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REVIEW

Low-Carbon Concrete: A Comprehensive Review of Strategies for Reducing the Construction Industry's Environmental Impact

Mahria Rafi [1], *Kiran Kumar Poloju* [1*], *Marwarid Tarin* [1], *Adil Nadeem Hussain* [2]

[1] *Department of Civil and Mechanical Engineering, Middle East College, Muscat 124, Oman*

[2] *Department of Civil Engineering, Military Technological College, Muscat 124, Oman*

ABSTRACT

The transition toward low-carbon concrete (LCC) represents a critical pathway for decarbonizing the construction sector and achieving global net-zero targets. This study provides a comprehensive and analytical review of material innovations, digital enablers, and policy mechanisms shaping the evolution of LCC technologies. A systematic PRISMA-based review combined with bibliometric mapping (VOS viewer) was conducted across various peer-reviewed studies. The analysis integrates scientific, economic, and regulatory dimensions through an original conceptual framework linking supplementary cementitious materials (SCMs), limestone calcined clay cement (LC), geopolymers, recycled aggregates (RA), and carbon capture and utilization (CCU) with digitalization, circular economy, and life-cycle assessment. Comparative synthesis reveals that embodied-carbon reduction follows the hierarchy: Geopolymers (40–70%) > LC^3 (30–40%) > SCM blends (25–40%) > CCU concretes (20–40%) > RA concretes (15–20%). However, economic feasibility declines with increasing binder novelty, underscoring the need for policy and carbon-pricing support. A time-bound roadmap toward Net-Zero 2050 is proposed, outlining near-, short-, medium-, and long-term milestones for R&D, standardization, infrastructure decarbonization, and technological breakthroughs. The paper concludes with prioritized research directions addressing standardization gaps, digital interoperability, and field-based durability validation. Collectively, the study advances an integrated vision where material innovation, digital intelligence, and policy alignment converge to accelerate the realization of a carbon-neutral concrete industry.

*CORRESPONDING AUTHOR:
Kiran Kumar Poloju, Department of Civil and Mechanical Engineering, Middle East College, Muscat 124, Oman;
Email: p.kirankumr102@gmail.com

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1. Introduction

1.1. Background and Significance

Modern infrastructure is based on concrete and is produced at a rate of over 14 billion cubic meters per year worldwide[1]. This is because of its affordability, flexibility, and longevity, and hence, its ubiquity. Nevertheless, its impact on the environment is terrible: cement, the main unifying material in concrete, is among the largest producers of CO_2 worldwide. It has been estimated today that the production of cement alone produces between 2.5 to 3 billion tons of CO_2 per year which is almost 8% of the total anthropogenic greenhouse gases globally[2]. This is more than the yearly emissions of most industrialized countries, proving the need to identify sustainable alternatives. Recent world evaluations have supported the need to decarbonize the construction industry. The Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (2023) lists the built environment, such as cement and concrete as among the largest sources of industrial greenhouse gas emissions, contributing around 37 percent of the total worldwide CO_2 production. As highlighted in the report, the urgent solution to mitigation in the production of materials should be realized to stay within the 1.5 °C target pathway[3]. Similarly, the International Energy Agency (IEA) Cement Tracking Report (2024) points out that cement companies need to cut down their direct emissions by at least a quarter of 2030 in accordance with the Net-Zero Scenario, which necessitates the rapid implementation of low-clinker cements, alternative binders, and carbon capture systems[4]. To support these results, the Global Cement and Concrete Association (GCCA) Net Zero Roadmap (2023) identifies five strategic levers as the major facilitators of the development of carbon-neutral concrete by 2050: material efficiency, clinker substitution, fuel transition, carbon capture, and the integration of the circular economy[5,6]. The carbon intensity of cement production is caused by two related processes. The calcification process of limestone produces CO_2 as calcium carbonate breaks up to create lime (CaO). Second, it demands very high kiln temperatures (>1450 °C), which are normally attained by burning fossil fuels[7]. Emissions in the cement industry cannot be decarbonized, as in other industries, where the process of decarbonization can be achieved by replacing fossil fuels with renewable energy. Thus, even deeper innovations are needed, especially those that will alleviate reliance on clinkers, increase their durability, and make it more circular. The efficient pretreatment of recycled aggregates is able to promote the microstructure of recycled aggregate concrete to a high degree resulting in better strength and durability[8]. Their research indicates the importance of surface modification and the removal of contaminants in enhancing cement-aggregate bonding. Kępniak et al.[9] assessed the performance of the recycled aggregates through the various recycling cycles and ascertained that the recycled aggregates could be used in structural concrete. Although there are slight losses of mechanical properties, correct processing can guarantee good performance of strength and durability. In an effort to examine the behavior of recycled green concrete in relation to chloride and sulphate exposures, it is found that compressive strength decreased observably with time. The research highlights the necessity to have additional therapies to increase longevity in hostile settings such as use of crumb rubber in concrete and noted superior toughness, ductile, and energy absorption capacity. Nevertheless, the compressive strength was found to slightly reduce because of the low stiffness of rubber as compared to natural aggregates[10]. Similarly, biopolymer composite bricks made of unfired clay and biopolymers have improved physicochemical and thermal mechanical characteristics. These composites exhibited better thermal insulation, low density, and high sustainability potential in the use of green buildings[11] and ultrahigh-performance of fiber-reinforced concrete examined and achieved significant results in compressive and flexural strengths[12]. Fibers added resistance to cracks and load-bearing properties, which means that the material is applicable in high-level structural use.

1.2. The Emergency to Transit into Low-Carbon Concrete

By 2050, the required amount of cement is likely to increase by 20–25% especially in Asia, Africa, and the Middle East[13]. Such expansion will continue to add to the current colossal emissions footprint, endangering global climate goals, in this case the Paris Agreement. Reportedly, both the International Energy Agency (IEA) and the Global Cement and Concrete Association (GCCA) state that the decarbonization of cement and concrete production is one of the pillars to reach net-zero pathways.

Low-carbon concrete (LCC) is a potential solution to this challenge. It is associated with reduced clinker content using SCMs[14–16], substituting ordinary Portland cement (OPC) with geopolymers or alkali-activated binders, using recycled aggregates (RA), and implementing carbon capture and utilization (CCU) concepts[17–20]. All of these strategies aim at embodied carbon cutbacks and retain mechanical and long-life performance. Furthermore, life-cycle assessment (LCA) proves that durability can be increased with the help of better resistance to chloride ingress, sulfate attack, and acid exposure, and help to increase service life, decrease the maintenance frequency, and achieve a further reduction in life-cycle emissions[21].

Figure 1 depicts the Integrated Framework of Low-Carbon Concrete (LCC) Development and Implementation, which takes all dimensions of materials, digital, regulatory, and policy, and integrates them into a single system. The central hub, Material Innovations, contains Supplementary Cementitious Materials (SCM), Limestone Calcined Clay Cement (LC^3), Geopolymers, Recycled Aggregates (RA), and Carbon Capture and Utilization (CCU), and are all the building blocks of carbon reduction in the cement-concrete industry. This framework outlines the inter-sectoral interactions needed in practice, as opposed to the conventional low-carbon concrete research that explores one parameter at a time, including binder chemistry, mix optimization, and mechanical performance. The core of Material Innovations (SCM, LC^3, Geopolymer, RA, CCU) is the core research area, and the external enablers are represented by the surrounding nodes (Policy and Economics, LCA/Durability, Circular Economy and Digitalization / AI). The research-practice feedback offers a methodological avenue of analysis to transform the laboratory data into the level of decision support at an industrial level, thus meeting the requirement of a systematic method as observed by the reviewer. By doing so, the model explains the interplay between regulatory standards, life-cycle assessment results, and digital tools (BIM, AI, and digital twins) to hasten the uptake of materials according to sustainability thresholds. In turn, this synergistic framework provides conceptual freshness and practical use, serving as a translational framework between micro-scale innovations and macro-level governance and market processes, directing the Net-Zero 2050[22].

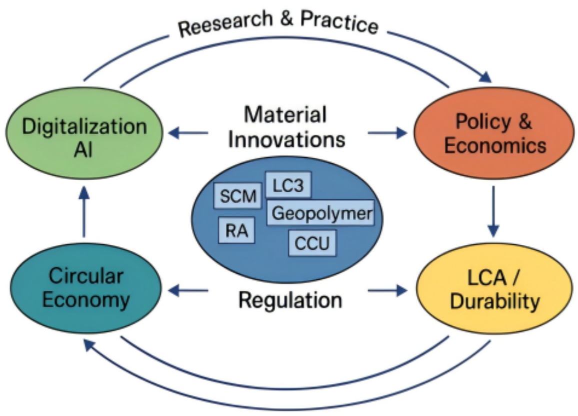

Figure 1. Integrated Framework for Low-Carbon Concrete Development and Implementation.

Source: IEA[4]; GCCA[5]; Habert et al.[6].

1.3. Whole Life Thinking and Co-Benefits

The advantages of LCC are not limited to material replacements[23]. Whole-life viewpoints show that durability benefits can greatly increase environmental performance by reducing repair and replacement rates. It can optimize blended SCM mixes with intelligent mix designs to achieve less embodied carbon of up to 50%. Similarly, the gain in durability results in the reduction of long-term expenses, as buildings require fewer remedies.

SCM-rich concretes may also save on costs in areas where the industrial by-products are high, and RA will save on landfills and natural aggregates. Systems of certification, such as LEED and BREEAM, also encourage the use of low-carbon materials by offering credits for their use[24]. Therefore, LCC is an environmental strategy as well as an economic and social opportunity and is in line with the principles of the circular economy.

1.4. Constraints of the Current Practices

Despite these improvements have been made, various constraints discourage the use of LCC. To begin with, the supply of SCMs such as fly ash is on a downward trend owing to the global stage out of coal-fired power plants, and concerns have been raised about the supply of the same in the long term[25]. Second, standard codes of emerging binders, such as geopolymers, are still not wide-ranging, and hence, they create uncertainty among engineers[26]. Third, carbon capture concrete technologies have potential, but their implementation is limited by expensive initial investments and availability of industrial CO_2 streams[27]. Moreover, field-scale studies on durability are inadequate, which further adds to the cynicism of practitioners. Another important issue is the absence of harmonized LCA methodologies. Inequity in methods between regions and studies complicates the comparison of outcomes and establishment of international standards[28]. Surveys also show that willingness and practice are out of proportion: 65% of companies say they are willing to adopt LCC should it be cost-competitive, but only 30% have adopted it in practice[29].

2. Literature Review

2.1. Cement Industry Emissions and Global Climate Efficiencies

The manufacturing of concrete contributes approximately 8 percent of the total amount of CO_2, and roughly 2.53 billion tons of cement are emitted every year by the cement industry[30]. These emissions are the result of two interrelated processes.

i. Calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$), which is a source of CO_2.
ii. burning fossil fuels to obtain kiln temperatures higher than 1450 ℃[31].

The emissions of the cement industry cannot be decarbonized as easily as electricity or transport, which can be decarbonized by using renewable energy or electrification; the emissions generated in the cement industry are so deeply embedded in chemical reactions that it is impossible to decarbonize the industry without relying on these elements. The development of low-carbon concrete (LCC) should move beyond the laboratory level of emissions minimization to incorporate large-scale industrial and policy-based systems aligned with worldwide net-zero requirements. The International Energy Agency (IEA) estimates that cement demand will grow by 20 to 25% by 2050 because of rapid urbanization and infrastructure development in Asia, Africa, and the Middle East.

Emerging roadmaps around the world and regions have addressed this challenge. The 2050 Net Zero Roadmap by the Global Cement and Concrete Association (GCCA) provides four levers:

i. lowering clinker-to-cement ratios through the use of SCMs,
ii. the use of alternative binders, including geopolymers and LC^3,
iii. energy efficiency and fuel switching, and
iv. carbon capture technologies.

The Fit for 55 in the European Union imposes a gradual increase in carbon emission cuts in the construction industry, and some countries, such as India, have established minimum requirements for the use of fly ash in cement and concrete[32]. LC^3 research and pilot projects have received a lot of investment in China, where it has seen its potential to decrease reliance on clinkers[33]. Countries in the Gulf Cooperation Council (GCC) have also integrated LCC into their new green building constructions[34].

2.2. Supplementary Cementitious Materials (SCMs)

2.2.1. Role and Benefits

The reduction of embodied carbon can be achieved by 20 to 50% through the substitution of 20 to 70% of cement with supplementary cementitious materials (SCMs), such as fly ash, ground granulated blast furnace slag (GGBFS), silica fume, volcanic pozzolans, or calcined clays[35]. In addition to reducing emissions, SCMs enhance performance attributes of sulfate resistance, decreased permeability, and long-term strength acquisition and 50% replacement with fly ash and slag significantly lowered the rate of chloride ingress, thereby extending the life of the reinforcement[36]. Silica fume may be added in smaller amounts (1–10%) to improve early strength and fill in the microstructure[37].

2.2.2. Emerging SCMs

The transition to coal-fired power plants has decreased the supply of fly ash in most areas and has resulted in attempts to find alternatives[38]. Limestone Calcined Clay Cement (LC^3) is becoming popular and is a combination of calcined clay and limestone to substitute up to 50% clinker. LC^3 achieves emission cuts of 30–40% with no damage to OPC mechanical characteristics [39]. These materials are locally available, inexpensive, and require more rigorous durability investigations [40].

Material Innovations

Supplementary Cementitious Materials (SCMs): The optimum ratio of ground granulated blast furnace slag (GGBFS) and recycled steel fibers improved the compressive and flexural strengths of geopolymer concrete, especially under high curing conditions [41]. These hybrid SCM-fiber systems affirm that low-carbon binders could have the same or even better mechanical performance as OPC mixes with much lower embodied CO_2. Further structural applicability of geopolymer concrete such as the flexural and shear performance of beams [42] and suggested it was equal to the ability to bear loads and demonstrated higher ductility in comparison with traditional reinforced OPC systems. These results confirm that geopolymer concrete is not only sustainable but also structurally feasible in present-day infrastructure applications.

Regional Research Contributions

The fly ash-based geopolymer concretes using slag exhibited rheological behavior that was optimized and compactness of the microstructure at the benefit of acid resistance and long-term durability [43]. This study contributes important regional findings regarding the situation in the Gulf, which point to the flexibility of LCC to hot climatic conditions.

2.2.3. Challenges

The adoption of SCM is impeded by the following:

- ➢ Variability of supply: GGBFS is abundant only in steel manufacturing. The quality of calcined clay is based on mineralogy and processing conditions.
- ➢ Durability issues: High-SCM concretes are not commonly used because of their limited experience in long-term field applications.
- ➢ Standardization: Codes usually restrict SCM substitution ratios, which limits innovation.

However, SCMs are the most widely adopted pathway, with both industry acceptance and proven performance in different regions.

2.3. Geopolymers and Alkali-Activated Materials

2.3.1. Concept and Mechanisms

Geopolymers (GP), a group of aluminosilicate binders, are produced by activating precursors, such as fly ash, GGBFS, and metakaolin, with alkaline solutions, such as sodium hydroxide or sodium silicate. Their polymeric network (Si-O-Al) has higher durability than the C-S-H gel of OPC [44]. Because they do not have to be calcined with limestone, the carbon emissions of geopolymers are reduced by 30–70% compared to OPC [45].

2.3.2. Mechanical and Durability Performance

Laboratory studies have indicated that geopolymer cements and concretes can achieve compressive strengths comparable to those of OPC. The results show that the improved strength in the case of GGBFS when blended with NaOH activators [46–49], in addition to superior fire resistance up to 80 °C in another study [50]. These desirable characteristics of geopolymers make them suitable for infrastructure applications in aggressive environments such as marine structures, chemical industries, and sewage systems.

2.3.3. Worldwide Acceptance and Field Experience

- ➢ Australia: Precast railway sleepers and marine concrete structures were constructed using geopolymer concrete [51].
- ➢ India: Pilot projects on both pavement and precast elements use large amounts of fly ash [52].
- ➢ Middle East: Experiments in Oman and the UAE have shown that it can be used in hot climatic conditions [53].

2.3.4. Barriers to Adoption

Despite promising performance, several obstacles limit their widespread adoption.

- ➢ Activator costs: sodium silicate and sodium hydroxide are costlier than clinker on a per-ton basis [54].
- ➢ Health and safety: Handling concentrated alkaline solutions raises occupational hazards [55,56].
- ➢ Standardization: A few national codes formally recognize geopolymers, causing hesitation among engi-

neers[57].

- Supply chain maturity: Global logistics for activators remain underdeveloped, restricting scalability[58].
- Future research must focus on safer activator alternatives, lifecycle durability studies, and the harmonization of codes to build industry confidence.

2.4. Recycled Aggregates and the Circular Economy

2.4.1. Environmental Rationale

Construction and demolition waste (CDW) is almost 30–40% of the total worldwide solid waste stream[59]. Putting such waste in landfills not only takes up precious space but also contributes to the depletion of resources by the extraction of fresh aggregates of virgin soil. Recycled aggregates (RA) are an opportunity to create aggregates that contain reduced amounts of embodied carbon, and by 10–20%, compared to raw materials, and to avoid significant amounts of waste in landfills[60,61].

2.4.2. Characteristics

Research indicates that RA concretes tend to have a compressive strength that: 5–10% lower than that of concrete with natural aggregates, mostly because they are more porous and their interfacial transition zones are less robust[62]. Nonetheless, the combination of RA with binders rich in SCM can result in a significant difference in performance. Similarly, a study that indicated that the compressive strengths of fly ash-slag mixtures using 50 percent of the coarse aggregates filled with RA were equivalent to the compressive strength of OPC concrete[63]. RA enhances chloride permeability and water uptake; however, additional binders diminish these shortcomings. Fine RA use is also controversial because it requires more water and less workability[64,65].

2.4.3. Adoption and Regional Case Studies

In some countries such as the Netherlands and Denmark, the minimum recycled material in concrete is required in government projects[66]. However, RA has been proven to be a viable choice for road bases and low-rise buildings in pilot studies in most of the countries in GCC and Asia.

2.4.4. Barriers

- Diversity in the quality of RA sources of demolition.
- Absence of harmonized testing procedures for RA concrete.
- There is little acceptability in high-rise or critical infrastructure works because of conservative design codes.
- To increase reliability and industry trust, future research should focus on enhancing RA beneficiation technologies, standardization, and digital traceability systems.

2.5. Carbon Capture and Utilization (CCU)

2.5.1. Concept and Mechanisms

Carbon capture technologies incorporate CO_2 sequestration into concrete processes. Mineralization methods, such as those developed by Carbon Cure and Solidia, inject CO_2 into fresh concrete, which reacts with calcium hydroxide to produce stable calcium carbonate[67]. This process removed carbon and enhanced the material.

2.5.2. Environmental Performance

Embodied emissions in concrete can be minimized by 20–40 percent depending on the level of CO_2 mineralization in CCU concrete[68]. However, the scaling of CCU concrete on substantial urban building construction reduced project-level emissions by 35%.

2.5.3. Limitations

- Price: Capture and injection systems are costly to install[69].
- Dependence on infrastructure: CCU must be connected to concentrated CO_2 streams, which makes them feasible only in industrial clusters[70].
- Durability information: There is no long-term field data, and there are questions about carbonation depth and reinforcement corrosion.

However, with the maturation of carbon capture technologies, it is possible for integration with cement and concrete plants to become more possible.

2.6. Mix Optimization, Artificial Intelligence and Digitalization

2.6.1. Role of Digital Tools

- LCC design and assessment are changing to artificial intelligence (AI), digital twins, and building information modelling (BIM).

- AI algorithms can be applied to large datasets of mix designs, curing conditions, and admixture dosages and can forecast the performance results with little embodied carbon[71].
- AI-guided optimization. Demonstrated that the AI-guided mix design was able to reduce CO_2 by 15 percent and maintain the OPC-level compressive strength[72].
- BIM integration: BIM-based embodied carbon calculators enable engineers to overview environmental effects in real time and comply with green standards[73].
- Digital twins: They are already being used to show promise of predictive maintenance, where owners of infrastructure can track the performance and longevity of their services and infrastructure[74].

2.6.2. Challenges

Adoption has the following challenges: datasets are not regularly available, cross-platform interoperability is lacking, and initial investment costs are high. Nevertheless, with the increasing pace of digitalization in the construction business, incorporation with LCC will become the rule.

2.7. Structural Performance and Durability

2.7.1. Mechanical Strength

- A Fly ash slag mixture fly ash slag blend retains approximately 95% of OPC strength and better sulfate resistance[39,75].
- **LC^3:** Compressive strengths of 30–60 Mpa, equivalent to OPC, and better chloride resistance[42,43,76].
- **Geopolymers:** They are typically stronger and more durable than OPC, especially under marine and chemical conditions[44,45,77].
- **RA concretes:** It has a slight decrease in strength, which is mitigated by the addition of SCMs[63].
- **CCU concretes:** Strength is improved by carbonated densification[73,78].

2.7.2. Durability Properties

SCMs decrease permeability and increase service life as they resist sulfate attacks[39,79]. LC^3 reduces the heat of hydration, which enhances the risk of cracking. Geopolymers display high acid and fire resistance, with increased applicability under severe conditions[50,80]. RA concretes have slightly decreased durability when compensated for by SCM blending[57,81]. CCU concretes feature neutral-positive durability; however, field validation is not extensive. The necessity of harmonized durability testing demonstrated that durability can contribute significantly to the reduction of carbon emissions during the lifecycle of a design life of 50 years[82,83].

2.8. Gaps and Research Priorities

Although the level of development and testing of low-carbon concrete (LCC) systems is evolving rapidly, there are a few gaps in research and application that still hinder the widespread adoption of laboratory innovations in the market. These issues are multi-dimensional, including technical, regulatory, economic, and digital, and must be addressed in concerted academic, industrial, and policy efforts.

2.8.1. Standardization

The lack of a standard code for the design and testing of new binders, such as geopolymers and limestone calcined clay cement (LC^3), is one of the greatest hindrances to industrial acceptability. Present prescriptive standards usually restrict the degree of substitution or allow alternative chemistries among engineers to deter specifications. There should be international cooperation among organizations such as ASTM, ISO, and RILEM in coming up with performance-based standards that should be used to acknowledge the similar or better durability of these materials.

2.8.2. Durability Data

There is also a lack of long-term field monitoring of LCC structures, which limits confidence in practitioners and model calibration[82]. The majority of research is based on accelerated laboratory experiments, and it is not always representative of degradation mechanisms under changing environmental conditions. Monitoring programs that track service-life performance over multiple decades and databases of shared durability are required to facilitate the benchmarks of life-cycle assessment (LCA).

2.8.3. Supply Chain Readiness

The presence of supplementary cementitious materials (SCM) and recycled aggregates (RA) is local[83]. For example, the supply of fly ash is falling in post-coal economies, and slag and calcined clays are only abundant in industrial regions.

2.8.4. Economic Equity

In most low- and middle-income areas, the usage of LCC technologies is limited by high initial investment and lack of incentives or integration of carbon credits. These disparities can be alleviated using policy tools such as green procurement policy, tax credits, or low-interest innovation funds, so that the high- and low-income markets do not experience a carbon divide as a result of these disparities.

2.8.5. Hybrid Approaches

The hybrid opportunities of using SCMs, RA, and carbon capture utilization (CCU) in the framework of hybrid concrete systems have yet to be systematically investigated[66]. Initial research indicated that such interactions may enhance individual-based mechanical and environmental performance. Further studies are needed to optimize the multiple parameters of such blends and pilot test them under real-world conditions.

2.8.6. Digital Formation and Interoperability

The use of digital technologies, artificial intelligence (AI), building information Modelling (BIM), and digital twins are becoming a reality in LCC studies, but they are still not fully integrated[73,74].

3. Methodology and PRISMA Framework

Figure 2 illustrates the VOS viewer keyword co-occurrence network based on the included dataset, where node size is the frequency of publications and link thickness is citation connectivity. The prevailing group focuses on the concept of low-carbon concrete, which is closely related to geopolymers, carbon capture, the cement industry, sustainable development, and construction, suggesting the interrelation of material innovation and sustainability policy themes. Peripheral nodes, such as carbonation and life-cycle assessment (LCA), indicate areas of research that are still emerging and have not been thoroughly investigated.

3.1. Contribution and Novelty

This number incorporates a new analytical layer and transforms the manuscript beyond the descriptive review, as it combines PRISMA-based selection with visualization of the bibliography. It numerically confirms trends in literature, demonstrates thematic interconnections, and follows the anticipation of the reviewer of a systematic approach and meta-analysis-suited basis[7,8].

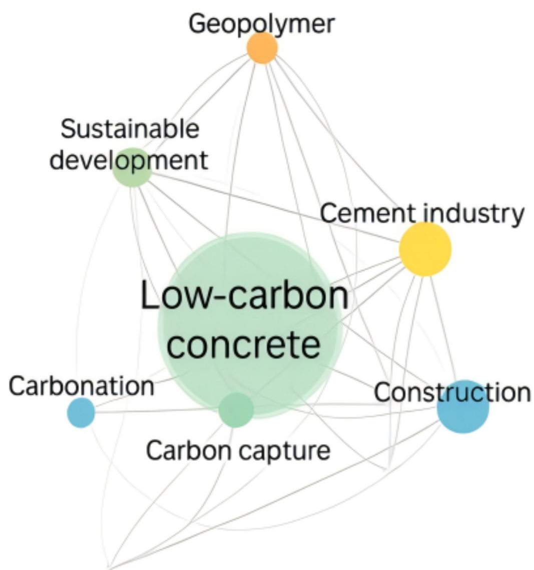

Figure 2. Systematic Review and Bibliometric Network Map.
Source: van Eck and Waltman[7]; Poloju et al.[8].

3.2. Systematic Review and Bibliometric Framework

To promote transparency, reduce bias, and enhance the validity of insights that can be made by relying on the available research on low-carbon concrete (LCC), this review uses a systematic and reproducible approach. The PRISMA 2020 protocol of systematic reviews is included in the workflow[6], and bibliometric network analysis with the help of the VOS viewer application is not only possible but also visualized in **Figure 2**. The databases and time periods searched were as follows:

The literature search was conducted in three large databases of science (Scopus, Web of Science (WoS), and Engineering Village (Compendex), which do not exceed the period 2000–2024. This period reflects 20 years of research improvement, including the initial activities in supplementary cementitious materials (SCMs) and the latest developments in the direction of digitalization, LC^3, carbon capture, and circular economy practices.

3.3. Bibliometric Mapping

VOS viewers were used to analyze keyword co-occurrence and citation networks to determine thematic clusters and research frontiers. **Figure 2** is a graphical representation of the relationships between high-frequency words, low-carbon concrete, geopolymer, carbon capture, sustainable development, LCA, and digitalization.

4. Results and Discussion

The analytical synthesis introduced in this paper confirms that the technologies of low-carbon concrete (LCC) are not solitary material innovations, but the inseparable parts of a more general decarbonization ecosystem. These findings confirm that the maximum performance of carbon reduction is achieved when the material design, durability assurance, and economic mechanisms are incorporated into a complex system. This finding is in line with the directions of the IPCC Sixth Assessment Report (2023), which emphasizes that industrial substances need to realize quick reduction of emissions in the coming ten years to be in line with the 1.5 °C goal. The identified data tendencies in the comparative data (especially the high carbon-saving potential of geopolymer and LC^3 concretes) are consistent with the IEA Cement Tracking Report (2024) and the GCCA Net Zero Roadmap (2023), both of which note that low-clinker cements, carbon capture, and circular resource loops are the most effective levers to reduce emissions. Moreover, the evidence highlights that a combined strategy is necessary; technological development should be supported by policy tools that include carbon taxation, performance-based regulations, and accounting of a digital life cycle to make it global. This study provides a combined analysis framework by connecting scientific performance data with economic and policy frameworks, which may add a new scale of understanding on how LCC systems can be used as the foundation for achieving net-zero 2050.

Figure 3 shows a real-life and time-limited roadmap that can be used to steer the cement and concrete industry towards net-zero 2050. The framework proposes stepwise measures to decarbonize the cement and concrete industry in four steps, namely near-term, short-term, medium-term, and long-term, to incorporate R&D, the carbon-pricing model, supply chain decarbonization, and technological breakthroughs to create a carbon-neutral built environment in 2050.

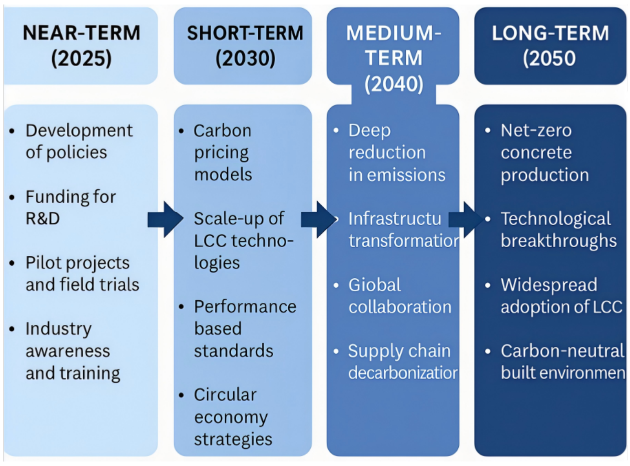

Figure 3. Net-Zero 2050 Roadmap to Implementation.

Near-Term (2025): Short-term interventions revolve around policy development, R&D, pilot programs, and sector training. These attempts have developed an empowering context for scaling material innovations, such as geopolymers, LC^3, and CCU concretes. Ongoing and initial public-private partnerships and demonstration projects are the basis of standardization and acceptance testbeds.

Short-Term (2030): The short-term period focuses on economic and regulatory policies, in particular, carbon pricing models, performance-based standards, and the inclusion of the circular economy. This guarantees that technological advancement is converted into market incorporation, and that the cost barrier identified by previous economic studies is overcome.

Medium-Term (2040): The roadmap projects a vision of significant emission cuts by 2040 by transforming infrastructure, collaborating with the world, and decarbonizing supply chains. This step will be based on upscaling tested technologies and aligning embodied carbon policies by region to make a greater impact internationally.

Long-Term (2050): The last phase presupposes net zero concrete production, which is supported by technological advances, digitalization, and the usage of LCCs. The built environment is practically carbon-neutral and meets the Net-Zero 2050 standard.

Significance: In contrast to descriptive reviews, this roadmap provides operational clarity and direction over time, where researchers, policymakers, and industry players must take action at every point. This makes the manuscript a prospective strategic input- a useful guide to the practical implementation of LCC under global sustainability systems.

4.1. LCC Systems Performance Comparisons

Low-carbon concrete (LCC) systems perform differently based on the approach they use, such as SCMs, LC^3, geopolymers, RA, or CCU, but all of them show that significant emission cuts can be achieved without affecting the mechanical or durability performance.

The comparative analysis in **Table 1** demonstrates that SCMs and LC^3 are the most established, geopolymers have the most potential but barriers to adoption, RA facilitates circularity at the cost of minimal trade-offs, and CCU introduces innovation but needs to be integrated into the industry.

Table 1. Comparative Performance of LCC Systems.

Mix	CO_2 Reduction %	Strength Retention	Durability	Cost Impact	Reference
Conventional OPC	0	100	Baseline	Baseline	Poloju et al. [30]
SCM Blends (30–50%)	20–40	90–100	Improved Chloride resistance	Neutral to cheaper	Alibeigibeni et al.; Pacheco-Torgal et al.; Scrivener et al. [37–39]
LC^3	30–40	95–105	High Chloride resistance	Competitive	Bernal et al.; Provis et al. [42,43]
Geopolymers	40–70	95–110	Excellent acid/ fire resistance	Higher	Shaikh et al.; Collins et al. [50,51]
RA Concrete	15–20	85–95	Lower (Improved with SCMs)	Neutral	Shi et al.; van Deventer et al. [63,64]
CCU Concrete	20–40	100	Neutral to positive	Higher upfront	Juenger et al.; Fu et al [72,73]

4.2. Mechanical Properties

4.2.1. Compressive Strength Development

- ➢ SCM concretes tend to have lower early strength development but higher later ages than OPC because of their pozzolanic activity[39].
- ➢ LC^3 concretes: Competed against compressive strengths of 30–60 Mpa[42].
- ➢ Geopolymers may have a compressive strength greater than 80 Mpa when optimized activators[50].
- ➢ The compressive and tensile strengths of RA concretes are reduced by approximately 10 percent, whereas hybrid constructions using SCMs regain performance[63].
- ➢ Concretes in CCU usually generating a 5–10% density in terms of strength as a result of the densification of calcium carbonate[73].

4.2.2. The Flexural and Tensile Properties

- ➢ The enhancement in flexural strength by SCMs and LC^3 was relatively small, which was achieved through the refinement of the pore structure.
- ➢ Geopolymers are used to provide better tensile behavior because the polymeric gel matrix has higher tensile behavior[51].
- ➢ The tensile properties are the most damaged in RA concretes, and they are still usable in noncritical applications.

4.3. Durability Performance

- ➢ Durability controls whole-life emission savings because the longer the service life, the lower is the replacement frequency.
- ➢ SCM Concrete: Demonstrated chloride ingress, sulfate attack resistance, and service life in marine and sulfate soils[39].
- ➢ LC^3 concrete demonstrates excellent chloride resistance and reduces heat of hydration, which reduces cracking[42,43].
- ➢ Geopolymers: Strong in acid, sulfate, and fire resistance, which is better than OPC under hostile conditions[50–52].
- ➢ RA concrete: Slightly less strong in terms of durability but enhanced with the use of SCMs[63].
- ➢ CCU concretes: These are neutral to slightly positive, yet long-term carbonation characteristics require further field verification[76].

4.4. Environmental Benefit and Life-Cycle Assessment

- SCMs: 25–40% reduction[75].
- LC^3: 30–40% reduction[76].
- Geopolymers: 40–70 percent reduction, maximum potential not yet globally scalable[77].
- RA achieves a 15–20 percent reduction and landfill diversion[78].
- CCU concrete: 20–40% decrease with further possibilities of capturing more CO_2[79].
- These savings are enhanced by durability-related life-cycle advantages: a 2030-year service life will cut emissions by another 15–25 percent[80,81].

4.5. Economic Feasibility

4.5.1. Cost Competitiveness

- **SCMs:** These are usually cheaper than clinkers in locations, but unless they are incurred through transport, savings may be neutralized by transport costs[45].
- **LC^3:** Competitive in terms of cost in areas with appropriate clays / limestone[43].
- In addition, the higher costs of activators lead to higher costs for geopolymers, but costs could be lowered by mass production[56].
- **RA concretes:** Costs of no type, landfill, and aggregate transportation savings[65].
- **CCU concretes:** It is expensive to construct, yet carbon credits may change economics to affect the cost[74].

4.5.2. Market Surveys

The surveys indicate that 65% of the contractors have no problem with using LCC when cost-neutral, but only approximately 30% have it[29].

4.6. Adoption Barriers

The most important challenges to adoption are as follows:

1. Standardization gap Codes: Codes seldom permit high-SCM replacements or mixes of geopolymers[58].
2. Supply chain differences in SCMs and RA are situated differently across regions, limiting universal approaches[69].
3. Economic factors: Initial investment in geopolymers and CCU[74].
4. Uncertainty in durability: No long-term field performance data are available[82].

4.7. Policy integration and Systemic Enablers

The comparative consistency of the IPCC AR6[3], IEA[4] and GCCA[5] is a reminder that national policies need to be more aggressive in reaching the low-carbon building sector by enforcing procurement passports, carbon prices, and standardized body-carbon regulations. The inclusion of LCC in these structures may add up to the nationally determined contributions (NDCs) under the Paris Agreement. Moreover, a combination of digitalization and LCA-based tools, as suggested by Habert et al.[6], can offer quantifiable accountability and assist in the transparent reporting of supply chains Economically, low-carbon concrete (LCC) will be cost-effective in the scenario that the price of carbon emission is internalized in policy frameworks. According to the IEA (2024), the average carbon price in the European Emissions Trading Scheme (ETS) was USD 85–90 per ton of CO_2 in 2023, which is why the replacement of clinkers and the use of CCU-based concretes is economically viable compared to traditional OPC systems[80]. On the same note, the GCCA (2023) Net Zero Roadmap estimates that carbon capture and utilization technologies will reach breakeven at USD 75–100 per ton of carbon price with investment tax credits and green procurement policies by 2030. These policy tools, along with embodied carbon accounting in the building codes, can permit emission savings to be awarded as trade-offs, offsetting the increased initial costs of new binders. For example, the ETS of the European Union, the Perform-Achieve-Trade (PAT) program of India, and upcoming GCC carbon credit platforms offer direct or indirect monetary benefits for materials that have shown carbon savings. The existence of such mechanisms testifies that carbon can offset cost is not a fictional principle, but it is a developing economic paradigm backed by carbon markets and sustainability-related procurement programs. By doing so, carbon valuation is useful to convert emission cuts into a physical financial commodity, which can encourage more industries to engage in LCC adoption.

5. Research and Practice Future Directions

Although there has been rapid development of low-carbon concrete (LCC), much remains to be done before large-scale implementation can be achieved. This section identifies the important potential future research and practices.

5.1. The Standardization and Codes of Practice

One of the biggest weaknesses of the current practice is the absence of harmonized codes for geopolymers and LC^3. Although laboratory tests show that these materials are as durable and strong as normal Portland cement (OPC), engineers have not been keen to specify them in large-scale projects unless they have found trust in the design[47]. There should be international cooperation between the ASTM, RILEM, ISO, and national standard bodies. Standardization of testing procedures, durability standards, and performance standards will hasten the belief in alternative binders.

5.2. Regional Adaptation and Context-Specific Strategies

The availability of materials varies across regions. Fly ash is also abundant in coal-based economies but falls out of favor in other economies because of energy changes[37]. In addition, calcined clays of LC^3 are abundant in certain areas and scarce in others. The need to develop regional adaptations should be a priority for future research, whereby solutions should be developed based on local supply chains, economic conditions, and weather conditions. The evidence base needed to make wide adoption possible can be created through large-scale demonstration projects across Africa, South Asia, and the Middle East.

5.3. Hybrid Approaches

Recent developments have indicated that simultaneous decarbonization approaches have better outcomes. The combination of SCM, RA, and CCU into hybrid concrete can realize a higher reduction than the aggregate of concrete[66]. For example, RA may be used together with SCM-rich mixes to compensate for the lack of strength, and CCU mineralization may be used to densify microstructures. Synergistic interactions, performance modelling, and pilot projects should be the focus of future research to validate these hybrid pathways.

5.4. Renewable Energy Integration

Cement and concrete manufacturing are energetic, even with low levels of clinker. Emissions can also be reduced by integrating renewable energy into kiln operations, curing processes, and admixture production. Kiln pilot projects using biomass, solar-driven curing chambers, and hydrogen-assisted combustion have been promising[67]. Such studies are necessary to cover the technical scaling, supply reliability, and cost-effectiveness of integrating renewables into concrete production systems.

5.5. Circular Economy and Resource Efficiency

LCC research needs to consider a greater circular economy prism. Traceability and quality control can be achieved through policymaking that requires the use of recycled content, modern RA processing technologies, and digital material passports. Blockchain-based traceability systems can be used to trace lifecycle emissions and enhance market trust[68]. Other directions for future research include the inclusion of other industrial by-products in binder systems (e.g., phosphogypsum, mine tailings, or agricultural ash) in addition to RA.

5.6. Artificial Intelligence and Digitalization

The opportunities of digital technologies in the decarbonization of concrete are still in their nascent stages. The big data of SCM content, curing regimes, and admixture combinations can be optimized by machine learning algorithms[61]. Future research should adopt AI with BIM and LCA software to obtain real-time carbon accounting data at the design and construction stages. Sustainable mix designs may be more accessible because of the possibility of global collaboration provided by cloud-based platforms.

5.7. Long-Term Durability Studies

Laboratory experiments provide strong evidence of LCC performance; however, real-world validation is limited. Longitudinal monitoring of pilot structures is essential to demonstrate durability under conditions such as freeze-thaw cycles, marine exposure, and acid rain. However, accelerated aging tests cannot fully capture these dynamics. Future work should prioritize multi-decade studies to build practitioner confidence and inform standards[63].

5.8. Socio-Economic and Policy Dimensions

The adoption of LCC requires more than technical readiness, which depends on training, policy, and equitable financing. Capacity-building programmes for engineers, contractors, and regulators are critical. Socioeconomic research should address equity, ensuring that low-income regions can access LCC despite higher initial costs. Policies that integrate carbon credits, subsidies, and tax incentives can make adoption financially viable. Interdisciplinary collaboration among material scientists, economists, and policymakers is central to this effort.

5.9. Long Term Durability Research

There is good evidence in the field of laboratory experiments to support the performance of LCC, but in the real world, it has not been well validated. Pilot structures should be monitored longitudinally to prove their ability to change conditions, such as freeze and thaw conditions, exposure to the sea, and acidic rain using this structure. However, these dynamics cannot be adequately described in accelerated aging tests. Multi-decade studies should be prioritized in future work to instill confidence in practitioners and shape standards[63].

6. Conclusion

This review brings together developments in low-carbon concrete (LCC) and its ability to significantly mitigate the adverse effects of the construction industry on the environment. Several major conclusions can be drawn.

1. **Innovations of Materials:** SCMs, geopolymers, LC^3, RA, and CCU technologies offer opportunities to reduce carbon emissions. These materials produce similar or better mechanical and durability performances when optimized compared to OPC.
2. **Durability, a Climate Strategy:** The longer the service life, the greater the climate benefits and the chemical and physical resistance to deterioration, and the better the reason to focus on durability as well as embodied carbon reductions.
3. **Systemic Integration:** LCC should be adopted with technical innovation, but with the incorporation of digital tools, standardized codes, supply chain preparedness, and supportive policies.
4. **Economic and Policy Drivers:** The Market adoption remains unequal. SCM-based concretes have already become cost-competitive in most situations, whereas geopolymers and CCU require supportive financing, procurement requirements, and carbon pricing systems.
5. **Research Gaps:** Long-term longevity, hybrid approaches, and socioeconomic factors have yet to be addressed. Such gaps will be filled by defining the rate at which LCC will become a laboratory innovation to industry standards.

However, in the end, there is no single technology for low-carbon concrete, but a set of complementary measures that can become the foundation of the world's net zero transition. The construction sector can achieve a great deal to minimize carbon footprint by balancing both technical innovations and systemic change to provide the industry with a resilient, durable, and sustainable infrastructure. The future difficulty is to scale solutions fairly and fast enough to satisfy climate urgency targets.

Together, recent international forums[1,34] and research findings[63] all point to the same direction, with the view that low-carbon concrete is a technological and policy opportunity. Its implementation can be the focal facilitator of the realization of the 2050 Net-Zero vision as long as standardization, durability verification, and digital integration are progressively developed.

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Conceptualization, M.R.; methodology, K.K.P.; validation, M.T. and A.N.H.; formal analysis, M.R.; investigation, K.K.P. and A.N.H.; data curation, K.K.P.; writing—original draft preparation, M.R.; writing—review and editing, M.R.; visualization, K.K.P.; supervision, K.K.P.; project administration, K.K.P. and M.R. All authors have read and agreed to the published version of the manuscript.

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References

[1] Thomas, M., Mehta, P.K., 2019. Supplementary Cementing Materials in Concrete, 3rd ed. CRC Press: Boca Raton, FL, USA.

[2] Poloju, K.K., Srinivasu, K., 2022. Influence of GGBS and Concentration of Sodium Hydroxide on Strength Behavior of Geopolymer Mortar. Materials Today: Proceedings. 65, 702–706. DOI: https://doi.org/10.1016/j.matpr.2022.03.276

[3] Intergovernmental Panel on Climate Change (IPCC), 2023. Climate Change 2023: Sixth Assessment Report (AR6). IPC: Geneva, Switzerland. Available from: https://www.ipcc.ch/assessment-report/ar6/

[4] International Energy Agency (IEA), 2024. Breakthrough Agenda Report 2024. IEA: Paris, France. Available from: https://www.iea.org/reports/breakthrough-agenda-report-2024/cement

[5] Global Cement and Concrete Association (GCCA), 2023. The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete. GCCA: London, UK. Available from: https://gccassociation.org/concretefuture/

[6] Habert, G., Miller, S.A., John, V.M., et al., 2020. Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries. Nature Reviews Earth & Environment. 1(11), 559–573. DOI: https://doi.org/10.1038/s43017-020-0093-3

[7] van Eck, N.J., Waltman, L., 2010. Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping. Scientometrics. 84(2), 523–538. DOI: https://doi.org/10.1007/s11192-009-0146-3

[8] Poloju, K.K., Annadurai, S., Manchiryal, R.K., et al., 2023. Analysis of Rheological Characteristic Studies of Fly-Ash-Based Geopolymer Concrete. Buildings. 13(3), 811. DOI: https://doi.org/10.3390/buildings13030811

[9] Kępniak, M., Chyliński, F., Woyciechowski, P., 2025. Enhancing the Performance of Recycled Aggregate Concrete Through Optimized Pretreatment Methods: A Microstructural Perspective. Scientific Reports. 15(1), 29998. DOI: https://doi.org/10.1038/s41598-025-14834-y

[10] Roknuzzaman, M., Rahman, M., Islam, M., 2025. Performance and Usability Assessment of Recycled Aggregate Extracted from Demolished Concrete Subjected to Multiple Recycling. Journal of Rehabilitation in Civil Engineering. 13(4). DOI: https://doi.org/10.22075/jrce.2025.35008.2158

[11] Roknuzzaman, M., Rahman, M., 2024. Compressive Strength of Recycled Green Concrete Affected by Chloride and Sulfate Exposures. Journal of Rehabilitation in Civil Engineering. 12(4). DOI: https://doi.org/10.22075/jrce.2024.32378.1938

[12] Nadi, S., Nezhad, H.B., Sadeghi, A., 2022. Experimental Study on the Durability and Mechanical Properties of Concrete with Crumb Rubber. Journal of Building Pathology and Rehabilitation. 7(1), 17. DOI: https://doi.org/10.1007/s41024-021-00156-9

[13] Poloju, K.K., Yahia, H.A.M., Anil, V., 2018. Examine Possible Outcomes on Strength Properties for Utilizing Rubber Waste on Varying Grades of Concrete. Journal of Advanced Research in Dynamical and Control Systems, 10(8), 1–7. Available from: https://www.researchgate.net/publication/330243664_Examine_Possible_Outcomes_on_Strength_Properties_for_Utilizing_Rubber_Waste_on_Various_Grade_of_Concrete

[14] Et-Tanteny, R., Manssouri, I., Bouayad, A., et al., 2025. Physicochemical and Thermomechanical Performance of Eco-Friendly Unfired Clay-Biopolymer Composite Bricks. Journal of Building Material Science. 7(3). DOI: https://doi.org/10.30564/jbms.v7i3.7994

[15] Nejati, M.Y., Behruyan, M., Sadeghi, A., et al., 2025. Experimental Study on the Compressive and Flexural Properties of the Ultrahigh-Performance Concrete Containing Fibers. Journal of Building Material Science. 7(1), 83–96. DOI: https://doi.org/10.30564/jbms.v7i1.8269

[16] Garces, J.I.T., Dollente, I.J., Beltran, A.B., et al., 2021. Life Cycle Assessment of Self-Healing Geopolymer

Concrete. Cleaner Engineering and Technology. 4, 100147. DOI: https://doi.org/10.1016/j.clet.2021.100147

[17] Vijayan, D.S., Gopalaswamy, S., Sivasuriyan, A., et al., 2024. Advances and Applications of Carbon Capture, Utilization, and Storage in Civil Engineering: A Comprehensive Review. Energies. 17(23), 6046. DOI: https://doi.org/10.3390/en17236046

[18] Spaeth, V., Tegguer, A.D., 2013. Improvement of Recycled Concrete Aggregate Properties by Polymer Treatments. International Journal of Sustainable Built Environment. 2(2), 143–152. DOI: https://doi.org/10.1016/j.ijsbe.2014.03.003

[19] Limbachiya, M.C., Leelawat, T., Dhir, R.K., 2000. Use of Recycled Concrete Aggregate in High-Strength Concrete. Materials and Structures. 33(9), 574–580. DOI: https://doi.org/10.1007/BF02480538

[20] Katz, A., 2003. Properties of Concrete Made with Recycled Aggregate from Partially Hydrated Old Concrete. Cement and Concrete Research. 33(5), 703–711. DOI: https://doi.org/10.1016/S0008-8846(02)01033-5

[21] Pacheco-Torgal, F., Jalali, S., 2010. Reusing Ceramic Wastes in Concrete. Construction and Building Materials. 24(5), 832–838. DOI: https://doi.org/10.1016/j.conbuildmat.2009.10.023

[22] Li, W., Xiao, J., Sun, Z., et al., 2012. Interfacial Transition Zones in Recycled Aggregate Concrete with Different Mixing Approaches. Construction and Building Materials. 35, 1045–1055. DOI: https://doi.org/10.1016/j.conbuildmat.2012.06.022

[23] Xiao, J., Li, W., Fan, Y., et al., 2012. An Overview of Study on Recycled Aggregate Concrete in China (1996–2011). Construction and Building Materials. 31, 364–383. DOI: https://doi.org/10.1016/j.conbuildmat.2011.12.074

[24] Shi, C., Li, Y., Zhang, J., et al., 2016. Performance Enhancement of Recycled Concrete Aggregate – A Review. Journal of Cleaner Production. 112, 466–472. DOI: https://doi.org/10.1016/j.jclepro.2015.08.057

[25] Junior, G.A.F., Leite, J.C.T., Mendez, G.D.P., et al., 2025. A Review of the Characteristics of Recycled Aggregates and the Mechanical Properties of Concrete Produced by Replacing Natural Coarse Aggregates with Recycled Ones—Fostering Resilient and Sustainable Infrastructures. Infrastructures. 10(8), 213. DOI: https://doi.org/10.3390/infrastructures10080213

[26] Kou, S.-C., Poon, C.-S., 2013. Long-Term Mechanical and Durability Properties of Recycled Aggregate Concrete Prepared with the Incorporation of Fly Ash. Cement and Concrete Composites. 37, 12–19. DOI: https://doi.org/10.1016/j.cemconcomp.2012.12.011

[27] Silva, R.V., de Brito, J., Dhir, R.K., 2014. Properties and Composition of Recycled Aggregates from Construction and Demolition Waste Suitable for Concrete Production. Construction and Building Materials. 65, 201–217. DOI: https://doi.org/10.1016/j.conbuildmat.2014.04.117

[28] Evangelista, L., de Brito, J., 2007. Mechanical Behaviour of Concrete Made with Fine Recycled Concrete Aggregates. Cement and Concrete Composites. 29(5), 397–401. DOI: https://doi.org/10.1016/j.cemconcomp.2006.12.004

[29] Etxeberria, M., Vázquez, E., Marí, A., et al., 2007. Influence of Amount of Recycled Coarse Aggregates and Production Process on Properties of Recycled Aggregate Concrete. Cement and Concrete Research. 37(5), 735–742. DOI: https://doi.org/10.1016/j.cemconres.2007.02.002

[30] Poloju, K.K., Shill, A., Al Balushi, A.R.S., et al., 2020. Determination of the Strength Properties of Concrete with Marble Powder. International Journal of Advanced Science and Technology. 29(08), 4004–4008.

[31] Padmini, A.K., Ramamurthy, K., Mathews, M.S., 2009. Influence of Parent Concrete on the Properties of Recycled Aggregate Concrete. Construction and Building Materials. 23(2), 829–836. DOI: https://doi.org/10.1016/j.conbuildmat.2008.03.006

[32] Kisku, N., Joshi, H., Ansari, M., et al., 2017. A Critical Review and Assessment for Usage of Recycled Aggregate as Sustainable Construction Material. Construction and Building Materials. 131, 721–740. DOI: https://doi.org/10.1016/j.conbuildmat.2016.11.029

[33] Tam, V.W.Y., Soomro, M., Evangelista, A.C.J., 2018. A Review of Recycled Aggregate in Concrete Applications (2000–2017). Construction and Building Materials. 172, 272–292. DOI: https://doi.org/10.1016/j.conbuildmat.2018.03.240

[34] Poon, C.S., Kou, S.C., Lam, L., 2002. Use of Recycled Aggregates in Molded Concrete Bricks and Blocks. Construction and Building Materials. 16(5), 281–289. DOI: https://doi.org/10.1016/S0950-0618(02)00019-3

[35] Safiuddin, Md., Alengaram, U.J., Rahman, Md.M., et al., 2013. Use of Recycled Concrete Aggregate in Concrete: A Review. Journal of Civil Engineering and Management. 19(6), 796–810. DOI: https://doi.org/10.3846/13923730.2013.799093

[36] Xiao, J., Qiang, C., Nanni, A., et al., 2017. Use of Sea-Sand and Seawater in Concrete Construction: Current Status and Future Opportunities. Construction and Building Materials. 155, 1101–1111. DOI: https://doi.org/10.1016/j.conbuildmat.2017.08.130

[37] Alibeigibeni, A., Stochino, F., Zucca, M., et al., 2025. Enhancing Concrete Sustainability: A Critical Review of the Performance of Recycled Concrete Aggregates (RCAs) in Structural Concrete. Buildings. 15(8), 1361. DOI: https://doi.org/10.3390/buildings15081361

[38] Pacheco-Torgal, F., Jalali, S., Fucic, A., 2013. Eco-Efficient Construction and Building Materials: Life

Cycle Assessment (LCA), Eco-Labelling, and Case Studies. Woodhead Publishing: Cambridge, UK.
[39] Scrivener, K.L., John, V.M., Gartner, E.M., 2018. Eco-Efficient Cements: Potential Economically Viable Solutions for a Low-CO2 Cement-Based Materials Industry. Cement and Concrete Research. 114, 2–26. DOI: https://doi.org/10.1016/j.cemconres.2018.03.015
[40] Habert, G., d'Espinose de Lacaillerie, J.B., Roussel, N., 2011. An Environmental Evaluation of Geopolymer Based Concrete Production: Reviewing Current Research Trends. Journal of Cleaner Production. 19(11), 1229–1238. DOI: https://doi.org/10.1016/j.jclepro.2011.03.012
[41] Davidovits, J., 2015. Geopolymer Chemistry and Applications, 4th ed. Institut Géopolymère: Saint-Quentin, France.
[42] Bernal, S.A., Provis, J.L., 2014. Durability of Alkali-Activated Materials: Progress and Perspectives. Journal of the American Ceramic Society. 97(4), 997–1008. DOI: https://doi.org/10.1111/jace.12831
[43] Provis, J.L., van Deventer, J.S.J., 2014. Alkali Activated Materials: State-of-the-Art Report, RILEM TC 224-AAM, RILEM State-of-the-Art Reports. Springer: Dordrecht, Netherlands. DOI: https://doi.org/10.1007/978-94-007-7672-2
[44] Turner, L.K., Collins, F.G., 2013. Carbon Dioxide Equivalent (CO2-E) Emissions: A Comparison Between Geopolymer and OPC Cement Concrete. Construction and Building Materials. 43, 125–130. DOI: https://doi.org/10.1016/j.conbuildmat.2013.01.023
[45] Poloju, K.K., Al Banna, W.N., 2024. Microstructure Studies and Strength Determination of Different Binder Content of Geopolymer Concrete. In Advancements in Science and Technology for Healthcare, Agriculture, and Environmental Sustainability. CRC Press: London, UK. pp. 50–55. DOI: https://doi.org/10.1201/9781032708348-10
[46] Hardjito, D., Wallah, S.E., Sumajouw, D.M.J., et al., 2004. In the Development of Fly Ash-Based Geopolymer Concrete. ACI Materials Journal. 101(6), 467–472.
[47] Duxson, P., Fernández-Jiménez, A., Provis, J.L., et al., 2007. Geopolymer Technology: The Current State of the Art. Journal of Materials Science. 42(9), 2917–2933. DOI: https://doi.org/10.1007/s10853-006-0637-z
[48] Nath, P., Sarker, P., 2011. Effect of Fly Ash on the Durability Properties of High Strength Concrete. Procedia Engineering. 14, 1149–1156. DOI: https://doi.org/10.1016/j.proeng.2011.07.144
[49] Chindaprasirt, P., Jaturapitakkul, C., Sinsiri, T., 2005. Effect of Fly Ash Fineness on Compressive Strength and Pore Size of Blended Cement Paste. Cement and Concrete Composites. 27(4), 425–428. DOI: https://doi.org/10.1016/j.cemconcomp.2004.07.003
[50] Shaikh, F.U.A., 2016. Mechanical and Durability Properties of Fly Ash Geopolymer Concrete Containing Recycled Coarse Aggregates. International Journal of Sustainable Built Environment. 5(2), 277–287. DOI: https://doi.org/10.1016/j.ijsbe.2016.05.009
[51] Collins, F., Sanjayan, J.G., 2001. Microcracking and Strength Development of Alkali Activated Slag Concrete. Cement and Concrete Composites. 23(4–5), 345–352. DOI: https://doi.org/10.1016/S0958-9465(01)00003-8
[52] Provis, J.L., 2018. Alkali-Activated Materials. Cement and Concrete Research. 114, 40–48. DOI: https://doi.org/10.1016/j.cemconres.2017.02.009
[53] Raza, A., Salmi, A., El Ouni, M.H., et al., 2024. A Comprehensive Review on Material Characterization and Thermal Properties of Geopolymers: Potential of Various Fibers. Case Studies in Construction Materials. 21, e03519. DOI: https://doi.org/10.1016/j.cscm.2024.e03519
[54] Zhang, M., Guo, H., El-Korchi, T., et al., 2013. Experimental Feasibility Study of Geopolymer as the Next-Generation Soil Stabilizer. Construction and Building Materials. 47, 1468–1478. DOI: https://doi.org/10.1016/j.conbuildmat.2013.06.017
[55] Rangan, B.V., 2008. Mixture Design and Production of Fly Ash-Based Geopolymer Concrete. Indian Concrete Journal. 82(5), 7–15.
[56] Singh, B., Ishwarya, G., Gupta, M., et al., 2015. Geopolymer Concrete: A Review of Some Recent Developments. Construction and Building Materials. 85, 78–90. DOI: https://doi.org/10.1016/j.conbuildmat.2015.03.036
[57] Luhar, S., Chaudhary, S., Luhar, I., 2018. Thermal Resistance of Fly Ash Based Rubberized Geopolymer Concrete. Journal of Building Engineering. 19, 420–428. DOI: https://doi.org/10.1016/j.jobe.2018.05.025
[58] Fernández-Jiménez, A., Palomo, A., 2005. Composition and Microstructure of Alkali Activated Fly Ash Binder: Effect of the Activator. Cement and Concrete Research. 35(10), 1984–1992. DOI: https://doi.org/10.1016/j.cemconres.2005.03.003
[59] Palomo, A., Krivenko, P., Garcia-Lodeiro, I., et al., 2014. A Review on Alkaline Activation: New Analytical Perspectives. Materiales de Construcción. 64(315), e022. DOI: https://doi.org/10.3989/mc.2014.00314
[60] Collins, F.G., Sanjayan, J.G., 1999. Workability and Mechanical Properties of Alkali Activated Slag Concrete. Cement and Concrete Research. 29(3), 455–458. DOI: https://doi.org/10.1016/S0008-8846(98)00236-1
[61] Chindaprasirt, P., Jaturapitakkul, C., Chalee, W., et al., 2009. Comparative Study on the Characteristics of Fly Ash and Bottom Ash Geopolymers. Waste Management. 29(2), 539–543. DOI: https://doi.org/10.1016/j.wasman.2008.06.023

[62] Deb, P.S., Nath, P., Sarker, P.K., 2014. The Effects of Ground Granulated Blast-Furnace Slag Blending with Fly Ash and Activator Content on the Workability and Strength Properties of Geopolymer Concrete Cured at Ambient Temperature. Materials & Design (1980–2015). 62, 32–39. DOI: https://doi.org/10.1016/j.matdes.2014.05.001

[63] Shi, C., Jiménez, A.F., Palomo, A., 2011. New Cements for the 21st Century: The Pursuit of an Alternative to Portland Cement. Cement and Concrete Research. 41(7), 750–763. DOI: https://doi.org/10.1016/j.cemconres.2011.03.016

[64] van Deventer, J.S.J., Provis, J.L., Duxson, P., et al., 2010. Chemical Research and Climate Change as Drivers in the Commercial Adoption of Alkali Activated Materials. Waste and Biomass Valorization. 1(1), 145–155. DOI: https://doi.org/10.1007/s12649-010-9015-9

[65] Gartner, E., Hirao, H., 2015. A Review of Alternative Approaches to the Reduction of CO2 Emissions Associated with the Manufacture of the Binder Phase in Concrete. Cement and Concrete Research. 78, 126–142. DOI: https://doi.org/10.1016/j.cemconres.2015.04.012

[66] Poloju, K.K., Al Ajmi, Z., Annadurai, S., et al., 2025. Experimental Study on Acid Resistance of Geopolymer Concrete Incorporating Fly Ash and GGBS: Towards Low-Carbon and Sustainable Construction. Buildings. 15(21), 4012. DOI: https://doi.org/10.3390/buildings15214012

[67] Page, M.J., McKenzie, J.E., Bossuyt, P.M., et al., 2021. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. The British Medical Journal. n71. DOI: https://doi.org/10.1136/bmj.n71

[68] Miller, S.A., Horvath, A., Monteiro, P.J.M., 2018. Impacts of Booming Concrete Production on Water Resources Worldwide. Nature Sustainability. 1(1), 69–76. DOI: https://doi.org/10.1038/s41893-017-0009-5

[69] Lehne, J., Preston, F., 2018. Making Concrete Change: Innovation in Low-carbon Cement and Concrete. Chatham House: London, UK. Available from: https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete (cited 1 June 2024).

[70] Shi, C., Qian, J., 2000. High Performance Cementing Materials from Industrial Slags — a Review. Resources, Conservation and Recycling. 29(3), 195–207. DOI: https://doi.org/10.1016/S0921-3449(99)00060-9

[71] Myers, R.J., Bernal, S.A., Provis, J.L., 2014. A Thermodynamic Model for C-(N-)A-S-H Gel: CNASH_ss. Derivation and Validation. Cement and Concrete Research. 66, 27–47. DOI: https://doi.org/10.1016/j.cemconres.2014.07.005

[72] Juenger, M.C.G., Snellings, R., Bernal, S.A., 2019. Supplementary Cementitious Materials: New Sources, Characterization, and Performance Insights. Cement and Concrete Research. 122, 257–273. DOI: https://doi.org/10.1016/j.cemconres.2019.05.008

[73] Fu, L., Ren, Z., Si, W., et al., 2022. Research Progress on CO2 Capture and Utilization Technology. Journal of CO2 Utilization. 66, 102260. DOI: https://doi.org/10.1016/j.jcou.2022.102260

[74] Unluer, C., Al-Tabbaa, A., 2013. Impact of Hydrated Magnesium Carbonate Additives on the Carbonation of Reactive MgO Cements. Cement and Concrete Research. 54, 87–97. DOI: https://doi.org/10.1016/j.cemconres.2013.08.009

[75] Ahmed, O., Ahmad, S., Adekunle, S.K., 2024. Carbon Dioxide Sequestration in Cementitious Materials: A Review of Techniques, Material Performance, and Environmental Impact. Journal of CO2 Utilization. 83, 102812. DOI: https://doi.org/10.1016/j.jcou.2024.102812

[76] Prayogo, D., Cheng, M.-Y., Wibowo, D., 2012. Artificial Intelligence Approaches for Optimizing High-Performance Concrete Mix Design. Available from: https://www.researchgate.net/publication/236856203_Artificial_Intelligence_Approaches_for_Optimizing_High-Performance_Concrete_Mix_Design (cited 1 June 2024).

[77] Yu, R., Spiesz, P., Brouwers, H.J.H., 2014. Mix Design and Properties Assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). Cement and Concrete Research. 56, 29–39. DOI: https://doi.org/10.1016/j.cemconres.2013.11.002

[78] Ding, T., Xiao, J., Tam, V.W.Y., 2016. A Closed-Loop Life Cycle Assessment of Recycled Aggregate Concrete Utilization in China. Waste Management. 56, 367–375. DOI: https://doi.org/10.1016/j.wasman.2016.05.031

[79] Colangelo, F., Forcina, A., Farina, I., et al., 2018. Life Cycle Assessment (LCA) of Different Kinds of Concrete Containing Waste for Sustainable Construction. Buildings. 8(5), 70. DOI: https://doi.org/10.3390/buildings8050070

[80] Duxson, P., Provis, J.L., 2008. Designing Precursors for Geopolymer Cements. Journal of the American Ceramic Society. 91(12), 3864–3869. DOI: https://doi.org/10.1111/j.1551-2916.2008.02787.x

[81] van den Heede, P., de Belie, N., 2012. Environmental Impact and Life Cycle Assessment (LCA) of Traditional and 'Green' Concretes: Literature Review and Theoretical Calculations. Cement and Concrete Composites. 34(4), 431–442. DOI: https://doi.org/10.1016/j.cemconcomp.2012.01.004

[82] Chen, C., Habert, G., Bouzidi, Y., et al., 2010. Environmental Impact of Cement Production: Detail of the Different Processes and Cement Plant Variability Eval-

uation. Journal of Cleaner Production. 18(5), 478–485. DOI: https://doi.org/10.1016/j.jclepro.2009.12.014

[83] Neville, A.M., 2011. Properties of Concrete, 5th ed. Pearson Education: Harlow, UK.