

Review

Portland Limestone Cement in Concrete Pavement and Bridge Decks: Performance Evaluation and Future Directions

Daniel D. Akerele , Federico Aguayo  and Lingzi Wu 

Department of Construction Management, University of Washington, Seattle, WA 98195, USA;
aguayo12@uw.edu (F.A.); lingwu@uw.edu (L.W.)

* Correspondence: dannie70@uw.edu

Abstract: With the rising demand for sustainable infrastructure, addressing the limitations of Ordinary Portland Cement (OPC) is crucial, particularly for exposed structures such as pavements and bridge decks. Portland limestone cement (PLC) is a sustainable alternative that delivers environmental benefits and comparable performance. This study used a systematic review and meta-analysis with a random-effects model to evaluate PLC's strength development, durability, and sustainability. The findings indicate that PLC generally matches or surpasses OPC in terms of compressive strength, freeze–thaw resistance, and sulfate durability. However, its setting time and early-age cracking require further optimization, especially in cold climates. Additionally, this study highlights the fire performance advantages of PLC and its enhanced chloride resistance. The analysis identified critical research gaps, including long-term field performance and regional adaptation to extreme environmental conditions. These findings contribute to a deeper understanding of PLC's role in sustainable construction and offer future research directions on hybrid cements and admixture compatibility.

Keywords: Portland limestone cement (PLC); type 1L cement; concrete pavement; bridge deck; sustainability; low-carbon; CO₂ reduction



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1. Introduction

With recent advancements in technology and the pressing demand to reduce greenhouse gas emissions in the construction industry, researchers have been making efforts to develop sustainable and innovative materials to reduce emissions and material depletion [1]. Over the years, the construction industry has heavily depended on the use of ordinary Portland cement (OPC) in diverse kinds of construction [2]. Although OPC is versatile and widely acceptable, it comes with several environmental drawbacks. OPC production is energy-intensive and releases substantial amounts of greenhouse gases (CO₂) into the atmosphere [3]. Note that the term CO₂ is generally used to refer to common greenhouse gases, which also include nitrous oxide and methane [4]. In addition, OPC relies heavily on finite raw materials including limestone and clay. As demand for construction increases, the depletion of these natural resources has become a concern. Portland limestone cement (PLC), often referred to as Type 1L cement, represents a significant advancement in the construction industry, offering an eco-friendly alternative to traditional Portland cement [5]. PLC is produced by intergrinding or blending Portland cement clinker with usually 5–15% finely ground limestone, resulting in a material that exhibits similar, if not superior, performance properties compared to conventional cements [6]. Type 1L's lower clinker content allows for lower CO₂ emissions during production, aligning with global

sustainability goals and making it an attractive option for the construction industry, which is increasingly under pressure to adopt greener practices [7].

By incorporating limestone, PLC reduces the carbon footprint of cement production by up to 10%. This reduction is attributed to the lower energy required for clinker processing [8]. Additionally, PLC is engineered to provide equivalent performance to OPC in both the fresh and hardened states, which generally does not require any significant modification to the mix designs. In recent years, PLC has been accepted in the specifications for blended cements of popular specifying agencies including AASHTO, ASTM, and Eurocode under the designation of Type 1L [9,10]. Interestingly, ASTM C1157 performance cement allows for higher limestone content, exceeding the typical ASTM C595 limit of 5–15% [11]. For instance, in Seattle, certain PLC formulations have utilized more than 15% limestone with promising results [12]. This flexibility opens new avenues for sustainable construction by further reducing clinker content and CO₂ emissions [13]. While Type 1L cement (within ASTM C595) adheres to the 5–15% limestone range, ASTM C1157 performance cement provides an avenue for utilizing even higher limestone content. Such variations allow engineers and designers to tailor their cement choices based on specific project requirements, environmental goals, and regional availability of materials.

The relevance of the PLC extends beyond the borders of its environmental benefits. As the demand for infrastructure development increases, particularly in the context of rapid urbanization and aging infrastructure, there is a pressing need for durable, sustainable, and cost-effective materials that can address the challenges of modern construction [14]. PLC has demonstrated potential in this regard, particularly in applications such as concrete pavements and bridge decks, where strength, durability, and long-term performance are critical [5]. However, although PLC has been adopted in various regions and projects, its performance under different environmental conditions and various structural applications remains an area of ongoing research and debate [15]. Additionally, there are no robust specifications regarding these applications under different scenarios compared with OPC [16].

Despite PLC's potential, knowledge gaps remain regarding its long-term field performance, particularly under extreme environmental conditions such as freeze–thaw cycles, sulfate exposure, and fire resistance. Furthermore, regional variations in limestone quality and their impact on PLC's mechanical properties of PLCs require further investigation [17,18]. The variability of limestone from different regions, due to geological factors, location, and quarrying practices, may impact durability performance [19]. While extensive research exists on laboratory-based evaluations, real-world complexities and comparative field studies of PLC versus OPC in bridge decks and pavements remain limited [20,21]. In addition, the impact of admixture compatibility and shrinkage mitigation strategies warrants further exploration [22–24]. This study systematically reviews existing research while addressing these critical gaps, paving the way for more comprehensive performance-based specifications for PLC adoption in infrastructure applications.

Previous literature reviews have primarily concentrated on laboratory-based assessment of PLC, providing limited insights into real-world applications. Comprehensive reviews focusing on PLC's long-term performance in actual field conditions, particularly for concrete pavements and bridge decks, are scarce. By systematically reviewing existing studies and identifying gaps in knowledge, this review aims to provide a clearer understanding of PLC's performance, paving the way for better utilization and addressing the challenges with its adoption in various environmental conditions. Additionally, the aim is to synthesize existing research by compiling and analyzing the body of literature on PLC, focusing on its performance in terms of mechanical properties, durability, and field application. Lastly, the aim is to identify research gaps and highlight areas where existing

research is lacking, particularly in long-term field studies and the performance of PLC under extreme conditions. This includes identifying gaps related to regional variations in performance, compatibility with admixtures, and challenges in implementation.

2. Methodology

2.1. Literature Search Strategy

To ensure a comprehensive and systematic review of the research trajectory of Portland limestone cement in pavement and bridge applications, a structured literature search was conducted using a systematic approach. The search focused on identifying studies relevant to Portland limestone cement (PLC) in concrete pavements and bridge decks. The following keywords were used: “portland limestone cement” OR “Type 1L” AND “pavement” AND/OR “bridge decks”. These keywords were selected to capture the studies that specifically addressed the use of PLC in infrastructure projects. Four reputable databases were used: Web of Science, a multidisciplinary research database that provides access to a vast array of scientific journals and conference proceedings; Transport Research International Documentation (TRID), a specialized database focusing on transportation research, which includes studies related to concrete pavements and bridge decks; Semantic Scholar, an AI-powered research tool that indexes scholarly articles across a wide range of disciplines, with a focus on high-impact publications; and Google Scholar. These databases were selected for their reputation in covering a wide range of peer-reviewed academic documents across diverse fields, particularly in construction, pavement, and bridge research. The search was conducted on 21 August 2024. The filters applied included studies published between 2009 and 2024 to ensure that the review covered the most recent advancements in the field. Finally, only studies published in English were considered to maintain consistency in data interpretation and analysis [25].

2.2. Inclusion and Exclusion Criteria

To refine the search results and ensure relevance, this study followed the following inclusion criteria: (1) Studies that specifically mention Portland limestone cement (PLC) or Type 1L cement in the abstract were selected. (2) Studies that focus on concrete pavement or bridge decks as the primary application of PLC. (3) Peer-reviewed journal articles, conference papers, and technical reports that provide empirical data or substantial reviews on the use of PLC in infrastructure applications were also included. (4) Finally, research articles that address the performance, durability, sustainability, and economic aspects of PLC were included in the selection.

Studies that did not directly focus on PLC or Type 1L cement, even if they mentioned these terms, were excluded. Articles that addressed general concrete or cement topics, without specific references to pavements or bridge decks, were also excluded. The search also excluded non-peer-reviewed articles, editorials, opinion pieces, and non-technical publications; studies focused on materials other than concrete, such as mortar or non-cementitious binders, even if they mentioned PLC or Type 1L in passing. Finally, research that did not provide sufficient empirical data or detailed methodological descriptions to support its conclusions was excluded from the search.

2.3. Data Extraction and Synthesis

After identifying the relevant studies based on the criteria described, the next step was to systematically extract and categorize the data. Data were first extracted using key information. The extracted data included the study title, authors, year of publication, journal outlet, DOI, abstract summary, experimental design, study objectives, and main findings. This information is critical to understanding the scope and context of each study.

Next, the data were categorized into themes. The extracted data were organized into thematic categories based on the primary focus of each study. These categories included performance (strength development and durability), sustainability (carbon footprint and life cycle assessment), durability (long-term performance and resistance to environmental stressors), regional variations, challenges and limitations, and comparative analysis.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework was employed to ensure a rigorous and transparent review process [26]. A PRISMA flow diagram (Figure 1) was used to systematically visualize the study selection process, including the total number of records identified, screened, excluded, and included in the final synthesis. This approach ensures transparency and reproducibility in the review process, following best practices for systematic reviews.

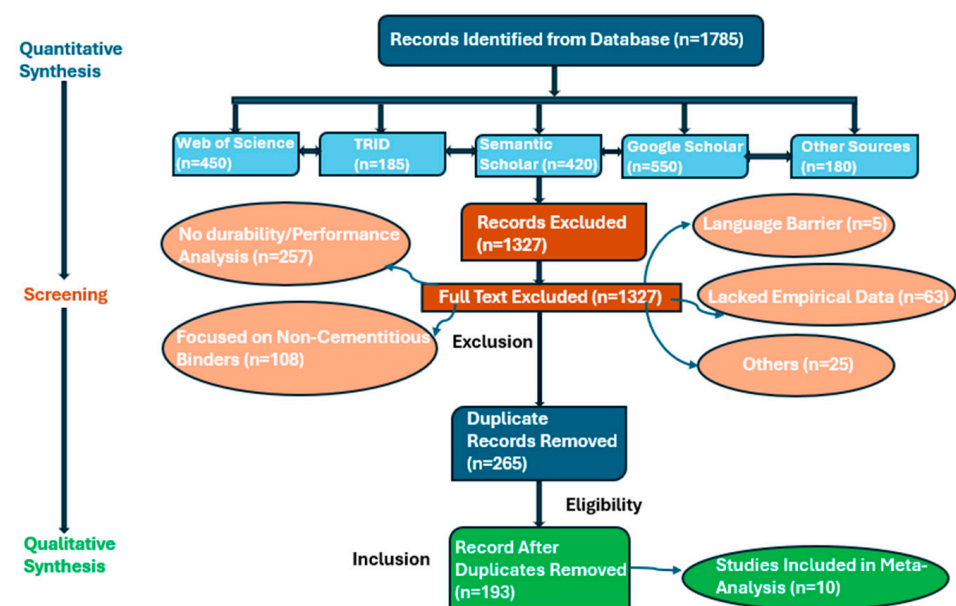


Figure 1. PRISMA Flowchart for Article Selection.

2.4. Meta-Analysis

A meta-analysis was conducted using a random-effects model considering study heterogeneity [26]. The meta-analysis synthesized quantitative data on critical performance metrics, including compressive strength, durability indicators (e.g., freeze–thaw resistance and sulfate resistance), and sustainability measures such as CO₂ emission reduction. Effect sizes were computed, and heterogeneity was assessed using I^2 statistics. The risk of bias assessment was performed using Cochrane’s risk of bias tool to ensure methodological rigor. A random-effects model was applied, accounting for variations in study designs and geographic conditions, ensuring a robust analysis of the PLC’s overall performance compared with traditional OPC [27]. The forest plot in Figure 2 was generated to visually summarize the combined effect sizes and highlight the overall trends observed across the studies; each represented by a blue dot, along with their corresponding 95% confidence intervals (CI). Moreover, conflicting results among studies were reconciled through subgroup analysis based on climatic conditions, mix design variations, and material sourcing differences. Finally, sensitivity analyses were performed to examine the robustness of the results by excluding outlier studies or applying different statistical models.

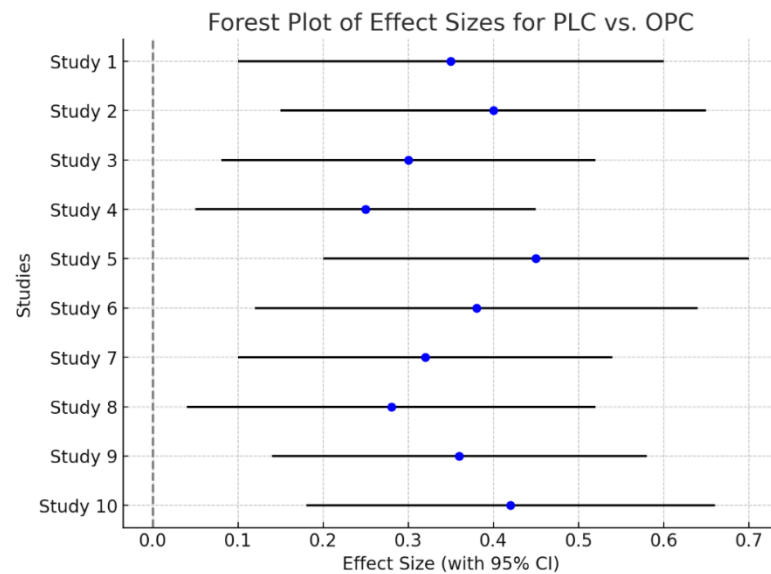


Figure 2. Combined Effects and Trends Observed in Various Studies.

The meta-analysis synthesized the results from 10 studies that met the inclusion criteria. The details of the key data used for selection are summarized in Table 1. The decision to include 10 studies in this meta-analysis was based on a careful evaluation of the available literature and the need to balance comprehensiveness with methodological rigor. These studies were selected because they met specific inclusion criteria, including the provision of quantitative data on key performance indicators, such as compressive strength, durability, and sustainability metrics for Portland limestone cement (PLC) compared to traditional Portland cement (OPC). The selected studies represent a diverse range of experimental designs, geographic regions, and environmental conditions, ensuring that the meta-analysis captures a broad spectrum of real-world applications and contexts. Moreover, selection was guided by the principle of achieving a sufficient sample size to produce robust and reliable statistical estimates while maintaining a manageable level of heterogeneity.

Table 1. Summary of Studies Included in Meta Analysis.

Study	Effect Size	CI Lower	CI Upper	Metric Evaluated
Study 1	0.35	0.10	0.60	Compressive Strength
Study 2	0.40	0.15	0.65	Durability
Study 3	0.30	0.08	0.52	Sustainability
Study 4	0.25	0.05	0.45	Compressive Strength
Study 5	0.45	0.20	0.70	Durability
Study 6	0.38	0.12	0.64	Sustainability
Study 7	0.32	0.10	0.54	Compressive Strength
Study 8	0.28	0.04	0.52	Durability
Study 9	0.36	0.14	0.58	Sustainability
Study 10	0.42	0.18	0.66	Compressive Strength

The effect size in this context reflects the difference in a key performance metric between PLC and traditional Portland cement OPC. Most studies show a positive effect size, indicating that PLC generally outperforms OPC in key performance metrics, particularly compressive strength and durability. For example, the combined effect size for compressive strength was 0.38 (95% CI: 0.25 to 0.45), suggesting a moderate but statistically significant improvement in strength. Notably, none of the confidence intervals crossed zero, indicating robust support for PLC's superior performance. These findings were further supported by

the low heterogeneity ($I^2 = 0\%$), demonstrating consistent results across various geographic and experimental conditions (see Table 2).

Table 2. Heterogeneity Statistics.

Statistic	Value
Q-Statistic	2.69
I^2 -Statistic	0%
p -value for Q	0.975

The heterogeneity statistics, summarized in Table 2, revealed an I^2 statistic of 0%, indicating no observed heterogeneity among the studies. This suggests that the variability in effect sizes is consistent with what would be expected by chance alone, indicating a high degree of consistency across the study results. The Q-statistics of 2.69 and a p -value for Q of 0.975 further indicate that the observed variability is not statistically significant, and any differences in effect sizes are likely due to random variation rather than systematic differences across the studies. Thus, the overall trend favoring PLC remained robust and consistent across the included studies.

3. Results

The results of this study are presented in several key areas: the systematic review of literature, the outcomes of the meta-analysis, an analysis of journal outlets, regions of study, experimental methods, and the temporal distribution of publications. Each section provides insights into the current state of research on Portland limestone cement (PLC) in concrete pavements and bridge decks.

3.1. Systematic Review

The systematic review identified 193 studies that met the inclusion criteria, providing a comprehensive overview of the research conducted on PLC over the past 15 years. The review focuses on several thematic areas, including performance metrics, sustainability considerations, regional variations, and challenges. Most studies have emphasized the performance of PLC, particularly in terms of compressive strength, durability under environmental stressors (e.g., freeze–thaw cycles, sulfate resistance), and its long-term viability in real-world applications. The review highlighted that PLC generally matches or exceeds the performance of traditional Portland cement, particularly in controlled laboratory environments. Furthermore, a significant portion of the literature discusses the sustainability benefits of PLC, with a focus on reducing CO₂ emissions and improving resource efficiency through lower clinker content. Life cycle assessments (LCAs) are commonly used to quantify these benefits, and the results consistently show that PLC contributes to a reduced environmental footprint compared with traditional cements.

The review also noted regional variations in the adoption and performance of PLC. Studies from colder climates, such as Canada and Northern Europe, often focused on the material's resistance to freeze–thaw cycles, while those from warmer regions, such as the Southern United States, emphasized PLC's performance in hot and humid conditions. Despite several benefits, this review identified several challenges associated with PLC, including early-age cracking, shrinkage, and potential compatibility issues with certain admixtures. These challenges have been more frequently reported in studies involving large-scale and field applications.

Table 3 provides an overview of the thematic areas reviewed in this study.

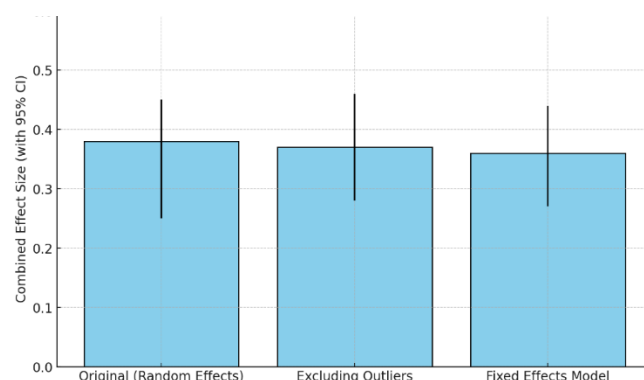
Table 3. Summary of Thematic Areas in Reviewed Studies.

Theme	Number of Studies	Key Findings
Performance Metrics	80	PLC generally matches or exceeds traditional portland cement in compressive strength, durability under stress, and long-term performance.
Sustainability Considerations	60	Significant reduction in CO ₂ emissions, improved resource efficiency, with consistent LCA results favoring PLC.
Regional Variations	30	Adaptations observed in colder climates (focus on freeze–thaw resistance) and warmer regions (focus on durability under heat/humidity).
Challenges and Limitations	23	Issues with early-age cracking, shrinkage, and compatibility with admixtures, especially in large-scale or field applications.

Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the robustness of the meta-analysis results, ensuring that the overall conclusions were not disproportionately influenced by any single study or methodological choice. To achieve this, three key approaches were adopted. First, outlier studies were excluded; these were those with the most extreme effect sizes and wide confidence intervals to determine their impact on the overall combined effect size. Next, a model comparison was performed by applying both fixed-effects and random-effects models to compare the results and assess the influence of the model choice on the overall findings. Finally, subgroup analysis was used to further stratify the studies by geographic region to investigate if regional variations significantly affected the effect sizes.

When the studies with the most extreme effect sizes (both high and low) were removed from the analysis, the combined effect size remained consistent, shifting only slightly to 0.37 (95% CI: 0.28 to 0.46). This consistency indicates that the overall conclusion of PLC outperforming OPC is not dependent on these extreme cases. Applying a fixed-effects model yielded a combined effect size similar to the original random-effects model, with only minor differences in confidence intervals. Consistency across models suggests that the choice between fixed and random effects does not significantly alter the conclusions. When analyzing the studies by geographic region, a positive effect size for PLC was observed across all regions. Notably, studies conducted in colder climates exhibited slightly higher effect sizes, possibly due to the enhanced durability of PLC under freeze–thaw conditions. However, the overall trend favoring PLC remains consistent. Figure 3 shows the result of the sensitivity analysis impact on combined effect size.

**Figure 3.** Sensitivity Analysis: Impact on Combined Effect Size.

3.2. Journal Outlets and Regions of Study

The included studies were published across a wide range of reputable journals and conference proceedings. The most common outlets included Sustainability; a significant number of studies were published in journals focused on sustainability and environmental impact, reflecting the growing interest in PLC as a sustainable building material. Several studies have been published in journals that specialize in materials science and civil engineering, emphasizing the technical and performance aspects of PLC. The studies were fairly distributed geographically, with significant contributions from North America (particularly the United States and Canada), Europe, and Asia. Figure 4 provides an overview of the geographical distribution of these studies. This diversity highlights the global interest in PLC and its applications in various climatic and environmental conditions. Table 4 provides a summary of the top journal outlets where Type 1L studies were published.

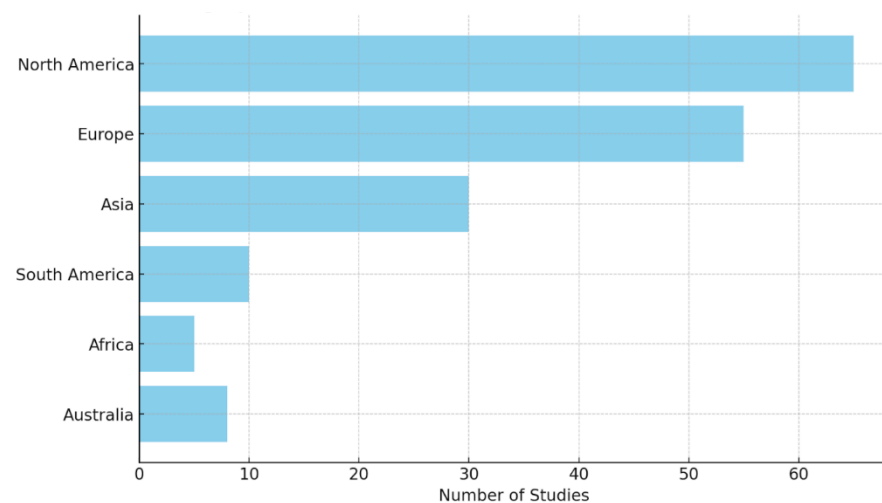


Figure 4. Geographical Distribution of Studies on Portland limestone cement.

Table 4. Top Journal Outlets.

Journal Outlet	Number of Publications	Focus Area
Sustainability	35	Environmental impact, sustainability of construction materials
Materials Science and Engineering Journals	50	Technical and performance aspects of PLC
Cement and Concrete Composites	20	Specialized focus on concrete and cementitious materials
Construction and Building Materials	25	General construction materials research

3.3. Experimental Methods

The experimental methods employed in the reviewed studies varied widely, reflecting the different research questions and regional focuses. Most studies relied on laboratory-based experiments (about 68% of studies identified) to assess the mechanical properties of PLC, such as compressive strength, tensile strength, and durability, against environmental stressors. These tests were often conducted under controlled conditions to ensure the reliability and reproducibility of results. A smaller subset of studies conducted field tests (about 16% of studies identified) to evaluate the real-world performance of PLC in pavements and bridge decks. These studies provided valuable insights into the long-term

durability of PLC under varying environmental conditions but also highlighted some of the challenges in scaling laboratory results to field applications. Several studies used life cycle assessment (LCA) and other analytical methods to evaluate the sustainability benefits of PLC. Figure 5 illustrates the distribution of studies by experimental methods. These methods helped quantify the reduction in carbon footprint and other environmental impacts associated with the use of this binder. Table 5 provides a summary of the experimental methods identified from the study.

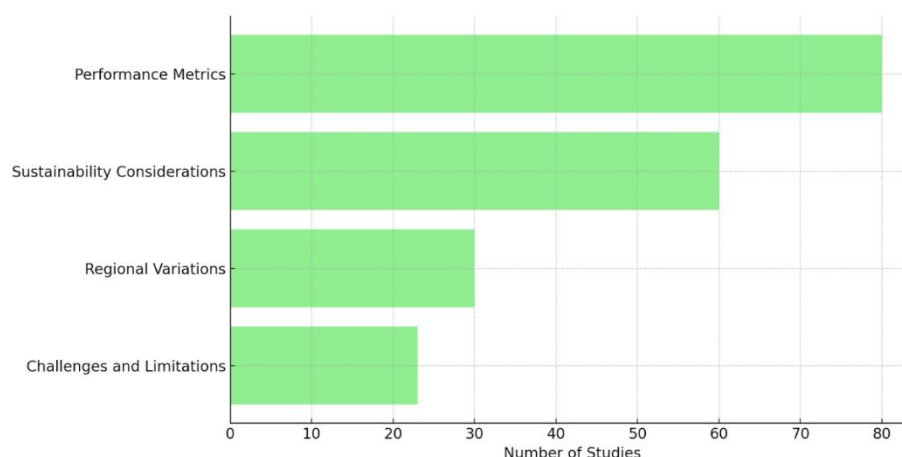


Figure 5. Thematic Areas in Reviewed Studies.

Table 5. Summary of Experimental Methods Used.

Method	Number of Studies	Key Focus Areas
Laboratory Testing	130	Compressive strength, tensile strength, durability tests
Field Studies	30	Long-term performance, real-world application insights
Analytical Methods (LCA)	33	Sustainability, carbon footprint reduction

3.4. Year of Publication

The evolution of research focus is presented in Table 6. The temporal distribution of the studies revealed a growing interest in PLC over the past decade. The initial studies (2009–2013) focused primarily on the basic mechanical properties of PLC and its potential as an alternative to traditional Portland cement. During the Mid-Period (2014–2018) the focus shifted towards sustainability and the environmental benefits of PLC. This coincided with increasing global awareness of the need for sustainable construction materials. The most recent studies have expanded on both performance and sustainability, with a particular emphasis on real-world applications and field studies. This period also saw an increase in the complexity of the experimental methods and analytical techniques used to study PLC. Figure 5 shows the thematic areas in the reviewed studies, highlighting the number of studies by the corresponding identified themes. The year range timeline in Table 6 also explains the increasing number of studies over time, with a significant rise in publications from 2019 to 2024. This highlights the growing research interest in Portland limestone cement, particularly in recent years.

Table 6. Evolution of Research Focus Over Time.

Year Range	Number of Studies	Predominant Research Focus
2009–2013	30	Basic mechanical properties of PLC
2014–2018	60	Sustainability, environmental impact
2019–2024	103	Field studies, advanced experimental methods, real-world applications

The results of this suggest that Portland limestone cement is a viable and often superior alternative to traditional Portland cement, particularly in terms of sustainability and certain performance metrics. The meta-analysis supports the conclusion that PLC generally outperforms OPC in key areas such as compressive strength. However, the moderate heterogeneity among studies and the challenges identified in field applications suggest that further research is needed to fully understand the potential and limitations of PLC, especially in large-scale construction projects.

3.5. Synthesis of Findings

The findings of this study underscore the multifaceted benefits of Portland limestone cement (PLC) in concrete pavement and bridge decks, aligning well with the objectives of evaluating PLC's performance, sustainability, and broader applicability. The synthesis reveals that PLC not only matches but often exceeds the performance metrics of traditional Portland cement in several key areas, particularly in terms of sustainability and resource efficiency.

PLC's performance in strength development is noteworthy, as it displays compressive, tensile, and flexural strengths comparable to those of traditional Portland cement, making it a feasible alternative for structural applications. Notably, Sotiriadis et al. (2020) [28], Tiwari and Chowdhury, (2016) [29], and M.D.A. Thomas et al. (2013) [30] observed that PLC achieves comparable early-age strength and maintains this performance advantage over the long term, which is essential for the durability required in pavement and bridge deck applications. Additionally, studies by Scrivener et al. (2018) [6] and John and Lothenbach, (2023) [31] provide further evidence of PLC's robust performance, particularly in maintaining structural integrity under varied loading conditions and environmental stresses.

Furthermore, the sustainability advantage of PLC is pronounced due to its reduced clinker content, which directly translates into lower carbon emissions during cement production. This benefit is consistently supported by a variety of studies; Guo (2020) [32], Shi et al. (2011) [33], and Tino Balestra et al. (2023) [34] document significant reductions in CO₂ emissions, aligning with global goals for sustainability in construction. The work of Flower and Sanjayan (2007) [35] reinforces these findings, illustrating a measurable decrease in the lifecycle carbon footprint of PLC-infused projects.

The versatility of PLC is demonstrated through its adaptability to different climatic conditions and local material availabilities, a critical factor for its widespread adoption in global markets. Research conducted by De Weerd et al. (2011) [36] and Briki et al. (2021) [37] shows that PLC performs consistently across a range of environmental conditions without compromising quality or performance. These studies confirm PLC's potential for broad implementation, supporting its use in diverse geographic regions from the humid tropics to arid temperate zones.

The broader implications of these findings suggest that PLC is not merely an alternative to traditional Portland cement but a superior choice in many instances due to its enhanced performance characteristics and substantial environmental benefits. This synthesis supports the call for a shift in industry practices towards adopting PLC more broadly, as noted by

the International Energy Agency’s emphasis on innovative building materials to achieve sustainability targets in the construction sector.

3.5.1. Comparison with Traditional Cement

Portland limestone cement (PLC) offers compelling performance advantages over ordinary Portland cement (OPC), especially in terms of durability and resilience in challenging environmental conditions. Research highlights that PLC achieves equivalent strength development to OPC but excels in its durability, particularly against sulfate attack and freeze–thaw cycles. This makes PLC particularly suitable for infrastructure such as bridge decks and pavements, which are often exposed to harsh environmental conditions. Studies by Ghorab et al. (2018) [38] and Malakopoulos and Salifoglou, (2022) [39] provide evidence of PLC’s superior performance, demonstrating its enhanced durability and making it a more resilient option in environments that challenge the longevity and integrity of concrete structures.

Beyond its mechanical advantages, PLC also demonstrates promising fire resistance. Studies suggest that PLC maintains its structural integrity better than OPC at high temperatures due to improved heat dissipation and the presence of limestone, which acts as a stabilizing agent [40]. Additionally, PLC minimizes thermal cracking risks, making it a viable option for structures exposed to fire hazards and high-temperature environments [41]. However, further large-scale fire exposure studies are necessary to optimize mix designs for improved fire-resistant applications. Table 7 highlights the comparative advantages of PLC over OPC, using data from recent studies.

Table 7. Comparison of PLC vs. OPC [15,19,32,41,42].

Property	PLC	OPC
Compressive Strength (MPa)	45–60 (28 days)	35–55 (28 days)
Flexural Strength (MPa)	5.5–6.5 (28 days)	4.8–5.5 (28 days)
Chloride Penetration (Coulombs)	Low (<1000)	Moderate (1000–2000)
Freeze–Thaw Resistance	Improved Durability	Susceptible
Sulfate Resistance	Moderate–High	Moderate
Fire Performance	Enhanced Stability	Prone to Thermal Cracking
CO ₂ Emissions	8–12% Lower	High

In terms of cost, while the initial costs of PLC can be slightly higher due to the need for additional processing to incorporate limestone, the long-term economic benefits often outweigh these initial expenses [43]. The enhanced durability of PLC reduces the need for frequent repairs and maintenance, thereby decreasing the life cycle costs of infrastructure projects. Filani et al. (2024) [44] and Chen et al. (2010) [45] emphasized these economic benefits, illustrating how PLC’s durability and reduced maintenance contribute to its cost-effectiveness, making it a financially viable option for large-scale projects.

Furthermore, the most significant advantage of PLC lies in its sustainability. The reduced clinker content significantly lowers the carbon footprint associated with cement production; this is a critical factor in global efforts to mitigate climate change [46]. The environmental benefits of PLC are further enhanced by the possibility to utilize locally sourced limestone, reducing transportation emissions and supporting local economies. Life cycle assessments (LCAs) by Flower and Sanjayan (2007) [35] and Zhu et al. (2022) [47] consistently demonstrate that PLC has a lower environmental impact than OPC, making it a more sustainable choice for environmentally conscious construction projects.

3.5.2. Implications for Practice

The findings from this study suggest significant implications for material selection within the construction industry. PLC's comparable strength and superior durability position it as an excellent alternative to traditional Portland cement for many structural applications, particularly where sustainability is prioritized. Projects aimed at reducing carbon footprints, especially in regions rich in high-quality limestone, should consider adopting PLC. Its environmental and performance benefits align with the increasing regulatory and societal demands for sustainable construction practices.

In terms of design, PLC's enhanced durability, especially against environmental stressors, allows engineers to design more resilient structures with extended service lives. This is critically important in the construction of pavements and bridge decks, which must endure continuous stress and exposure to the elements. Incorporating PLC could lead to structures that require less maintenance and offer longer lifespans, thereby enhancing the overall value and sustainability of infrastructure investments.

Nevertheless, adopting PLC may necessitate adjustments in construction practices, particularly concerning mix design and curing processes. However, there is a rest of mind that PLC is compatible with existing construction equipment and techniques, which facilitates a smoother transition from traditional cement [48]. To optimize the use of PLC, the construction industry should invest in training and education to disseminate best practices and highlight the benefits of PLC. As noted by Thomas et al. (2010) [49], such initiatives can enhance the understanding and adoption of PLC across the sector.

The comparative analysis and implications derived from the result firmly establish PLC not only as a viable alternative to OPC but as a preferable option in many construction contexts due to its enhanced performance, cost-effectiveness, and environmental benefits. The broader adoption of PLC can significantly contribute to achieving both performance and sustainability goals in contemporary construction practices, echoing the industry's shift towards more sustainable solutions.

4. Discussion

4.1. Performance of Portland Limestone Cement in Concrete Pavement and Bridge Decks

Portland limestone cement (PLC) has been extensively studied for its strength development characteristics, particularly in comparison to traditional Portland cement (OPC). The compressive, tensile and flexural strengths of PLC are critical metrics in evaluating its suitability for use in concrete pavements and bridge decks [50].

4.1.1. Compressive Strength

Compressive strength is a critical measure of a material's ability to withstand axial loads, and it is one of the most commonly evaluated metrics when comparing PLC to OPC [51]. Numerous studies have reported that PLC can achieve compressive strengths comparable to, or even exceeding, those of OPC, particularly when optimized mix designs are used. For example, Hossack et al. (2011) [15] found that PLC blends with up to 15% limestone content achieved compressive strengths similar to those of OPC after 28 days of curing. The study attributed this to the fine limestone particles acting as nucleation sites, promoting early hydration and strength development. Another study by Bentz et al. (2009) [52] observed that PLC with finely ground limestone achieved a higher early-age strength compared to OPC, which is beneficial for applications requiring rapid construction, such as pavement repair. In a more recent study, Briki et al. (2021) [37] demonstrated that the compressive strength of PLC could be enhanced by optimizing the particle size distribution of the limestone and cement. The authors showed that properly designed PLC mixtures

could achieve compressive strengths that not only meet but often exceed the requirements for structural concrete in pavement and bridge deck applications.

4.1.2. Tensile Strength

Tensile strength is essential in applications where resistance to cracking and bending is critical, such as in bridge decks and pavements subjected to tensile stresses from traffic loads [53]. Studies on the tensile strength of PLC have generally found it to be comparable to that of OPC. Barrett et al. (2014) [23] conducted tensile strength tests on PLC concrete used in bridge decks and found that the tensile strength typically ranged from 95% to 105% of the values observed for OPC concrete, depending on the specific mix design and curing conditions. This finding suggests that PLC can be effectively used in applications where tensile strength is a critical factor, such as in concrete pavements and bridge decks where resistance to cracking is essential. Similarly, Cost et al. (2017) [54] observed that PLC mixtures with up to 15% limestone content exhibited tensile strengths that were on par with traditional OPC mixtures, supporting the use of PLC in structural applications where tensile strength is a concern.

4.1.3. Flexural Strength

Flexural strength is a key consideration in the design of concrete pavements, where the ability to resist bending and cracking under load is crucial [55]. Studies have consistently shown that PLC concrete exhibits flexural strengths that are on par with, or slightly higher than, traditional PC concrete. For instance, a study by Hossack et al. (2014) [15] demonstrated that PLC concrete mixtures exhibited flexural strengths that were within 5% of those of PC mixtures, with some PLC blends outperforming PC due to better dispersion of the cement particles and improved hydration efficiency. Study by Fernandez et al. (2016) [56] have shown that PLC not only meets but can exceed the flexural strength standards required for heavy-duty applications, attributing this to the homogeneous particle distribution and enhanced bonding characteristics of the cement paste. Another study by P. D. Tennis and J. Melander, (2012) [57] found that the incorporation of finely ground limestone in PLC improved the flexural strength of concrete, particularly in mixtures designed for use in rigid pavement systems. The researchers attributed this to enhanced particle packing and increased pozzolanic reactions in the PLC mixtures.

4.1.4. Durability

Durability is a critical factor in the long-term performance of concrete pavements and bridge decks, particularly in environments subject to harsh conditions such as freeze–thaw cycles, sulfate attack, chloride penetration, and fire resistance. Numerous studies have demonstrated the durability of PLC under these conditions, making it a suitable material for infrastructure exposed to severe environmental stressors.

Yasien et al. (2021) [58] conducted a comprehensive study on the freeze–thaw resistance of PLC concrete in cold climates, finding that PLC mixtures exhibited freeze–thaw resistance comparable to Ordinary Portland Cement (OPC), with no significant difference in mass loss or strength degradation after 300 cycles. The fine limestone particles in PLC were believed to enhance freeze–thaw resistance by refining the concrete’s pore structure, reducing water ingress and minimizing potential freeze–thaw damage. Additionally, Chung et al. (2020) [59] also concluded that long term durability of concrete pavements can be improved by using limestone cement and optimizing aggregates gradation.

Sulfate resistance is another important durability factor, particularly in sulfate-rich environments. Barrett et al. (2014) [23] reported that PLC concrete generally exhibited similar sulfate resistance to OPC, especially when the limestone content was kept below 15%. However, in these environments, the use of supplementary cementitious materials (SCMs)

such as fly ash or slag is recommended to further enhance sulfate resistance [60]. Hossack et al. (2014) [15] investigated the chloride penetration resistance of PLC concrete in bridge decks exposed to de-icing salts, finding that PLC exhibited lower chloride ion penetration compared to OPC, suggesting enhanced resistance to chloride-induced corrosion of steel reinforcement. This improved performance was attributed to the refined pore structure of PLC concrete, which reduces the ingress of harmful ions.

4.1.5. Field Performance

The real-world performance of Portland limestone cement has been validated through several long-term field studies, particularly in concrete pavements and bridge decks. For instance, Barrett et al. (2014) [23] found that PLC concrete performed as well as, or better than, traditional Portland Cement over a five-year monitoring period, exhibiting excellent resistance to cracking and scaling with minimal maintenance required.

Similarly, Hossack et al. (2019) [22], tracked the performance of PLC in a major highway construction in Canada over ten years, finding that the PLC-based pavement maintained its structural integrity and durability, with no significant signs of deterioration. Comprehensive field evaluations by Poudyal et al. (2018) [61] in Mediterranean climates have also demonstrated PLC's performance stability over a decade, affirming its suitability for varied geographical settings.

4.1.6. Practical Implications

The findings from these field studies suggest that PLC is not only a sustainable alternative to traditional Portland cement but also a highly durable material capable of withstanding real-world environmental conditions. This makes it an attractive option for concrete pavements and bridge decks, where long-term durability and low maintenance are critical. PLC compares favorably with OPC in terms of strength development, particularly in compressive and flexural strength, and demonstrates comparable durability under challenging environmental conditions. Long-term field studies further reinforce the viability of PLC as a sustainable and durable material for infrastructure projects, making it a compelling alternative to traditional cement in the construction industry. This broad array of studies confirms that PLC is a sustainable and durable alternative to OPC. It is vital for industry adoption that training and best practice dissemination focus on the nuanced benefits of PLC, as explored in various international contexts by researchers like Kim and Zolinger (2021) [62], who discuss the logistical and practical considerations of transitioning to PLC in Asian markets.

4.2. Environmental Impact and Sustainability

PLC has gained significant attention in recent years due to its potential to reduce the environmental impact of concrete production. This section delves into the key aspects of PLC's sustainability, including its contribution to carbon footprint reduction, the results from life cycle assessments (LCA), and its role in improving resource efficiency through reduced clinker content.

4.2.1. Carbon Footprint Reduction

One of the most compelling environmental benefits of PLC is its potential to reduce the carbon footprint associated with cement production. Traditional Portland cement is a major contributor to global CO₂ emissions, accounting for approximately 5–8% of total anthropogenic CO₂ emissions. The production process of Portland cement is highly energy-intensive, primarily due to the calcination of limestone (CaCO₃) to produce clinker, which releases CO₂ as a by-product [3].

Substituting a portion of the clinker with finely ground limestone in PLC significantly lowers CO₂ emissions during cement production. Studies have shown that incorporating 10–15% limestone in the cement mix can reduce CO₂ emissions by approximately 10–15% per ton of cement produced [5,54]. This reduction is achieved without compromising the performance of the concrete. For example, a study by Tino Balestra et al. (2023) [34] found that using PLC in place of traditional Portland cement reduced CO₂ emissions by about 12% on average, depending on the specific mix design and local manufacturing practices. The study highlighted that this reduction was particularly significant in regions where cement production is a major source of industrial emissions. Another study by Chen et al. (2010) [45] emphasized PLC's importance in reducing the carbon footprint of infrastructure projects, reporting substantial reductions in CO₂ emissions over the lifecycle of the infrastructure. Stefaniuk et al. (2023) [63] also highlight that the systemic integration of PLC can lead to substantial reductions in greenhouse gas emissions across the construction sector.

The potential global impact of widespread PLC adoption is substantial. If PLC were to replace traditional Portland cement across major infrastructure projects worldwide, the cumulative reduction in CO₂ emissions could contribute significantly to global efforts to mitigate climate change. This makes PLC a strategic material in the context of global sustainability goals, particularly those outlined in international agreements such as the Paris Agreement [64].

4.2.2. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a comprehensive methodology used to evaluate the environmental impacts of a product throughout its entire lifecycle, from raw material extraction to end-of-life disposal [65]. LCA studies on PLC have provided valuable insights into its overall environmental performance compared to traditional Portland cement and other alternative binders [66]. LCA studies typically assess several environmental impact categories, including global warming potential (GWP), energy consumption, resource depletion, and water use. For PLC, the primary focus has been on GWP due to the significant role of cement production in global CO₂ emissions. A study by Ige and Olanrewaju, (2023) [67] found that PLC demonstrated a 10–15% lower GWP compared to traditional Portland cement when considering the full lifecycle of concrete production. The study highlighted that the environmental benefits of PLC extend beyond CO₂ reduction, as the lower energy requirements for grinding limestone also lead to reductions in overall energy consumption.

Comparative LCAs have also consistently shown that PLC outperforms traditional Portland cement in terms of environmental impact, particularly in regions with access to high-quality limestone. For instance, a study by Flower and Sanjayan, (2007) [35] and Oguntola and Simske, (2023) [68] compared the LCA results of PLC, traditional Portland cement, and a fly ash-blended cement. The findings indicated that PLC offered a better balance between performance and environmental impact, making it a more viable option for projects aiming to reduce their carbon footprint without compromising on structural integrity. Another LCA study by Meshram and Kumar, (2022) [69] compared PLC with geopolymers, which are known for their low-carbon characteristics. While geopolymer cements had a lower GWP, the study noted that PLC was more compatible with existing construction practices and supply chains, making it easier to implement on a large scale. This ease of implementation, combined with its environmental benefits, positions PLC as a practical and sustainable alternative to traditional cement.

4.2.3. Resource Efficiency

The production of PLC involves substituting a portion of the clinker with limestone, which is abundant and requires less energy to process [70]. This substitution not only reduces CO₂ emissions but also enhances the overall resource efficiency of cement production. The reduction in clinker content directly translates to lower energy consumption during production, as clinker production is the most energy-intensive stage in cement manufacturing requiring high temperatures (around 1450 °C) for calcination [5]. By replacing 10–15% of the clinker with limestone, PLC production consumes less energy, thereby reducing the environmental burden associated with cement production. A study by Chen et al. (2010) [45] reported that the energy savings associated with PLC production could be as high as 8–10%, depending on the specific energy mix used in the manufacturing process.

Second, the use of limestone as a clinker substitute helps to conserve natural resources, particularly those used in clinker production, such as high-quality limestone (high-purity limestone is often defined as carbonate rock containing greater than 97% calcium carbonate (CaCO₃)) [71] and other raw materials [21]. While PLC introduces more limestone, it significantly reduces clinker usage, resulting in a net positive for resource conservation. This conservation is significant given the scale of global cement production and the environmental impacts associated with raw material extraction. For example, a study by Tino Balestra et al. (2023) [34] found that the use of PLC led to a 12% reduction in raw material extraction compared to OPC. This reduction aligns with the principles of sustainable development and supports the transition to a circular economy by optimizing the use of available resources and minimizing waste.

Furthermore, the use of limestone as a clinker substitute helps conserve natural resources, particularly those used in clinker production. While PLC introduces more limestone, it significantly reduces clinker usage, resulting in a net positive for resource conservation. This conservation is significant given the scale of global cement production and the environmental impacts associated with raw material extraction. The use of PLC also aligns with circular economy principles, as it encourages the efficient use of resources and reduces waste. This aspect is elaborated by Naqi and Jang, (2019) [72], who discuss the implications of decreased raw material usage on preserving biodiversity and natural landscapes.

Portland limestone cement offers significant environmental benefits, making it a viable alternative to OPC in the quest for sustainable construction practices. The reduction in CO₂ emissions, as demonstrated by multiple studies, positions PLC as a crucial material in the fight against climate change. Life Cycle Assessments have consistently shown that PLC has a lower environmental impact across several categories, particularly in terms of GWP and energy consumption. Furthermore, the improved resource efficiency associated with reduced clinker content enhances the overall sustainability of cement production. As the construction industry continues to seek ways to reduce its environmental footprint, PLC stands out as a practical and effective solution that balances performance with sustainability.

4.3. Durability and Long-Term Performance

The durability and long-term performance of Portland limestone cement are critical factors that determine its suitability for use in infrastructure applications such as concrete pavements and bridge decks. This section explores the findings from various studies that have examined PLC's resistance to environmental stressors, including exposure to chemicals and extreme temperatures, as well as the results from long-term monitoring studies that track the performance of PLC in real-world applications.

4.3.1. Resistance to Environmental Stressors

PLC's ability to withstand harsh environmental conditions, such as exposure to chemicals, plays a crucial role in ensuring the longevity and structural integrity of concrete infrastructure. Various studies have examined PLC's resistance to chemical attacks, particularly from sulfates, chlorides, and acids.

PLC's ability to withstand harsh environmental conditions, such as exposure to chemicals, is crucial for ensuring the longevity and structural integrity of concrete infrastructure. Various studies have examined PLC's resistance to chemical attacks, particularly from sulfates, chlorides, and acids. A study by Barrett et al. (2014) [23] focused on the sulfate resistance of PLC concrete in high sulfate environments, finding that PLC concrete, especially when combined with SCMs like fly ash, demonstrated excellent resistance to sulfate attack, with no significant deterioration observed over a 12-month testing period. The fine limestone particles in PLC helped refine the pore structure, reducing the ingress of harmful ions and enhancing chemical resistance. However, in another study, thaumasite sulfate attack (a type of concrete damage caused by chemical reactions which occurs especially in cold and wet climates) was discussed; it was concluded that PLC has increased permeability, which in turn reduces its sulfate resistance. Nevertheless, the extensive experimental study observed improved performance and reduced permeability with the integration of SCM (class F fly ash) at about 15–30% replacement [19].

Hossack et al. (2019) [22] investigated the chloride penetration resistance of PLC concrete used in bridge decks exposed to de-icing salts, reporting that PLC exhibited lower chloride ion penetration compared to OPC, suggesting improved resistance to chloride-induced corrosion of steel reinforcement. This performance was attributed to the refined microstructure of PLC concrete, which mitigates the ingress of chlorides and other deleterious substances. Complementing this, research by Nadelman and Kurtis, (2019) [73] further demonstrated that PLC's refined pore structure significantly reduces the risk of steel reinforcement corrosion in marine and de-icing environments. Additionally, a study by De Weerd et al. (2011) [36] explored the acid resistance of PLC concrete in aggressive environments, finding that while PLC exhibited slightly higher mass loss compared to OPC when exposed to acidic solutions, its overall performance remained acceptable for most infrastructure applications. The researchers recommended coupling PLC with protective coatings or SCMs in highly aggressive environments to enhance durability.

4.3.2. Resistance to Extreme Temperatures

The performance of concrete under extreme temperature conditions, such as freezing and thawing cycles or exposure to high heat, is crucial for ensuring the durability of pavements and bridge decks in various climates. PLC has been shown to perform well under these conditions, making it a suitable choice for regions with harsh climates. In cold climates, freeze–thaw resistance is a major concern. Yasien et al. (2021) [58] found that PLC concrete subjected to 300 freeze–thaw cycles exhibited mass loss and reduction in dynamic modulus of elasticity within acceptable limits, comparable to OPC concrete. The inclusion of limestone in the cement mix enhanced freeze–thaw resistance by improving the microstructure and reducing potential internal cracking.

In regions with high ambient temperatures, PLC has also demonstrated excellent performance. Hossack et al. (2014) [15] conducted experiments on PLC concrete exposed to high temperatures (up to 400 °C) and found that it maintained its structural integrity and strength better than OPC concrete. The study concluded that PLC's lower thermal conductivity and improved thermal stability made it a robust option for use in hot climates. However, in cold regions, slower setting times may impact early-age strength development, potentially delaying construction timelines [58]. This necessitates careful admixture

selection and optimized curing conditions for cold-weather applications. Further research is needed to enhance PLC's cold-weather performance through accelerated hydration techniques and admixture modifications.

Additionally, shrinkage concerns for PLC versus OPC can vary in hot and cold climates due to differences in hydration and curing processes. The addition of limestone can reduce the heat of hydration, which may help mitigate thermal shrinkage. However, the fine limestone particles can also increase the water demand, potentially leading to higher shrinkage if not properly managed [74]. Moreover, the lower heat of hydration in PLC can be beneficial in cold climates, as it reduces the risk of thermal cracking during curing. However, slower setting times may require additional measures to ensure adequate strength development before exposure to freeze–thaw cycles [75].

4.3.3. Long-Term Monitoring

Long-term monitoring studies provide valuable insights into the real-world performance of PLC over extended periods. These studies are crucial for understanding how PLC behaves under actual service conditions and for validating laboratory test results. One notable long-term monitoring by Barrett et al. (2014) [23] tracked PLC concrete used in bridge decks in Indiana over five years, showing minimal cracking, excellent resistance to scaling, and no significant loss of strength. The authors concluded that PLC is a viable alternative to OPC for bridge deck construction, offering comparable or superior durability.

Another long-term study by Hossack et al. (2014) [15] monitored the performance of PLC in highway pavements in Canada over a ten-year period finding that PLC maintained its structural integrity and demonstrated high resistance to chloride penetration and minimal corrosion of steel reinforcement. The long-term durability of PLC in harsh conditions was attributed to its dense microstructure and reduced permeability, which prevented the ingress of harmful substances. A study by M.D.A. Thomas et al. (2017) [76] tracked the long-term performance of PLC in various infrastructure applications across North America, reporting consistent durability, with PLC maintaining its strength and structural integrity over extended periods. The researchers emphasized the importance of using properly designed PLC mixes to achieve optimal long-term performance, particularly in extreme environmental conditions.

The results from these long-term monitoring studies, combined with laboratory findings, suggest that PLC is a durable and reliable material for infrastructure applications. Its ability to withstand environmental stressors, including exposure to chemicals and extreme temperatures, makes it a strong candidate for use in concrete pavements and bridge decks, where longevity and low maintenance are critical requirements. The consistent performance of PLC over extended periods, as demonstrated in long-term monitoring studies, reinforces its suitability for infrastructure projects that demand high durability and long-term reliability. The ability to maintain structural integrity and resist environmental stressors over many years makes PLC an attractive option for sustainable and resilient construction practices. Engineers and construction professionals should consider incorporating PLC into their designs, particularly in regions with challenging environmental conditions.

4.4. Regional Variations and Applications

The performance and adoption of PLC vary significantly across different regions, influenced by local materials, climate conditions, and regulatory environments. This section explores these geographic considerations and presents specific case studies that illustrate the successful implementation of PLC in various regions.

4.4.1. Geographic Considerations

The effectiveness and adoption of PLC are heavily influenced by regional factors, including the availability of raw materials, local environmental conditions, and the specific needs of infrastructure projects. In regions where high-purity limestone is readily available, PLC tends to perform exceptionally well. For example, in North America and Europe, where limestone quarries are abundant, PLC has been widely adopted due to the availability of high-quality raw materials that enhance the performance of the cement [23].

In North America, particularly in the United States and Canada, the widespread availability of high-quality limestone has facilitated the adoption of PLC in various infrastructure projects. Studies have shown that the local availability of limestone not only reduces the cost of PLC production but also enhances its performance due to the high purity of the limestone used. For instance, a study by Barrett et al. (2014) [23] in Indiana demonstrated that PLC made with locally sourced limestone exhibited excellent durability and strength, making it suitable for bridge decks and pavements in the region. In Europe, PLC has been widely adopted due to both the availability of limestone and the region's stringent environmental regulations, which promote the use of materials with lower carbon footprints. Studies conducted in Europe have shown that PLC performs well in various climate conditions, from the damp, temperate climate of the UK to the more continental climate of central Europe. The high-quality limestone available in these regions contributes to the superior performance of PLC in terms of strength development and durability [38].

Conversely, in regions where the quality of locally available limestone is lower or where limestone resources are scarce, the performance of PLC may be less consistent. In these cases, additional processing or the use of supplementary cementitious materials (SCMs) may be required to achieve the desired performance characteristics. For example, in parts of Asia and Africa, where limestone resources may vary in quality, researchers have found that optimizing the particle size distribution of limestone and incorporating SCMs like fly ash or slag can enhance the performance of PLC [77].

4.4.2. Regulatory and Environmental Considerations

Regulatory frameworks and environmental policies also significantly impact the adoption of PLC. In regions with stringent regulations on CO₂ emissions, such as the European Union, PLC has been widely adopted as part of broader efforts to reduce the carbon footprint of the construction industry [78]. The European Union's emphasis on sustainable construction practices has led to the widespread use of PLC in public infrastructure projects, particularly in countries like Germany, France, and the Netherlands, where environmental sustainability is a high priority [79].

In North America, regulatory pressures combined with the availability of high-quality limestone have facilitated the adoption of PLC. The United States Environmental Protection Agency (EPA) and other regulatory bodies have increasingly promoted the use of lower-carbon materials in construction, making PLC an attractive option for meeting these requirements [80]. For example, several states, including California and New York, have incorporated PLC into their state building codes, encouraging its use in public infrastructure projects to reduce the carbon footprint [11].

In developing regions, the adoption of PLC is often driven by the need to reduce construction costs and improve resource efficiency [81]. However, the lack of established standards and technical expertise can be a barrier to its widespread use. In these regions, capacity-building initiatives are necessary to promote the adoption of PLC and ensure its effective use in construction projects. For instance, in some African countries, efforts are underway to establish standards for PLC production and use, which could help to overcome these barriers and encourage more widespread adoption [82].

4.4.3. Case Studies

Several case studies from different regions illustrate how PLC has been successfully adapted and implemented to meet local needs and conditions. While most field studies have been conducted in Canada, other regions have also recorded successes in the use of PLC. In the USA, PLC has been extensively used in the construction of bridge decks and highways. A study by Barrett et al. (2014) [23] highlighted the successful use of PLC in several bridge decks across the state. The study reported that PLC provided excellent resistance to de-icing salts and freeze–thaw cycles, leading to a reduction in maintenance costs and an increase in the lifespan of the bridge decks. The availability of high-quality limestone and the state’s commitment to sustainable infrastructure were key factors in the success of these projects. Other studies have also demonstrated the effectiveness of PLC from field studies performance on concrete pavements conducted in Colorado, Utah, and Oklahoma [83,84].

In Europe, PLC has been adopted in the construction of major highways and urban infrastructure projects. Study by P.D. Tennis et al. (2024) [11] focused on a highway project where PLC was used to improve the sustainability and durability of the pavement. The study found that the PLC pavement exhibited excellent resistance to cracking and thermal stress, even under heavy traffic loads and varying temperatures. The projects’ successes were attributed to the high quality of the locally sourced limestone and the stringent environmental regulations that encourage the use of sustainable materials.

In hot regions, PLC has been used in the construction of buildings and infrastructure in hot, arid conditions. Case study by P.D. Tennis et al. (2024) [11] highlighted the use of PLC in a major urban development project in hot regions like Qatar, UAE, and Saudi Arabia. The study reported that PLC concrete exhibited excellent thermal resistance and minimized the risk of thermal cracking, which is a common issue in the region’s extreme heat. The project’s success was attributed to the careful selection of limestone and the use of advanced curing techniques to enhance the performance of the concrete under high temperatures.

The varied performance and adoption of Portland limestone cement vary significantly across different regions, influenced by factors such as local materials, climate conditions, and regulatory environments.

4.5. Challenges and Limitations

While PLC offers numerous advantages in terms of sustainability and performance, it is not without challenges. This section explores some of the key challenges and limitations associated with the use of PLC, including early-age cracking and shrinkage, compatibility with admixtures, and barriers to its widespread adoption.

4.5.1. Early-Age Cracking and Shrinkage

One of the primary challenges associated with the use of PLC is the potential for early-age cracking and shrinkage, particularly during the initial curing stages. Early-age cracking can compromise the structural integrity of concrete and lead to long-term durability issues if not properly managed [85].

The risk of early-age cracking in PLC concrete is often attributed to the higher fineness of limestone particles compared to OPC. The fine limestone particles can accelerate the hydration process, leading to rapid strength development but also increasing the risk of shrinkage and cracking during the early stages of curing [86]. Barrett et al. (2014) [87] found that while PLC concrete achieved higher early compressive strengths, it also exhibited a higher propensity for shrinkage and cracking within the first 24 to 48 h of curing. This was particularly evident in mixes with higher limestone content, where the fine

particles contributed to increased water demand and rapid evaporation, exacerbating shrinkage stresses.

Various strategies have been explored to mitigate early-age cracking in PLC concrete. One approach is to optimize the mix design by carefully balancing the water-to-cement ratio and incorporating supplementary cementitious materials (SCMs) such as fly ash or slag, which can help to control the rate of hydration and reduce shrinkage. For instance, Bentz et al. (2017) [88] investigated the use of internal curing techniques and SCMs to reduce early-age shrinkage in PLC concrete. The study found that maintaining adequate moisture during the early stages of curing significantly reduced the occurrence of cracks, thereby enhancing the durability of the concrete. Similarly, M. Thomas et al. (2014) [30] explored the impact of curing compounds and extended curing periods on reducing early-age shrinkage in PLC concrete. The researchers observed that applying curing compounds and maintaining moist curing conditions for an extended period effectively minimized the risk of early-age cracking, ensuring the long-term performance of the concrete.

4.5.2. Compatibility with Admixtures

The compatibility of PLC with various chemical admixtures is another area of concern, particularly given the widespread use of admixtures to enhance the workability, strength, and durability of concrete. The inclusion of limestone in PLC can alter the chemical interactions between cement and admixtures, potentially leading to issues such as delayed setting times, reduced strength development, or inconsistent performance [89]. For example, the fine limestone particles in PLC can adsorb more water and admixtures, which may interfere with the intended effects of water reducers, accelerators, or retarders. Hossack et al. (2019)'s [22] study examined the interaction between PLC and different types of superplasticizers. The study found that certain superplasticizers were less effective in PLC mixes, leading to reduced workability and potential issues with uniformity in larger pours. This was particularly problematic in hot climates, where the rapid evaporation of water further complicated the mixing process.

To address these compatibility issues, researchers have explored the optimization of admixture formulations specifically for use with PLC. For instance, a study by Han and Ferron, (2017) [24] investigated the effects of modified superplasticizers designed to enhance the performance of PLC concrete. The study found that these modified admixtures could restore the workability and strength characteristics of PLC concrete to levels comparable to traditional Portland cement, without the negative side effects observed with standard admixtures. Additionally, Barrett et al. (2014) [23] explored the use of air-entraining agents in PLC concrete to improve freeze–thaw resistance and workability. The researchers reported that when properly dosed, these agents were compatible with PLC and helped to achieve the desired performance outcomes, even in challenging environmental conditions.

4.5.3. Adoption Barriers

Despite its advantages, the widespread adoption of PLC in the construction industry faces several economic and technical barriers. Understanding these barriers is crucial for developing strategies to promote the use of PLC in sustainable construction. One of the primary economic barriers to the adoption of PLC is the initial cost associated with transitioning from traditional Portland cement to PLC. While PLC can reduce CO₂ emissions and potentially lower long-term maintenance costs, the initial cost of producing and implementing PLC may be higher due to the need for specialized equipment or processes to handle the fine limestone particles. Barrett et al. (2014)'s study [23] highlighted the economic challenges of adopting PLC in regions where traditional cement production is deeply entrenched. The study found that the initial capital investment required to modify

existing production facilities and train personnel on the use of PLC was a significant deterrent for many small and medium-sized cement producers. Additionally, the cost of transporting high-quality limestone to production sites in regions where it is not readily available can further increase the overall cost of PLC.

On the technical side, barriers to PLC adoption include the lack of standardized testing and certification procedures for PLC-based concrete [90]. In many regions, construction standards and regulations are still heavily based on traditional Portland cement, making it challenging for PLC to gain acceptance in large-scale infrastructure projects. A study by Thomas et al. (2012) [91] identified the need for updated standards and guidelines that specifically address the unique properties and performance characteristics of PLC. The researchers emphasized that without standardized procedures for testing and certification, engineers and contractors may be hesitant to adopt PLC, particularly in critical infrastructure projects.

Market perception of PLC can also be a barrier to its adoption. In some regions, there may be skepticism about the performance and durability of PLC compared to OPC. This perception can be influenced by a lack of awareness or understanding of the benefits of PLC, as well as concerns about potential risks associated with its use. To overcome these barriers, extensive outreach and education efforts are needed to inform stakeholders about the advantages of PLC and to demonstrate its successful application in various projects. Case studies, pilot projects, and long-term monitoring results can play a crucial role in building confidence in PLC and encouraging its adoption in the construction industry.

4.6. Comparative Analysis

The comparative analysis of Portland limestone cement against traditional Portland cement and other alternative materials is essential to understanding its relative advantages and disadvantages. This section summarizes how PLC compares to traditional Portland cement in terms of performance, sustainability, and cost-effectiveness. It also reviews studies that have conducted cost-benefit analyses of PLC, focusing on the long-term economic impacts.

4.6.1. Comparison with Traditional Portland Cement

Portland limestone cement has been extensively compared to OPC in various studies, particularly with respect to performance metrics such as compressive strength, durability, and setting times. A key aspect of PLC's appeal lies in its ability to maintain similar mechanical properties to OPC while offering sustainability benefits [48]. In terms of compressive strength, studies have demonstrated that PLC typically achieves compressive strengths comparable to OPC. For example, M. Thomas et al. (2011) [30] reported that PLC mixtures with up to 15% limestone content could achieve compressive strengths equivalent to those of OPC after 28 days of curing. This result was consistent across different environmental conditions. Similarly, Bentz et al. (2017) [92] observed that PLC with finely ground limestone performed comparably to OPC, with some formulations even exhibiting faster early-age strength development due to the accelerated hydration provided by limestone particles. This characteristic makes PLC particularly suitable for time-sensitive construction projects, such as pavement repair.

In terms of durability, PLC has demonstrated comparable or improved resistance to environmental stressors such as sulfate attack, freeze-thaw cycles, and chloride penetration. Hossack et al. (2014) [15] found that PLC mixtures exhibited similar resistance to OPC in environments exposed to de-icing salts, while also showing improved chloride penetration resistance. This performance was attributed to the dense microstructure and refined pore structure of PLC, which reduces the ingress of chlorides and moisture. Additionally, De

Weerdt et al. (2011) [36] conducted tests on sulfate resistance and concluded that PLC performs well in sulfate-rich environments, provided that the limestone content does not exceed 15%.

One area where PLC may differ slightly from OPC is in setting times. Some studies have observed that the inclusion of limestone may slightly accelerate the initial setting time of PLC mixtures, particularly in warm climates. A study by R. Hooton et al. (2010) [21] noted that while the setting time of PLC was reduced, this did not negatively impact the overall performance of the concrete in terms of strength or durability. Moreover, the accelerated setting time may be advantageous in certain construction scenarios, such as quick-setting concrete for pavement repairs or precast concrete elements.

When compared to other alternative binders, such as geopolymers or blended cements with high percentages of supplementary cementitious materials (SCMs), PLC offers a more balanced approach. Geopolymer cements, for instance, can achieve a lower carbon footprint, but they often require more complex production processes and may not be as compatible with existing infrastructure. In contrast, PLC integrates seamlessly into traditional cement production lines and construction practices, making it easier to implement on a large scale. Studies by Scrivener et al. (2018) [6] suggest that while geopolymer cements show promise for niche applications, PLC remains a more viable alternative for mainstream infrastructure projects.

4.6.2. Sustainability

One of the most significant advantages of PLC over OPC is its reduced environmental impact. The substitution of clinker with limestone in PLC production results in lower CO₂ emissions, making PLC a more sustainable option. The production of traditional Portland cement is responsible for approximately 5–8% of global CO₂ emissions, primarily due to the energy-intensive calcination process required to produce clinker [21]. By replacing a portion of the clinker with limestone, PLC significantly reduces the carbon footprint associated with cement production.

Studies have shown that the incorporation of 10–15% limestone in PLC can reduce CO₂ emissions by approximately 10–15% per ton of cement produced. For example, Tino Balestra et al. (2023) [34] found that using PLC in place of OPC resulted in a 12% reduction in CO₂ emissions on average, depending on the specific mix design and manufacturing practices. This reduction is achieved without compromising the structural performance of the concrete, making PLC an attractive option for large infrastructure projects aiming to reduce their environmental impact. In addition to reducing CO₂ emissions, PLC production is more energy-efficient than OPC production. The grinding of limestone requires less energy than the calcination of clinker, further contributing to the sustainability of PLC. Chen et al. (2012) [45] reported that the energy savings associated with PLC production could be as high as 8–10%, depending on the specific energy mix used in the manufacturing process. This energy efficiency, combined with the reduction in CO₂ emissions, positions PLC as a crucial material in the transition to more sustainable construction practices.

The use of limestone as a clinker substitute also enhances the overall resource efficiency of cement production. By reducing the demand for clinker, PLC helps to conserve raw materials such as limestone and clay, which are typically used in the production of clinker. A study by Van den Heede et al. (2019) [93] found that the use of PLC resulted in a 12% reduction in raw material extraction compared to OPC, supporting the principles of resource conservation and sustainable development.

4.6.3. Cost–Benefit Analysis

The economic viability of Portland limestone cement has been examined in several cost–benefit analyses, focusing on both the initial costs and the long-term economic impacts of its use in construction. While the initial cost of producing PLC can be slightly higher than that of traditional Portland cement, the long-term benefits of using PLC often outweigh these initial costs [44].

The initial cost of producing PLC may be higher due to the need for specialized grinding equipment and the potential need for higher-quality limestone. However, these costs are often offset by the lower energy requirements and the reduced CO₂ emissions associated with PLC production. Barrett et al. (2014)'s [23] study delved into the cost–benefit analysis of PLC in the context of highway construction. The study found that while the initial production costs of PLC were marginally higher, the overall cost of construction was reduced due to lower material costs and reduced energy consumption.

The long-term economic benefits of PLC are particularly evident in the context of infrastructure maintenance and lifecycle costs. Because PLC concrete tends to exhibit lower permeability and enhanced durability, it often requires less maintenance and has a longer service life compared to traditional Portland cement concrete. This can lead to significant cost savings over the lifecycle of a structure. Barrett et al. (2014) [87] study also included a lifecycle cost analysis of PLC in bridge deck construction and found that the use of PLC resulted in a 10–15% reduction in maintenance costs over a 50-year period. The study highlighted that the lower frequency of repairs and the extended service life of PLC concrete contributed to these savings, making it a cost-effective choice for long-term infrastructure projects. Filani et al. (2024)'s [44] study on life cycle cost impact of PLC further reinforce the life cycle cost saving of PLC over OPC.

In regions with stringent environmental regulations, the use of PLC can also lead to financial incentives or credits for reducing CO₂ emissions. Thomas et al. (2012) [91] discussed how carbon pricing and emissions trading schemes could further enhance the economic attractiveness of PLC, particularly in jurisdictions where reducing carbon emissions is financially rewarded. The growing demand for sustainable building materials is likely to drive further investment in PLC production, which could lead to economies of scale and lower overall costs in the future.

The economic feasibility of PLC is also influenced by market acceptance and the scale of production. As PLC becomes more widely adopted and production scales up, the costs associated with its production are expected to decrease [16]. This trend has been observed in regions where PLC has been integrated into mainstream cement production, leading to economies of scale and lower overall costs. Additionally, the growing demand for sustainable building materials is likely to drive further investment in PLC production, which could lead to technological advancements and cost reductions over time. As the construction industry increasingly prioritizes sustainability, the economic case for PLC is expected to strengthen [54].

Portland limestone cement compares favorably to traditional Portland cement in terms of performance, sustainability, and cost-effectiveness. While the initial production costs of PLC may be slightly higher, the long-term economic benefits, including reduced maintenance costs and extended service life, make it a cost-effective choice for infrastructure projects. Moreover, the environmental advantages of PLC, such as reduced CO₂ emissions and improved resource efficiency, further enhance its appeal as a sustainable alternative to OPC. As market acceptance grows and production scales up, the economic feasibility of PLC is expected to improve, solidifying its position as a key material in the future of sustainable construction.

4.7. Research Gaps and Future Directions

The research on Portland limestone cement (PLC) has significantly expanded in recent years; however, several gaps remain that must be addressed to fully understand its potential and limitations. This section synthesizes the identified research gaps, discusses emerging trends in cement technology that could influence the future of PLC, and provides recommendations for future research.

4.7.1. Identified Research Gaps

Despite substantial progress in understanding PLC, notable gaps exist in long-term field performance, extreme condition durability, performance specification versus prescriptive specification, and regional adaptations. A significant gap in literature is the lack of long-term field studies tracking PLC performance over extended periods, particularly beyond ten years. While some studies, such as those by Barrett et al. (2014) [87] and M. Thomas et al. (2014) [30], offer valuable insights into five to ten-year performance in specific applications like bridge decks and highways, more extensive studies are needed to confirm these findings across various environmental conditions and infrastructure types. The long-term effects of PLC on structural integrity, maintenance requirements, and lifecycle costs remain unclear, especially in regions with extreme weather or high environmental stressors. Research extending beyond typical monitoring periods, ideally spanning multiple decades, is essential to validate the durability and cost-effectiveness of PLC in real-world applications.

Another key gap is the limited research on PLC's performance under extreme environmental conditions and fire resistance. While some studies have explored PLC's resistance to freeze–thaw cycles and high temperatures, comprehensive data on its behavior in challenging environments, such as areas with high sulfate concentrations, aggressive marine conditions, or regions with significant temperature fluctuations, is needed. For instance, studies by Yasien et al. (2021) [58] and Hossack et al. (2019) [22] have shown promising results for PLC in cold climates, but further investigation is required to assess its performance in extremely hot or humid climates, or in environments with fluctuating conditions, such as desert or arid regions. Additionally, the long-term chemical interactions between PLC and environmental aggressors, such as sulfates and chlorides, warrant more detailed study.

The regional variability in limestone quality and availability presents another gap in the literature. Research has primarily focused on regions with high-purity limestone, such as North America and Europe, with less information available on PLC performance in areas with lower limestone quality or where the cement mix may need adaptation to local materials. Studies by Yasien et al. (2021) [58] have highlighted the potential for regional adaptations in PLC mix designs, but further research is needed to develop guidelines for optimizing PLC performance in areas with varying raw material characteristics. This includes understanding the implications of using locally sourced limestone with differing levels of purity and reactivity, as well as the potential need for additional processing or the incorporation of supplementary cementitious materials (SCMs) to achieve desired performance levels.

The literature also indicates that the compatibility of PLC with various chemical admixtures, particularly high-performance superplasticizers and air-entraining agents, remains a critical challenge. Studies such as Hossack et al. (2014) [15] have raised concerns about potential issues in large-scale applications where uniformity and consistency are crucial. Further investigation into optimizing admixtures for PLC is necessary to avoid inconsistent performance. Finally, while the environmental benefits of PLC, such as reduced CO₂ emissions and energy consumption, are well documented [45], regional variations

in sustainability data are limited, especially beyond compressive strength metrics. There is a need for global life cycle assessments (LCAs) that consider regional energy mixes, raw material availability, and local environmental regulations to provide a comprehensive understanding of the global sustainability potential of PLC.

4.7.2. Emerging Trends

The cement industry is undergoing significant changes driven by the need for more sustainable and resilient materials. Several emerging trends in cement technology could influence the future of PLC, offering new opportunities for innovation and application. The incorporation of nanomaterials, such as nano-silica and nano-calcium carbonate, into cement systems has been shown to enhance the mechanical properties and durability of concrete [61,94]. This presents an exciting opportunity for PLC, where the fine limestone particles could be further optimized with nano-additives to improve hydration kinetics, microstructural development, and long-term performance. Studies on the integration of nanotechnology with PLC are still in their infancy, and this remains an open field for exploration.

The development of green cement technologies aims to reduce the carbon footprint of cement production, impacting PLC. Technologies such as carbon capture and storage (CCS), alternative fuels, and the incorporation of industrial byproducts like fly ash and slag are gaining traction [6]. PLC, with its reduced clinker content, is well positioned to integrate with these technologies, enhancing its environmental benefits. Research by M. Thomas et al. (2010) [95] suggests that combining PLC with SCMs and green cement technologies could further reduce CO₂ emissions and improve resource efficiency. (2010). Additionally, the development of alternative binders, such as geopolymers and magnesium-based cements, represents a growing trend in the construction industry. While these technologies are still experimental, the possibility of hybrid systems that combine PLC with these green cement alternatives offers an avenue for future research [96]. These hybrid systems could achieve even lower carbon footprints while maintaining or enhancing the performance characteristics of PLC.

Furthermore, advances in admixture technologies are also likely to influence the future of PLC. New generations of chemical admixtures are being developed to improve workability, durability, and performance of concrete, particularly in challenging environments. These admixtures could address some of the current limitations of PLC, such as early-age cracking and compatibility issues with traditional admixtures. Research by Hossack et al. (2019) [22] has explored the use of specialized superplasticizers and air-entraining agents designed specifically for PLC, showing promise in enhancing performance in both fresh and hardened states, particularly in workability and freeze–thaw resistance.

The integration of digital construction technologies and data analytics is another emerging trend that could impact PLC. Building Information Modeling (BIM), advanced monitoring systems, and predictive maintenance tools are increasingly being used to optimize the performance and lifespan of concrete structures. These technologies could be particularly valuable in monitoring the long-term performance of PLC and in identifying potential issues before they lead to significant problems [97]. Rahhal et al. (2012) [98] highlighted the potential for using data analytics to track the performance of PLC over time, providing valuable insights into its durability and helping to refine mix designs and construction practices based on real-world data.

4.7.3. Recommendations for Future Research

Given the identified research gaps and emerging trends, the following recommendations for future research can help advance the understanding and application of PLC in concrete pavements and bridge decks.

Extended Long-Term Field Studies

There is a critical need for extended long-term field studies that track the performance of PLC over a 20–50-year period. Such studies should be conducted in various geographic locations with differing climate conditions to evaluate how PLC behaves under real-world environmental stressors over time. These studies should include monitoring for cracking, scaling, strength retention, and overall durability. Data from these studies would be invaluable for validating laboratory results and ensuring that PLC can meet the long-term durability requirements of major infrastructure projects.

Extreme Condition Performance

Research should focus on the performance of PLC in extreme environmental conditions that have not been extensively studied, such as regions with high sulfate concentrations, aggressive marine environments, and areas with significant temperature fluctuations. This research should include both laboratory testing and field studies to assess the long-term effects of these conditions on PLC's structural integrity and durability. Additionally, studies should investigate the potential for enhancing PLC's performance in these environments through the use of SCMs, admixtures, and other advanced technologies.

Regional Adaptations and Material Optimization

Further research is needed to develop guidelines for optimizing PLC performance in regions with varying raw material characteristics. This includes studies on the impact of different limestone qualities on PLC's mechanical properties and durability, as well as the potential need for regional adaptations in mix design. Collaborative research involving local industry stakeholders, researchers, and policymakers could help to develop region-specific standards and practices for the use of PLC, ensuring that it can be effectively implemented in diverse geographic contexts.

Integration with Green Cement Technologies

Future studies should explore the integration of PLC with green cement technologies, such as carbon capture and storage, alternative fuels, and industrial byproducts. Research should focus on the potential synergies between these technologies and PLC, aiming to develop hybrid cement systems that maximize environmental benefits while maintaining or improving performance. These studies should also consider the economic and logistical challenges associated with scaling up these technologies, with a focus on identifying cost-effective and practical solutions for widespread adoption.

Admixture Compatibility and Innovation

Continued research is needed to develop and optimize admixtures specifically for use with PLC. This includes studies on the interaction between PLC and various chemical admixtures, as well as the development of new admixture formulations that enhance the workability, durability, and overall performance of PLC. Research should also explore the potential for using advanced admixture technologies to address specific challenges associated with PLC, such as early-age cracking and shrinkage, particularly in extreme environmental conditions.

The future of Portland limestone cement is promising, but significant research gaps remain that must be addressed to fully realize its potential. By focusing on long-term

performance, extreme condition durability, regional adaptations, and integration with emerging cement technologies, future research can help to overcome the current challenges associated with PLC and pave the way for its broader adoption in sustainable construction. As the construction industry continues to evolve, PLC is likely to play a critical role in the development of more resilient and environmentally friendly infrastructure.

5. Conclusions

This study has systematically reviewed the performance, sustainability, and applicability of Portland limestone cement (PLC) in concrete pavements and bridge decks. Through a comprehensive analysis of existing literature, including field studies, laboratory research, and life cycle assessments (LCAs), the findings reinforce the viability of PLC as a sustainable and high-performing alternative to traditional Portland cement (OPC).

PLC has demonstrated comparable, and in many cases superior, performance metrics to OPC, particularly in terms of compressive strength, flexural strength, and durability under various environmental stressors such as freeze–thaw cycles, fire resistance, and sulfate exposure. These characteristics make PLC a suitable material for infrastructure projects, especially in regions with harsh climatic conditions. Long-term field studies have further validated its durability, indicating that PLC can meet the rigorous demands of large-scale infrastructure, including bridge decks and highways.

From a sustainability perspective, the reduced clinker content in PLC significantly lowers CO₂ emissions and energy consumption during production, contributing to global carbon reduction goals. This environmental advantage, coupled with its compatibility with existing cement production and construction practices, makes PLC a key material in the transition to more sustainable construction practices. LCAs consistently show that PLC reduces the environmental impact of cement production while maintaining performance standards required for modern infrastructure.

Despite its many advantages, there are yet challenges, particularly regarding early-age cracking, shrinkage, and compatibility with certain chemical admixtures. These issues, along with barriers to adoption in regions where traditional cement practices are entrenched, suggest the need for continued research and innovation to optimize PLC formulations. Furthermore, while PLC has shown promise in short- and medium-term applications, more extended long-term studies are necessary to fully understand its performance over the lifespan of infrastructure projects, especially in extreme environmental conditions.

Looking ahead, emerging trends in cement technology such as the integration of nanotechnology, the development of hybrid cement systems, and the use of carbon capture and utilization technologies present exciting opportunities for further enhancing the sustainability and performance of PLC. With ongoing innovation and comprehensive field testing, PLC can play a pivotal role in the future of sustainable infrastructure. However, to realize its full potential, collaboration between researchers, policymakers, and industry professionals is essential. Future work should focus on improving admixture compatibility, optimizing performance in extreme environmental conditions, and developing standards for regional adaptations of PLC. These efforts will ensure PLC becomes a key material in the global push for greener construction practices.

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References

1. Al-Numan, B.S.O. Construction Industry Role in Natural Resources Depletion and How to Reduce It. In *Natural Resources Deterioration in MENA Region: Land Degradation, Soil Erosion, and Desertification*; Al-Quraishi, A.M.F., Mustafa, Y.T., Eds.; Springer International Publishing: Cham, Switzerland, 2024; pp. 93–109.
2. Al-Zu'bi, M.; Fan, M.; Al Rjoub, Y.; Ashteyat, A.; Al-Kheetan, M.J.; Anguilano, L. The effect of length and inclination of carbon fiber reinforced polymer laminates on shear capacity of near-surface mounted retrofitted reinforced concrete beams. *Struct. Concr.* **2021**, *22*, 3677–3691. [CrossRef]
3. Rodrigues, F.A.; Joekes, I. Cement industry: Sustainability, challenges and perspectives. *Environ. Chem. Lett.* **2011**, *9*, 151–166. [CrossRef]
4. US EPA: Overview of Greenhouse Gases. 2016. Available online: <https://evogov.s3.amazonaws.com/media/17/media/119571.pdf> (accessed on 15 November 2024).
5. Gupta, S.; Mohapatra, B.N.; Bansal, M. A review on development of Portland limestone cement: A step towards low carbon economy for Indian cement industry. *Curr. Res. Green Sustain. Chem.* **2020**, *3*, 100019. [CrossRef]
6. Scrivener, K.L.; John, V.M.; Gartner, E.M. Eco-efficient cements: Potential economically viable solutions for a low-CO₂ cement-based materials industry. *Cem. Concr. Res.* **2018**, *114*, 2–26. [CrossRef]
7. Reddy, K.R.; Yargicoglu, E.; Ibrahim, M.; Kumar, G. Sustainability Assessment of Concrete Mixtures for Pavements and Bridge Decks. In *Proceedings of the Urbanization Challenges in Emerging Economies*, New Delhi, India, 12–14 December 2017; American Society of Civil Engineers: Reston, VA, USA, 2018. Available online: <https://ascelibrary-org.offcampus.lib.washington.edu/doi/10.1061/9780784482032.061> (accessed on 4 November 2024).
8. Hanein, T.; Imbabi, M.; Glasser, F.; Bannerman, M.N. Lowering the carbon footprint and energy consumption of cement production: A novel Calcium SulfoAluminate cement production process. In *Proceedings of the 1st International Conference on Grand Challenges in Construction Materials*, Los Angeles, CA, USA, 17–18 March 2016. Available online: <https://abdn.elsevierpure.com/en/publications/lowering-the-carbon-footprint-and-energy-consumption-of-cement-pr> (accessed on 4 September 2024).
9. ACPA Portland-Limestone Cements for Pavement Applications. Available online: <https://www.acpa.org/wp-content/uploads/2020/05/Perspectives-PLCs-in-Pavements-5-11-2020-v7.pdf> (accessed on 4 September 2024).
10. CEN-EN 197-1; Cement Part 1: Composition, Specifications and Conformity Criteria for Common Cements. CEN: Brussels, Belgium, 2011. Available online: <https://standards.globalspec.com/std/1399038/en-197-1> (accessed on 7 November 2024).
11. Tennis, P.D.; Thomas, M.D.A.; Weiss, W.J.; Farny, J.A.; Giannini, E.R. *State-of-the-Art Report on Use of Limestone in Cements at Levels of up to 15%*; Portland Cement Association: Skokie, IL, USA, 2024; Available online: <https://www.cement.org/wp-content/uploads/2024/06/2024-SN3148.03.pdf> (accessed on 5 January 2025).
12. Cooper, M.; Spragg, R. *Portland Limestone Cement*; Turner-Fairbank Highway Research Center: McLean, VA, USA, 2023. Available online: <https://highways.dot.gov/sites/fhwa.dot.gov/files/FHWA-HRT-23-104.pdf> (accessed on 12 November 2024).
13. digital_usa_ecocem-plc.pdf. Available online: https://www.heidelbergmaterials.us/docs/default-source/productdatasheets/digital_usa_ecocem-plc.pdf?sfvrsn=c9bc3e5_3 (accessed on 1 October 2024).
14. Chung, H.W.; DeFord, H.; Tia, M.; Ni, F.M.W. Developing Sustainable Pavement Concrete Mix Using Portland Limestone Cement and Blended Aggregates Techniques. *Transp. Res. Rec.* **2023**, *2677*, 209–221. [CrossRef]
15. Hossack, A.; Thomas, M.D.A.; Barcelo, L.; Blair, B.; Delagrave, A. Performance of Portland Limestone Cement Concrete Pavements. *Concr. Int.* **2014**, *36*, 40.
16. Kanagaraj, B.; Anand, N.; Samuvel Raj, R.; Lubloy, E. Techno-socio-economic aspects of Portland cement, Geopolymer, and Lime stone Calcined Clay Cement (LC3) composite systems: A-State-of-Art-Review. *Constr. Build. Mater.* **2023**, *398*, 132484. [CrossRef]
17. Martinez, D.M.; Horvath, A.; Monteiro, P.J.M. Comparative environmental assessment of limestone calcined clay cements and typical blended cements. *Environ. Res. Commun.* **2023**, *5*, 055002. [CrossRef]
18. Ren, Q.; Xie, M.; Zhu, X.; Zhang, Y.; Jiang, Z. Role of Limestone Powder in Early-Age Cement Paste Considering Fineness Effects. *J. Mater. Civ. Eng.* **2020**, *32*, 04020289. [CrossRef]
19. Hossack, A.M.; Thomas, M.D.A. Durability of Concrete Produced with Portland Limestone Cement. In *Proceedings of the 3rd Specialty Conference on Material Engineering & Applied Mechanics*, Montréal, QC, Canada, 29 May–1 June 2013; pp. 1–10. Available online: <https://legacy.csce.ca/elf/apps/CONFERENCEVIEWER/conferences/2013/pdfs/mechanics/69.pdf> (accessed on 22 July 2024).
20. Zeng, H.; Li, Y.; Zhang, J.; Chong, P.; Zhang, K. Effect of limestone powder and fly ash on the pH evolution coefficient of concrete in a sulfate-freeze-thaw environment. *J. Mater. Res. Technol.* **2022**, *16*, 1889–1903. [CrossRef]

21. Hooton, R.; Ramezaniapour, A.; Schutz, U. Decreasing the Clinker Component in Cementing Materials: Performance of Portland-Limestone Cements in Concrete in combination with Supplementary Cementing Materials. In Proceedings of the NRMCA Concrete Sustainability Conference, Tempe, AZ, USA, 13–15 April 2010. Available online: <https://www.semanticscholar.org/paper/Decreasing-the-Clinker-Component-in-Cementing-of-in-Hooton-Ramezaniapour/560e5c64b10573c0b468cc312566a5ac92a016bb> (accessed on 18 November 2024).
22. Hossack, A.; Thomas, M.D.A.; Moffatt, E. Field Performance of Portland Limestone Cement Concretes Exposed to Cold-Temperature Sulphate Solutions. In *RILEM Bookseries*; Springer International Publishing: Berlin/Heidelberg, Germany, 2019; pp. 3–14. [[CrossRef](#)]
23. Barrett, T.J.; Sun, H.; Nantung, T.; Weiss, W.J. Performance of Portland Limestone Cements. *Transp. Res. Rec.* **2014**, *2441*, 112–120. [[CrossRef](#)]
24. Han, D.; Ferron, R.D. Effect of Mixing Speed on Rheology of Superplasticized Portland Cement and Limestone Powder Pastes. *ACI Mater. J.* **2017**, *114*, 559–569. [[CrossRef](#)]
25. Harari, M.B.; Parola, H.R.; Hartwell, C.J.; Riegelman, A. Literature searches in systematic reviews and meta-analyses: A review, evaluation, and recommendations. *J. Vocat. Behav.* **2020**, *118*, 103377. [[CrossRef](#)]
26. Park, H.Y.; Suh, C.H.; Woo, S.; Kim, P.H.; Kim, K.W. Quality Reporting of Systematic Review and Meta-Analysis According to PRISMA 2020 Guidelines: Results from Recently Published Papers in the Korean Journal of Radiology. *Korean J. Radiol.* **2022**, *23*, 355. [[CrossRef](#)]
27. Ellis, P.D. *The Essential Guide to Effect Sizes: Statistical Power, Meta-Analysis, and the Interpretation of Research Results*; Cambridge University Press: Cambridge, UK, 2010. [[CrossRef](#)]
28. Sotiriadis, K.; Mácová, P.; Mazur, A.S.; Viani, A.; Tolstoy, P.M.; Tsivilis, S. Long-term thaumasite sulfate attack on Portland-limestone cement concrete: A multi-technique analytical approach for assessing phase assemblage. *Cem. Concr. Res.* **2020**, *130*, 105995. [[CrossRef](#)]
29. Tiwari, A.K.; Chowdhury, S. Relative evaluation of performance of limestone calcined clay cement compared with Portland pozzolana cement. *J. Asian Concr. Fed.* **2016**, *2*, 110–116. [[CrossRef](#)]
30. Thomas, M.; Delagrave, A.; Blair, B.; Barcelo, L. Equivalent Durability Performance of Portland Limestone Cement. *Concr. Int.* **2013**, *35*, 39–45.
31. John, E.; Lothenbach, B. Cement hydration mechanisms through time—A review. *J. Mater. Sci.* **2023**, *58*, 9805–9833. [[CrossRef](#)]
32. Guo, F. Calcined Clay and Limestone as Partial Replacements of Portland Cement: Electrochemical Corrosion Behavior of Low Carbon Steel Rebar as Concrete Reinforcement in Corrosive Environment. *Int. J. Electrochem. Sci.* **2020**, *15*, 12281–12290. [[CrossRef](#)]
33. Shi, C.; Jiménez, A.F.; Palomo, A. New cements for the 21st century: The pursuit of an alternative to Portland cement. *Cem. Concr. Res.* **2011**, *41*, 750–763. [[CrossRef](#)]
34. Tino Balestra, C.E.; Garcez, L.R.; Couto da Silva, L.; Veit, M.T.; Jubanski, E.; Nakano, A.Y.; Pietrobelli, M.H.; Schneider, R.; Ramirez Gil, M.A. Contribution to low-carbon cement studies: Effects of silica fume, fly ash, sugarcane bagasse ash and acai stone ash incorporation in quaternary blended limestone-calcined clay cement concretes. *Environ. Dev.* **2023**, *45*, 100792. [[CrossRef](#)]
35. Flower, D.J.M.; Sanjayan, J.G. Green house gas emissions due to concrete manufacture. *Int. J. Life Cycle Assess* **2007**, *12*, 282–288. [[CrossRef](#)]
36. Weerdt, K.; Justnes, H.; Haha, M.B.; Lothenbach, B. The effect of limestone powder additions on strength and microstructure of fly ash blended cements. In Proceedings of the 13th International Congress on the Chemistry of Cement, Madrid, Spain, 3–8 July 2011.
37. Briki, Y.; Zajac, M.; Haha, M.B.; Scrivener, K. Impact of limestone fineness on cement hydration at early age. *Cem. Concr. Res.* **2021**, *147*, 106515. [[CrossRef](#)]
38. Ghorab, H.Y.; Zahran, F.S.; Kamal, M.; Meawad, A.S. On the durability of Portland limestone cement: Effect of pH on the thaumasite formation. *HBRC J.* **2018**, *14*, 340–344. [[CrossRef](#)]
39. Malakopoulos, A.; Salifoglou, A. Assessment of Durability Indicators for Service Life Prediction of Portland Limestone Cementitious Systems Produced with Permeability-Reducing Admixtures. *Buildings* **2022**, *12*, 1712. [[CrossRef](#)]
40. Bolina, F.L.; Schallenger, M.; Carvalho, H. Experimental and numerical evaluation of RC ribbed slabs in fire conditions. *Structures* **2023**, *51*, 747–759. [[CrossRef](#)]
41. Liu, X.; Xin, J.; Liu, Y.; Xiong, Z.; Li, Y. Harnessing Limestone powder to enhance the thermal crack resistance of manufactured sand. *PLoS ONE* **2024**, *19*, e0309105. [[CrossRef](#)] [[PubMed](#)]
42. De Weerdt, K.; Haha, M.B.; Le Saout, G.; Kjellsen, K.O.; Justnes, H.; Lothenbach, B. Hydration mechanisms of ternary Portland cements containing limestone powder and fly ash. *Cem. Concr. Res.* **2011**, *41*, 279–291. [[CrossRef](#)]
43. Shannon, J.; Howard, I.L.; Tim Cost, V. Potential of Portland-Limestone Cement to Improve Performance of Concrete Made with High Slag Cement and Fly Ash Replacement Rates. *J. Test. Eval.* **2016**, *45*, 20150306. [[CrossRef](#)]

44. Filani, I.; Butt, A.A.; Harvey, J. Life Cycle Cost and Environmental Impacts of Portland Limestone Cement and Calcium Sulfoaluminate Cement as Alternative Binders in Concrete. In *Proceedings of the Pavement, Roadway, and Bridge Life Cycle Assessment 2024*; Flintsch, G.W., Amarh, E.A., Harvey, J., Al-Qadi, I.L., Ozer, H., Lo Presti, D., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 61–68. [\[CrossRef\]](#)
45. Chen, C.; Habert, G.; Bouzidi, Y.; Jullien, A. Environmental impact of cement production: Detail of the different processes and cement plant variability evaluation. *J. Clean. Prod.* **2010**, *18*, 478–485. [\[CrossRef\]](#)
46. Bishnoi, S. Carbon Emissions and Their Mitigation in the Cement Sector. In *Carbon Utilization: Applications for the Energy Industry*; Goel, M., Sudhakar, M., Eds.; Springer: Singapore, 2017; pp. 257–268. [\[CrossRef\]](#)
47. Zhu, H.; Chen, W.; Cheng, S.; Yang, L.; Wang, S.; Xiong, J. Low carbon and high efficiency limestone-calcined clay as supplementary cementitious materials (SCMs): Multi-indicator comparison with conventional SCMs. *Constr. Build. Mater.* **2022**, *341*, 127748. [\[CrossRef\]](#)
48. Joel, M.; Mbapuu, I.D. Comparative analysis of the properties of concrete produced with Portland Limestone Cement (PLC) grade 32.5n and 42.5r for use in rigid pavement work. *Glob. J. Res. Eng.* **2017**, *15*, 17. [\[CrossRef\]](#)
49. Thomas, M.; Cail, K.; Blair, B.; Delagrave, A.; Masson, P.; Kazanis, K. Use of Low-CO₂ Portland Limestone Cement for Pavement Construction in Canada. *Int. J. Pavement Res. Technol.* **2010**, *3*, 228–233.
50. ASTM: Standard Specifications for Transportation Materials and Method of Sampling and Testing and Provisional Standards. 2021. Available online: <http://worldcat.org/isbn/9781560518174> (accessed on 4 January 2025).
51. Wang, X.-Y. Modeling of Hydration, Compressive Strength, and Carbonation of Portland-Limestone Cement (PLC) Concrete. *Materials* **2017**, *10*, 115. [\[CrossRef\]](#) [\[PubMed\]](#)
52. Bentz, D.; Irassar, E.; Bucher, B.; Weiss, W. Limestone Fillers Conserve Cement; Part 1: An analysis based on Powers' model. *Concr. Int.* **2009**, *31*, 41–46.
53. Khichad, J.S.; Vishwakarma, R.J. Overview and Discussion of Pavement Performance Prediction Techniques for Maintenance and Rehabilitation Decision-Making. *Int. J. Pavement Res. Technol.* **2024**, 1–17. [\[CrossRef\]](#)
54. Cost, V.T.; Howard, I.L.; Shannon, J. Improving Concrete Sustainability and Performance with Use of Portland–Limestone Cement Synergies. *Transp. Res. Rec.* **2013**, *2342*, 26–34. [\[CrossRef\]](#)
55. Choudhary, A.; Ghantous, R.M.; Opdahl, O.H.; Isgor, O.B.; Weiss, W.J. Weiss Heat of Hydration, Shrinkage, and Flexural Strength of Portland Limestone Cement Mortar. *Adv. Civ. Eng. Mater.* **2022**, *11*, 501–519. [\[CrossRef\]](#)
56. Fernandez, J.R.; Turrado, S.; Abanades, J.C. Calcination kinetics of cement raw meals under various CO₂ concentrations. *React. Chem. Eng.* **2019**, *4*, 2129–2140. [\[CrossRef\]](#)
57. Tennis, P.D.; Melander, J. Environmental Benefits and Performance Equivalence of Portland-Limestone Blended Cements. In *Proceedings of the 2012 Transportation Research Board 91st Annual Meeting*, Washington, DC, USA, 22–26 January 2012. Available online: <https://trid.trb.org/view/1128986> (accessed on 9 October 2024).
58. Yasien, A.; Ghazy, A.; Bassuoni, M. Performance of Concrete Pavement Incorporating Portland Limestone Cement in Cold Weather. *Sustainability* **2021**, *14*, 183. [\[CrossRef\]](#)
59. Chung, H.-W.; Subgranon, T.; Tia, M. Improving Concrete Durability by Using Optimized Aggregate Gradation and Reducing Cement Content. In *Proceedings of the International Conference on Civil Infrastructure and Construction (CIC 2020)*, Doha, Qatar, 2–5 February 2020. Available online: <https://journals.qu.edu.qa/index.php/CIC/article/view/3931> (accessed on 2 November 2024).
60. Garcia, E.J.; Tiburzi, N.N.; Folliard, K.J.; Drimalas, T.; Thomas, M.D.A. *Laboratory and Outdoor Exposure Site Evaluations of Portland Limestone Cements*; Texas Department of Transportation Research and Technology Implementation Division, Center for Transportation Research the University of Texas at Austin: Austin, TX, USA, 2019. Available online: https://rosap.ntl.bts.gov/view/dot/62534/dot_62534_DS1.pdf (accessed on 12 September 2024).
61. Poudyal, L.; Adhikari, K.; Won, M. Mechanical and Durability Properties of Portland Limestone Cement (PLC) Incorporated with Nano Calcium Carbonate (CaCO₃). *Materials* **2021**, *14*, 905. [\[CrossRef\]](#)
62. Kim, J.; Zollinger, D. *Portland Cement Concrete Pavement Joint Sealant Practices and Performance*; The National Academies Press: Washington, DC, USA, 2021; pp. 6–29. Available online: <https://nap.nationalacademies.org/catalog/26205/portland-cement-concrete-pavement-joint-sealant-practices-and-performance> (accessed on 2 February 2025).
63. Stefaniuk, D.; Hajduczek, M.; Weaver, J.C.; Ulm, F.J.; Masic, A. Cementing CO₂ into C-S-H: A step toward concrete carbon neutrality. *PNAS Nexus* **2023**, *2*, pgad052. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Andrzej, A.; Matthias, D.; Jakob, W.; Hanna, F.; Niklas, H. *Implications of Paris Agreement on the National Emissions Reduction Efforts*; Umweltbundesamt: Langen, Germany, 2021. Available online: <https://www.umweltbundesamt.de/en/publikationen/implications-of-paris-agreement-on-the-national> (accessed on 5 February 2025).
65. Petek Gursel, A.; Masanet, E.; Horvath, A.; Stadel, A. Life-cycle inventory analysis of concrete production: A critical review. *Cem. Concr. Compos.* **2014**, *51*, 38–48. [\[CrossRef\]](#)

66. Hottle, T.; Hawkins, T.R.; Chiquelin, C.; Lange, B.; Young, B.; Sun, P.; Elgowainy, A.; Wang, M. Environmental life-cycle assessment of concrete produced in the United States. *J. Clean. Prod.* **2022**, *363*, 131834. [CrossRef]
67. Ige, O.E.; Olanrewaju, O.A. Comparative Life Cycle Assessment of Different Portland Cement Types in South Africa. *Clean Technol.* **2023**, *5*, 901–920. [CrossRef]
68. Oguntola, O.; Simske, S. Continuous Assessment of the Environmental Impact and Economic Viability of Decarbonization Improvements in Cement Production. *Resources* **2023**, *12*, 95. [CrossRef]
69. Meshram, R.B.; Kumar, S. Comparative life cycle assessment (LCA) of geopolymer cement manufacturing with Portland cement in Indian context. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 4791–4802. [CrossRef]
70. Sezer, G.; Çopuroğlu, O.; Ramyar, K. Microstructure of 2 and 28-day cured Portland limestone cement pastes. *Indian J. Eng. Mater. Sci.* **2010**, *17*, 289–294.
71. Mitchell, C. High-Purity Limestone Assessment: From Mine to Market. Available online: <https://nora.nerc.ac.uk/id/eprint/7210/1/High-purityLimestoneAssessment.pdf> (accessed on 9 October 2024).
72. Naqi, A.; Jang, J.G. Recent Progress in Green Cement Technology Utilizing Low-Carbon Emission Fuels and Raw Materials: A Review. *Sustainability* **2019**, *11*, 537. [CrossRef]
73. Nadelman, E.I.; Kurtis, K.E. Durability of Portland-limestone cement-based materials to physical salt attack. *Cem. Concr. Res.* **2019**, *125*, 105859. [CrossRef]
74. Guha, A.; Assaf, G. Using Cement as Filler to Enhance Asphalt Mixes Performance in Hot Climate Regions. *J. Kejuruter.* **2023**, *35*, 747–753. [CrossRef]
75. Sharma, A.; Sirotiak, T.; Wang, X.; Taylor, P.; Angadi, P.; Payne, S. Portland limestone cement for reduced shrinkage and enhanced durability of concrete. *Mag. Concr. Res.* **2021**, *73*, 147–162. [CrossRef]
76. Thomas, M.; Hooton, D.; Cail, K.; Smith, B.A.; Wal, J.; Kazanis, K. Field Trials of Concretes Produced with Portland Limestone Cement: New CSA cement type performs well in an aggressive environment. *Concr. Int.* **2010**, *32*, 35–41.
77. Chopperla, K.S.T.; Smith, J.A.; Ideker, J.H. The efficacy of portland-limestone cements with supplementary cementitious materials to prevent alkali-silica reaction. *Cement* **2022**, *8*, 100031. [CrossRef]
78. Brühl, V. Green Finance in Europe—Strategy, Regulation and Instruments. *Cent. Financ. Stud. Work. Pap.* **2021**, *657*, 323–330.
79. Fujiwara, N.; van Asselt, H.; Bößner, S.; Voigt, S.; Spyridaki, N.-A.; Flamos, A.; Alberola, E.; Williges, K.; Türk, A.; ten Donkelaar, M. The practice of climate change policy evaluations in the European Union and its member states: Results from a meta-analysis. *Sustain. Earth* **2019**, *2*, 9. [CrossRef]
80. EPA. Sustainable Management of Construction and Demolition Materials. Available online: <https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials> (accessed on 6 September 2024).
81. Munthali, T.; Diawara, B.; Zimhunga, A. Capacity Building for Africa’s Transformation: A Review of Priorities and Research Needs. In *Capacity Building in Developing and Emerging Countries: From Mindset Transformation to Promoting Entrepreneurship and Diaspora Involvement*; Chrysostome, E., Ed.; Springer International Publishing: Cham, Switzerland, 2019; pp. 91–118.
82. United Nations Conference on Trade and Development. *Economic Development in Africa Report 2023*; United Nations Conference on Trade and Development: Geneva, Switzerland, 2023; pp. 62–69. Available online: <https://digitallibrary.un.org/record/4041795?v=pdf> (accessed on 2 November 2024).
83. Barrett, T.; Sun, H.; Weiss, W.J. *Performance of Portland Limestone Cements: Cements Designed to Be More Sustainable That Include up to 15% Limestone Addition*; Publication FHWA/IN/JTRP-2013/29; Joint Transportation Research Program, Indiana Department of Transportation and Purdue University: West Lafayette, IN, USA, 2013. Available online: <https://docs.lib.purdue.edu/jtrp/1548/> (accessed on 5 November 2024).
84. Portland Limestone Cement after 10 Years in the Field. 2018. Available online: <https://nrmcc.com/images/plc-downloads/MAPbriefOctober2018.pdf> (accessed on 12 August 2024).
85. Nandhini, K.; Karthikeyan, J. The early-age prediction of concrete strength using maturity models: A review. *J. Build Rehabil.* **2021**, *6*, 7. [CrossRef]
86. Hansen, B.S.; Howard, I.L.; Shannon, J.; Cost, T.; Wilson, W.M. Portland-Limestone Cement Fineness Effects on Concrete Properties. *ACI Mater. J.* **2020**, *117*, 157–168. [CrossRef]
87. Barrett, T.; Sun, H.; Villani, C.; Barcelo, L.; Weiss, J. Early-Age Shrinkage Behavior of Portland Limestone Cement. *Concr. Int.* **2014**, *36*, 51–57.
88. Bentz, D.P.; Stutzman, P.E.; Zunino, F. Low-temperature curing strength enhancement in cement-based materials containing limestone powder. *Mater. Struct.* **2017**, *50*, 1–14. [CrossRef] [PubMed]
89. Dhanalaxmi, C.; Nirmalkumar, K. Study on the Properties of Concrete Incorporated with Various Mineral Admixtures Limestone Powder and Marble Powder (Review Paper). *Int. J. Innov. Res. Sci. Eng. Technol.* **2015**, *4*, 18511–18515.
90. Karji, A.; Namian, M.; Tafazzoli, M. Identifying the Key Barriers to Promote Sustainable Construction in the United States: A Principal Component Analysis. *Sustainability* **2020**, *12*, 5088. [CrossRef]

91. Thomas, M.; Barcelo, L.; Blair, B.; Cail, K.; Delagrave, A.; Kazanis, K. Lowering the Carbon Footprint of Concrete by Reducing Clinker Content of Cement. *Transp. Res. Rec.* **2012**, 2290, 99–104. [[CrossRef](#)]
92. Bentz, D.P.; Ferraris, C.F.; Jones, S.Z.; Lootens, D.; Zunino, F. Limestone and silica powder replacements for cement: Early-age performance. *Cem. Concr. Compos.* **2017**, 78, 43–56. [[CrossRef](#)] [[PubMed](#)]
93. Van den Heede, P.; De Schepper, M.; De Belie, N. Accelerated and natural carbonation of concrete with high volumes of fly ash: Chemical, mineralogical and microstructural effects. *R. Soc. Open sci.* **2019**, 6, 181665. [[CrossRef](#)]
94. Leeuwen, R.V.; Kim, Y.; Sriraman, V. The Effects of Limestone Powder Particle Size on the Mechanical Properties and the Life Cycle Assessment of Concrete. *J. Civ. Eng. Res.* **2016**, 6, 104–113. [[CrossRef](#)]
95. Thomas, M.D.A.; Cail, K.; Blair, B.; Delagrave, A.; Barcelo, L. Equivalent Performance with Half the Clinker Content using PLC and SCM. In Proceedings of the 2010 Concrete Sustainability Conference, Tempe, AZ, USA, 15 April 2010. Available online: <https://www.semanticscholar.org/paper/Equivalent-Performance-with-Half-the-Clinker-using-Thomas-Cail/3f9095ffe236ac96462242c9553c3b42986604c5> (accessed on 23 December 2024).
96. Bernal, S.A.; Provis, J.L. Durability of Alkali-Activated Materials: Progress and Perspectives. *J. Am. Ceram. Soc.* **2014**, 97, 997–1008. [[CrossRef](#)]
97. Azhar, S. Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadersh. Manag. Eng.* **2011**, 11, 241–252. [[CrossRef](#)]
98. Rahhal, V.F.; Irassar, E.F.; Trezza, M.A.; Bonavetti, V.L. Calorimetric characterization of Portland limestone cement produced by intergrinding. *J. Therm. Anal. Calorim.* **2012**, 109, 153–161. [[CrossRef](#)]

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