, id. 04016058.
[190] 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.
[191] Asghar, R. and S. U. Khattak. Predicting the residual flexural capacity of fire exposed reinforced concrete beams using gene expression programming. *Department of Civil Engineering, Capital University of Science and Technology*, Vol. 8, Islamabad, Pakistan, 2023.
[192] Asghar, R., M. F. Javed, R. Alrowais, A. Khalil, A. M. Mohamed, A. Mohamed, et al. Predicting the lateral load carrying capacity of reinforced concrete rectangular columns: gene expression programming. *Materials*, Vol. 15, 2022, id. 2673.
[193] Asghar, R., M. F. Javed, M. Ali, T. Najeh, and Y. Gamil. Numerical and artificial intelligence based investigation on the development of design guidelines for pultruded GFRP RHS profiles subjected to web crippling. *Scientific Reports*, Vol. 14, 2024, id. 10135.
[194] Asghar, R., M. F. Javed, M. Saqib, A. Alaskar, M. Ali, and R. Nawaz. Multi-expression programming based prediction of the seismic capacity of reinforced concrete rectangular columns. *Engineering applications of artificial intelligence*, Vol. 131, 2024, id. 107834.
[195] Azam, M., N. Abbas, K. G. Kumar, and S. Wali. Transient bioconvection and activation energy impacts on Casson nanofluid with gyrotactic microorganisms and nonlinear radiation. *Waves in Random and Complex Media*, 2022, (accessed May 10, 2024).
[196] Awan, A. U., S. Abid, and N. Abbas. Theoretical study of unsteady oblique stagnation point based Jeffrey nanofluid flow over an oscillatory stretching sheet. *Advances in Mechanical Engineering*, 2014.
[197] Lanjwani, H. B., S. Saleem, M. S. Chandio, M. I. Anwar, and N. Abbas. Stability analysis of triple solutions of Casson nanofluid past on a vertical exponentially stretching/shrinking sheet. *Advances in Mechanical Engineering*, Vol. 13, No. 11, 2021, id. 16878140211059679.
[198] Fuzhang, W., M. I. Anwar, M. Ali, A. S. El-Shafay, N. Abbas, and R. Ali. Inspections of unsteady micropolar nanofluid model over exponentially stretching curved surface with chemical reaction. *Waves Random Complex Media*, 2022, (accessed May 10, 2024).
[199] Long, X., M. Hui Mao, T. Xiong Su, Y. Tai Su, and M. Ke Tian. Machine learning method to predict dynamic compressive response of concrete-like material at high strain rates. *Defence Technology*, Vol. 23, 2023, pp. 100–111.
[200] 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.
[201] 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. 1–17.
[202] Huang, H., M. Li, W. Zhang, and Y. Yuan. Seismic behavior of a friction-type artificial plastic hinge for the precast beam–column connection. *Archives of Civil and Mechanical Engineering*, Vol. 22, No. 4, 2022, id. 201.
[203] Ahmad, S. A., S. K. Rafiq, H. U. Ahmed, A. S. Abdulrahman, and A. M. Ramezanianpour. Innovative soft computing techniques including artificial neural network and nonlinear regression models to predict the compressive strength of environmentally friendly concrete incorporating waste glass powder. *Innovative Infrastructure Solutions*, Vol. 8, 2023, id. 119.
[204] 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.
[205] Orouji, M. and E. Najaf. Effect of GFRP rebars and polypropylene fibers on flexural strength in high-performance concrete beams with glass powder and microsilica. *Case Studies in Construction Materials*, Vol. 18, 2023, id. e01769.
[206] Jiang, Y., T.-C. Ling, K. H. Mo, and C. Shi. A critical review of waste glass powder–Multiple roles of utilization in cement-based materials and construction products. *Journal of Environmental Management*, Vol. 242, 2019, pp. 440–449.
[207] de Jesús Arrieta Baldovino, J., R. L. dos Santos Izzo, and A. Ekinci. Strength, durability, and microstructure of lime production residue glass powder binder-based geomaterial. *Acta Geotechnica*, Vol. 18, 2023, pp. 1593–1606.

[208] Khan, Q. S., T. J. McCarthy, and M. N. Sheikh. Experimental investigations of foamed concrete with recycled waste glass powder wall panels. *Structural Concrete*, Vol. 23, 2022, pp. 3929–3944.
[209] Soliman, N. A. and A. Tagnit-Hamou. Development of ultra-high-performance concrete using glass powder–Towards ecofriendly concrete. *Construction and Building Materials*, Vol. 125, 2016, pp. 600–612.
[210] He, H., J. Shi, S. Yu, J. Yang, K. Xu, C. He, et al. Exploring green and efficient zero-dimensional carbon-based inhibitors for carbon steel: From performance to mechanism. *Construction and Building Materials*, Vol. 411, 2024, id. 134334.
[211] Luo, Y., X. Liu, F. Chen, H. Zhang, and X. Xiao. Numerical simulation on crack–inclusion interaction for rib-to-deck welded joints in orthotropic steel deck. *Metals (Basel)*, Vol. 13, No. 8, 2023, id. 1402.
[212] 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.
[213] D'Amore, G. K. O., M. Caniato, A. Travan, G. Turco, L. Marsich, A. Ferluga, et al. Innovative thermal and acoustic insulation foam from recycled waste glass powder. *Journal of Cleaner Production*, Vol. 165, 2017, pp. 1306–1315.
[214] Vafaei, M. and A. Allahverdi. High strength geopolymer binder based on waste-glass powder. *Advanced Powder Technology*, Vol. 28, 2017, pp. 215–222.
[215] Abellán-García, J., A. Núñez-López, N. Torres-Castellanos, and J. Fernández-Gómez. Factorial design of reactive concrete powder containing electric arc slag furnace and recycled glass powder. *Dyna*, Vol. 87, 2020, pp. 42–51.
[216] Danish, A., T. Ozbakkaloglu, M. A. Mosaberpanah, M. U. Salim, M. Bayram, J. H. Yeon, et al. Sustainability benefits and commercialization challenges and strategies of geopolymer concrete: A review. *Journal of Building Engineering*, Vol. 58, 2022, id. 105005.
[217] Purchase, C. K., D. M. Al Zulayq, B. T. O'Brien, M. J. Kowalewski, A. Berenjian, A. H. Tarighaleslami, et al. Circular economy of construction and demolition waste: A literature review on lessons, challenges, and benefits. *Materials*, Vol. 15, 2021, id. 76.
[218] Siddika, A., A. Hajimohammadi, and V. Sahajwalla. Powder sintering and gel casting methods in making glass foam using waste glass: A review on parameters, performance, and challenges. *Ceramics International*, Vol. 48, 2022, pp. 1494–1511.
[219] Paul, D., K. R. Bindhu, A. M. Matos, and J. Delgado. Eco-friendly concrete with waste glass powder: A sustainable and circular solution. *Construction and Building Materials*, Vol. 355, 2022, id. 129217.