Decarbonizing India's Building Construction through Cement Demand Optimization: Technology and Policy Roadmap

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ABSTRACT

India targets economic, infrastructural, and energy growth to meet the demands of its urban population, growing at the rate of 31.14%. The Indian construction market has anticipated adding 24.8 billion sq. m to its residential and 1.6 billion sq. m to its commercial building stock by 2027. The local construction market predominantly relies on cement as the most commonly used construction material. The Indian cement industry is the second-largest producer of cement, after China with 75% of the total production being used by the building sector. The production of cement is emission intensive in nature and despite the noteworthy progress in enhancing energy efficiency of its production the GHG emissions are still significantly high and increasing. Therefore, there is an urgent need to explore other methods beyond energy efficiency to limit cement related emissions. This paper estimates the demand for the new building stock in India and the associated demand for cement by 2047. It explores the potential of various alternate low carbon cement materials, and demand optimization techniques to reduce cement consumption for meeting future building construction demand in India. It evaluates existing policies to assess their intent to support building decarbonization. The analyses show that existing low carbon strategies would reduce the embodied carbon but are not sufficient enough to fully decarbonize the future building stock. It provides recommendations to accelerate deployment of market ready low carbon solutions and encourage for innovation and research on carbon neutral materials to achieve building construction decarbonization.

Keywords
Embodied emissions, Building constructions, Cement, Design Optimization, Decarbonization strategies, Alternate cement

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1. BACKGROUND

India's CO_2 emissions are of global concern due to the large-scale infrastructural development and subsequent rise in energy demand. As per the 2018 data compiled by the International Energy Agency, India produced about 2.65 billion metric tons of CO_2 (IEA 2020), making it the third-largest emitter of greenhouse gases globally (Timperley 2019). Construction and buildings contribute to nearly 20% of India's emissions each year (Friedrich, Ge and Pickens 2020). The situation will only get grimmer as its rate of urbanization is expected to grow to 50.3% by 2050 from 32.7% in 2015 (de la Rue du Can, et al. 2019). While most developed economies have already built a significant chunk of their infrastructure, India's infrastructure is yet to match its demand. It is forecasted to see massive growth in the future. Moreover, due to developmental schemes like the Smart City Mission, Pradhan Mantri Awas Yojna, and the National Infrastructural Plan, the demand for building construction activities will spur shortly. India's ongoing focus is on creating energy-efficient buildings in the coming decade. However, since quite a few countries around the globe are on the pathway to net-zero carbon buildings, India will soon have to follow and devise a strategy of its own.

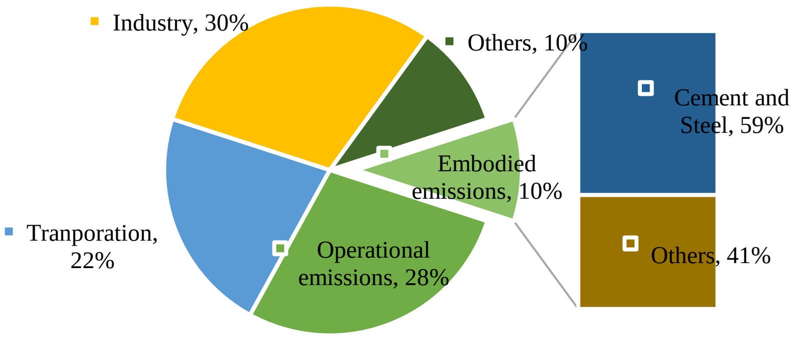

Figure 1: Sector-wise contribution in the global GHG emissions. *Source*: (UNEP 2020)

The embodied carbon emitted during building construction has a significant share in the global emissions index. As shown in Figure 1, embodied emissions primarily due to building materials amount to 10% of the annual global GHG, whereas building operational emissions occupy 28% area under the chart (Architecture 2030 2020). Cement and steel are the top contributors to embodied emissions coming from building constructions and account for almost 60% of the total embodied emissions globally, thereby making it critical to explore green alternatives that can help decarbonize our buildings. The residential, commercial and industrial building segment alone consumes around 75% of the total cement produced in the country. This paper focuses on identifying low-carbon alternatives to replace the existing cement from construction, thereby making it greener and more sustainable. The results presented in this paper will help India achieve its Intended Nationally Determined Contributions (INDCs) pledged during the Paris Agreement - reduce the emissions intensity of its gross domestic product (GDP) by 33 to 35 percent by 2030 when compared to the 2005 levels (BEE, Climate Change 2021).

2. INTRODUCTION

Diminution in sizes and expansion in floor areas represent one of the biggest drivers of construction demand. India's residential building stock is forecasted to grow 3.4x to reach 52.5 billion m^2 by 2047 from 15.47 billion m^2 in 2017, while the commercial building stock is predicted to grow 7.5x to reach 6.8 billion m^2 by 2047 from 0.9 billion m^2 in 2017 (IESS 2047 Niti Aayog 2021). To meet the construction demand, reliability on primary construction materials such as steel, cement, and aluminum will increase drastically. The paper will discuss the embodied emissions due to the consumption of cement in the building sector. In India, cement has an emissions intensity of 0.672 tCO_2/ton, which is marginally below the world average and far less when compared to USA (0.781) and UK (0.739) (GCCA 2018). Though Indian cement industry is highly energy efficient but still the GHG emissions are significant which makes the construction industry highly unsustainable and environmentally damaging. Through this research, we explore options to ensure that all upcoming structures follow a sustainable trajectory by replacing conventional practices with low carbon options without adversely impacting the structural properties and durability of buildings. This paper will act as a catalyst for the manufacturing industry, construction industry professionals such as architects, contractors, and developers, and policymakers who draft and revise several codes and policies to support decarbonization.

India's ongoing efforts to reduce the construction of inefficient buildings and their subsequent impact on the climate are visible through many codes and policies at the national level. The Government of India prioritized commercial buildings due to the fragmented character of residential buildings. Energy Conservation Building Code (ECBC) was launched in 2007, followed by the launch of Eco-Niwas Samhita in 2018, targeting a reduction in the energy demand and enhanced thermal comfort in buildings. These existing codes focus only on addressing the operational emissions through energy efficiency measures, leaving behind the embodied emissions. In addition, India has also devised multiple green rating systems such as Green Rating for Integrated Habitat Assessment (GRIHA), Indian Green Building Council (IGBC), Leadership in Energy and Environmental Design (LEED) to encourage and promote sustainable design. Based on a study by "Architect 2030", it is estimated that between 2020 and 2050, embodied emissions will account for 50% of the total construction sector emissions (Architecture 2030 2020). This signifies the necessity of considering embodied emissions upfront while strategizing the construction sector's decarbonization. It will require a shift away from conventional building materials and construction methods towards low carbon alternatives.

For this study, our focus will remain on decarbonizing building construction in India through optimizing the demand for conventional cement. Reflecting upon the past trend of cement production, India is the second-largest producer of cement after China and accounts for 7% of the total installed capacity across the globe (Cement Manufacturers Association 2021).

3. METHODOLOGY

As a first step, the national policy landscape of India was analyzed to identify ongoing efforts to support the decarbonization of the new and existing building stock of India. The projected cement consumption in business as usual scenario is estimated based on the projected floor area of commercial and residential buildings by 2047 and cement consumption intensity for a typical commercial and residential building. As a next step, various low carbon alternative strategies (or interventions) have been identified, which have a significant potential to reduce embodied carbon by replacing or reducing the conventional cement. The interventions which are in advanced stages have been analyzed with different market penetration level to understand the emission reduction possible by 2047. It concludes with identifying the steps needed to accelerate the low carbon transition in building construction.

4. NATIONAL POLICY LANDSCAPE

With an average lock-in period of 50 to 60 years, the inefficient building stock of India is increasing. If new buildings do not include sustainable design practices and low carbon material approaches during their initial construction stage, retrofitting them later may not be sustainable or economical. Commercial buildings in India are growing at a rate of 9% per annum (BEE, ECBC Commercial 2021), and this high growth rate has brought energy efficiency to the forefront. The Ministry of Power (MoP), Government of India introduced Energy Conservation Building Codes - Commercial (ECBC-C) in May 2007, which sets minimum standards for commercial buildings having a connected load of 100kW or contact demand of 120 KVA and above (Ministry of Power 2018).

The Bureau of Energy Efficiency in India launched the Residential Energy Conservation Building Code in 2018, named Eco Niwas Samhita (ENS), to enhance thermal performance and reduce energy consumption. ENS also ensures 20% savings in annual electricity bills if the building shows compliance under the parameters set in phase 1 (Ministry of Power 2018). This code is still in its voluntary adoption phase, with effort underway to fast-track its implementation nationwide. India also has a comprehensive National Building Code (NBC) instrumental in providing guidelines to regulate all building construction activities across the country. The NBC has an exclusive section on green/sustainable technology alternatives reflecting the state-of-the-art and contemporary international best practices to promote ecologically appropriate construction in India.

ECBC and ENS are progressive codes designed to push the building sector towards net-zero energy targets of 2050. Most of the recommendations stated under these codes only intend to control the operational emissions of buildings by reducing user energy demand. To follow the net-zero pathway, India cannot look at operational emissions in isolation. The following sections will discuss different technological interventions to limit the embodied emissions from the construction segment.

5. ANALYSIS

5.1. ESTIMATION OF ANTICIPATED CEMENT CONSUMPTION BY THE BUILDING SECTOR BY 2047

As highlighted previously, India's residential building stock is forecasted to grow 3.4x, and commercial building stock to grow 7.5x by 2047 compared to the 2017 data (de la Rue du Can, et al. 2019). 2050 might set an essential benchmark for India under the Paris Agreement as it is planning to pledge becoming net-zero through decarbonization efforts (Jaiswal and Kwatra 2021). Thus, it is of utmost importance to access the market and evaluate how much cement demand is expected to grow to meet the building stock numbers. It is also essential to understand the emissions we target to reduce each decade until we meet our target to become net zero. Table 1 summarizes the decadal projections concerning 2017 if the ongoing practice continues.

Table 1: Calculated embodied GHG emissions from the building sector due to cement consumption for years 2017, 2027, 2030, and 2047

Year	Particulars	Residential	Commercial	Total
2017	Building Stock of India (in billion m2)	15.47	0.90	16.37
	Cement consumption (in million tons)	3,311	161	3,472
	GHG emissions (in $MtCO_2$)	2,225	108	2,333
2027	Building Stock of India (in billion m2)	24.80	1.60	26.40
	Cement consumption (in million tons)	5,307	286	5,594
	GHG emissions (in $MtCO_2$)	3,566	192	3,759
2037	Building Stock of India (in billion m2)	39.27	3.34	42.61
	Cement consumption (in million tons)	8,404	598	9,002
	GHG emissions (in $MtCO_2$)	5,647	402	6,049

2047	Building Stock of India (in billion m2)	52.53	6.80	59.33
	Cement consumption (in million tons)	11,241	1,217	12,459
	GHG emissions (in $MtCO_2$)	7,554	818	8,372

Source 1: (IESS 2047 Niti Aayog 2021); (GCCA 2018); The cement consumption per unit area was extracted based upon expert consultation with contractors and developers. Average cement consumed in residential buildings = 214kg/m2; Average cement consumed in commercial buildings = 179kg/m2; GHG emissions intensity factor= 0.672 tCO2/ton of cement.

The residential sector GHG emissions are expected to become 3.6x to 7,554 $MtCO_2$, and commercial sector emissions will increase by 7.6x to 818 $MtCO_2$ by 2047 and contribute more to warming Earth. The upcoming section will explore different strategies to regulate cement consumption through decarbonization interventions.

5.2. STRATEGIES TO DECARBONIZE CONSTRUCTION SECTOR WITH FOCUS ON EMBODIED EMISSIONS

Embodied emissions associated with building constructions are due to the consumption of building materials and construction & demolition processes. Of all the building materials used, cement is among the most used building material and is responsible for a significant chunk of embodied emissions. There is a need to reduce the consumption or replace it with low carbon alternatives to decrease these emissions. This paper discusses the various supply-side and demand-side interventions through which the emissions related to cement consumption can be addressed, as illustrated in Figure 2.

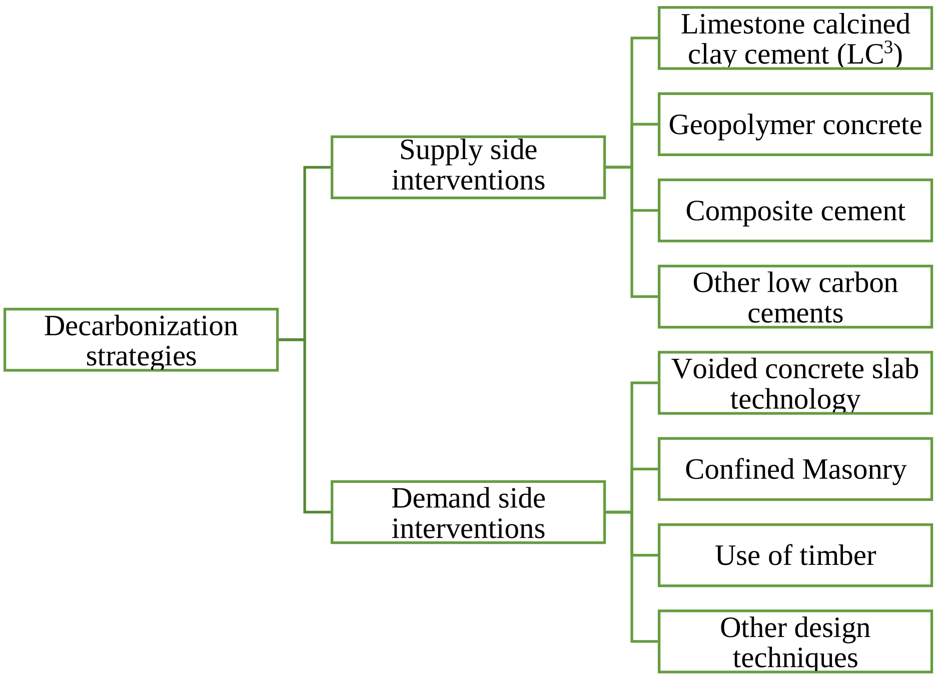

Figure 2: Supply and demand-side interventions for reducing embodied emissions

5.3. ALTERNATE LOW CARBON CEMENT (SUPPLY SIDE INTERVENTIONS)

Cement is produced through a controlled chemical combination of cement, aluminum, silicon, iron, and others, using limestone as the primary raw material and is a very emissions-intensive process. Replacing conventional cement with alternate low carbon cement can reduce the associated embodied emissions. Such cement is discussed in this section.

5.3.1. Limestone Calcined Clay Cement (LC^3).

LC^3 cement is a blend of 50% clinker, 15% low-grade limestone, 30% calcined clay, and 5% gypsum (Scrivener, et al. 2018). Unlike ordinary Portland cement, which contains 90-95% clinker (emissions-intensive element of cement) in the total product mix, LC^3 contains only about 50% of the clinker. Due to this, it has lower emissions intensity as compared to OPC. The raw materials required for its production are readily available in India. Moreover, the production of LC^3 requires low-grade limestone and reduces the requirement for importing high-grade limestone, as used in the case of OPC.

5.3.2. Geopolymer concrete (GC).

Geopolymers are produced by activating pozzolanic materials (rich in silica and alumina) with alkaline solutions like sodium hydroxide, sodium silicate, and others at required temperatures. Industrial waste products like fly ash, ground granulated blast furnace slag (GGBFS), LD slag, silica fumes, red mud, pond ash, and others can be used as a raw material for the production of geopolymer concrete. Of these materials, fly ash and blast furnace slag are readily available in India at various locations. GC is a clinker-less cement, and hence it has the highest CO_2 reduction potential w.r.t OPC. A typical composition of geopolymer concrete produced using fly ash comprises 35% coarse aggregate, 35% fine aggregate, 20% fly ash, 8% activators, and 2% water. (Tempest, et al. 2015)

5.3.3. Composite cement.

The blend of Portland clinker, fly ash, and slag in appropriate proportion produces composite cement (CII 2016). Fly ash and slag are the waste products from the thermal power plants and iron & steel industry. This cement finds its use in various applications like Precast concrete (pipe and block), Building construction, and civil engineering works, dams and retaining walls, etc. As per IS 16415:2015 (Bureau of Indian Standards 2019), the permitted material proportion for composite cement is given in Table 2

Table 2: Composition of composite cement

Material	Proportion (percentage by weight)
Portland Clinker	35-65
Fly ash	15-35
Granulated Slag	20-50

5.3.4. Comparison of various low carbon cement.

Various low carbon cement has been compared based on different parameters in Table 3. It highlights the status of development of each alternative cement in terms of availability of standards, pilot demonstrations, availability of raw materials in the country.

Table 3: Parametric comparison of low carbon alternatives

Alternative cement options	Raw Material availability in India	Status of BIS Standard	Pilot Project Status	Challenges to implementation in India
LC^3	Yes; Reserves in 2015:	Draft standard developed	Country: India; Year: 2014, 2018; Application: Residential and	1. Establish the feasibility of transporting Clay to cement plants

	Calcined Clay – 2,941 million tons Limestone - 16,336 million tons (IBM 2017)	and submitted to BIS	office building (EPFL 2021)	2. Instill confidence among consumers on the benefits and applicability of LC^3
Geopolymer Concrete (fly ash/GGBFS)	Yes; Fly ash production in 2020 - 226.13 million tons (CEA 2020) GGBFS production in 2018 – 27 million tons (NITI Aayog 2018)	In Progress: Standard (IS 17452: 2020) available only for un-reinforced pre-cast application like paver blocks, etc. It is not recommended for structural elements yet. (BIS 2020)	Country: Australia; Year: 2014; Category: Office building (Geoploymer institute 2013) Country: India; Year: 2017; Application: NTPC Road, Pothole Repair in Roads in Chennai, Sewage treatment plant (NTPC 2017)	1. Lack of consistency in constituent ingredients of fly ash (silicon and aluminum content) and the fineness of fly ash and GGBFS 2. Lack of skilled labor to handle highly alkaline activator solutions and also to prepare mixtures with precise accuracy
Composite Cement	Yes; Same as above	Available; IS 16415: 2015	Already being used for commercial applications	1. Availability of both fly ash and GGBFS at one location 2. Requirement of separate silos for fly ash, GGBFS, and clinker

From Table 3, it can be inferred that composite cement is produced in India. Still, to increase its utilization, there is a need to develop business models for increased deployment of composite cement in the upcoming constructions. For LC^3, successful pilot demonstrations had been conducted to prove its applicability, and the process of standard development for its commercial utilization is in the later stages. Similarly, for geopolymer concrete, various successful pilot projects in India and around the globe were conducted. The Bureau of Indian Standards (BIS) has initiated the process for its standard development for structural applications. Moreover, the raw materials required for producing the discussed low-carbon alternate materials would be readily available in India in the near future. The studies suggest the demand for coal for electricity generation would peak around 2028 under a high renewable energy scenario (Spencer, et al. 2019). The privatization of coal mines by the Indian government (in 2020) ensures ramp-up in the production of coal and hence the fly ash production. Coal India Limited (accounting 82% of India's coal production) targets to produce one billion tons of coal by 2024 (PIB 2019) (currently producing 604 million tons).

5.3.5. Other low carbon cement.

Apart from the alternatives mentioned above, few more options are being explored across the globe. Table 4 lists these materials and the status of the development happening on these materials.

Table 4: Other low carbon alternative and their development status

Alternate material	Development status
Belite-rich Portland cement	Intensive research is going on in China to develop this cement for its mass scale applications for replacing Portland cement. (Tongbo and Yuliang 2016)
Belite -Ye'elimite-Ferrite (BYF) cement/ Calcium sulfoaluminate (CSA)	This cement is still in the R&D phase, and the work is being carried by three European cement companies: Heidelberg, LafargeHolcim, and Vicat. (Gartner and Sui 2017)
Carbonated calcium silicate cement (CCSC)	CCSC is being developed by a US-based company named Solidia Technologies, Inc. They have received a patent, and this product is in the advanced stages of development. They have partnered with LafargeHolcim in the US to commercialize their creation in 2019. (LafargeHolcim 2019)
Magnesium Oxide-based cement derived from magnesium silicates (MOMS)	This cement was developed by a company named "Novacem," based in the UK in 2008. This cement is still in the research phase. (The American Ceramic Society 2011)

5.3.6. The emissions reduction potential of alternative low carbon cement.

Figure 3 depicts the CO_2 emission reduction potential of various alternatives and compares their performance to traditional OPC. The percentage reduction in GHG emissions has been extracted based on different case studies presented in the analysis section above. Higher the reduction potential, more sustainable and greener the material, means priority must be laid on that material.

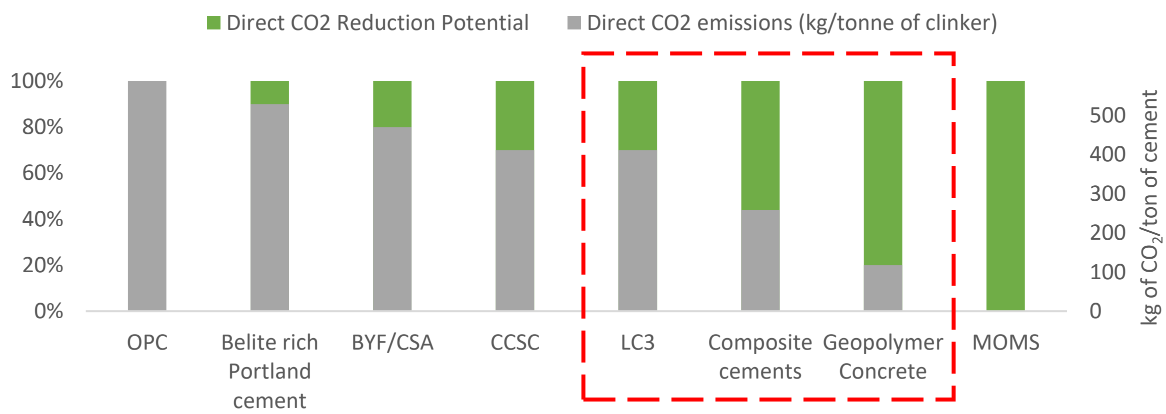

Figure 3: Emissions reduction potential of various low carbon alternative w.r.t OPC. *Sources*: *(Scrivener, et al. 2018), (Hassan, Arif and Shariq 2019), (CII 2016), (Naqi and Jang 2019), (Sahu and Meyer 2020) , (The American Ceramic Society 2011)*

From Figure 3, it can be observed that the CO_2 reduction potential of various low carbon alternate materials ranges from 10% to more than 100% compared to OPC. Among these materials, **LC^3, composite cement, and geopolymer concrete** (as highlighted in the figure above) are viable alternatives with a reduction potential of **30%, 56%, and 80%** respectively, compared to OPC. Credit also goes to the easy availability of raw material in India, which can help in accelerating the supply and demand in the market at a much faster pace.

5.4. DESIGN OPTIMIZATION TECHNIQUES (DEMAND SIDE INTERVENTIONS)

The amount of cement/concrete used during the construction of a building is mainly dependent on the design of a building. Reducing the utilization of building materials would directly impact the embodied emissions from the building construction activities. A few of the most prominent strategies are discussed in this section.

5.4.1. Voided concrete slab technology/bubble deck technology.

In a building, a slab accounts for most of the weight of a building. This weight puts strain on the slab and exerts a burden on the foundation and framework of buildings. One way to reduce the concrete consumption in the slab is by creating engineered voids in the slab. These voids are filled with spherical or oval or hollow cubical structures made of recycled plastics and are placed so that they do not impact the strength of the design. Since beams and columns are the load-bearing components of the building, these voided structures are generally placed away from them. The benefits of this technology include the reduced weight of the building due to lighter slabs and hence thinner columns & beams and more lightweight foundations; longer span length, reduced material consumption, etc.

5.4.2. Confined Masonry.

Confined masonry is a construction technique in which masonry walls carry the load of the building. These masonry walls are enclosed by horizontal and vertical Reinforced Concrete (RC) elements like tie beams and tie- columns. The RC features provide confinement and strength to the masonry walls and protect them against seismic loads. In this technique, the load is carried by the walls. The RC elements are used to confine the walls. Seller RC elements (compared to RC frame buildings) are required in confined masonry structures, reducing concrete and steel usage in the construction (Borah, Singhal and Kaushik 2019). This technology was used in IIT Gandhinagar for the construction of hostel buildings and faculty and staff houses.

Table 5: Concrete savings in confined masonry technique *(IITGN 2015)*

Building Type	Construction technique	Build-up area (m^2)	Concrete used (m^3)	Percentage savings
Academic buildings	RC frame with Masonry infill	45,200	39,000	_
6 Hostels (Ground+3)	Confined Masonry	35,943	13,049	41.8%
30 Faculty and staff houses (Ground+2)	Confined Masonry	49,270	15,266	34.8%

From Table 5, it can be observed that in the case of confined masonry, less amount of concrete is utilized (0.30 m^3/ unit area for faculty and staff housing; 0.36 m^3/unit area for hostels), whereas, in the academic building, 0.86 m^3/unit area of concrete was used. Since this technology seems promising for residential buildings, which means it can be used in low-cost housing projects under PMAY.

5.4.3. Use of Timber.

In the earlier times, the wood used to be the dominant building construction material in India. With the widespread use of concrete and steel, the use of timber in construction has decreased significantly. But with the development of cross-laminated timber in Europe in the early 1990s, the use of wood in the multi-story building has started picking up. The use of wood in the construction sector will help to reduce the usage of concrete by a significant amount. To enhance timber used in construction, India needs to implement sustainable forest management practices and learn from international best practices on timber harvesting and forest management from countries like Canada, Australia, etc. There are few examples from around the globe, shown in Table 6, where different timber products were used to reduce the consumption of concrete.

Table 6: Examples of buildings constructed using timber products

Building	Description	Concrete avoided (m^3)
Forte, Melbourne, Australia; 2012	10-story apartment building	1,000
Library at the Dock, Melbourne; 2014	3-story Library	574
T3, Minneapolis, U. S; 2016	7-story office	3,600
Treet Apartment, Norway; 2015	14- story apartment block	935
Brock Commons, Vancouver, Canada	18-story student residence	2,650

Source: (Beyond Zero Emissions 2017)

The amount of concrete saved would vary from project to project. It is evident from Table 6 that timber can be used to reduce the consumption of cement in commercial and residential building constructions.

5.4.4. Reduction potential and status of optimization techniques.

Table 7 shows the concrete reduction potential of various demand optimization techniques and their adoption status worldwide.

Table 7: Demand reduction potential and adoption status of optimization techniques

Technology	Concrete reduction potential (%)	Current status
Voided concrete slab	25-30% (CobiaxUSA 2019)	• Used worldwide across various geographies in the US, Europe, etc. • In India, adoption is shallow due to limited awareness and confidence among designers and developers
Confined masonry	38% (IITGN 2015)	• This technique is already in practice in many countries like Italy, Mexico, Chile, Peru, Iran, China, and others • Only a few pilots are done in India
Use of timber	39% (Teh, et al. 2017).	• Timber is increasingly used in various nations across the US and Australia. • Currently, India is meeting its timber requirements mostly from imports. With the lifting of a ban on the use of timber for structural applications by the Union Environment Ministry on July 01, 2020 (earlier imposed in 1993) (CPWD 2020)., it is envisaged that domestic timber production will scale up.

5.4.5. Other innovative technologies.

Design for deconstruction and *3-D printing* are some of the other design optimization techniques explored around the globe. Design for Deconstruction (DfD) is a technique in which buildings are constructed to be disassembled and reused for some other purposes and in new constructions. On the other hand, 3-D printing is a technique in which computer-controlled sequential layering is done to create three-dimensional structures. With the use of this technique, structures can be made in a faster and efficient manner. Also, very minimal material is wasted during the construction as compared to conventional methods.

6. DISCUSSION

Due to cement consumption, India's GHG emissions in 2017 were close to 2,225 $MtCO_2$ from the residential sector and 108 $MtCO_2$ from the commercial sector, reaching a soaring high number of 2,333 $MtCO_2$ (as depicted in Table 8). The decadal surge in GHG emissions under BAU scenario and with the adoption of low carbon interventions has been estimated based upon the additional residential and commercial floor area that India will add by 2027, 2037, and 2047.

Table 8: Potential reduction in GHG emissions by the adoption of supply-side and demand-side interventions by 2027, 2037, and 2047 under different scenarios

Particulars	Supply-side interventions (Alternate materials)			Demand-side interventions (Design optimization techniques)		
	LC^3	GC	Composite cement	Voided concrete slab	Confined masonry	Use of timber
GHG reduction potential	30%	80%	56%	28%	38%	39%
GHG Emissions in 2017	2,333	2,333	2,333	2,333	2,333	2,333
BAU scenario: GHG emissions by 2027	3,759	3,759	3,759	3,759	3,759	3,759
GHG emission by 2027 - 25% replacement	3,477	3,007	3,233	3,496	3,402	3,392
GHG emission by 2027 - 50% replacement	3,195	2,255	2,706	3,233	3,045	3,026
GHG emission by 2027 - 75% replacement	2,913	1,504	2,180	2,970	2,688	2,659
GHG emission by 2027 - 100% replacement	2,631	752	1,654	2,706	2,331	2,293
BAU scenario: GHG emissions by 2037	6,049	6,049	6,049	6,049	6,049	6,049
GHG emission by 2037 - 25% replacement	5,595	4,839	5,202	5,626	5,474	5,459
GHG emission by 2037 - 50% replacement	5,142	3,629	4,355	5,202	4,900	4,870
GHG emission by 2037 - 75% replacement	4,688	2,420	3,508	4,779	4,325	4,280
GHG emission by 2037 - 100% replacement	4,234	1,210	2,662	4,355	3,750	3,690
BAU scenario: GHG emissions by 2047	8,372	8,372	8,372	8,372	8,372	8,372
GHG emission by 2047 - 25% replacement	7,744	6,698	7,200	7,786	7,577	7,556

GHG emission by 2047 - 50% replacement	7,116	5,023	6,028	7,200	6,781	6,740
GHG emission by 2047 - 75% replacement	6,488	3,349	4,856	6,614	5,986	5,923
GHG emission by 2047 - 100% replacement	5,861	1,674	3,684	6,028	5,191	5,107

Note: GHG emissions in $MtCO_2$

A step-wise strategy must be adopted to slowly increase the penetration rate in the local market to facilitate the market transition from traditional to more sustainable and greener construction practices. For this research, penetration levels have been estimated at 25%, 50%, 75%, and 100% for each supply-side and demand-side intervention presented above. Understanding each material's individual GHG reduction potential will unlock opportunities.

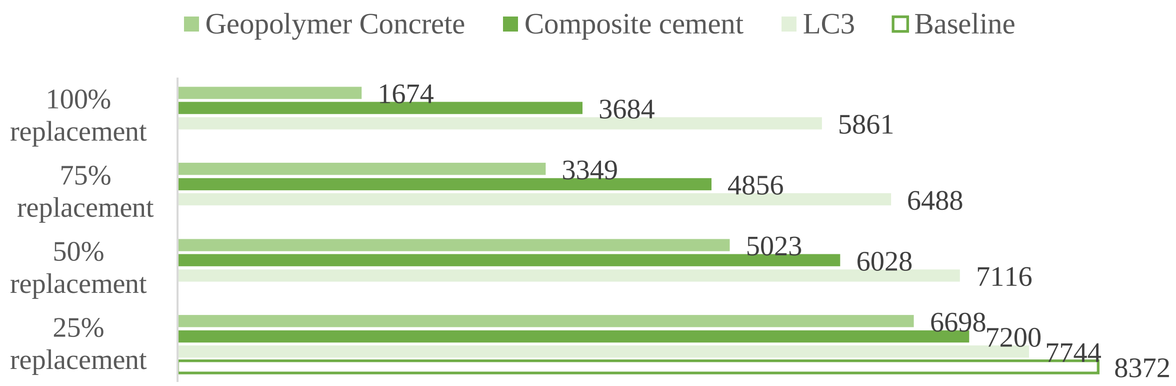

Figure 4: Reduction in GHG emissions in $MtCO_2$/ton of cement by 2047- Supply-side interventions

Figure 4 depicts that, of the discussed supply-side interventions, GC would significantly reduce the embodied emissions from the construction sector due to significant reduction in the consumption of conventional cement. It is evident that 100% replacement of OPC with GC is going to bring down the emissions to 1,674 $MtCO_2$, however it is now enough to meet zero emission target by encompassing for the projected 8,372 $MtCO_2$.

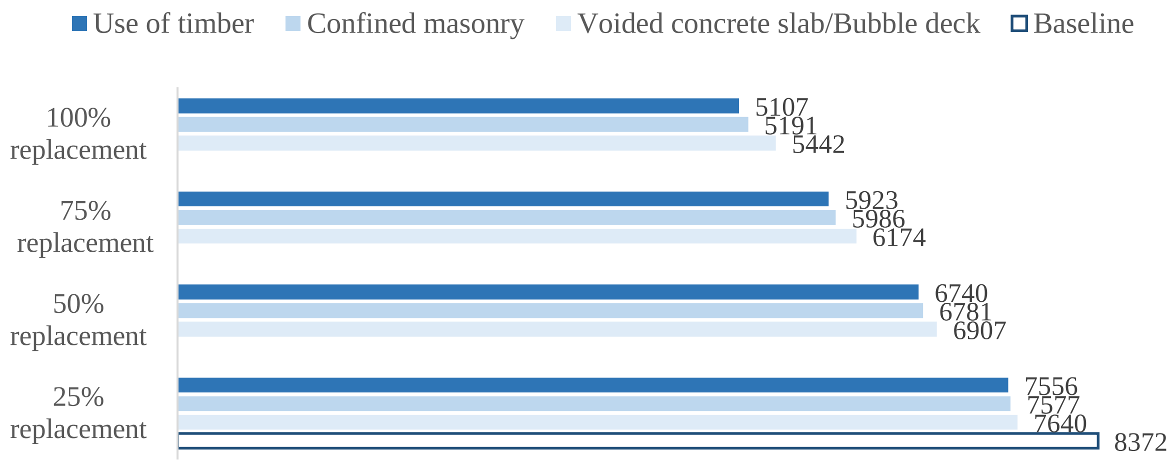

Figure 5: Reduction in GHG emissions in $MtCO_2$/ton of cement by 2047- Demand-side interventions

From the demand side interventions presented in Figure 5, it can be observed that using timber for the construction of buildings would have a more significant impact in reducing the embodied GHG emissions from the building construction. Timber's reduction potential is followed by confined masonry and voided slab systems. Interestingly, for India to expedite its journey towards net-zero, a combination of the presented supply-side and demand-side interventions can be promising. However, further technology innovation is necessary to encompass a significant chunk of GHG emissions for India by 2050, which cannot be addressed through a market transformation based only on the presented six strategies. As mentioned previously, some less explored options in India, such as zero carbon cements, design for deconstruction, 3-D printing and others, should be prioritized and converted into viable commercial models quickly. A combined effect of multiple solutions is the only way to achieve net-zero emissions under India's cement-related construction industry.

7. CONCLUSION

The building construction sector in India will witness a considerable surge in the upcoming decades, which implies an increase in embodied emissions from the building constructions. Hence, there is a strong need to establish a balance between growth and maintaining environmental sustainability through accelerated adoption of discussed demand and supply-side mitigation strategies. There is a need to carry out a feasibility analysis for each of the interventions in the Indian context. Some of the suggested policy interventions, market mechanisms, and awareness creation strategies are presented below.

8.1 Policy Interventions

Informed policymaking can deliver substantial benefits to the construction industry at the forefront of adoption, particularly technology innovation and finance. The policy support is critically needed in the following areas-

- Expediting the development of BIS standard for LC^3, Geopolymer Concrete and others through partnership of manufacturers, research institutions, and academia.
- Enabling policies for mandatory government procurement in buildings and infrastructure development projects.
- Establishing linkages with Energy Conservation Building Code (ECBC) and Eco Niwas Samhita (ENS) facilitates low carbon alternatives in commercial and residential buildings, respectively.
- Enabling policies that encourages innovation, research and development of carbon neutral materials. Financial support through mechanisms like Green Climate Fund and Technology Innovation Grant will support research in this area.

8.2 Market Mechanism

While it is essential to innovate and find low-carbon solutions to help decarbonize the building sector, it is also equally important to stimulate the market. We must create a favorable investment landscape for cement manufacturers to determine a smooth transition. Some of the market mechanisms for the promotion of LC^3, Geopolymer concrete, and other green options are listed below:

- Inclusion of the proposed low carbon cement in the National Building Code of India

- Eco-Labelling / Green Certificates for low carbon cement to help users identify green alternatives quickly and make an informed choice
- Promotion through existing Green Building Rating Systems of India such GRIHA, IGBC, and LEED
- From India's trajectory to low carbon in the field of buildings and transport, there is evidence that financial incentives in the form of tax rebates and lowered interest rates are well in place. Thus, exploring fiscal measures/incentives to boost demand and fastrack manufacturing transformation is necessary.

8.3 Raising Awareness

When proposing new materials and technologies, it is essential to raise awareness amongst the user industry for faster and deeper penetration. Nonetheless, the industry must also prioritize training and capacity-building activities for its supporting staff. The following measures can be undertaken to conduct nationwide awareness campaigns on low carbon alternatives:

- Building partnerships with industry bodies like the Indian Institute of Architects (IIA), Construction Federation of India (CFI), Builders Association of India (BAI), Real estate developers association, and others.
- Awareness programs in different regions for architects, developers, contractors, state housing boards, CPWD, PWD, and other construction agencies.
- Developing case studies on the pilot projects implemented so far, including cost-benefit analysis for dissemination.

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