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Optimizing Cement Efficiency and Cost-Effectiveness: Engineering Solutions Towards Sustainability

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Abstract

Cement production is an energy-intensive process that contributes significantly to global CO_2 emissions. To address these challenges, there should be improvements in cement quality, demand reduction, and the adoption of sustainable production practices. Considering global variations in raw materials and manufacturing methods, extensive research is required to adjust its chemical and physical properties in order to reduce CO_2 emissions.

Cement strength, typically measured by compressive strength, is influenced by factors like fineness and raw material quality. While traditionally assessed by specific surface area, modern LASER diffraction technology allows precise measurement of particle size distribution (PSD). This study demonstrates that engineering PSD alone can enhance cement's strength and durability. By engineering PSD, we can increase cement efficiency, achieving desired strength while reducing overall cement usage. The research exhibits that a 25% improvement in cement efficiency can lead to a 15% reduction in CO_2 emissions. These results underline the potential of PSD optimization for achieving significant environmental benefits without compromising construction standards. PSD optimization emerges as a viable strategy to reduce the carbon footprint of the cement industry.

This study thus helps to achieve the objectives of the Paris Agreement of NET zero carbon emissions by maintaining the technical and functional integrity of construction materials.

Keywords: Carbon Footprint, Climate Change, Efficiency, NET Zero, Paris Agreement, Particle Size Distribution (PSD)

A. Introduction

The Paris Agreement sets ambitious targets for India, aiming for a 45% reduction in GDP emissions intensity by 2030 and achieving net-zero emissions by 2070. The construction sector, responsible for 17% of India's greenhouse gas emissions, plays a key role in this challenge, with the cement industry being one of the largest contributors. To meet these targets, it is essential for cement companies to adopt decarbonization strategies, including enhancing energy efficiency, utilizing alternative fuels like biomass, and reducing clinker content through additives such as fly ash and slag. Achieving net-zero emissions will also necessitate the widespread implementation of advanced technologies like carbon capture, utilization, and storage (CCUS). These efforts are critical to aligning with the goals of the Paris Agreement and advancing sustainable construction practices in India.

Cement is one of the construction materials contributing significantly to the carbon footprint. India ranks second in cement production after China with an annual production of 380MT, which is 8% of total global cement production. The amount of CO_2 released during cement production is affected by various factors at various stages such as mining activities for raw material extraction, transportation during production and post-production, and fossil fuel combustion in kilns. CO_2 emissions can be broadly classified into two categories: combustion & transportation (40% of total emissions) and calcination (60% of total emissions).

The cement industry's CO_2 emissions demand urgent decarbonization, which can be achieved through technological strategies or material substitution.

Studies by Cormos (2022) [4] and Pisciotta et al. (2023) [16] explored CO_2 capture technologies such as post-combustion and oxy-combustion methods, emphasizing energy penalties, CO_2 capture rates, and overall feasibility. These studies also highlighted key aspects, including the IPCC's 1.5°C goal and the costs of carbon capture and storage (CCS).

Neeraja et al. (2023) [13] demonstrated that replacing 10-30% of cement with industrial waste, such as fly ash and slag, can reduce environmental impact while maintaining concrete durability. Similarly, Nehdi et al. (2024) [14] reviewed emerging technologies aimed at achieving carbon neutrality, particularly in response to escalating climate crises. Obrist et al. (2021) [15] projected that specific energy consumption in cement production could decline from 3.0 GJ/tcement in 2015 to 2.3 GJ/t cement by 2050, with CO_2 emission intensity decreasing from 579 kgCO_2/t cement to 466 kgCO_2/t cement during the same period. The projected reductions in CO_2 emissions and energy consumption are attributed to advancements in energy efficiency and a lower clinker content.

The chemical and physical parameters of cement indeed play a crucial role in its carbon footprint. The proportions of limestone, clay, and other raw materials significantly influence cement strength, chemical reactions, and energy demands, thereby impacting the carbon footprint. Physical properties, such as particle size, affect reactivity, hydration, and energy use in production and transport. The fineness of cement influences setting time, strength, and energy consumption during grinding. Optimizing these parameters is essential to minimize the carbon footprint and enhance production efficiency.

All the stages of carbon capture during cement production vary across the globe; however modification of particle size of cement can be standardized across the globally.

To achieve a reduction in carbon emission three parameters need to be studied and dealt with; i) Cement quality, ii) Reducing the cement demand iii) Implementing sustainable production practices. The cement quality is defined by compressive strength, fineness and quality of raw materials. The overall cement demand is bound to increase due an increase in population. This paper describes an approach to meeting cement demand by enhancing efficiency, thereby reducing the carbon footprint. The objective of the study is to reduce carbon footprint through engineering PSD for optimization of cement quantity at the production level.

Methodology of the Work

1. **Production of Stimulated Cement**:
   - Develop a novel stimulated cement formulation using engineered particle size distribution.
   - Implement the innovative "Stimulated Cement" formulation for enhanced performance.
2. **Efficiency of Stimulated Cement**:
   - Evaluate the strength efficiency of the stimulated cement.
   - Assess its environmental efficiency to ensure sustainability.
3. **Optimization of Cement**:
   - Optimize the quantity of materials used in cement production.
   - Achieve cost optimization for economic feasibility.
4. **Materials & Methodology**

Samples and specimens were prepared to check the properties of cement such as flow table value, compressive strength, setting time, heat of hydration, normal consistency value, Particle size (fineness). Concrete specimens were prepared to perform compressive strength and durability tests, such as acid attack and permeability tests. For mortar specimens Standard sand, conforming to IS 650-1991 and ASTM C778 [1], with a specific gravity of 2.46 and negligible chloride content, was used. Fine and coarse aggregates used for concrete samples were of natural origin, with specific gravities of 2.75 and 2.88, and water absorption values of 3.15% and 1.5%. Water, a vital component influencing both fresh and hardened properties of concrete, was utilized in compliance with IS 456-2000 standards, ensuring a pH of ≥ 6 and freedom from impurities. Concrete mixes of grades M25 and M40 were designed following IS 10262-2019 guidelines, and specimens were prepared using both conventional OPC and stimulated cement. Strength tests were conducted at 1, 3, 7, and 28 days to compare conventional and stimulator-enhanced mixes. This study provides detailed data on material properties and mix proportions. The production process for the "Stimulator" is outlined as follows:

a. Production of Stimulator:

The "Stimulator" is produced through the micronization of commercially available OPC, wherein the cement is ground to particle sizes finer than 25 µm. This grinding process is performed using a jet mill. The jet mill, with a diameter of 300 mm, processes input feed material of 200 mesh size while maintaining a gas pressure of 7–8 kg/cm². The principle of micronization in a jet mill involves using a high-speed jet of compressed air, gas, or high-pressure superheated steam to create particle collisions, leading to size reduction. As the jet mill operates without moving parts, it eliminates the risk of contamination from external grinding media.

b. Experimental combinations basic testing on cement & Stimulator.

The particle size distribution (PSD) of cement was measured using laser diffraction technique (ISO 13320, ASTM-E 3340) [2] for particles ranging from 0.1–1000µm, with consistent results obtained after repeated tests. The flow table test, performed as per IS: 5512[8] and ASTM-C 124[3], evaluated mortar workability using a sand-to-cement ratio of 1:2.75, maintaining a flow of 110 ± 5 mm and recording water requirements. Normal consistency and setting times of cement combinations were determined using Vicat's apparatus as per IS:4031 (Parts 4 and 5) [9,10]. Optimal OPC-stimulator combinations were selected based on PSD, water demand, and setting times, with the heat of hydration measured following IS:4031 (Part 9) [11]. The results of above-mentioned tests are presented in Table 8 for OPC and S45. The selection of the optimized Cement mix (S45) was based on a comprehensive experimental program outlined in the earlier publication [6]. This program involved a series of tests on cement and mortar, including flow table test, needle penetration test (NC value), initial setting time (IST), final setting time (FST), compressive strength, and particle size distribution (PSD) analysis. The results of these tests guided the selection of S45 as the most suitable mix for the subsequent experiments and analysis.

Table 8: Properties of cement (OPC & S45)

Sr. No.	Property	OPC	S45	*% change*
A	Chemical Content			
i	Silicates (C_3S+ C_2S) (%)	61.45	63.21	--
ii	Aluminates (%)	20.38	21.53	--
B	Specific Gravity	3.15	3.15	--
C	Blaine's Fineness, cm^2/g	3650.3	5390	*(+47.67%)*
D	Water requirement			
i	Normal Consistency (%)	28	34	***(+21.42%)***
ii	Flow table Values in mm	100	105	***(+5%)***
E	Setting Times			
i	Initial Setting Time, minutes	160	48	*(-70%)*
ii	Final Setting Times, minutes	270	175	*(-35%)*
F	Heat of hydration cal/g	86.38	88.55	*(+2.15%)*
G	Compressive strength			
	3	23	28	***(+21.73%)***
	7	38.35	48	***(+25.16%)***
	28	53	66	***(+24.52%)***

c. Engineering of PSD

The average particle size of OPC, Stimulator and S40-S50 is 8-10 microns respectively and the Particle size distribution of these cement mixes are presented in Figure 1.

Synergetic effect of PSD of OPC and stimulator combines the advantages of broader PSD of OPC and finer particles from later thus optimizing the overall PSD for best performance. S40 & S50 exhibit double peak PSD thus clearly depicting the presence of macro as well as micro cement particles.

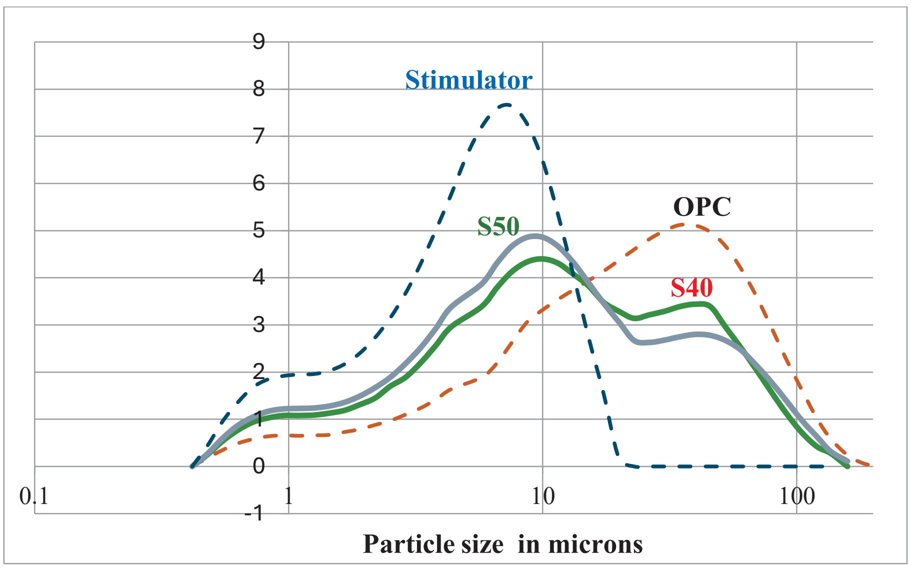

Figure 16: Comparison of Particle size distribution

d. Optimization of cement quantity in concrete

As shown in Table 8, compressive strength of S45 is approximately 20-25% higher than OPC, hence the optimization of cement quantity was found experimentally through trial and error for two grades of concrete i.e. M25 and M40.

For M25 and M40 grade concrete, 8-10% and 20-25% less cement is required to achieve the target mean strength as compared to their equivalent concrete samples with OPC only. The graphical presentation of the effect of optimization is show in Figure 17.

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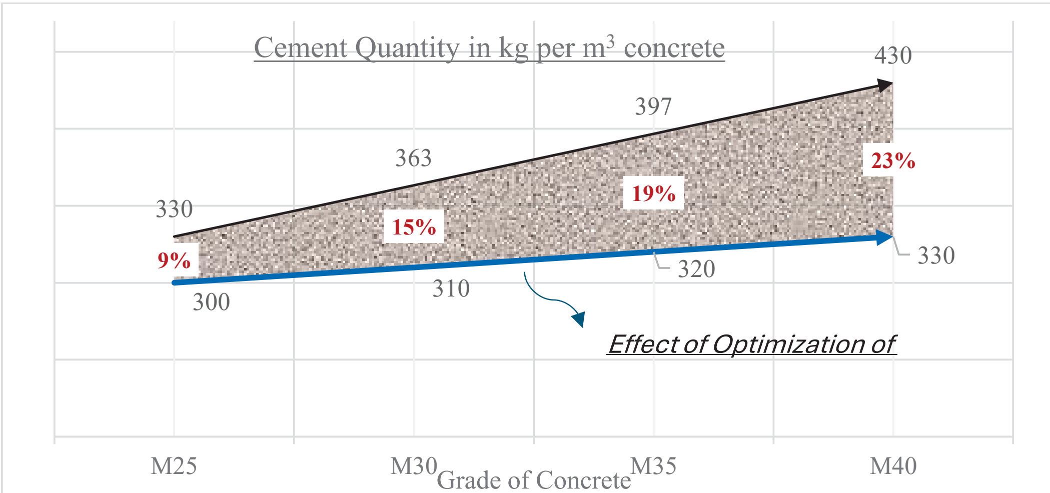

Figure 17: Optimization of cement quantity in concrete (M25 & M40)

B. Carbon footprint of cement Sustainability and Carbon footprint –Environmental Concern

a. Carbon footprint of cement

The global push to reduce CO_2 emissions involves all sectors, including the cement industry, which accounts for about 8% of total carbon dioxide release. The International Energy Agency (IEA) reports a worldwide CO_2 emmision of approximately 372GT. Researchers are exploring methods to reduce CO_2 emissions at different stages of cement production. Researchers have calculated the carbon footprint of cement at each step is and presented in Table 9.

Table 9: Carbon footprint calculations of cement at every stage of production

I	**Pre-Production**			
A	**Mining of Raw Materials**			
	For	**1**	tonne of cement requires	**1.5 tonne of limestone**
	Cement/Clinker =	**0.95**		

		1	tonne of cement requires	**1.053 tonne of clinker**
	For	**1**	tonne of limestone releases	**3.13 kg of CO_2**
		1	tonne of cement requires	**1.5 tonnes of limestone**
		1.5	tonne of limestone releases	**4.695 kg of CO_2**
B	**Transportation of Raw Materials**			
	D Transport=	**50**	km Coefficient =	**0.15 kg CO_2/ton-km**
	For	**1**	tonne of limestone	**7.5**
	for	**1.5**		**11.25 kg of CO_2**
II	**Production**			
C	**C. Calcination(Chemical Reaction)**			

$CaCO_3$ (limestone) (100.09g/mol) → CaO (Quick Lime) 56 g/mol + CO_2 (44 g/mol)

		1	tonne of clinker releases	**440 kg of CO_2**
		1.053	tonne of clinker releases	**463.15 kg of CO_2**
D	**Coal (Fuel Burning)**			
		1	kg of coal releases	**3.67 kg of CO_2**
		1	tonne of cement requires	**200 kg of coal**
		1	tonne of cement releases	**734 kg of CO_2**
E.	**Electricity consumed for Grinding of materials**			
			Units of electricity consumed in kWh	
i	Crushing Raw Materials		**15**	
ii	Raw Material Grinding		**30**	
iii	Clinker Grinding		**35**	
iv	Material Handling		**10**	

v	Packing and Dispatch	**10**		
	Total amount of electricity	**100**		
		1	kWh of electricity releases	**0.85 kg of CO_2**
		100	kWh of electricity releases	**85 kg of CO_2**
	Clinker to cement grinding	**35**	kWh of electricity releases	**29.75 kg of CO_2**

The summarization and sum total of carbon footprint of cement is displayed in Table 10 which depicts that Calcination and Coal burning in Kiln contributes to about 35 & 56% of total CO_2 released.

Table 10: Summarization of carbon footprint values of cement

Sr. No.	**Process**	**CO_2 released in kg**	**% of total Carbon footprint released during production**
I	Pre-production		
A.	Mining of Raw materials		
	Limestone extraction/mining	4.695	0.4
B.	Transportation of raw materials	11.25	0.9
II	Production		0.0
C.	**Calcination (Chemical Reaction)**	**463.15**	**35.7**
D.	**Coal (Fuel Burning)**	**734**	**56.5**
E	Electricity consumed		0.0
	Only for grinding clinker to cement	29.75	2.3
	Other process involving electricity	55.25	4.3
Total Carbon Footprint 1298 kg **of CO_2 per 1 tonne of cement production**			

b. Effect of optimization of PSD on carbon footprint of cement

With the use of 40-50% of stimulated cement in the total cement mix, the requirement of cement reduces by 25% for a given value of compressive strength. As stated in Table 11, the total carbon footprint of OPC is 1,204kg at the production level. However, stimulated cement requires extra grinding which consumes 30 kWh of electricity there by increasing total carbon footprint of stimulated cement as presented in Table 11.

Table 11: Effect of optimization of cement quantity on Carbon footprint & cost

Sr. No.	Details	Amount of CO_2 released (kg)	Cost in INR ₹
I	1 Tonne of OPC	1298	₹ 8,000
II	CO_2 released during "Stimulator" production		
b)	Electricity required for grinding OPC to Stimulator 30 kWh of electricity	29.8	₹2,800
	1 tonne stimulator	1327.8	₹10,800
III)	1 tonne of modified cement S45	1311.4	₹9,260
IV)	0.75 tonnes of modified cement (S45)	983.5 (-24.22%)	₹6,945(-13.18%)

c. Environmental efficiency of cement

The relation between global warming potential of cement to its compressive strength is established found by using equation (II) stated below [7]. Increase in fineness leads to an increase in environmental efficiency as depicted graphically in Figure 18. S40-S50 are 10-19% efficient than OPC samples from environmental aspect.

$$Environmental\ Efficiency, EE\left(\frac{MPa}{kgCO2}\right) = \frac{28\ days\ compressive\ strength\ in\ MPa}{Global\ warming\ potential\ of\ cement, (kg)} x\ 100 \qquad \text{II}$$

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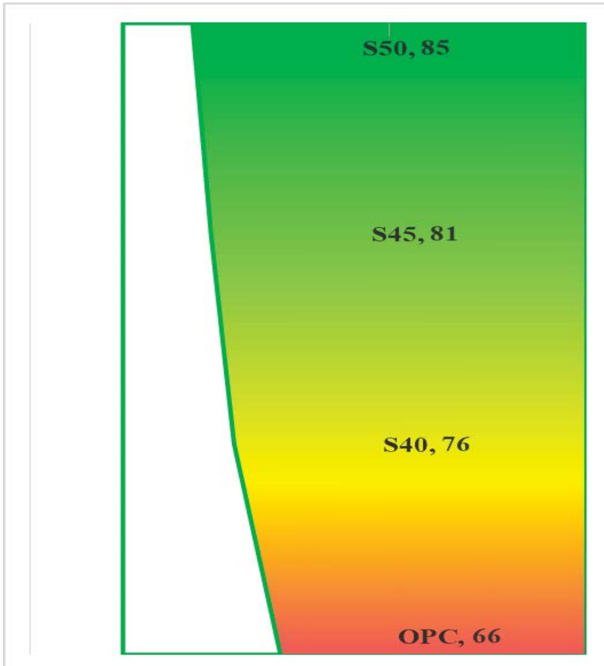

Figure 18: Environmental efficiency values of cement mixes

Though grinding of cement requires extra energy in the form of electricity it is compensated by the enhanced efficiency of cement samples leading to a reduced carbon footprint as witnessed in Table 11.

Future scope- Cement production

Under the Paris Agreement, India has committed to reducing it's the emission's intensity of it's GDP by 45% by the year 2030 (relative to 2005 levels) and achieving net-zero emissions by 2070. The construction sector, responsible for approximately 17% of India's total greenhouse gas emissions in 2019, plays a pivotal role in this effort, with the cement industry emerging as one of the most carbon-intensive contributors. To align with the Paris Agreement's objectives, global emissions from cement production need to decline by at least 16% by 2030. The optimization technique presented in this study demonstrates how the carbon footprint of the cement production can be reduced by 25%, offering a substantial pathway for India to achieve its climate commitments while promoting sustainability in the construction sector.

Conclusions

- **Enhanced Mechanical Performance:** The optimized S45 mix exhibited a 25% improvement in compressive strength compared to the baseline OPC mix
- **Resource Optimization:** The S45 mix achieved a 25% reduction in cement content while maintaining the same target compressive strength, leading to significant resource optimization and reduced material costs by 15%.
- **Improved Workability:** The optimized mix demonstrated a 5% reduction in water requirements, suggesting improved workability and potentially enhanced durability.
- **Reduced Environmental Impact:** The optimized S45 mix exhibited a 24% reduction in embodied carbon emissions, contributing to a lower environmental impact compared to the conventional OPC mix.
- **Enhanced Sustainability:** The combination of reduced cement consumption, improved workability, and reduced environmental impact underscores the enhanced sustainability of the optimized S45 mix.

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