

DECARBONIZING CONSTRUCTION MATERIALS (CEMENT): A COMPREHENSIVE FRAMEWORK FOR REDUCING EMBODIED CARBON

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Abstract - The construction sector is a major contributor to global greenhouse gas emissions, with cement production alone accounting for a substantial portion due to its energy-intensive processes and cement clinker manufacturing. This research investigates strategies for reducing the carbon footprint of cement-based construction materials through material innovation, lifecycle assessment (LCA), and process optimization, improved supply chain efficiency, and adoption of sustainable construction techniques. The study proposes an integrated framework that combines material-level interventions, design optimization, and policy support to achieve low-carbon construction. The study adopts a comprehensive methodology involving literature synthesis, case study evaluation, and analysis of alternative materials such as coal bottom ash, Alccofine, and nano-enhanced additives (Graphene oxide GO) the analysis emphasize that lifecycle-based thinking are critical in achieving meaningful emission reductions while maintaining structural performance and economic feasibility.

Key Words: Decarbonization, Cement, Embodied Carbon, Sustainable Construction, Life Cycle Assessment.

1. INTRODUCTION

The continuous expansion of urban infrastructure has led to an unprecedented demand for construction materials, particularly cement, which forms the backbone of modern structural systems. Despite its widespread application, cement production is associated with significant environmental concerns due to the release of carbon dioxide during clinker formation and fuel combustion. These emissions make the construction sector a major contributor to climate change.

Decarbonization within this sector involves systematically lowering emissions across the entire lifecycle of construction activities, beginning from raw material extraction and extending to demolition and reuse stages. Lifecycle-based evaluation methods provide a comprehensive means of identifying emission-intensive phases and guiding strategic interventions. As highlighted in the dissertation, the majority of environmental impact is determined during early design decisions, making material selection a critical factor in sustainability outcomes.

Unlike operational emissions, which can be reduced over time, embodied carbon is fixed once construction is

completed. This necessitates a proactive approach in selecting materials and construction methods that minimize carbon intensity from the outset. The present study addresses this requirement by examining feasible strategies for reducing emissions associated with cement-based materials.

2. SCOPE

The scope of the study is confined to cement and concrete materials used in building construction and infrastructure projects. It includes the assessment of alternative materials, lifecycle-based evaluation of emissions, and analysis of construction practices that influence carbon output. The research primarily considers cradle-to-gate emissions, while also acknowledging the importance of end-of-life considerations in long-term sustainability.

The findings of this study are intended to provide practical insights for engineers, architects, and policymakers involved in the design and execution of construction projects.

3. METHODOLOGY

The research adopts a comprehensive and integrative methodology combining qualitative analysis and analytical evaluation. The initial phase involved an extensive review of existing literature on decarbonization strategies, cement production processes, and sustainable construction practices. This provided a theoretical foundation for understanding the key factors influencing carbon emissions in the construction sector.

The study then focused on the evaluation of alternative materials that can partially replace conventional cement. Materials such as coal bottom ash, Alccofine, and graphene-based additives were analyzed for their potential to reduce clinker content and improve the overall performance of concrete. These materials were selected based on their availability, environmental benefits, and compatibility with existing construction practices.

Case studies were examined to understand the practical implementation of sustainable construction strategies and to evaluate their effectiveness in reducing carbon emissions. The analysis of these projects provided valuable insights into the challenges and opportunities associated with the adoption of low-carbon materials.

Lifecycle assessment was used as a conceptual framework to evaluate the environmental impact of construction materials across different stages of their lifecycle. The methodology outlined in the dissertation integrates material study, case study analysis, and lifecycle evaluation to develop a comprehensive understanding of decarbonization strategies.

4. LITERATURE-BASED ANALYSIS

The review of existing research indicates that cement production contributes significantly to global carbon emissions, accounting for approximately 7–8% of total emissions. Several studies have highlighted the importance of reducing clinker content as a primary strategy for lowering emissions. The use of supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume has been widely recognized as an effective approach to achieving this goal.

Recent advancements in material science have introduced innovative alternatives such as geopolymers and nano-enhanced concrete, which offer improved performance and reduced environmental impact. These materials not only reduce emissions but also enhance durability and structural efficiency, making them suitable for modern construction applications.

The literature also emphasizes the role of lifecycle assessment in evaluating the environmental performance of construction materials. By considering emissions across all stages of the lifecycle, LCA provides a comprehensive understanding of the impact of different materials and helps identify opportunities for improvement.

5. CASE STUDIES

The case studies considered in this research illustrate the practical application of sustainable construction approaches in diverse project contexts. Projects such as the CEPT Library, Rohtak Dome, 3D Printpod, and Chitlapakkam Residence demonstrate how innovative material choices and design strategies contribute to reducing embodied carbon.

5.1. Rohtak Domes @ Tekulodu, Andhra Pradesh

The Rohtak Domes (also known as Rohtak thin-shell concrete domes) are an innovative low-cost, energy-efficient construction technique developed and popularized in Rohtak, Haryana (India), mainly for mass housing and



Fig -1: Rohtak Domes (Interior)



Fig -2: Rohtak Domes (Interior)

Advantages: Eco-friendly less cement and steel (lower embodied carbon). Thermally comfortable dome shape minimizes heat gain. Aesthetic natural curvature looks elegant. Durable and earthquake-resistant due to shell action. Low cost & quick to build using local skills.

Table -1: Compared to conventional RCC slab construction

Parameter	RCC Slab	Rohtak Dome	Savings
Concrete thickness	120–150 mm	25–40 mm	70–75% less concrete
Steel reinforcement	High	Low	35–40% less steel
Shuttering	Heavy	Very low	93% saved
Cement use	High	Reduced by thin section	Up to 60–65% saving

5.2. Residence @ Chitalapakkam, Tamil Nadu

Graphene oxide a nanotech material is used for concrete structures like columns, beam and slab, and for plastering work. The strength of the building structure is increased by adding graphene oxide to concrete, according to specialists. Additionally, aids in setting concrete 50% quicker than usual, resulting in shorter curing times. saves 40% of the total construction cost and reduces construction time at the site.

GRAPHENE OXIDE IN CONSTRUCTION INDUSTRY- Based on experts consideration, the addition of graphene oxide in concrete increases the strength of the building structure. Also helps in setting the concrete 50% faster than that of regular, which means curing times reduces saves construction time at site 40% reduction in the overall construction cost.

Table -2: BOQ

III RCC works			
1	Providing and laying in position of concrete using 12mm to 20mm graded metal and good river sand and OPC cement 43 grade resistance cement as approved by the Architects, including formwork, all leads and lifts, scaffolding wherever required, its removal after the period of setting of concrete, curing but excluding cost of steel reinforcement placed in position (paid for separately) all as per the drawings / specification etc all complete. For each cement bag 0.01 to 0.06mm of GO added Based upon the expected output		
RCC M25 Grade			
a	in columns in footings	1705	190 Cu.ft 323950
b	in columns F.B	176	240 Cu.ft 42240
c	in columns in super structure G.F	220	245 Cu.ft 53900
d	in columns in super structure F.F	275	250 Cu.ft 68750
e	in columns in super structure S.F	220	255 Cu.ft 56100
f	in columns in super structure T.F	220	260 Cu.ft 57200
g	in columns in super structure Terrace floor	121	265 Cu.ft 32065

Due to the reduction in the curing period of structural components & introduction of many parallel activity 37 days has been saved in this G+3 project. Originally estimated cost without graphene oxide Rs. 2,05,54,075 (two crore five lakh fifty-four thousand seventy five rupees). Each bag of cement added with 0.04mg of GO – for concrete mixture used for structure. 0.01 mg for –plastering of wall. Based on this scenario, GO can save 9-12% of cost in overall construction cost for a 3 storey building. The percentage of cost saving increases with the increase in the no. of storey in the building. Maximum saving cost percentage upto 40%.

A key observation across these projects is the influence of early-stage planning on environmental performance. Projects that incorporated sustainability considerations during the design phase exhibited lower material consumption and improved efficiency. The adoption of prefabrication techniques further minimized waste generation, while the use of locally available resources reduced transportation-related emissions.

Despite these advantages, several challenges were identified, including limited availability of alternative materials and lack of standardized guidelines for their application. Economic factors, particularly higher initial costs, also

influence decision-making. Nevertheless, these case studies confirm that sustainable construction practices can achieve measurable environmental benefits without compromising structural requirements.

6. REACTIONS OF BY-PRODUCTS MIX WITH CEMENT CONCRETE

OPC + Coal Bottom Ash (CBA) + Alccofine-1203 + Graphene Oxide (GO)

A concise reaction pathway / phase-evolution timeline (what forms when), and a simple illustrative CO₂-saving estimate for cement replacement. Both ground coal bottom ash (CBA) and Alccofine-1203 act primarily as supplementary cementitious materials (SCMs). They supply reactive silica and alumina (and in Alccofine's case also a very fine particle packing / latent hydraulic reactivity) which react with CH to produce extra binding gel (C-S-H, C-A-S-H). For silica + alumina (CBA has both SiO₂ and Al₂O₃).

Alccofine-1203 (ultra-fine low-Ca silicate additive) behaves similarly to reactive micro-silica/ground slag: it improves packing (filler/nucleation), exhibits latent hydraulic reactivity, and participates in pozzolanic consumption of CH to form denser C-S-H / C-A-S-H. Ground CBA's efficiency depends strongly on its glassy (amorphous) fraction and fineness ground CBA with higher amorphous Si/Al is more pozzolanic.

Graphene Oxide (GO) does not become a major new hydrate phase; it acts at the nano-scale to modify nucleation, crystal habit, ion adsorption, and microstructure. Carboxyl and hydroxyl groups on GO bind Ca²⁺ and act as nucleation sites.

Combined system: OPC + CBA + Alccofine + GO — reaction cascade

First minutes → hours (early age) C₃S hydrates → produces C-S-H + CH (baseline). Alccofine micro-particles act as nucleation sites and filler: accelerate surface hydration and reduce initial porosity. (Latent hydraulic nucleation). GO sheets adsorb Ca²⁺ and provide nano nucleation sites → faster/denser early C-S-H. Days (1-28 d) Pozzolanic reaction: amorphous SiO₂/Al₂O₃ from CBA & Alccofine react with CH → additional C-S-H and C-A-S-H, reducing free CH and refining microstructure. Net result: increased gel volume (C-S-H), reduced porosity, improved strength and durability. Long term (>28 d) Continued slow pozzolanic conversion of CH to C-(A)-S-H; dependence on fineness and amorphous fraction. Graphene oxide improves crack-bridging at nanoscale and slows microcrack growth (durability gain).

Simple illustrative CO₂ saving estimate is typical emission intensity for cement/clinker varies by region; recent industry numbers put direct process emissions in the range is ~0.6-0.9 ton of CO₂ per t cement/clinker depending on

mix and region. Use a conservative representative value ~ 0.8 ton of CO_2 / ton of cement for simple estimates.

Table -2: Practical Mix Design Example (for M40 grade)

Material	Quantity (kg/m ³)
OPC (53 grade)	325
CBA	125
Alccofine 1203	40
Graphene Oxide	0.15
Fine Aggregate	650
Coarse Aggregate	1200
Superplasticizer	4.5
Water	195

7. OBSERVATIONS

The findings of this study indicate that cement production remains a major source of carbon emissions, primarily due to the energy-intensive nature of clinker manufacturing. The use of alternative materials such as coal bottom ash and Alccofine can significantly reduce emissions by decreasing the clinker content in concrete.

Lifecycle assessment reveals that emissions are not limited to the production stage but are distributed across various stages of the construction process, including transportation and on-site activities. This highlights the importance of adopting a holistic approach to decarbonization that considers the entire lifecycle of construction materials.

The study also identifies the role of digital technologies, such as Building Information Modeling (BIM) and lifecycle assessment tools, in optimizing material usage and improving decision-making. These technologies enable better visualization, analysis, and management of construction processes, leading to improved efficiency and reduced emissions.

8. RECOMMENDATIONS

The study recommends adopting an integrated approach to decarbonization that combines material innovation, efficient design, and sustainable construction practices. The use of supplementary cementitious materials should be encouraged to reduce clinker content and associated emissions.

Design optimization should focus on minimizing material usage and improving structural efficiency, while construction practices should emphasize waste reduction and energy efficiency. The adoption of lifecycle assessment tools and environmental product declarations can support informed decision-making and improve transparency.

Policy interventions are essential to promote the use of low-carbon materials and technologies. These include the introduction of carbon regulations, incentives for sustainable construction, and the development of standardized guidelines for lifecycle assessment.

9. RESULTS AND INFERENCE

The analysis indicates that the adoption of alternative materials and sustainable construction practices can lead to significant reductions in carbon emissions. The use of SCMs and optimized mix designs can reduce emissions by up to 30%, while improvements in supply chain efficiency and construction practices can further enhance these reductions.

The study also highlights the importance of early-stage decision-making, as the majority of emissions are determined during the design phase. Projects that incorporate sustainability considerations at this stage achieve better environmental performance and long-term benefits.

By using OPC 65 % + Coal Bottom Ash 25 % + Alccofine 8 % + GO 0.03 % (w/b = 0.4). The optimal decarbonized high-performance binder offering: 30 % CO_2 reduction, 20 % higher compressive/flexural strength, Significantly enhanced durability, Stable setting & reduced shrinkage, Good workability with PCE superplasticizer.

REFERENCES

- [1] Josefine A. Olsson, Sabbie A. Miller, Joshua D. Kneifel, "A review of current practice for life cycle assessment of cement and concrete," researchgate, July 2024, DOI:10.1016/j.resconrec.2024.107619
- [2] Avuthu Narender Reddy, Meena Thiruvadi, "A COMPREHENSIVE OVERVIEW ON PERFORMANCE OF ALCCOFINE CONCRETE," researchgate, May 2017
- [3] Arunchaitanya Sambangi, Nagarjuna Kundeti, Sai Charan S, Reshma Srimani S, Abhilash Nadukuditi, "Effect of fly ash and alccofine as cementitious materials on M40 grade concrete," researchgate, March 2023, DOI:10.1016/j.matpr.2023.03.192
- [4] Mohit Choudhary, Susheel Kumar, "Effect of addition of Alccofine on Coal Bottom Ash Concrete Properties," researchgate, Nov 2023, DOI:10.55524/ijircst.2023.11.4.10
- [5] Danyang Cheng, David M. Reiner, Fan Yang, Can Cui, Jing Meng, Yuli Shan, Yunhui Liu, Shu Tao & Dabo Guan, "Projecting future carbon emissions from cement production in developing countries," researchgate, Dec 2023, DOI:10.1038/s41467-023-43660-x
- [6] M.J. Mohammad Nasir, P. Ravi Prakash, Mayank Suman, "An automated BIM-GRIHA15-LCA framework for building sustainability assessment," sciencedirect, May 2025, doi.org/10.1016/j.job.2025.111908