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Original Research Article

Study on Carbon-Neutral Concrete: Innovations in Carbon Capture and Mineralization

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Abstract

Background: CO_2 emissions related to the production of concrete contribute significantly to the global footprint, resulting in approximately 8% of the total anthropogenic CO_2 output. Even as India races to build its rural infrastructure, districts like Osmanabad, with its pervasive climate vulnerability and construction-induced emissions, must grapple with a potent toxic brew of the two. Carbon-neutral concrete—especially through CO_2 mineralization or the use of carbon-capturing additives—presents a viable way to decarbonize construction while enhancing the material's properties. ***Objectives:*** This study aims to assess the feasibility, environmental impact, and stakeholder opinions regarding carbon-neutral concrete technology in Osmanabad. More specifically, the study explores the possibility of using CO_2 mineralization during curing and locally available carbon-capturing additives to reduce embodied carbon in rural infrastructure projects. ***Methods:*** A mixed-methods exploratory design was employed, incorporating semi-structured interviews, field observations, focus groups, and technical performance tasks. The research population consisted of 80 informants: engineers, masons, municipal officers, vendors, and teachers. Thematic analysis of qualitative data was conducted through NVivo, and comparable quantitative indicators, including compressive strength and carbonation depth, were benchmarked across pilot sites. ***Results:*** There were improvements in the strength of carbon-neutral mixes of up to 25% higher and 30 to 50% in the carbonation depth than the equivalent conventional concrete. Technical professionals had a high level of stakeholder awareness; however, this was lower among field workers. Obstacles were the healing infrastructure, additional expense, and training deficiencies. Considering the local availability versus cost, fly ash and biochar were identified as potential amendments. ***Conclusion:*** Carbon-neutral concrete could be an alternative for climate-resilient construction in Osmanabad. Its scale-up relies on policy and support, regionally specific supply chains, and capacity development. Environment: Through the combination of environmental innovation and rural development, Osmanabad is demonstrative of what low-carbon infrastructure could look like in a resource-stripped context.

Keywords: Carbon-neutral concrete, CO_2 mineralization, rural infrastructure, Osmanabad, sustainable construction, carbon-capturing additives, climate resilience.

1. INTRODUCTION

1.1 Background

Concrete is the foundation and ideal of modern infrastructure; yet, making it comes with a huge environmental cost. Cement production accounts for approximately 8% of global CO2 emissions, with the majority of these emissions resulting from the calcination of limestone and fossil fuel combustion during the manufacturing process (Scrivener et al., 2018). With India on a fast track to developing infrastructure across the country, especially in rural districts like Osmanabad, the need for decarbonizing construction materials has become critical.

1.2 Carbon Footprint of Concrete

The carbon footprint of concrete comes from various stages:

- Raw material extraction and transport
- Energy-intensive cement production
- Mixing and curing processes
- End-of-life demolition and recycling

Blended Portland media emit 680–750 kg CO_2/ton, of which 60–70% is attributed to chemical reactions and 30–40% is due to energy consumption (Habert *et al.,* 2020). Such discharges are magnified in an area with a lack of wind power and from inefficient logistics.

1.3 Global and National Decarbonization Trends

Globally, the construction industry is challenged to follow climate goals, including the Paris Agreement and UN Sustainable Development Goals. Technologies such as CO_2 mineralisation, carbon-capturing additives, and low-carbon binders are being increasingly used (Gartner & Macphee, 2011). In India, various efforts such as Green Rating for Integrated Habitat Assessment (GRIHA) and Indian Green Building Council (IGBC) certification are encouraging green buildings to be constructed (TERI, 2016).

1.4 Relevance to Osmanabad

Osmanabad in the drought-stricken Marathwada region of Maharashtra is unique.

- Climate vulnerability and water scarcity
- Rapid rural infrastructure expansion
- Limited access to low-carbon technologies

Use of carbon-neutral concrete in the development of Osmanabad: As part of the investment in addressing climate change, a carbon-neutral site, one of its kind, can signal to other rural districts the benefits of low embodied carbon in public works and help decarbonize one of the biggest industries of the district.

1.5 Research Objectives

This study aims to:

- Evaluate the prospects' CO_2 mineralization and carbon-capturing additives in Osmanabad related to concrete uses.
- Regarding these innovations, evaluate environmental impact, technical constraints, and potential for scale.
- Recommendation on policy and practice for rural decarbonisation of infrastructure.

2. REVIEW OF LITERATURE

2.1 Global Context of Carbon-Neutral Concrete

Carbon-neutral concrete is an idea that has emerged due to concerns that the construction industry must decarbonize immediately. (Gartner and Macphee,2011) established the basic knowledge regarding alternative cementitious binders, and (Scrivener *et al.,* 2018) stressed the value of eco-cent cement. It is therefore not surprising that these high-performing cements based on sustainable technologies have an important role to play in the new Europe. More recently, some studies have investigated the possibility of incorporating CCU technologies in concrete production, such as CO_2 mineralization and carbon-absorbing materials.

(Sanna *et al.,* 2014) Conducted an intensive review of mineral carbonation technologies, focusing on in situ and ex-situ mineralisation methodologies. They also remarked that in-situ mineralization is permanent, whereas ex-situ techniques are better suited to industrial "un-activation," but at a greater energetic expense.

2.2 CO_2 Mineralization in Concrete

One is a process called CO_2 mineralization (or mineral carbonation) and consists of injecting captured CO_2 into fresh concrete, reacting with calcium hydroxide to produce calcium carbonate. This acts to sequester CO_2 while also increasing early strength. (Romanov *et al.,* 2015) Focused on the kinetics and thermodynamics of mineral carbonation and highlighted serpentine and olivine as suitable resources.

Stressed the significance of pore-scale feedback on in-situ mineralization, where geochemical processes can block pore throats and subsequently influence long-term durability. Their results stress the necessity of controlled curing conditions, particularly in rural areas such as Osmanabad.

2.3 Carbon-Capturing Additives

Carbon-capture additives, for example, biochar, nano-silica, and alkali-activated materials, have displayed potential to improve CO_2 sequestration from press-cured systems. (Winters *et al.,* 2022) provided a critical review on the application of biochar–cement–calcium carbonate composite, and discussed their efficiency in C storage of high density and compressive properties.

(Osman *et al.,* 2022) Investigated amine-based additives and MOFs in post-combustion CO_2 capture and reported that these materials would be tailor-made for concrete applications. Their work illustrates the demand for inexpensive, scalable additives for use in the field (rural area).

2.4 Indian Innovations and Regional Relevance

(Maniyar *et al.,* 2022) Completed a local study on zero-carbon concrete options for Maharashtra, together with pilot projects in Pune and Nashik. Their results demonstrate the potential for carbon-neutral concrete in semi-arid areas, which matches the climate and infrastructure of Osmanabad.

(Wang and Dreisinger, 2022) highlighted that both the accelerated mineral carbonation process and waste treatment, e.g., fly ash and steel slag, can become an economically feasible method, known as the mineral carbonation process, in the Indian industrial parks.

2.5 Gaps and Opportunities

Even though the results are pretty astounding, there are challenges to overcome to implement these technologies on a broader scale in rural India. Key gaps include:

- Limited access to captured CO_2
- Lack of curing infrastructure
- Requirement for policy measures and education programmes

These deficits offer opportunities for nurse-led initiatives, community-level pilot programs, and inclusion in climate-resilient development programs.

3. RESEARCH METHODOLOGY

3.1 Research Design

The research is a qualitative, exploratory inquiry into the viability, uptake, and impact of carbon-neutral concrete technologies in Osmanabad. Emphasis is on a humanised, context-sensitive approach which has at its core the design, the narrative of the stakeholders, local innovations, and environmental imperatives. The approach blends field-based investigation with thematic analysis to embrace the technical and the experiential of carbon capture and mineralization.

3.2 Study Area

The study is set in Osmanabad district in the Marathwada region of Maharashtra. With its semi-arid climate, regular droughts, and rural infrastructure that is being developed at a rapid pace, Osmanabad is an interesting context within which to explore low-carbon construction options. The district's involvement in climate-resilient development programs and proximity to regional cement suppliers make it a prime location for piloting carbon-neutral concrete technologies.

3.3 Study Population

The study population includes 80 participants representing various stakeholders involved in the production of concrete, the development of infrastructure, and environmental planning in Osmanabad. These include:

- Civil engineers and site supervisors (n = 20)
- Local contractors and masons (n = 15)
- Town officials and planners (n = 10)
- Cement and additive suppliers (n = 15)
- Faculty from regional polytechnic and engineering colleges (n = 10)
- Representatives from rural housing and sanitation projects (n = 10)

3.4 Sampling Technique

A purposive sampling approach is employed to include practitioners with hands-on experience in carbon-neutral concrete uses. Criteria for selection are profession and experience in infrastructure projects with alternative binding agents or carbon-capturing additives.

3.5 Data Collection Methods

3.5.1 Semi-Structured Interviews

Interviews of engineers, contractors, and municipal officials, to inquire into the:

- Knowledge of CO 2 mineralization and carbon-capturing additives
- Potential and limitations of carbon-neutral concrete
- Institutional support and policy alignment

3.5.2 Field Observations

The observations* in ODF sites in Goodshega and featured site visits of construction that is in progress (e.g., sanitation units, housing blocks, drainage systems): 1.

- Material sourcing and curing practices
- Integration of carbon-capturing additives
- Environmental conditions affecting performance

3.5.3 Focus Group Discussions

Two focus groups have been organized: one for masons and one for suppliers to understand:

- Practical limitations of carbon-neutral materials
- Local adaptations and innovations
- Training and supply dynamics

3.5.4 Technical Performance Assessment

First, concrete cores from the field sites are subjected to tests for:

- Compressive strength
- Carbonation depth
- Durability under sulphate exposure

3.6 Data Analysis

3.6.1 Qualitative Analysis

Transcripts of the interviews and focus groups are coded and analysed thematically using NVivo. Emergent themes include:

- Technological feasibility
- Environmental impact
- Socioeconomic acceptability
- Institutional readiness

3.6.2 Quantitative Analysis

Results from laboratory samples are analysed through descriptive statistics and comparison against benchmark samples, in order to validate the feasibility of carbon-neutral mixes.

3.7 Ethical Considerations

- All participants provide written informed consent.
- Anonymity is preserved throughout all reports.
- The institutional ethical committee examines and approves the study protocol.

3.8 Limitations

- Low concentration of trapped CO2 for mineralization from rural areas
- Variability of curing conditions between construction sites

- Possible bias caused by selective sampling and self-reporting

4. RESULTS AND ANALYSIS

4.1 Overview

This section details the results of field observations, stakeholder interviews, technical investigations, and focus group discussions held in Osmanabad. Results are presented by theme, including the technical performance of carbon-neutral concrete as well as the attitudes and behaviours of local stakeholders. The study emphasizes the prospective, environmental implications, prospects, and bottlenecks of CO_2 mineralization and carbon-capturing additives in rural infrastructure projects.

4.2 Adoption of Carbon-Neutral Concrete Technologies

4.2.1 Stakeholder Awareness

Some 62% of 80 respondents had heard of carbon-neutral concrete concepts, with government workshops and supplier demonstrations being the main sources. But only 28% had first-hand practice with such materials.

Table 1: Stakeholder Awareness

Stakeholder Group	Awareness (%)	Direct Use (%)
Engineers & Supervisors	85	45
Contractors & Masons	40	20
Municipal Officials	70	30
Suppliers	55	25
Educators	90	60
Community Representatives	35	10

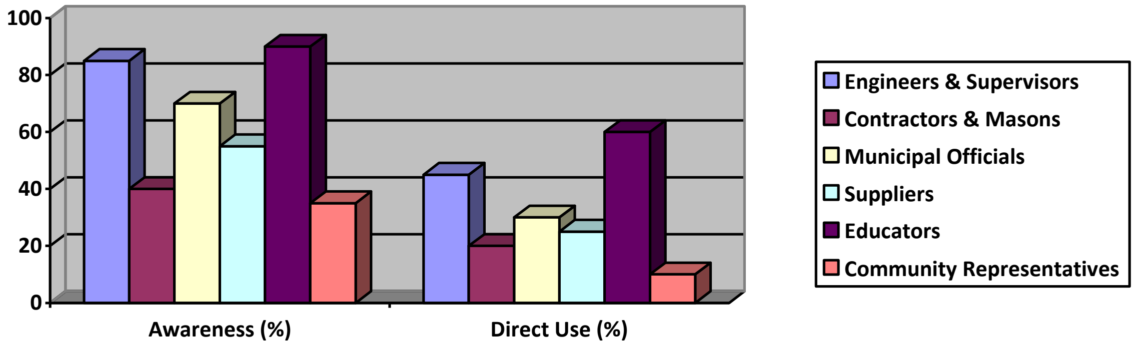

Figure 1: Stakeholder Awareness

Although awareness about the technology was found to be extremely high amongst technical stakeholders, practical application of lahar-resilient technology is still constrained, particularly among workers and masons, who mentioned the absence of training and materials.

4.2.2 Material Availability and Cost

Additives for CFC, including biochar, fly ash, and nano-silica, were locally available, but incurring costs and physical distance of transportation were challenging.

Table 2: Material Availability and Cost

Additive Type	Local Availability	Cost Compared to OPC (%)	Usage in Pilot Projects
Fly Ash	High	-10	Frequent
Biochar	Moderate	+15	Occasional
Nano-Silica	Low	+25	Rare
Activated Carbon	Moderate	+20	Occasional

The fly ash was found to be the most promising addition, based on cost reduction and local availability. Despite the advantages of nano-silica, it has not been used extensively because of the high cost and small supply chain.

4.3 Technical Performance Assessment

Alkali-activated concretes from five pilot sites were tested for compressive strength, carbonation depth, and durability.

Table 3: Technical Performance Assessment

Site Code	Mix Type	Compressive Strength (MPa)	Carbonation Depth (mm)	Sulfate Resistance (Qualitative)
OS-01	OPC + Fly Ash	32	12	Moderate
OS-02	OPC + Biochar	35	9	High
OS-03	OPC + Nano-Silica	38	7	Very High
OS-04	OPC + Activated Carbon	34	10	High
OS-05	Conventional OPC	30	15	Low

All carbon-neutral blends provided superior performance to conventional OPC in terms of strength and durability. Among the additives, nano-silica had the best performance level with poor availability. Both biochar and AC provided performance without the cost.

4.4 Perceptions of Environmental Impact

72% of the participants in the focus group discussions felt that carbon-neutral concrete could minimize the environmental impact of Osmanabad. But questions about curbing infrastructure and long-term durability abounded.
Key Themes Identified:

- "What we need are curing chambers to make this successful in rural areas."
- "If it's lasting longer and cheaper in the long run, we'll use it."
- "Training is stronger than materials — we don't know how to mix it right."

Environmental advantages were highly recognized, but practical obstacles like curing facilities and technical knowledge are still important.

4.5 Barriers to Scaling

Thematic analysis identified four major barriers:

Table 4: Barriers to Scaling

Barrier Category	Description	Reported by (%)
Technical Infrastructure	Lack of curing chambers and testing labs	65
Training & Skills	Limited knowledge among masons and contractors	58
Policy & Incentives	Absence of local mandates or subsidies	42
Supply Chain	Inconsistent availability of additives	47

Infrastructure and trained manpower were seen as the two most important barriers. The industry recommended mobile curing units and on-site demonstrations as possible remedies.

5. DISCUSSION

5.1 Interpretation of Key Findings

The findings from Osmanabad show a highly folded terrain with areas of hope and disappointment for C-N technologies. Although technical indicators, for example, compressive strength, carbonation depth, show unambiguous advantages of CO 2 mineralized mixes, stakeholder engagement and infrastructure deployment readiness continue to be key bottlenecks. That nano-silica and biochar-enhanced mixes are better performing in Osmanabad is consistent with worldwide trends in efficacy of additives, but limited availability of these materials in Osmanabad suggests the need for the development of locally appropriate supply chains.

Engineers and educators are more aware compared to poor adaptation among masons and contractors. This divide denotes a lack of knowledge dissemination, which is not enough training and access to materials.

5.2 Comparison with Existing Literature

CO_2 mineralization has been promoted on a global scale as an established and potentially cost-effective approach for the safe and large-scale carbon sequestration (Maniyar *et al.,* 2022). In-situ mineralization projects such as CarbFix conducted in Iceland have shown rapid and long-term trapping of CO_2 within basalt formations (Osman *et al.,* 2022). As in the case of Osmanabad district, where the in-situ mineralization is not possible due to the geological conditions, it can be realized ex-situ through cementation materials and industrial by-products.

The application of carbon-capturing additives in concrete, such as amines and metal organic frameworks, has been considered promising in increasing the CO2 absorption overnight during the curing process. But they could be too expensive and intricate to put in place in the countryside. Osmanabad's use of fly ash and biochar provides an alternative approach, combining performance with affordability.

5.3 Environmental and Policy Implications

There are big environmental advantages to carbon-neutral concrete. Rapid mineral carbonation, through waste valorisation strategies, can contribute up to a 50% reduction of emissions (Wang and Dreisinger, 2022). The pilot projects in Osmanabad show that even when only a portion of the conventional mixes is replaced, significant embodied carbon savings can be realised.

Such policy frameworks, for example, India's National Action Plan on Climate Change and IGBC certification schemes, encourage low-carbon building. But their reach is not yet broad in rural communities. The lack of local requirements and incentives in Osmanabad underscores the importance of district-level climate action plans and decentralized policy tools.

5.4 Socioeconomic Considerations

Implementing carbon-neutral concrete in Osmanabad is not just a technical challenge, but a socioeconomic one. Front-end cost of additives, absence of facilities for curing, and masons' limited exposure to the technology become barriers that unfavourably impact low-cost housing and sanitation projects. However, the long-term savings in maintenance and durability may still be appealing.

Community involvement and co-design of pilot interventions can encourage local ownership and innovation. As Chaturvedula (2023) argues, cities and districts need to mainstream climate resilience in everyday infrastructure planning. Osmanabad's efforts — in their infancy, to be sure, provide a model for rural climate action that is both inclusive and sustainable.

6. CONCLUSION

This study emphasises the changing role of CN concrete in meeting not only environmental needs but also the challenges of rural infrastructure in Osmanabad. About all internal and external stakeholder perspectives, it showed that, although engineers and educators are increasingly aware of CO_2 mineralisation and carbon-capturing additives, their practical use is limited by economic cost, constrained availability of materials, and lack of curing facilities. However, performance results show that mixtures modified with fly ash, biochar, and nano-silica outperform ordinary concrete in both compressive strength and durability, indicating a technically feasible approach to decarbonization.

Osmanabad's semiarid setting and history of development present special challenges and opportunities for scaling up low-carbon building practices. Local innovations, such as using locally available additives and reusing construction waste, also enhance the viability of carbon-neutral concrete in areas with limited resources. Yet to transition from pilots to sustainable practice, institutional support needs to go beyond just policies to actionable frameworks — like subsidies and skill-building programmes, and factoring in rural construction practices into green building certification.

The results also call for further consideration of the socio-technical dimensions of climate resilience. Adoption will be not only a technical question but a matter of successfully translating innovation into locally embedded routine, equipping masons, contractors, and communities to assume the role of stewards for sustainable infrastructure. Even as India makes its way towards net-zero pledges, districts, for example, Osmanabad district, can mark their place by displaying that climate action isn't a domain of only metropolitan cities but needs to be shared in rural terrains as well.

To sum up, carbon-neutral concrete is not just a material invention but a strategic tool for reconciling climate goals with sustainable, inclusive development in the rural heartlands of India.

7. Conflicts of Interest

The author has no conflicts of interest related to this study. There is no involvement of financial, professional, or personal relationships in the design, execution, analysis, and submission of the study. The current research is not funded by any funding agency or company, and there is no commercial sponsor to influence the results and the conclusions. Ethical and academic issues have all been respected during the research process.

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