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Next-generation cementitious binders for low-carbon concrete: mechanisms, performance, and challenges

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Abstract. The construction industry works to reduce carbon emissions to achieve global climate-mitigation and net-zero objectives. It is under increasing pressure to develop low-carbon building materials. Cement production alone accounts for approximately 7–8% of all man-made CO_2 emissions worldwide; thus, it is crucial to develop new generations of cementitious binders to enable low-carbon concrete construction. This lecture-note review provides a comprehensive overview of next-generation low-carbon binder systems from an engineering perspective. These include supplementary cementitious materials (SCM), limestone-calcined-clay cement (lc3), alkali-activated materials and geopolymers, as well as carbon-based technologies currently being developed. A critical examination of the binding mechanisms by which emissions can be reduced, the performance of fresh and hardened binder systems, the durability characteristics of these binder systems, and the implications of their use in structural designs are presented. The role of life-cycle assessment (LCA) in evaluating the true environmental sustainability of various low-carbon binder systems was also discussed, with a focus on the durability–carbon trade-offs that will influence long-term binder-system performance. The identification of key challenges associated with variability of binder materials, standardization, supply-chain constraints, and obtaining reliable long-term performance data, this review emphasized that achieving effective decarbonization of concrete will require an integrated approach that includes both material design and structural-performance assessment.

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1 Introduction

The building construction industry must reduce its carbon footprint to meet global climate change mitigation targets and net-zero commitments. Concrete is the most widely used material in building construction and, as such, plays a central role in meeting this challenge due to its reliance on Ordinary Portland Cement (OPC) as the primary binding material. While concrete itself is not inherently carbon-intensive, the production of OPC has been associated with significant greenhouse gas emissions, high energy demand, and resource consumption [1,2]. Therefore, reducing the carbon footprint of concrete is now a critical research priority and the driver for the development of new generation cementitious binder systems that balance mechanical performance, durability, and life-cycle sustainability[3].

Cement manufacturing globally generates approximately 7 – 8% of total anthropogenic co_2 emissions, which places it among the largest industrial sources of co_2 emissions in the world [4]. These emissions are primarily derived from two mechanisms: (i) calcination of limestone, during which calcium carbonate decomposes into calcium oxide, and co_2 is released as an unavoidable process emission, and (ii) combustion of fossil fuels required to achieve kiln temperatures of about 1450 °c [5]. Recent studies suggest that nearly 60% of cement related co_2 emissions are process-based; thus highlighting the limited potential of energy-efficiency measures alone to achieve deep decarbonisation[6]. It is important to distinguish between cement-related emissions and concrete-related emissions. While cement production dominates embodied carbon, the overall environmental impacts of concrete are strongly influenced by mix design efficiency, structural optimisation, materials utilisation, and service-life [7]. Structurally optimised and efficiently designed concrete structures can significantly reduce emissions when assessed on a per-service-year basis. Therefore, meaningful emission reduction requires both low-carbon binder development and performance-driven concrete design[8].

Conventional OPC-based concrete faces significant sustainability challenges, despite proven mechanical performance and widespread use. Cement production is highly energy consumptive, relies on non-renewable raw materials, and remains dependent on fossil fuels. Although incremental strategies, including alternative fuels, improved kiln efficiency, and clinker quality optimisation have led to modest emission reductions, recent research consistently indicates that these strategies are insufficient to meet long-term net-zero targets. The continued dependence on high clinker content results in substantial embodied carbon even in optimised OPC systems [9]. As global infrastructure demand continues to increase, incremental improvements within the framework of conventional OPC are unlikely to offset absolute emission increases. This has resulted in a growing consensus that deep decarbonisation of concrete cannot be achieved through the optimisation of OPC [10,11].

Contemporary research has shifted from a strength-centric approach toward sustainability-driven binder design. Next-generation cementitious binders aim to reduce clinker content using SCM, engineered blended cements, alkali-activated materials, and carbon-based technologies. Not only do these systems lower embodied carbon, but they can also enhance durability, refine microstructural properties, and, in some cases, enable permanent carbon sequestration. Importantly, low-carbon binders should not be viewed directly as replacements for OPC [12,13]. Instead, they represent a systems-level approach to sustainable concrete design that integrates material chemistry, fresh and hardened performance, structural behaviour, durability, and life cycle impacts. Current research emphasises that sustainable concrete design requires balancing mechanical performance, serviceability requirements, and environmental benefits rather than focusing solely on compressive strength [14,15].

The objective of the study is to provide a comprehensive, engineering-oriented review of next-generation cementitious binders for low-carbon concrete. The scope includes binder mechanisms, fresh and hardened performance, structural and serviceability considerations, sustainability, and LCA perspectives and challenges to large-scale adoption. Unlike chemistry-focused reviews, this work will emphasise relevance to structural engineers, materials researchers, and policymakers, and the importance of performance-driven design and durability-driven sustainability assessments.

2 Carbon footprint of conventional cementitious systems

The carbon footprint of traditional cement-based systems is primarily generated from the manufacturing of OPC due to the production of clinker; therefore, identifying the primary source of emissions within OPC production is vital for evaluating realistic alternatives and justification of the shift to alternative cement-based binders.

Table 1. Sources of co₂ emissions in conventional OPC production

Emission source	Typical contribution (%)	Mitigation potential
Calcination (process emissions)	55–60	Low without binder change
Fuel combustion	30–35	Moderate
Electricity use	5–10	Limited

2.1 Clinker production and calcination emissions

The dominant source of emissions associated with clinker production is the calcination reactions that occur when limestone is transformed into clinker. During the calcination process, limestone decomposes into calcium oxide (CaO) and releases carbon dioxide (CO_2). Due to its inherent nature, this reaction generates emissions independent of the type of energy used to produce it and produces approximately 55–60% of total CO_2 emissions associated with cement use.

Therefore, the amount of emissions produced is directly dependent upon the clinker factor, defined as the percentage of clinker present in the cement; the greater the percentage of clinker contained in the cement, the larger the amount of carbon contained in the cement. The clinker factor is the single most important variable affecting the carbon footprint of cement. Therefore, the reduction of clinker is considered the most effective method for reducing the carbon footprint of cement-based systems.

2.2 Energy consumption in opc manufacturing

In addition to the emissions generated during clinker production, opc manufacturing requires a significant amount of thermal and electrical energy to maintain the temperature required to form clinker, typically around 1450 °c. Thermal energy, primarily provided by fossil fuels, and electrical energy, used for grinding and handling materials, both contribute to fuel-related emissions. While there have been several studies exploring alternative fuels and improving kiln efficiencies, the overall emissions-reduction potential of these approaches is relatively small compared to emissions-reduction opportunities available through clinker-factor reduction. Thus, energy optimisation is insufficient for achieving the level of decarbonization necessary for cement-based systems absent complementary binder-composition modifications.

2.3 Why partial replacement is more realistic than full replacement

While full replacement of opc has been studied in experimental systems, the majority of researchers agree that partial clinker replacement is currently the most feasible and scalable method for decarbonising cement-based systems. The main challenges to developing full replacement solutions include performance issues, long-term durability concerns, cost, availability of raw materials, and regulatory approval. Conversely, partial replacement provides an incremental path toward decarbonization, while maintaining compatibility with the current production infrastructure, construction methods, and regulatory framework. Therefore, the consensus among current researchers supports this methodology as the best approach for transitioning toward low-carbon concrete over the next few decades.

3 Classification of low-carbon cementitious binders

Low-carbon cementitious binders may be classified by their method of reducing CO_2 emissions, the type of chemical reaction they undergo, and the degree of compatibility with traditional concrete production methods. Based on current research, these binders may be grouped into the following four categories: supplementary cementitious materials (SCM); engineered blended cements, including limestone calcined clay cement (LC3); alkali-activated materials and geopolymers; and carbon-based technologies that allow CO_2 to be incorporated directly into the cementitious binder matrix. Each category has its own advantages and disadvantages in terms of performance, scalability, and sustainability.

Table 2. Comparison of low-carbon cementitious binders

Binder type	**Typical clinker reduction**	**Key advantages**	**Key limitations**	**Durability performance**	**Early-age strength**	**Maturity level**
Scm-based	20–50%	Compatibility, durability	Early strength, availability	High	Moderate	Commercial
Lc3	40–50%	Performance equivalence, scalability	Calcination control	Very high	Comparable	Pre-commercial
Aams/ geopolymers	80–100%	High durability, low carbon	Activators, standardization	Excellent	Variable	Emerging
Carbon-based	Variable	Co_2 sequestration	Scale-up, verification	Case-dependent	Improved	Pilot

3.1 Supplementary cementitious materials

SCM is the oldest and currently the most commonly used category of low-carbon binders. Fly ash, ground granulated blast furnace slag (GGBS), and silica fume are examples of common SCM, as well as various forms of waste ashes generated from agriculture and industry, such as rice husk ash and sugarcane bagasse ash. In addition to substituting clinker in the manufacture of Portland cement, these materials also enhance the strength and durability of the hardened paste by way of pozzolanic and latent hydraulic action, thereby reducing the embodied carbon of the binder and providing a finer pore structure.

Typically, SCMs are used at partial replacement levels of 20 – 50 % for fly ash and GGBS and 5 – 10 % for silica fume, depending on the desired level of performance. Although SCMs can increase the long-term strength of the concrete and provide better resistance to chloride ingress, many problems have been identified with their use, including delayed strength development, variability in the quality of the scm, and decreasing availability of traditional SCMs. Nevertheless, SCM remains the principal means of achieving incremental reductions in the carbon footprint of concrete, given its compatibility with existing standards and building practices.

3.2 Limestone calcined clay cement (LC3)

Limestone calcined clay cement (LC3) represents an engineered low-carbon binder system developed to reduce clinker content while retaining the performance of OPC. Lc3 is made up of clinker, calcined clay (metakaolin), limestone, and gypsum. As a result of the combination of alumina-rich calcined clay and limestone, LC3 can achieve up to 40-50 % clinker reduction. The clinker reduction efficiency of LC3 stems from the synergistic interactions between alumina-rich calcined clay and limestone during hydration that stabilise carboaluminate phases.

These interactions make up for the reduction in clinker content, thus providing compressive strengths and durability characteristics equal to or greater than those achieved with opc, especially at longer ages. Lc3 has shown improved resistance to chloride penetration and sulfate attack compared to opc. Because clay resources are abundant, and because calcination temperatures are generally lower than those required for opc production, LC3 is considered an increasingly viable option for regionalized and scaled-up low-carbon construction applications.

3.3 Alkali-activated materials and geopolymers

Alkali-activated materials (AAMS) and geopolymers represent a unique group of low-carbon binders that differ from Portland cement in their chemical behavior. AAMS and geopolymers are made from aluminosilicate-rich precursor materials such as fly ash, slag, or metakaolin that are activated using alkaline solutions. The binding mechanism involves the dissolution of the precursor phase(s) followed by polycondensation that produces a dense three-dimensional aluminosilicate network.

AAMS and geopolymers offer several attractive properties, including high compressive strength, excellent chemical resistance, and enhanced durability under severe environmental conditions, at a fraction of the embodied carbon of opc. Nevertheless, the widespread adoption of AAMs and geopolymers is hindered by their sensitivity to curing conditions, handling, and safety concerns associated with alkaline activators, variability of precursor materials, and the lack of uniformity among design codes and specifications. Research is ongoing to develop more robust and performance-based specifications for AAMS and geopolymers so that they can be more easily applied to a variety of different building types and applications.

3.4 Carbon-based technologies

Carbon-based technologies represent a new category of low-carbon binders that go beyond merely reducing emissions to actively incorporating CO_2 into the cementitious binder matrix. The two main approaches are CO_2 curing and mineral carbonation, where CO_2 reacts with calcium- or magnesium-rich phases to produce relatively stable carbonate compounds. Both of these processes enable permanent and long-lasting sequestration of co_2 while potentially increasing early-age strength and modifying surface properties.

Recent studies have demonstrated improved dimensional stability, durability, and surface hardness in carbonated concrete systems. However, numerous technical challenges exist with respect to controlling the carbonation process, supplying CO_2, scaling up the technology, and verifying the net carbon savings of each process. In spite of these challenges, several pilot-scale and commercial demonstrations suggest that carbon-based technologies will become an integral component of a comprehensive strategy for producing low-carbon and carbon-sequestered concretes.

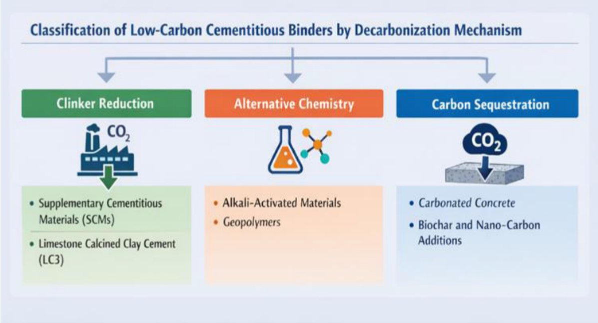

Fig.1. Classification of low-carbon cementitious binders by decarbonization mechanism

4 Fresh and hardened performance of low-carbon concrete

The low-carbon concrete performs when it is still fresh and once it has hardened. This will help to determine if it is viable for use in building structures, if it will perform reliably during its lifetime, and how durable it will be. The properties of low-carbon concrete will differ from those of OPC-based systems because the amount of cement clinker used is reduced, and alternative methods of chemical reactions are utilised. Therefore, the performance characteristics of low-carbon concrete must be understood to implement them safely and effectively in structural uses.

4.1 Fresh state behaviour

Most low-carbon concrete mixes have issues with workability and flowability because of the added fine particles or supplementary materials such as calcined clay or precursors activated by alkalis. These finer particles typically increase the surface area and angle of the particles; thus, they tend to create a greater yield stress and a higher viscosity. This results in a reduced slump and an increased sensitivity to changes in water content. Thus, the conventional mix designs may not apply directly to low-carbon concrete, and the emphasis is now on rheology-based designs and research.

Compatibility of admixtures with water demand plays a significant role in wet-state performance. Most low-carbon binders interact differently with superplasticizers, especially polycarboxylate ether (PCE)-type admixtures. This leads to decreased dispersion efficiency and/or rapid slump loss. Recent studies suggest there is a necessity to optimise admixtures, tailor the dosages of admixtures, and assess the compatibility of each binder to achieve acceptable workability and to avoid degrading strength and/or durability.

4.2 Strength Development Characteristics

Strength development in low-carbon concrete often varies significantly from opc-based systems. Early-age strength in SCM-rich and LC3-based concretes is usually lessened due to lower amounts of clinker and slower pozzolanic reactions. Conversely, later age strengths in SCM-rich and LC3-based concretes are normally increased due to continuing hydration and secondary reaction products that continue to compact the microstructure over time. Strength development at various ages is dependent upon curing conditions, especially for alkali-activated and blended systems with high levels of replacements. Curing conditions must provide sufficient moisture and temperature to initiate pozzolanic and geopolymer reactions. Studies show that using optimal curing conditions can greatly minimise the strength difference between low-carbon and conventional concretes at earlier ages, allowing for their use in structural applications where early strength is critical.

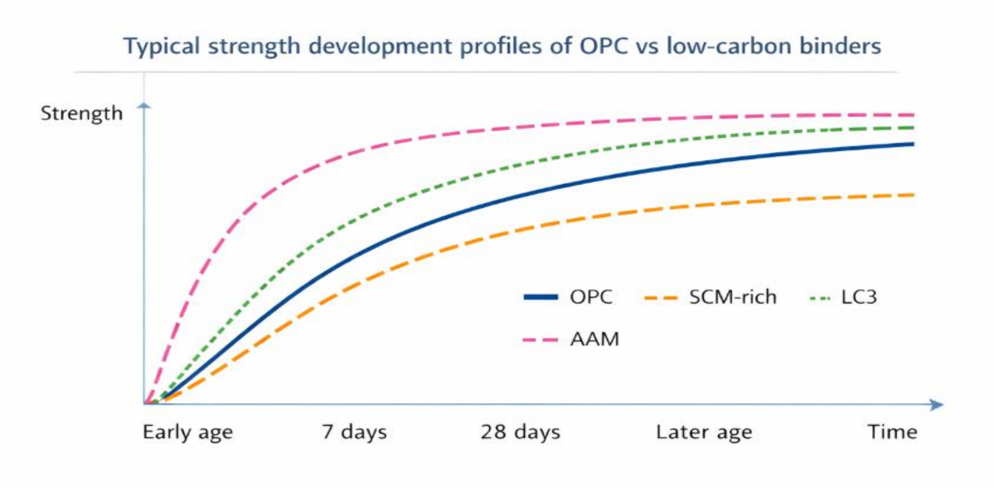

Fig.2. Typical strength development profiles of OPC vs low-carbon binders

4.3 Volume stability and setting behavior

Volume stability is a major concern in low-carbon concrete since reduced clinker content and differing hydration kinetics can modify shrinkage and creep behaviors. Several studies have shown that drying shrinkage is increased in high-scm or alkali-activated systems due to the refined pore structure and larger paste volume. Elevated creep deformations were observed in some low-clinker concretes, and this may affect the long term deflection and serviceability performance of structural elements made from these types of concretes. The setting behaviour of low-carbon concrete is also influenced by binder composition and reaction mechanisms. Low-carbon binders may exhibit delayed or accelerated setting times, depending on the type of material, fineness, and activator chemistry. Such variations require close monitoring of mix proportions and construction schedules. There is a growing body of research supporting performance-based limitations on shrinkage, creep, and setting time, especially for new binder systems.

4.4 Durability performance

Many low-carbon concrete systems exhibit improved durability when properly formulated. Reduced permeability and refined pore structure in scm-rich and LC3 concretes often provide improved resistance to chloride penetration, making them suitable for marine and harsh environments. Resistance to sulfate attack has also been demonstrated to be enhanced due to reduced calcium hydroxide content and modified hydrate assemblages. Permeability and acid attack resistance depend heavily on binder chemistry and environmental exposure conditions.

Some alkali-activated and carbonated systems have been shown to possess improved chemical resistance, while other types of systems may be susceptible to certain environments. Studies that monitor the long-term behavior of low-carbon concretes increasingly emphasize that durability, not just the compressive strength of a low-carbon concrete system, defines the true sustainability of the low-carbon concrete, through the extended service life of structural elements, and reduction in required maintenance and replacement costs.

5 Structural performance and design considerations

Structural adoption of low-carbon concrete depends not only on the material performance but also on the structural behavior of the concrete and compatibility with existing structural design philosophies. While numerous low-carbon binders can obtain compressive strengths equal to those of OPC-based concretes, the differing elastic moduli, time-dependent behaviours, and cracking responses will require attention in designing the structural components. This section covers the key implications of low-carbon binders on the behavior of reinforced concrete, serviceability performance, and structural reliability.

5.1 Compatibility with reinforced concrete systems

Compatibility with reinforced concrete (RC) systems is the first and most important condition to allow structural use of low-carbon concrete. Research indicates that the bond behaviour between the steel reinforcing and the SCM-rich and LC3-based concretes is comparable to the behaviour of opc systems if adequate curing and mix optimization are achieved. In addition, the SCM-rich concretes can refine the interfacial transition zone to improve the bond strength at the interface at later ages. The crack control behaviour may differ among the low-carbon concretes because of the variation of elastic modulus, shrinkage, and creep. The low-carbon concretes with higher paste volume or the refined pore structure may show an increase in crack sensitivity if they are not adequately detailed. Therefore, the reinforcement detail, crack width control, and serviceability check will be very important. Current research shows that the conventional RC detailing rules generally apply, but conservative assumptions should be made in order to ensure structural reliability for high replacement or unconventional binder systems.

5.2 Elastic modulus, creep, and deflection

One of the most important structural differences between low-carbon and OPC-based concretes is the difference in elastic modulus and time-dependent deformation behaviour. Reduced clinker content and changed hydrate composition can reduce the elastic modulus even though the compressive strength is similar. The reduced elastic modulus directly affects the stiffness, deflection and vibrations of the structural member. Creep behavior is also affected by the binder composition and the curing conditions. Several studies indicated that the creep strain was larger in high SCM or alkali activated system than in OPC based system, which can cause larger long-term deflection and redistribute the internal forces. Thus, serviceability limit states - rather than ultimate strength - are usually governing the design. These results show that it is necessary to explicitly take account of the modulus and creep parameters when applying low-carbon concrete to a structural element.

5.3 Strength-based vs serviceability-based design

In traditional concrete design, the design is almost exclusively strength-driven, using the compressive strength as the main performance criterion. However, research clearly demonstrates that serviceability criteria (deflection, cracking, long-term deformation, etc.) Are usually more important for low-carbon concrete than the ultimate strength capacity. Therefore, the design concept of low-carbon concrete must be changed from the conventional strength-based design to a serviceability-controlled and performance-based design approach. Although the low-carbon concretes can fulfil the strength requirement, the stiffness and deformation behavior can be quite different from those of opc based concrete; the design assumptions in the structural analysis and design must be modified accordingly. Current research recommends that material-specific properties should be included in the design model instead of relying solely on the strength-based correlation obtained from opc system.

5.4 Structural safety and reliability

Low-carbon concrete systems have been shown to provide sufficient load-bearing capacity when designed and cured properly. Experimental and analytical studies demonstrated that the ultimate limit state performance, including flexural and shear capacity, of SCM-based and LC3 systems can be comparable to those of conventional concrete. However, performance uncertainty remains a concern because of the variability in material properties, curing sensitivity, and lack of long-term field data for some binder types. Therefore, this uncertainty affects the reliability assessment and safety margins applied in the design. As a consequence, the current research stresses the importance of conservative partial safety factors, performance-based verification, and continuous monitoring to ensure the structural reliability, thus allowing for wider application of low-carbon concrete in load-bearing applications.

Table 3. Structural design implications of low-carbon binders

Parameter	Opc assumption	Low-carbon reality	Design implication
Elastic modulus	Strength-based	Binder-dependent	Serviceability governs
Creep	Moderate	Often higher	Deflection control
Crack width	Standard	Sensitive	Conservative detailing
Reliability	Well-defined	Higher uncertainty	Performance-based design

6 Sustainability and life-cycle assessment (lca) perspective

A sustainability analysis of low-carbon concrete should address both the reductions in greenhouse gas emissions associated with low-carbon concrete, as well as its life-cycle performance characteristics. Reducing clinker content in cement will directly lower the amount of CO_2 emitted during the production of the material, however, the total environmental benefit associated with low-carbon binders is dependent upon how they influence the practices used during construction, the service life of the structure, the frequency and type of maintenance required, and the end-of-life scenario. Therefore, life cycle assessment (LCA) has become a valuable tool for the objective comparison of traditional Portland cement (OPC) cementitious systems with low-carbon cementitious systems.

6.1 Embodied Carbon Reduction Potential

The primary way in which low-carbon cementitious binders provide opportunities to reduce the embodied carbon of cement and concrete is through the substitution of clinker in cement and concrete with SCMs, low-carbon cements such as lc3, and alkali-activated binders. The majority of comparative LCA studies have demonstrated that blended systems utilizing SCMs, LC3, or alkali-activated binders can produce 20-50% less CO_2 emissions on a cradle-to-gate basis compared to OPC-based systems, depending on the replacement level of the SCM or alternative binder, the source of the materials, and the regional energy profile. Clinker reduction remains the greatest factor influencing the embodied carbon intensity of the various low-carbon binder alternatives. However, the actual percentage of CO_2 reduction achieved through the use of low-carbon binders can vary substantially among studies due to the fact that the lca studies differ in terms of system boundary definitions, allocation procedures, transportation assumptions, and regional energy profiles. In addition, because there is no standard functional unit, it is difficult to compare the results of different studies directly. Therefore, current research emphasises the need for developing and using a standardized functional unit, as well as transparent reporting to facilitate comparison of OPC-based systems and low-carbon concrete systems.

6.2 Life-cycle stages of concrete

A complete sustainability analysis must evaluate all phases of the life cycle of concrete, which includes raw material extraction, binder and concrete production, transportation, construction, service life, and end-of-life phases. Although many studies have focused on assessing only the cradle-to-gate phase of the life cycle of concrete, there is an increasing interest in assessing the full environmental impact of concrete structures through cradle-to-grave and cradle-to-cradle assessments.

In addition to affecting the material production phase of the life cycle of concrete, the use of low-carbon binders can potentially affect several other phases of the life cycle of concrete. For example, the alteration of curing requirements, construction practices, and maintenance intervals can affect emissions produced during the construction and service phases of the life cycle of concrete. In addition, the end-of-life scenario, which could include recycling, carbonation during service, and reuse of concrete as secondary materials, can alter the net carbon balance of the life cycle of concrete. Research has demonstrated that failure to consider these downstream phases of the life cycle of concrete can result in underestimating or overestimating the sustainability benefits of low-carbon binders.

6.3 Durability–carbon trade-offs

Recent LCA studies have identified another significant aspect of the relationship between low-carbon binders and sustainability: durability-carbon trade-offs. While increased replacement levels of low-carbon binders tend to decrease initial embodied carbon, this increase in replacement levels may also negatively affect durability performance and service life if not carefully engineered. Service life is a determining factor of the true sustainability of concrete structures. Structures with longer service lives and moderate embodied carbon typically outperform low-carbon systems with shorter service lives when evaluated on a life-cycle basis. Increasingly, researchers advocate for the development of carbon emissions that are expressed on a per-service year or per functional performance basis to emphasise the significance of durability-driven mix design and performance-based assessment frameworks.

6.4 Importance of LCA alongside strength evaluation

While reliance solely on compressive strength as an indicator of performance can result in inaccurate "low-carbon" claims, especially when environmental benefits are evaluated without consideration of life-cycle impacts, a concrete mixture with reduced embodied carbon but compromised durability or increased maintenance requirements may perform poorly from a sustainability standpoint when evaluated over its full life cycle. Therefore, integration of LCA with the evaluation of mechanical and durability performance is crucial for making informed decisions about the selection of low-carbon binders. Current best practice promotes holistic sustainability assessment that combines material-level carbon metrics, structural performance, service life prediction, and end-of-life factors. This integrated approach allows designers and policymakers to determine what low-carbon concrete options are truly sustainable rather than selecting based on simple or incomplete environmental indicators.

7 Challenges and barriers to large-scale adoption

In order to overcome the existing challenges to implementing low-carbon concrete, it is necessary to provide the building industry with information on how to utilize low-carbon binders in construction. Therefore, one purpose of this report is to identify current and potential future opportunities for utilizing low-carbon binders and other low-carbon cementitious materials, and to provide a summary of relevant research and development activity, as well as industry perspectives.

7.1 Material variability and quality control

A major issue in using low-carbon binders is that supplementary cementitious materials (scms) derived from waste have variable characteristics depending upon the source and treatment of the scm. For example, the chemical composition, particle size distribution, and pozzolanic reactivity of fly ash, blast furnace slag, and agricultural waste ashes are all affected by the source and treatment of the scm. Such variability can result in unpredictable variations in the workability and mechanical properties of freshly mixed and hardened concrete, respectively; thus, it is difficult to develop reliable mixing proportions and quality control procedures for low-carbon binders.

To ensure that low-carbon binders perform consistently, it will be necessary to establish robust quality control procedures, which would involve material characterization, preliminary testing to qualify scm sources, and process control during both scm production and concrete batching. Research currently underway has emphasized the need for performance-based acceptance criteria for low-carbon binders, especially those made from waste-derived scm's, since the physical properties of these materials are likely to vary significantly from traditional scm's.

7.2 Supply chain and regional constraints

Availability and transportation of low-carbon binder constituents are extremely regional and can create logistical and economic barriers. Fly ash and slag are becoming increasingly scarce in areas that are transitioning from coal-fired electricity generation to natural gas or from blast furnace operation to electric arc furnaces. Transportation distance can reduce the environmental benefit of the low-carbon binder by increasing the associated greenhouse gas emissions. Recent research has highlighted the potential for the use of locally available alternative materials, such as agricultural residues and natural clays, to eliminate dependence on central supply chain logistics and thereby minimize the regional barriers to the use of low-carbon binders. However, the integration of local materials will require localized characterization, processing equipment, and adaptations to the mixture designs, which could limit the rate of adoption at scale.

Industry familiarity is another non-technical, yet very important barrier to the adoption of low-carbon concrete. Contractors, suppliers, and designers often resist using new materials because of perceived risks in terms of constructability, performance uncertainty, and liability. A lack of experience with alternative binders can decide to depart from traditional OPC-based materials. To overcome the knowledge gap, demonstrations of low-carbon concrete, training programs, and documentation of performance will be required to increase familiarity with the material among industry stakeholders. Best practice indicates that low-carbon concrete technologies should be introduced gradually through pilot projects, which will provide stakeholders with clear guidance and documentation of performance.

8 Future research directions

Future research on low-carbon concrete is increasingly driven by the integration of data-driven and performance-based approaches. low-carbon concrete research will continue to evolve through the continued development of the integration of artificial intelligence (ai) and machine learning (ml) and its application to improve the ability to identify complex inter-relationships between cement binder chemical composition, curing environmental conditions, mechanical properties of low-carbon binders and durability indicators, as well as reduce embodied carbon through optimized binder proportioning using ai-assisted mixing and other forms of process optimization. The AI-assisted mixing approach will allow for binder proportioning that is no longer limited to traditional "trial and error" methods and will enable the designer to simultaneously minimize the carbon footprint associated with the production and transportation of the binder while meeting strength, workability, and durability requirements of the low-carbon system. This type of process optimization will be especially beneficial to low-carbon binder systems with high levels of variability in their raw materials, which will limit the effectiveness of traditional empirical design methods.

There is an increasing movement away from the traditional prescriptive material limits used in the durability design of concrete towards service-life oriented evaluation methods. In the future, binder systems are anticipated to be hybrid and multi-component, utilizing combinations of SCMs, alkali-activated systems, and carbon-based technologies to maximize the reduction in carbon emissions while ensuring the structural reliability of the low-carbon binder system. The successful implementation of these new binder systems will also require the development of new digital tools that can support the transition of structural design practices to carbon-aware structural design practices through the utilization of BIM, LCA, and structural analysis software. These digital tools will enable designers to include carbon metrics directly into their design decisions and facilitate the holistic optimization of material selection, structural performance, and sustainability outcomes.

9 Conclusion

The carbon footprint of concrete needs to be decreased to meet the long term goals of climate targets, and this study proves that the replacement of OPC is required; it should be done by means of performance-driven design and not solely through the replacement of materials. The methods of reducing the amount of clinker in opc by utilizing supplementary cementitious materials, engineered blended cements, alkali-activated systems, and carbon-based technologies can reduce the embodied carbon of a structure, while providing functional performance with proper design.

Research evidence shows that low-carbon cementitious binders can provide the structural requirements for buildings, which include strength and load-bearing capacity, as long as the differences in stiffness, deformation, and cracking behaviour are considered. As a result, the durability and life cycle performance are the governing elements of sustainability, as a short service life, or an increase in the need for maintenance, can eliminate the benefits of initial carbon savings. Therefore, the use of a life cycle assessment must go hand-in-hand with a mechanical evaluation to ensure credible sustainability claims. Future improvements will depend on the development of hybrid binder systems, ai assisted mix design, and performance-based design frameworks. Digital tools that integrate carbon metrics into material selection and structural design will be crucial for designing durable, low-carbon, and climate-resilient concrete structures.

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