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EDITORIAL

I am glad to bring to you the latest edition of the CMA Journal *Cement, Energy and Environment* through which we have endeavoured to bring to you the evolving perspectives of the Cement Industry on latest in practices, processes and operations in the sector.

The Indian Cement industry has been closely engaged with various Ministries and Departments of the Government of India to drive a low carbon growth path. Various articles presented in this issue narrate the Industry's initiatives being made in this direction. Sustainability makes business sense after all!

Hope you find the Journal useful and informative. As always, we welcome your comments and views on the Journal.

APARNA DUTT SHARMA
Secretary General

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Advanced Kiln Fuel Optimization: Strategies for Sustainable Cement Production

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ABSTRACT

Fuel efficiency in cement kilns is not merely a cost-saving measure; it represents a sophisticated interplay of thermodynamics, chemical reactions, and advanced process engineering. For example, the application of predictive models in kiln operations has demonstrated how precise monitoring of variables like secondary air temperature and kiln inlet stability can substantially reduce inefficiencies.

By integrating advanced process controls with thermodynamic principles, operators can optimize heat utilization, enhance combustion stability, and achieve measurable improvements in clinker quality and energy consumption.

With energy expenses contributing up to 40% of cement production costs, addressing inefficiencies in kiln operations can profoundly affect sustainability metrics, such as carbon emissions reduction and resource conservation, in addition to enhancing operational profitability.

This article explores into the intricate technical aspects of kiln fuel efficiency, providing detailed insights, actionable solutions, and the latest advancements supported by quantitative data.

INTRODUCTION

Cement kilns operate at the heart of the manufacturing process, converting raw meal into clinker through high-temperature pyroprocessing. This transformation is inherently energy-intensive, with theoretical heat requirements for clinker formation ranging from 400-420 kcal/kg. However, real-world operations often exceed 700 kcal/kg due to heat losses, equipment inefficiencies, and process variability. Optimizing fuel efficiency demands a comprehensive understanding of key parameters, including combustion stability, heat transfer mechanisms, and material properties.

Energy losses in kilns stem primarily from radiation, convection, and system inefficiencies. For instance, kiln shell temperatures exceeding 200°C can account for radiation losses as high as 15%. Similarly, suboptimal preheater performance and cooler inefficiencies exacerbate energy wastage.

To address these challenges, modern cement plants are leveraging advanced technologies such as computational fluid dynamics (CFD), artificial intelligence (AI), and high-performance materials.

HEAT CONSUMPTION BENCHMARKS

Theoretical vs. Practical Heat Consumption

The theoretical minimum energy for clinker production is dictated by the endothermic decomposition of limestone and subsequent reactions forming alite and belite. However, practical operations often require 680-720 kcal/kg due to unavoidable inefficiencies. Plants operating above 800 kcal/kg must evaluate system-wide heat losses, focusing on preheater, kiln seals, and cooler performance.

SOURCES OF HEAT LOSS AND MITIGATION STRATEGIES

Radiation Losses: Excessive kiln shell temperatures result in significant radiation losses. Advanced refractory linings with thermal conductivity below 1.5 W/mK have demonstrated reductions in heat loss by up to 10 kcal/kg. For example, a 2 MTPA plant achieved an 8 kcal/kg reduction by replacing standard linings with high-performance refractories.

Preheater Inefficiencies: Cyclone separators in preheaters must achieve high separation efficiency (>85%) with minimal pressure drop (<50 mmWC). CFD simulations have proven instrumental in optimizing cyclone geometries, enhancing thermal efficiency and reducing pressure drop

Cooler Inefficiencies: Modern grate coolers with recuperation efficiencies exceeding 75% can recover over 220 kcal/kg of clinker. Retrofitting older coolers with advanced designs has reduced specific heat consumption by up to 100 kcal/kg in multiple case studies.

QUANTITATIVE PERFORMANCE GAINS

By upgrading the preheater system with advanced cyclone designs and optimizing cooler efficiency through enhanced airflow patterns and heat recovery mechanisms, a 1.5 MTPA cement plant achieved a significant reduction in heat consumption from 820 kcal/kg to 710 kcal/kg. These upgrades included the use of high-efficiency separators in the preheater, which minimized pressure drops and improved heat transfer, as well as the incorporation of cross-bar cooler technology to enhance clinker cooling and recuperation. This holistic approach not only translated to annual savings of $1.5 million but also reduced thermal losses, extended equipment lifespan, and improved overall process stability. These examples highlight the economic viability of targeted process improvements.

COMBUSTION OPTIMIZATION

Importance of Combustion Stability

Efficient combustion ensures uniform flame temperatures, minimizes unburnt carbon, and reduces thermal losses. Unstable combustion can lead to inconsistent clinker quality, increased CO emissions, and elevated specific heat consumption. Achieving stable combustion requires precise control of air-to-fuel ratios and flame dynamics.

Advanced Combustion Control Systems

- Flame Monitoring Cameras: Real-time flame imaging systems allow operators to dynamically adjust air-fuel ratios. AI-driven flame monitoring has reduced CO emissions from 0.3% to below 0.1% in several plants, simultaneously improving fuel utilization.
- Gas Analyzer Integration: Online analyzers measuring O_2, CO, and NOx concentrations with accuracies of ±2 ppm enable precise combustion control. Maintaining O_2 levels at 1.5-2% ensures complete combustion, while keeping CO levels below 0.1% minimizes fuel wastage.

Quantitative Case Study

A German cement plant using alternative fuels with calorific values of 15 MJ/kg implemented AI-based flame monitoring systems. This intervention reduced specific heat consumption by 4.5%, saving $2.2 million annually while maintaining clinker quality.

Data Analytics and Predictive Optimization

Predictive Analytics in Kiln Operations

Advanced data analytics platforms are redefining kiln operations by integrating seamlessly with existing kiln systems to provide real-time insights into critical parameters. These platforms utilize predictive modelling and machine learning algorithms to monitor variables such as secondary air temperature, kiln inlet stability, and heat recovery efficiency.

By analysing historical and live operational data, they can identify inefficiencies, predict potential disruptions, and recommend actionable solutions, thereby enabling operators to optimize fuel consumption and maintain consistent clinker quality.

For example, a cement plant in Europe reported a 6% reduction in specific heat consumption and a 20% decrease in kiln stoppages after implementing such an advanced analytics system. Predictive models based on historical data can anticipate inefficiencies and recommend corrective actions, ensuring optimal fuel efficiency and process stability.

Key Metrics for Monitoring

1. **Secondary Air Temperature (SAT):** Maintaining SAT above 1000°C is crucial for efficient heat transfer. Fluctuations of ±50°C can increase specific heat consumption by 3-5%, making stable SAT control a priority.
2. **Kiln Inlet Temperature Stability:** Variability exceeding ±30°C disrupts clinker mineralogy, reducing the formation of alite and increasing free lime content. Stable inlet temperatures ensure consistent clinker quality..

Case Study Insight

A Saudi Arabian plant implemented machine-learning algorithms to optimize SAT and preheater exit temperatures. These measures reduced kiln stoppages by 25% and improved specific heat consumption by 6%, yielding annual savings of $1.8 million.

ENHANCING CLINKER COOLER EFFICIENCY

Grate Cooler Optimization

Grate coolers are essential for maximizing heat recovery from clinker. Cross-bar designs with optimized airflow patterns achieve recuperation efficiencies above 75%, ensuring effective clinker cooling and minimizing thermal losses.

Heat Recuperation Impact

Lowering clinker discharge temperatures by 10°C reduces specific heat consumption by 5 kcal/kg. Advanced cooler systems can achieve discharge temperatures as low as 110°C without overburdening the cooler.

Quantitative Benefits

Modernizing coolers in a 2 MTPA plant reduced clinker discharge temperatures from 150°C to 120°C, delivering energy savings worth $1.9 million annually. Additionally, the lower temperatures extended refractory life by 15%, reducing maintenance costs.

ALTERNATIVE FUELS

Challenges of High TSR (>50%)

High Thermal Substitution Rates (TSR) introduce variability in fuel properties, complicating combustion control and kiln stability. Issues such as high sulfur content can lead to buildups, thermal shocks, and reduced refractory lifespan.

Technical Mitigations

1. **Emission Control:** Online gas analysers ensure SO_2 and NOx emissions remain within acceptable limits, protecting kiln refractories and maintaining stable heat profiles.
2. **Refractory Innovations:** High-performance spinel refractories with superior thermal shock resistance improve durability under extreme conditions.

CASE STUDY

A Southeast Asian plant operating with 65% TSR faced challenges such as fluctuating heat profiles, higher alkali content, and emission spikes. By implementing AI-driven emission control and alkali bypass systems, the plant achieved significant improvements.

These measures not only stabilized kiln operations but also addressed the variability of alternative fuels, reducing clinker rejections by 15%, cutting fuel costs by $1.5 per ton, and extending refractory life by 18 months. These measures reduced clinker rejections by 15%, cut fuel costs by $1.5 per ton, and extended refractory life by 18 months.

CONCLUSIONS

Fuel efficiency in cement kilns is a multifaceted challenge requiring a holistic approach that combines advanced technologies, data-driven solutions, and fundamental process optimization. By addressing inefficiencies in heat consumption, combustion stability, clinker cooling, and alternative fuel usage, the cement industry can achieve significant reductions in energy costs and environmental impact.

Key takeaways include the necessity of precise heat loss management through improved refractory linings, optimized preheater and cooler designs, and leveraging predictive analytics to anticipate and mitigate inefficiencies. The integration of AI, machine learning, and real-time monitoring tools has emerged as a game-changer, offering unprecedented control over critical process parameters such as SAT, O_2 levels, and kiln inlet temperatures.

Moreover, the adoption of high TSR rates and the transition to alternative fuels, while presenting technical challenges, is a viable path toward reducing the carbon footprint of cement manufacturing. Advanced emission control systems, coupled with innovative refractory materials, ensure that kiln stability and clinker quality are maintained under these conditions.
Ultimately, achieving best-in-class fuel efficiency is not merely about cutting costs—it is a vital component of the global effort to produce sustainable and environmentally responsible cement.

By embracing innovation, investing in R&D, and implementing proven strategies, the cement industry can redefine its approach to energy efficiency, paving the way for a more sustainable future.

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Solid AFR feeding system for coprocessing in kiln system at MCW-unit-4

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My Home Industries Pvt. Ltd, Mellacheruvu Cement works (MCW), Telangana state was established in the year 1998 with an installed capacity of 0.2 mtpa and has now attained a capacity of 10.0 MTPA. Solid AFR (Alternative Fuels and Raw Materials) feeding systems in cement kilns play a significant role in improving energy efficiency, reducing CO2 emissions, and supporting low-carbon strategies in cement production. The use of AFRs in cement kilns helps in transitioning toward a circular economy by utilizing waste materials, while also reducing the consumption of traditional fossil fuels like coal. Recently My home industries expanded a brown field project having 10000 TPD clinker capacity of Kiln in which the scope of installation of AFR feeding was more adequate and Feeding system was installed in the year of 2024

SOLID AFR FEEDING SYSTEMS IN CEMENT KILNS

Cement production, especially the clinker production process in the rotary kiln, is one of the most energy-intensive processes, contributing significantly to CO2 emissions. AFRs are used in cement plants to partially replace fossil fuels like coal, reducing both cost and environmental impact. The key solid AFR feeding technologies used in cement kilns include:

Types of Solid AFRs Used in Cement Kilns:

- RDF(Refuse Derived Fuel) coming from nearby localities
- Firewood Chips
- Palm Fiber
- Plastic Hazardous waste

Feeding / Dosing Methods:

- **Pre-processing and Size Reduction:** Some AFRs, especially municipal waste (RDF) must undergo size reduction or shredding before being fed into the kiln system. The define size are maintain for ensuring proper burning inside kiln system (Pre-Calciner inlet)

Fig:1 Separation of stone & iron

Fig:2 Shredding machine

- **Mechanical Conveying:** After size reduction, all that product materials store in storage and then from there all material conveying through long conveyer belt to feeding point
- **Feeding Control:** All feed materials coming from weigh feeder to feeding / dosing point through belt conveyor system. These feeding materials are controlled through double pneumatic gate through flap valve in specific time interval.
- **Safety Interlocking :**
  1. Auto MV Water Spray System for Belt Conveyor & Cable cellar
  2. Auto Water Curtain System
  3. Auto Sprinkler System
- Apart from this process safety PID interlocking also provided as follows,
  1. AFR Feeding trip if PC Coal firing , PH fan trip
  2. If PC CO reach 2500 PPM then AFR dosing reduced to 5 TPH

Benefits of Using AFRs in Cement Kilns:

- Simultaneous energy recovery and safe disposal of municipal solid waste, hazardous and non-hazardous solid waste, bio mass and agricultural waste, expired FMCG products and ETP & sewage sludge.
- Replacing the fossil fuel energy with energy from the waste streams.
- Reduction of GHG emissions of cement manufacturing and waste disposal.
- Avoidance of environment, health and safety hazards due to landfills
- EPR Compliance
- GHG Emissions intensity reduction to comply with BEE CO2 intensity reduction targets and aligning with the net zero ambition.

AFR Laboratory

As of now no special lab available for solid AFR system, however we are testing the Solid AFR in our existing Liquid AFR lab.

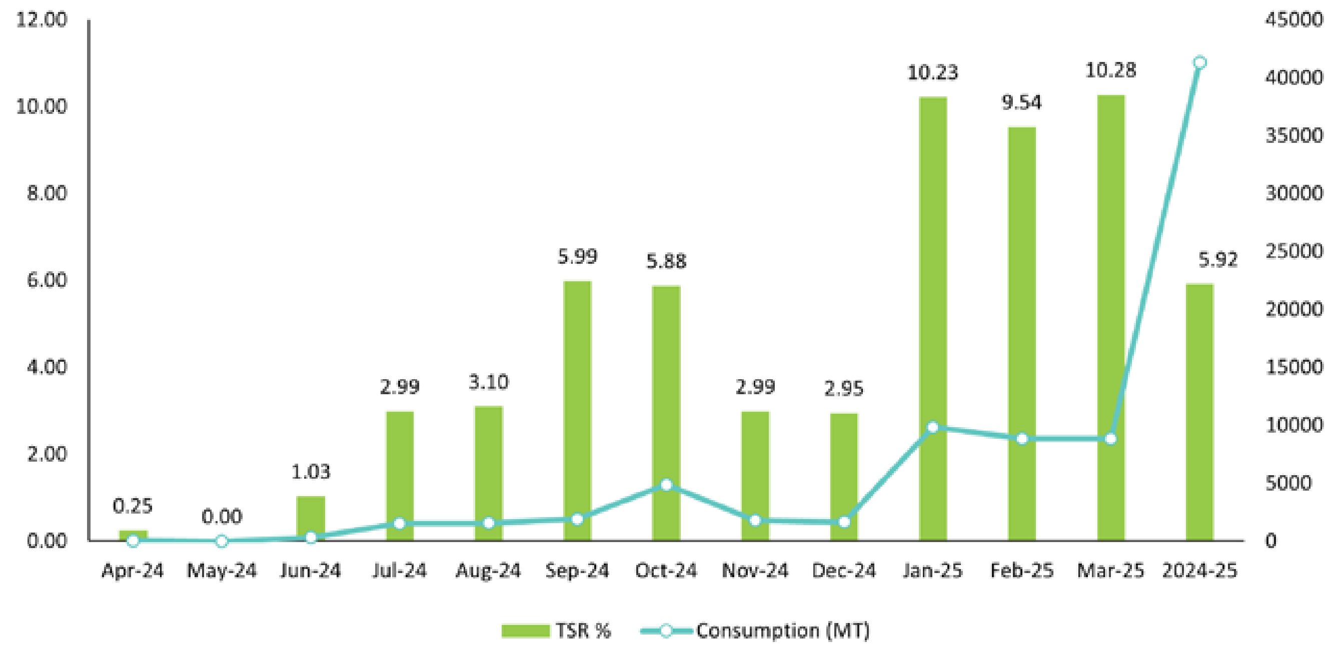
The following parameters are tested in AFR Laboratory

- Moisture
- Chloride
- Ash
- NCV

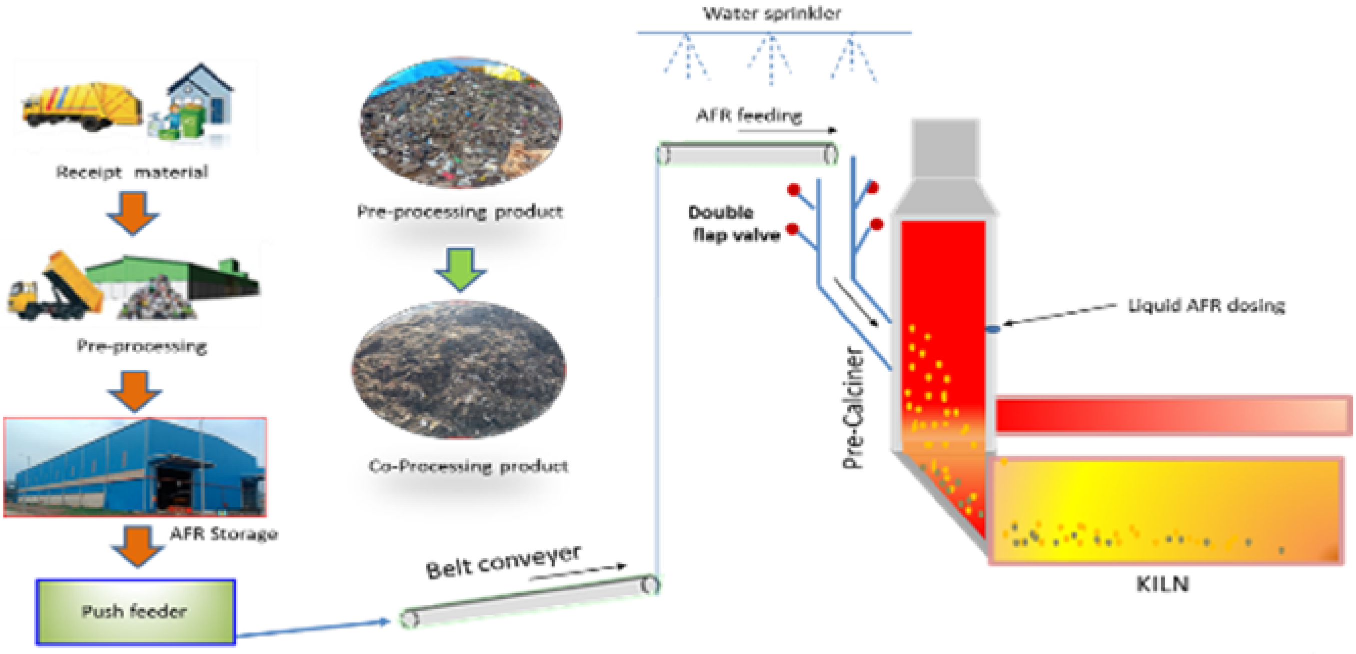
Operational problems faced during enhancing TSR and overcoming the problems

- More dosing's solid AFR leads to high CO formation (Higher dosing quantity of AFR yet not experienced due to low kiln run day)
- handling high moisture variation in solid AFR is the most challenging and difficult to control the operation

2024-25 Solid AFR consumption & TSR Details:



Flow Diagram of Solid AFR feeding



INSTALLATION OF 40 TPH SOLID WASTE MATERIAL FEEDING SYSTEM

SALIENT FEATURES

Co-processing system of Solid Waste:

The Solid AFR feeding System with a capacity of 40 tph for feeding alternate fuels into the kiln system through calciner is supplied by M/s. Sanghavi Engineering, Hyderabad. The system consists of storage shed (6000 m3) material handling capability PEB Storage & Processing Shed - 72m x 31m x 15m with 3.0 m high concrete walls on both sides, health and safety features like state of the art fire detection and control system, Heat detection, cameras, Auto Sprinkling system leachate collection system and odour control system. Hydraulic operated storage cum extraction device with a holding capacity of 200 M^3 which is currently the biggest capacity in the country, with regulated extraction depending on desired feed rate The conveying system comprises of Chain belt conveyor with level controlling mechanism, magnetic separator for ferrous separation, weigh feeder, belt conveyors, metallic conveyor, and time based Motorized single flap double stage valves in SS-310 flap construction with Emergency shutoff gates above and below flap valves. Water sprinkers all considered throughout the conveyors, water curtain systems in pre heater building. The co processing system is completely automated and operated centrally from plant DCS. All drives are with VFD's, all the instruments are ATEX certified and all the drives are flame proof, all belts and cables are FRLS type. Chute block detectors are provided in all chutes to avoid jamming issues. Double flap valves in the pre heater building will ensure uniform feeding of AFR material to the Pre-Calciner without any false air entry into the system. Solid AFR feeding system is in operation since April-24.


AFR Storage


Pre-processing material


Push feeder


CB Conveyer


Magnetic separator


Weigh Feeder feederrage

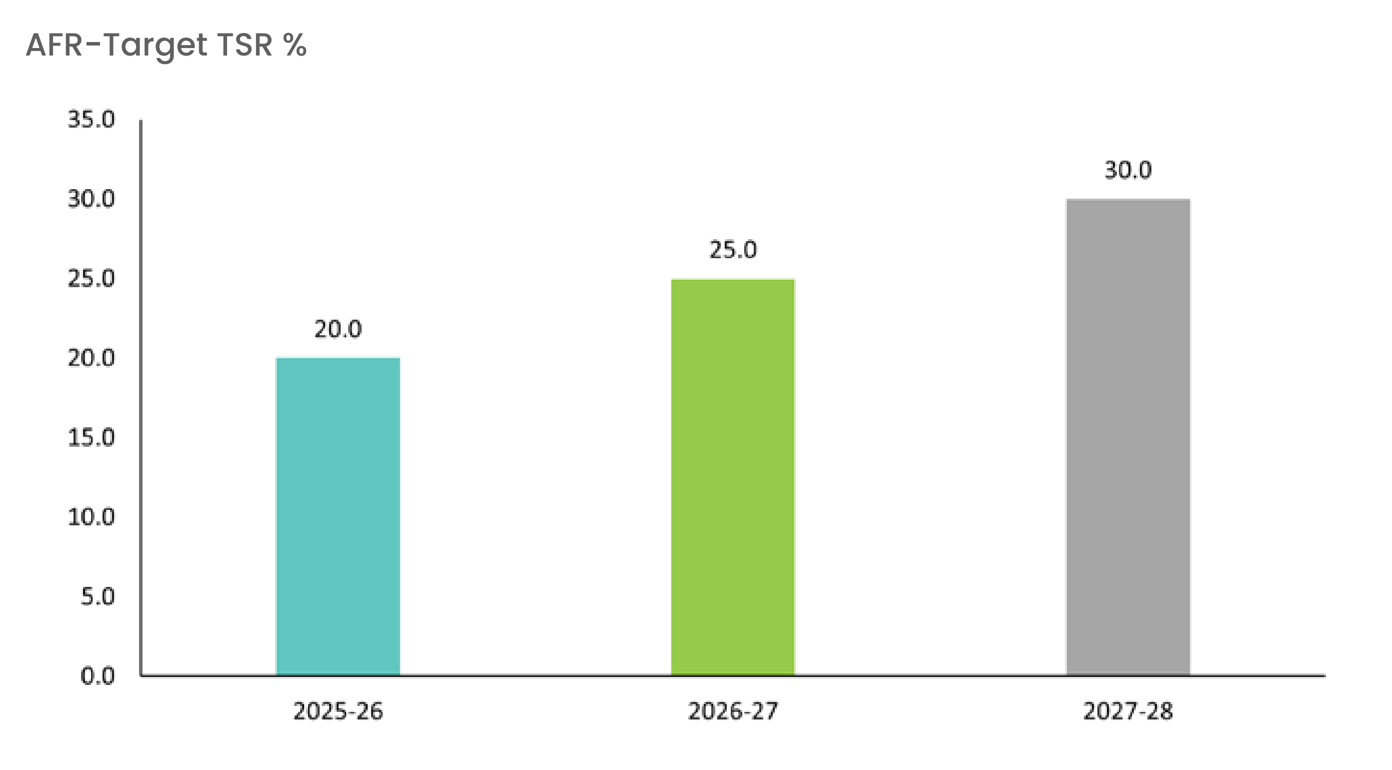

Long Conveyer belt


Apron feeder


Flap gate

FUTURE TARGET:

MHIPL is committed to increasing Alternative fuels to reduce fossil fuel consumption and GHG emissions. We are targeting for 30% TSR in next 2 to 3 years, we are further planning to install Chloride bypass system to increase AFR to 50 TSR by 2040.



Energy Optimizing Furnace Slag (EOF)- A Potential Supplementary Cementitious Material for Portland Blended Cement with Improved Properties

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ABSTRACT

CO_2 emission is a common cause of concern for the entire cement sector. This makes the blended cement with lower clinker factor, more significant. On the other hand, energy optimizing furnace slag (EOF Slag), being a byproduct of steel industries draws the concern of waste management and pollution. Despite being mineralogically rich, the EOF slag is almost untouched and has not been explored for a significant scope of recyclability. Herein the mineralogy and microstructure of EOF slag have been studied with different sophisticated analytical techniques including optical polarizing microscopy, and X-ray diffraction. This experimental investigation has found the EOF slag as a potential supplementary cementitious material (SCM) to make blended cement. Different compositions of Portland slag cement (PSC) have been made by using the processed and ground EOF slag. Different performance parameters of the developed cement have been evaluated to find the suitability of EOF slag in cement as well as for optimization of its dosage. The reactivity of the EOF slag in cement hydration has been analyzed by correlating the quantitative XRD data, Heat of Hydration of the developed cement, and derived physical parameters. It has been found that ground EOF slag (GEOFS) is a potential supplementary material for Portland slag Cement (PSC) with the 2.5 to 7.5 % replacement of ground granulated blast furnace slag (GGBS, a proven SCM as well as a mineral admixture). Further, the application of the developed blended cement has been validated with the concrete trial. Overall this work has addressed two global concerns of industrial sectors like recyclability of industrial waste materials and the development of a new SCM to reduce the clinker factor in cement for the reduction of the carbon footprint of cement.

Keywords: EOF Slag, Circularity, Sustainability, Cement, Concrete.

1.0 INTRODUCTION AND LITERATURE REVIEW

The necessity of shelter for living is the prime driving factor for gradual evolution of the civilized society. Hence the effort to make a safe space for living is still on the track of evolution. The journey of today's gigantic skyscrapers started from natural narrow caves and holes in ancient times. The biggest breakthrough in the field of construction of houses and monuments is the invention of Portland cement and concrete. Portland cement is a hydraulic binder that offers excellent fast irreversible binding properties by simple chemical processes like hydration. The conventional Ordinary Portland Cement (OPC) is composed of two components clinker (~95%) and gypsum (~5%).

Clinker is the principal component of conventional Portland cement which provides the hydraulic binding property. Conventionally clinker is manufactured by pyro-treatment (~ 1450 °C) of lime-stone and some other supplementary raw materials (to maintain a certain chemical stoichiometry) in a rotary kiln. Primarily, limestone undergoes calcination at the temperature range of 800-900 °C to form calcium oxide (lime) and carbon dioxide [1]. Beyond that temperature range (900-1450 °C) lime reacts with available other oxides (i.e SiO_2, Al_2O_3, Fe_2O_3) to form different cementitious phases including tri-calcium silicate (C_3S, elite), di-calcium silicate (C_2S, belite), tri-calcium aluminate (C_3A), tetra-calcium aluminoferraite (C_4AF) etc [2]. As one mole of CO_2 is generated by the calcination of one mole of calcium carbonate, the process of clinkerization causes severe CO_2 emission. As a consequence, the cement sector solely contributes ~8 % of global CO_2 emissions [3]. Hence the reduction of clinker factor in cement is the most common and relevant challenge for cement and concrete research. Blended cement has been introduced to the market to address this concern. Blended cement are composed of clinker, gypsum, and some supplementary cementitious materials (SCM). Hence the usage of SCM directly reduces the clinker content in cement. SCMs are not able to provide any binding properties individually. However these materials exhibit some pozzolanic or hydraulic reactivity while blended with OPC and provide excellent binding properties [4]. Fly ash, ground granulated blast furnace slag (GGBS), calcined clay, etc. are well-known SCMs, which are already in practice to make blended cement.

Slag is a byproduct of metallurgy. The high melting oxide impurities (silica, alumina, etc.) present in the molten metals react with added flux materials (limestone, dolomite, etc.) and generate a low melting as well as low-density floating material.

This material is being separated from the molten metal physically and is termed as slag. Iron and steel industries generate several types of slags. Although the iron-making slag (blast furnace slag) is a proven SCM for cement making the steel making slags are still almost unexplored from the aspect of Circular Economy. Almost 150-200 Kg of steel-making slags are generated from 1 ton of liquid steel [5]. This significant amount of slag is usually being dumped or used for landfilling. This demands a huge land space and draws severe environmental pollution concerns. Hence an efficient scope to reuse those steel-making slag may promote a circular economy as well as address the concern about environmental hazards.

Energy Optimizing Furnace (EOF) is a primary steel-making furnace where the carbon content of hot metal gets oxidized by efficient O_2 blowing through sub-merged tuyeres and supersonic lances. After oxidation of carbon, CO comes out from the hot metal bath and is further burnt in the presence of atmospheric O_2 to form CO_2. Slags are also generated from the reaction of remaining impurities and added flux materials. The slag generated by the steel refining process from EOF is termed EOF slag. This slag is also almost untouched to date from the aspect of circular economy. There are few reports available in the existing literature on the utilization of EOF slag. Sabapathi et al. (2017) have reported the utilization of surface modified EOF slag as a coarse aggregate for concrete [6]. Malathy et al. (2021) have reported the surface-modified EOF Slag aggregates for concrete and their performance in corrosive environments [7]. But to date the development of any value-added material from EOF slag is yet to be explored.

This article deals with the exploration of EOF slag as a potential SCM to make blended cement. Initially, EOF slag has been characterized with different analysis techniques including Optical microscope, XRF, and XRD analyses. Based on the results, different compositions of blended cement (ingredients: clinker, GGBS, ground EOF slag, and gypsum) have been prepared. To assess the performance of the developed cements all the performance parameters have been analyzed (according to IS: 4031). The tolerance ranges of ground EOF slag (GEOFS) in blended cement have been optimized concerning maximum usage of GEOFS without compromising the compressive strength and other parameters. Finally, the optimized blended cement has been used for concrete trials to evaluate its applicability in concrete.

2.0 MATERIALS AND METHODS

2.1. **Material:** EOF slag (from JSW Steel Ltd, Salem Works, India), GGBS, and OPC (from JSW Cement Ltd, Vijayanagar Works, India).

2.2. **Pre-application processing of EOF Slag** The collected EOF slag was gray and with an irregular shape (<10 mm). First, the slag sample (20 Kg) was kept in a hot-air oven at 110 °C for 5 h to remove the moisture contained. Then the moisture-free slag sample was crushed using a lab-scale jaw-crusher to make a smaller granule size (< 3 mm). Then the crushed slag sample was passed through a magnetic separator to isolate the metallic iron particles. Finally, the non-magnetic EOF slag was ground finely using a lab-ball mill. The specific surface area of the ground EOF sample was maintained at ~350 m2/Kg. This ground EOF slag (GEOFS) was used for further characterizations and applications.

2.3. **Preparation of blended cement** The collected OPC Cement was composed of clinker (~93 %) and mineral gypsum (7 %). The specific surface area of OPC and GGBS were 350 and 345 M2/Kg. Different compositions of blended cement were made (50 Kg each) by blending OPC (50 %), GGBS (35-50 %) and GEOFS (0-15 %). Thus the produced blended cements belong to the Portland Slag Cement (PSC) class. The prepared cements were used for different applications and trials, explained later.

2.4. **Materials characterization** Optical microscopy of GEOFS and GGBS was performed in an optical polarizing microscope (Make: Leica, Model: DM4P). The image acquisition was performed in transmitted polarized light. The elemental compositions of GEOFS was analyzed by XRF analysis (Instrument: ARL 9900 Series, Thermo Scientific). The XRD analysis of GEOFS, Portland Cement Clinker, and GGBS samples were performed for phase identification and quantification (Instrument: Empyrean 200684, Panalytical).

2.5. 2.5 Evaluation of physical parameters according to Indian standard (IS 4031)

2.6. Different physical parameters were evaluated according to the Indian Standard (IS: 4031). The normal consistency, and setting times were determined as per the procedure mentioned in IS: 4301. The cement paste was cast using proper molds (as per IS: 4031) to evaluate the soundness behavior of cement. After 1 day of curing these casted samples are analyzed for autoclave and Le-Chatelier expansion. Finally, cement-sand mortar was prepared by manual mixing and cast in cubical molds. After demolding the mortar cubes emerged for water curing. The compressive strength was determined by using a Compressive Strength Testing Machine (CTM) after 1, 3, 7, and 28 days of curing.

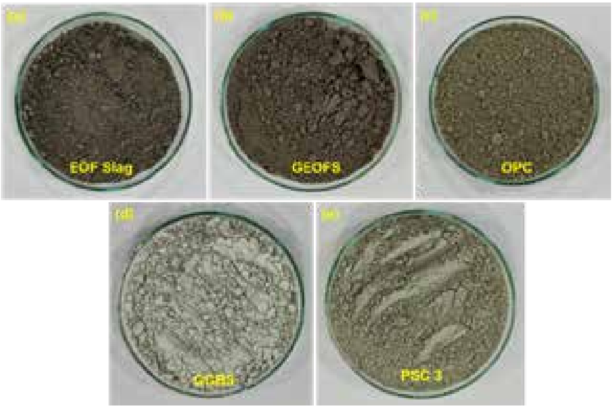
2.7. **Determination of heat of hydration** The heat of hydration of prepared samples (PSC 1 to PSC 5) was determined in an isothermal calorimeter (TAM Air, from TA Instrument). 2.5 g of each sample was taken in a glass ampule and followed by the addition of 1 g of water. The ampule was shaken gently for homogeneous mixing. Then the ampule was sealed with a cap and put in the sample chamber of an isothermal calorimeter for measurement of heat flow and total heat liberation.

2.8. **Concrete application** Lab-scale concrete trials of developed blended cement were conducted for M30 design to evaluate the applicability as well as the compressive strength in concrete. After concrete mixing the workability of the concrete was checked followed by concrete cube casting for compressive strength determination after water curing for 3, 7, and 28 days.

3.0 RESULTS AND DISCUSSION

3.1. **Pre-application processing of EOF slag and preparation of blended cement** The moisture content of collected EOF slag was ~2% (weight %). Then the experiment to separate magnetic content has found ~12% segregated magnetic material. Then the GEOFS was blended with OPC and GGBS to make different compositions of blended cements (PSC 1 to PSC 5). The compositions of these samples have been demonstrated in Table 1. Among the all prepared blended cement grades, PSC 1 has having least GEOFS content (0 %) and PSC 5 has having maximum GEOFS content (10 %). The PSC 1 sample was considered as a control sample to assess the performance of GEOFS as a cement additive. Digital images of EOF slag, GEOFS, GGBS, OPC, and PSC 3 have been

Figure 1: Digital images of (a) EOF slag, (b) GEOFS, (c) GGBS, (d) OPC, and (e) PSC 3.

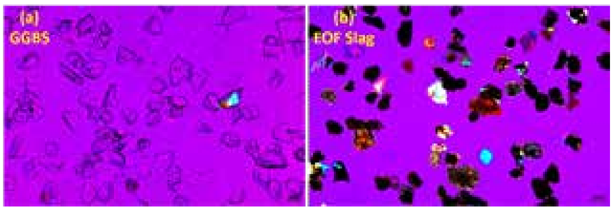


3.2 MATERIALS CHARACTERIZATION

Optical Microscopy: Fig. 2 demonstrates the optical microscopy images of GGBS (a) and GEOFS (b). The particle size chosen for this analysis of both materials are 90 µ < sample < 45 µ. In this figure, most of the GGBS particles were found transparent. This supports the glassy amorphous nature of GGBS. Again GEOFS has demonstrated glittering colorful particles. This implies the birefringence properties of crystalline particles. Hence it can be assumed that GEOFS is predominantly crystalline.

Grades of blended cement	Composition of blended cement (%)		
	OPC [350 M2/Kg]	GGBS [345 M2/Kg]	GEOFS [350 M2/Kg]
PSC 1	50	50	0
PSC 2	50	47.5	2.5
PSC 3	50	45	5
PSC 4	50	42.5	7.5
PSC 5	50	40	10

Figure 2: Optical polarizing microscopy images of (a) GGBS, (b) GEOFS.



XRF Analysis: Table 2, has demonstrated the elemental compositions of GEOFS and GGBS in the form of corresponding oxides, derived from XRF analysis. From this result, it has been found that the CaO and SiO2 content of GEOFS are 31.53 % and 13.13 %. The other major oxides are Fe2O3 (20.20 %), MgO (18.33 %), Al2O3 (4.87 %), MnO (3.48 %) etc. From this composition, it has been found that the ratio of CaO and SiO2 content is 2.37. So at molten condition, CaO and SiO2 may combine for some calcium silicate-based cementitious phases like Dicalcium silicate, tricalcium silicate, etc. Different phases present in GEOFS have been investigated further by XRD analysis.

Table 2. XRF analysis report of GEOFS

Components	Content in GEOFS (%)
Loss on Ignition	6.262
CaO	31.530
MgO	18.330
SiO2	13.130
Al2O3	4.870
Fe2O3	20.200
MnO	3.480

XRD Analysis: Fig. 3 demonstrates the XRD diffractograms of GGBS Portland clinker and GEOFS samples. Appeared broad signal of the GGBS sample suggests the amorphous nature of the material. The sharp signals of both the diffractograms of clinker and EOF slag suggest the predominated crystalline nature of both samples. Moreover, there are certain signals appeared in both the diffractograms of EOF slag and clinker (marked with a red dotted arrow in Fig 3). Those common signals [(30.1 °, 32.1 °) and (29.4 °, 34.26 °)] are probably responsible for crystalline phases of dicalcium silicate (denoted by C2, Fig. 3) and tricalcium silicate (denoted by C3, Fig. 3) [8]. Hence it is confirmed that EOF slag contains some cementitious phases as similar to clinker.

Figure 3: X-ray diffractograms of GGBS, Clinker, and GEOFS.

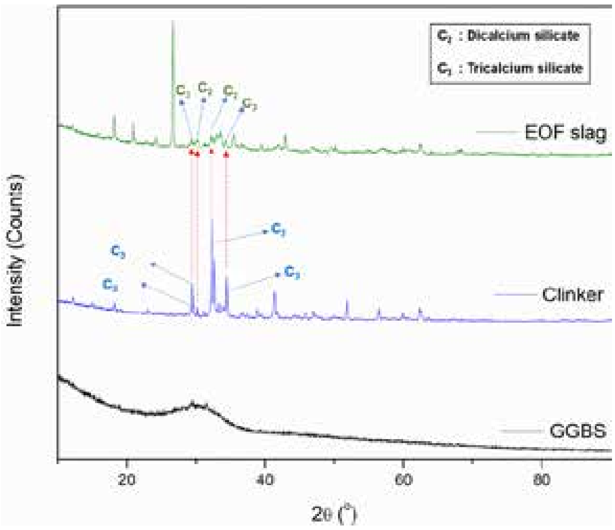
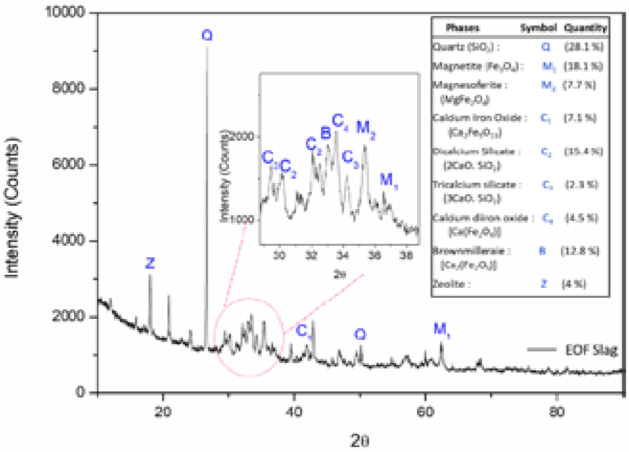


Fig. 4 represents the individual diffractogram of EOF slag with phase identification and phase quantification data. The quantitative analysis was performed by Rietveld analysis using the ICSD database (ICSD:161510, PANICSD:98-016-1510). The identified crystalline phases and their quantities are as follows. Quartz (SiO2): 28.1 %; Magnetite (Fe3O4): 18.1 %; Magnesoferite (MgFe2O4): 7.7 %; Calcium Iron Oxide (Ca2Fe9O13): 7.1 %; Dicalcium Silicate (2CaO, SiO2): 15.4 %; Tricalcium Silicate (3CaO.SiO2): 2.3 %; Calcium Diiron Oxide' (CaFe2O4): 4.5 %; Brownmillerite (Ca2Fe2O5): 12.8 %; Zeolite: 4 %. Among those identified phases dicalcium silicate and tricalcium silicate offer hydraulic binding properties, whereas zeolite provides significant pozzolanic reactivity in cement hydration reactions (Zheng 2023). Hence the XRD analysis suggests that GEOFS has the potential to be a supplementary cementitious material.

Figure 4: X-ray diffractogram of GEOFS with phase identification and quantification data.



3.3 EVALUATION OF PHYSICAL PARAMETERS ACCORDING TO INDIAN STANDARD (IS 4031)

The developed blended cement (PSC 1 to PSC 5) was analyzed for different physical parameters according to Indian Standard (IS: 4031). Table 3 and Fig. 5 have demonstrated the results accordingly. Normal Consistency (N.C) of the blended cement (PSC 1 – PSC 5) are 28.0 %, 26.75 %, 26.75 %, 26.5 %, 26.5 % and 26.75 % respectively (Table 3). The slightly lower N.C of all PSC 2 to PSC 5 (N.C>27) than PSC 1 (N.C: 28) indicates that the addition of GEOFS causes a slight reduction of water demand in developed blended cement. Le-Chatelier and autoclave expansion studies have demonstrated (Table 3) very negligible extent of expansions (within the permissible limit as per IS: 4031) for all the grades [limit of Le-Chatelier expansion: 10 mm (Max.), the limit of Autoclave expansion: 0.8 % (Max.)]. The determined setting times (initial and final) of the developed cement have shown that the addition of GEOFS did not affect the normal setting of PSC Cement (Table 3).

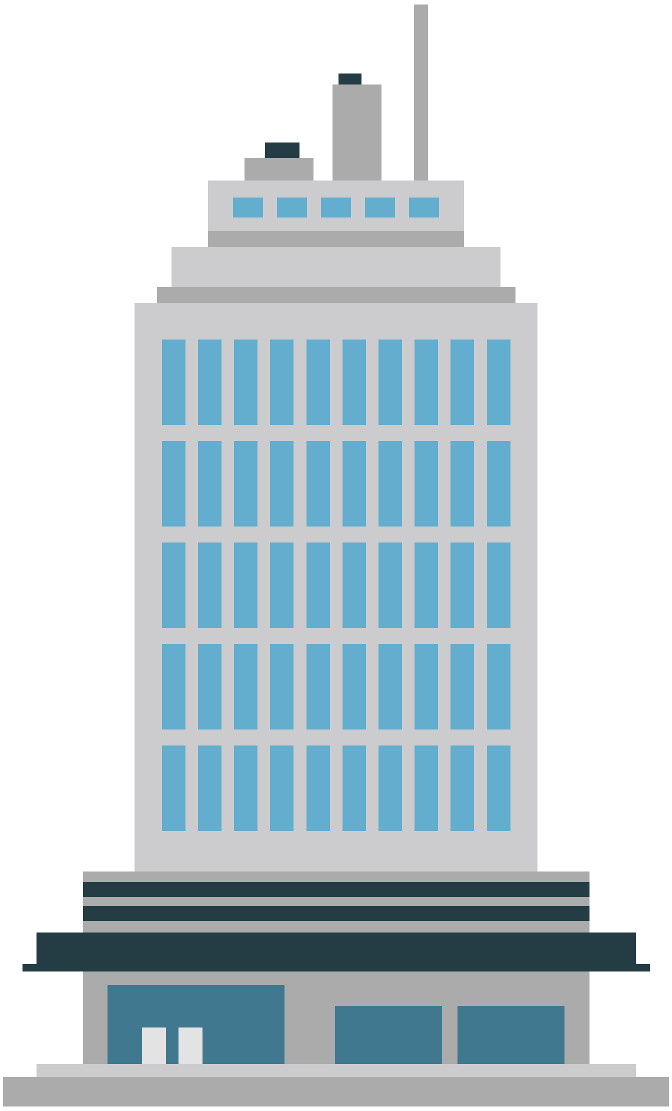


Table 3: Physical parameters of blended cement.

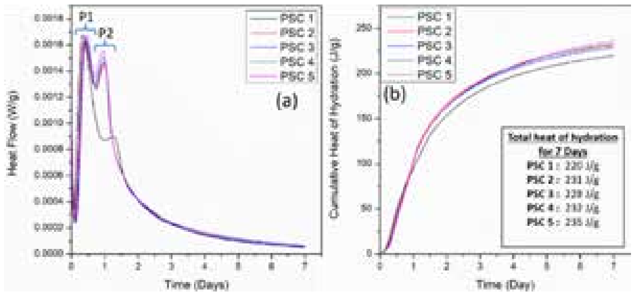
Physical Parameters	PSC 1	PSC 2	PSC 3	PSC 4	PSC 5
Normal Consistency	28	26.75	26.75	26.5	26.5
Soundness Test					
Le chatelier Expansion (mm) [IS: 4031: Maximum 10 mm]	0.00	1.00	0.00	1.00	1.00
Autoclave Expansion (%) [IS: 4031: Maximum 0.8%]	0.003	0.004	0.006	0.008	0.012
Setting time					
Initial setting time (minutes) [IS: 4031: Minimum 30 min]	140	145	135	125	125
Final setting time (minutes) [IS: 4031: Maximum 600 mm]	190	225	230	215	220
Determination of Compressive Strength					
Curing time	**Compressive strength (MPa)**				
1 Day	17.35	19.10	19.35	19.75	18.75
72±1 Hrs (3 Days)	28.53	32.07	29.03	30.66	29.53
168±2 Hrs (7 Days)	38.00	44.93	42.80	44.37	40.90
672±4 Hrs (28 Days)	57.16	64.63	63.83	63.00	61.30

3.4 Determination of Heat of Hydration

The measurement of heat flow and total heat of hydration were measured for 7 days. Fig 6 has demonstrated the Heat flow curve concerning the hydration reaction coordinate (Fig 6. a) and cumulative liberated heat (heat of hydration) concerning the reaction coordinate (Fig. 6.b). The heat flow curve (Fig. 6.a) has demonstrated the two heat flow maxima (Peak P1 and Peak P2, Fig 6. a) for all five samples almost in the same time intervals. After those peaks, the curves were found to be declining in nature. This indicates the occurrence of maximum reaction rates of the cement hydration. Although the curves were found to be declining in nature after these peaks, those didn't meet the baseline or zero (Y axis). This indicates the continuous heat liberation and continuation of cement hydration reaction for all samples. Comparing the nature of the curve of all samples it was found that the PSC 1 has demonstrated the Peak P2 with lower height compared to the other four samples. This indicates that some additional exothermic heat flow happened in the other four samples (PSC 2 to PSC 5). Hence it is clear that the addition of GEOFS (PSC 2 – PSC 5) provides some additional reactivity.

Again from the cumulative heat vs time plot (Fig. 6.b), it was found that the cumulative heat of hydration of PSC 1 (for 7 days) is less than comparatively other four samples (PSC 2 - PSC 5). Hence the additional heat of hydration found in PSC 2 – PSC 5 can be considered as contributed by GEOFS reactivity. So the determination of heat of hydration experiment supports the existence of additional reactivity of GEOFS in blended cement hydration.

Figure 6: (a) Heat flow curve concerning hydration reaction coordinate (or time) and (b) Plot of cumulative liberated



3.5 Concrete application

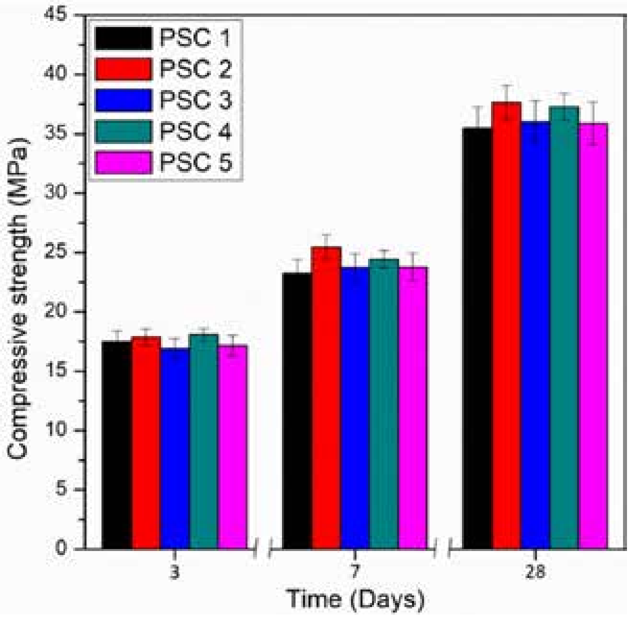
Concrete is the principal mode of application of cement for civil construction. Concrete provides the structural strength of a building or any civil structure in the form of columns, beams, roof basement, precast blocks, etc. Hence lab lab-scale concrete trial has been performed with the developed blended cements (PSC 1 to PSC 5). The concrete mix design, workability of concrete, fresh wet density, and CS after water curing have been demonstrated in Table 4. It was found that all the developed cement samples (without GEOFS and with GEOFS) showed comparable workability (till 1 h) with gradually decreasing slump height for concrete. This supports the compatibility of GEOFS for concrete applications which provides similar workability with control (PSC 1: Cement without GEOFS). Moreover, an increasing fresh wet density of the concrete mix was found while moving from PSC 1 to PSC 5. This can be explained by considering the more replacement of low-density GGBS (Bulk Density: 1.003 g/cc) by high-density GEOFS (1.222 g/cc) in PSC 2 to PSC 5.

Table 4: Details of concrete trial for blended cements.

M30 Concrete mix design					
Material	Quantity per M3 (Kg)				
PSC Cement	440				
20 mm Aggregate	641				
12.5 mm Aggregate	427				
Crushed stone sand	725				
Water	185				
Results of Concrete Trial					
Parameter	PSC 1	PSC 2	PSC 3	PSC 4	PSC 5
Fresh wet density (Kg/M3)	2403	2412	2418	2420	2423
Workability (Slump Height); Unit: mm					
Initial	125	135	130	135	130
30 min	100	100	100	95	100
60 min	65	65	70	70	65
Determination of Compressive Strength					
Curing time	**Compressive strength (MPa)**				
72±1 Hrs (3 Days)	17.50	17.86	16.90	18.05	17.15
168±2 Hrs (7 Days)	23.24	25.47	23.73	24.43	23.77
672±4 Hrs (28 Days)	35.47	37.60	36.00	37.27	35.87

Compressive strengths of the casted cubes have been demonstrated in Table 4 and Fig. 7. Concrete cubes for all five cement samples demonstrated gradually increasing CS with a progressive time scale (3 days-7 days-28 days). This indicates that the normal cement hydration process with time in all concrete cubes, is in progress. Comparing the trend of CS of the concrete cubes of all five cement samples (PSC 1 to PSC 5), it was observed that 28 days' CS of PSC 2, 3, and 4 is higher than PSC 1. PSC 5 showed a similar CS to PSC 1. This indicates that the addition of GEOFS shows a positive effect on strength gain for the dosage of 2.5 % to 7.5 %. Beyond that, some negative effects appear which cause the decrease in CS. This result exactly reflects the trend of CS that appeared for the mortar cubes (Table 3, Fig. 5). Hence GEOFS can be considered as a potential supplementary cementitious material as well as a performance enhancer for PSC cement making, to provide enhanced compressive strength by addition in an optimized dosage (2.5 to 7.5 % w.r.t total cement).

Figure 7: Compressive Strength Vs Curing time plot of concrete cubes of blended cement.



4.0 CONCLUSIONS

This experimental work has explored EOF slag as a value-added, potential supplementary cementitious material, which was almost untouched from the aspect of utilization so far. Mineralogical and microstructural analyses using different advanced analytical techniques have found that EOF slag is rich in minerals and has significant potential to be recycled. The optical polarizing microscopy and XRD analysis have revealed that the material is highly crystalline. Moreover, the qualitative XRD analysis has shown that there are some common cementitious crystalline phases of EOF slag and Portland cement clinker like di-calcium silicate and tri-calcium silicate. There is another crystalline phase named Zeolite, which shows good pozzolanic behavior for cement hydration. The developed blended cement with a 2.5 to 7.5 % addition of GEOFS has demonstrated significant improvement in compressive strength for both mortar and concrete applications, compared to the control sample (PSC 1, without GEOFS). The heat of hydration determination by the isothermal calorimetry technique has proven the existence of additional reactivity of GEOFS in cement hydration. Hence it is believed that this present work will enlighten a new route of application of a steel plant waste material(EOF Slag) to make a value-added material like cement. This is a potentially sustainable approach from the aspect of waste management as well as circular economy.

NOMENCLATURE

EOF	Energy optimization Furnace
SCM	Supplimentary Cementitious Material
PSC	Portland Slag Cement
OPC	Ordinary Portland Cement
GEOFS	Ground EOF Slag
XRD	X-Ray Diffraction
C2S	Dicalcium Silicate
C3S	Tricalcium Silicate
C3A	Tricalcium Aluminate
C4AF	Tetracalciumaluminoferrate

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Transition of Cement Industry towards net zero-Sustainability vs Opportunity- A Shree Cement stride

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ABSTRACT

The transition of the cement industry towards net zero is not just a sustainability imperative, but also a significant opportunity for process and product innovation, market expansion for low carbon cement & concrete and potentially access new market segments focused on sustainability. Thus creating a pathway for future growth by achieving net zero requires substantial investment in research and development, adoption of new production methods, and policy support to overcome the technical challenges involved.

The cement industry is becoming more sustainable by using less energy, reducing emissions, and using alternative materials and fuels. Key aspects are described below.

SUSTAINABILITY ASPECTS:

- Reduced environmental impact: The primary goal is to reduce greenhouse gas emissions from cement production, a major contributor to climate change, by implementing cleaner technologies and alternative materials.
- Resource efficiency: Transitioning to net zero encourages optimizing raw material usage and energy consumption within the production process.
- Circular economy: Incorporating recycled materials and waste streams as alternative fuel and raw material sources can further reduce emissions and promote sustainability.

OPPORTUNITY ASPECTS:

- Market differentiation: Offering low-carbon concrete products can attract environmentally conscious customers and give companies a competitive edge.
- New market segments: Emerging green building standards and government

regulations are driving demand for sustainable construction materials, opening up new market opportunities.
- Innovation driver: The pursuit of net zero necessitates research and development of innovative technologies like carbon capture and storage (CCS), leading to advancements in cement production.
- Investment potential: Green financing and sustainability-focused investors are increasingly looking to support companies actively transitioning towards net zero.

KEY CHALLENGES IN THE TRANSITION:

- Technological limitations: Current technologies for low-carbon cement production are still in development and may not be widely scalable.
- Cost considerations: Implementing new technologies can involve significant upfront costs, potentially impacting profitability.
- Policy landscape: Regulatory frameworks and incentives are crucial to encourage the adoption of sustainable practices across the industry. Overall, while the transition to net zero in the cement industry presents significant sustainability challenges, it also opens up a substantial opportunity for companies to innovate, capture new markets, and establish a leadership position in the growing demand for sustainable construction materials.

The transition of the cement industry towards net zero is not just a sustainability imperative, but also a significant opportunity for process and product innovation, market expansion for low carbon cement & concrete and potentially access new market segments focused on sustainability. Thus creating a pathway for future growth by achieving net zero requires substantial investment in research and development, adoption of new production methods, and policy support to overcome the technical challenges involved.

INTRODUCTION

The Cement industry is regarded as a hard-to-abate sector in terms of reducing its carbon footprint. In recent times, the industry is increasingly witnessing more stringent environmental regulations and need for eco-friendly sustainable products. Shree cement actively promotes sustainability as its core business strategy with a focus on the preservation of natural resources and enhancing resource use efficiency. Shree Cement has not added any new thermal power capacity over the last few years and would progressively reduce the share of existing thermal power in its overall power consumption. Keeping this objective in mind, it has also rapidly scaled up its renewable power capacity, which has risen from 244 MW in FY 2020-21 to 480 MW in FY 2023-24.

The cement industry is becoming more sustainable by using less energy, reducing emissions, and using alternative materials and fuels.

Shree cement has set Science Based Targets to reduce its carbon emissions.Initiatives and developments undertaken by the Shree cement towards Net Zero emissions are as under:

- Preheater cyclones and Calciner to reduce thermal energy consumption
- Waste heat recovery systems from clinker kilns
- Solar power
- Alternative materials and fuels
- Green cements (PPC, PSC & CC) to reduce CO2 emissions using industrial waste, such as fly ash and blast furnace slag, synthetic gypsum in production of cement
- Using biomass and plastic waste as fuels
- Using admixtures to reduce the amount of cement needed in concrete

Shree cement maintained its leadership position in utilizing green electricity (Waste Heat Recovery, Wind and Solar) within total electricity consumption. The Company has consistently overachieved its targets in PAT Cycles and has been honored with the 'Best Performer' award for achieving the highest number of energy-saving certificates in both PAT Cycle I and PAT Cycle II by the Bureau of Energy Efficiency.

INITIATIVES UNDER DEVELOPMENT

- Using green hydrogen as a fuel.
- Using carbon capture, utilization, and storage (CCUS) to prevent CO2 from being released.
- Using carbon mineralization to convert CO2 into stable mineral forms.
- Using precast refractories.
- Using advanced blending techniques.

The Company's initiatives to minimize its water consumption including installation of Air-Cooled Condensers in its thermal power plants and the establishment of Waste Heat Recovery based power plants have been highly successful. A case study of WHR plant is discussed below.

In cement industry utilization of heat of waste gases is a hot topic and not picked up in India due to high cost of installation and technological risk.

SCENARIO BEFORE WHR

In the clinker burning process, a large amount of heat is consumed for burning limestone at 1450 degree C to form clinker. From the total heat consumed in the burning process, around 55% is for burning process and the rest 45% is discharged as sensible heat through the exhaust gases of Pre-Heater(PH), AQC, radiation & sensible heat carried out by clinker. However, around 10% of the heat, extracted from the PHs & AQCs, is used in drying the raw material and coal while grinding. The rest 35% is generally emitted to the atmosphere as waste heat. The waste exit gases from the pre-heater (PH) pass through a Gas Conditioning Tower (GCT) for dissipating the energy then passed through the Electrostatic Precipitator before being released into the atmosphere. However, waste gases from air clinker cooler (AQC) pass through the Electrostatic Precipitator before being released into the atmosphere. A schematic diagram of clinkerization unit (Fig-1) has been sighted here.

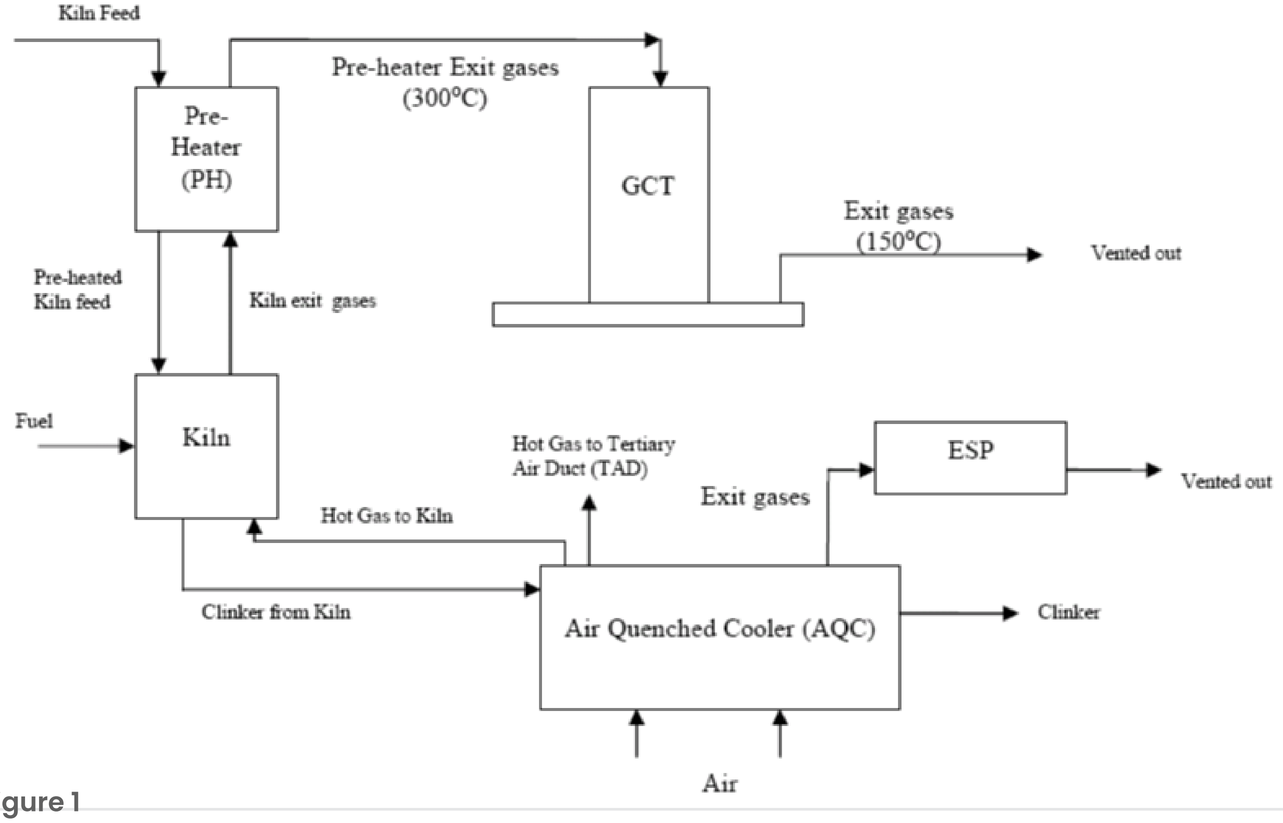


Figure 1

CHALLENGES FOR WHR SYSTEM

- Large capital requirement
- Non-availability of proven technology indigenously.
- Special design requirements due to
  - The dust concentration in the flue gases is sticky, abrasive and corrosive in nature. Hence, the dust can accumulated on the surface of the boiler tubes. With continued accumulation of the dust, the passage of the flue gas through the WHRB can blocked. As a result, a pressure imbalance can be created across the Waste Heat Recovery Boiler and the operation of the kiln can adversely affect. The operation of the kiln will to be stopped for over numbers of hours. Cement manufacturing being a continuous process, losses (production and financial) on account of stoppages are very high.
  - The Waste Heat Recovery Boiler can have

impact upstream and downstream of the system. Dust accumulation on the outside of the boiler tubes would make the heat transfer ineffective initially, affecting the operation of the power plant.

- After the installation of WHRB, increase in pressure drop in Preheater section is most critical issue. This may resulted in low fan margin consequently decreases in production.
- During forced or planned shutdown of the boiler, the pre heater exit gases will again need to be routed through the Gas Cooling tower. For, this purpose, Shree installed a pre-heater exit valve which weighs 25T, is 18 m in height and 3.4m length. As the valve to be installed is huge in size and is heavy, requires time and hard labor to open or closed.
- There are some other technical problems related with WHRB which are further the complication in the smooth operation of the waste heat recovery project. : Dew point limits for WHRB, Water starvation and circulation ratio hampering, Pressure drop permissible in the unit, Operational Constraints of pre heater exit fans etc.

PARAMETERS PREMEDITATED FOR DEVELOPMENT OF WHR SYSTEM FOR POWER GENERATION

- Sources and uses of waste heat
- Upset conditions occurring in the plant due to heat recovery
- Dust content and Buildups in boiler
- Pressure drop across the boiler
- Temp and enthalpy of waste gases
- Dew points of gases
- Availability of space
- Suitable option for co-generation etc.

REMEDIATION

In order to control the problems on the account of the dust, we implemented a dust dislodging system i.e. mechanical hammering system on the left and right of each section of the WHRB. The function of the dust dislodging system, as the name implies, is to remove the dust from the WHRB panels. The salubrious operation of the dust dislodging is very critical for proper functioning of the WHRB.

IMPLEMENTATION OF WHR

In order to successful utilization of the waste heat, Shree first installed R&D boiler at Unit-I. After detail study and review of process and other parameters of R&D boiler, system was designed and implemented for 43 MW cogeneration power units through waste heat utilization in all existing clinkerization units. The project activity involves implementation of new and innovative technology (utilize waste heat from six stage preheater) for the recovery of the waste heat from exit gases of pre-heater and clinker cooler. The schematic diagram of clinkerization unit after implementation of WHR system has been sighted here (Fig-2).

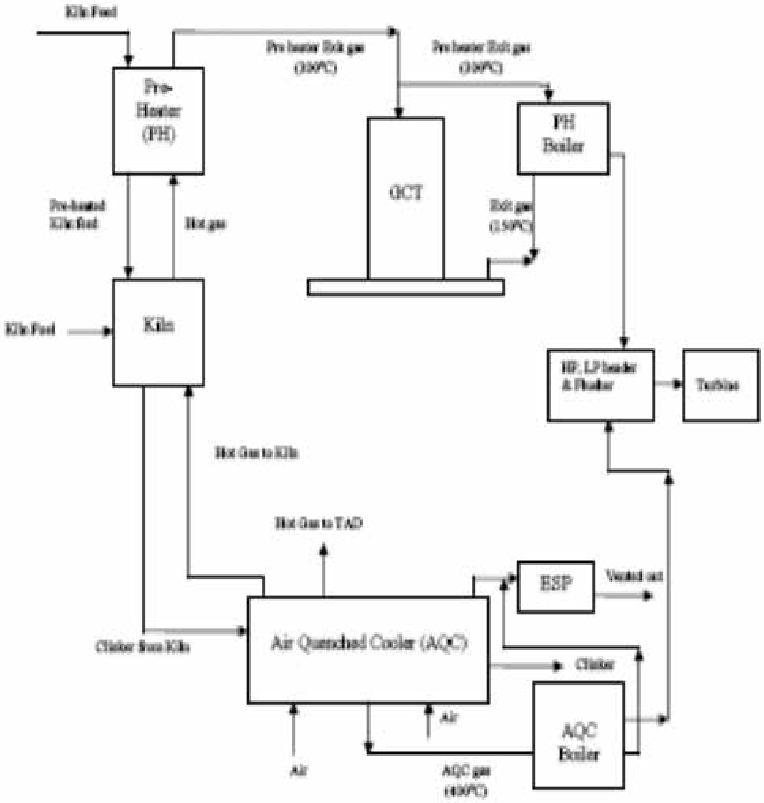
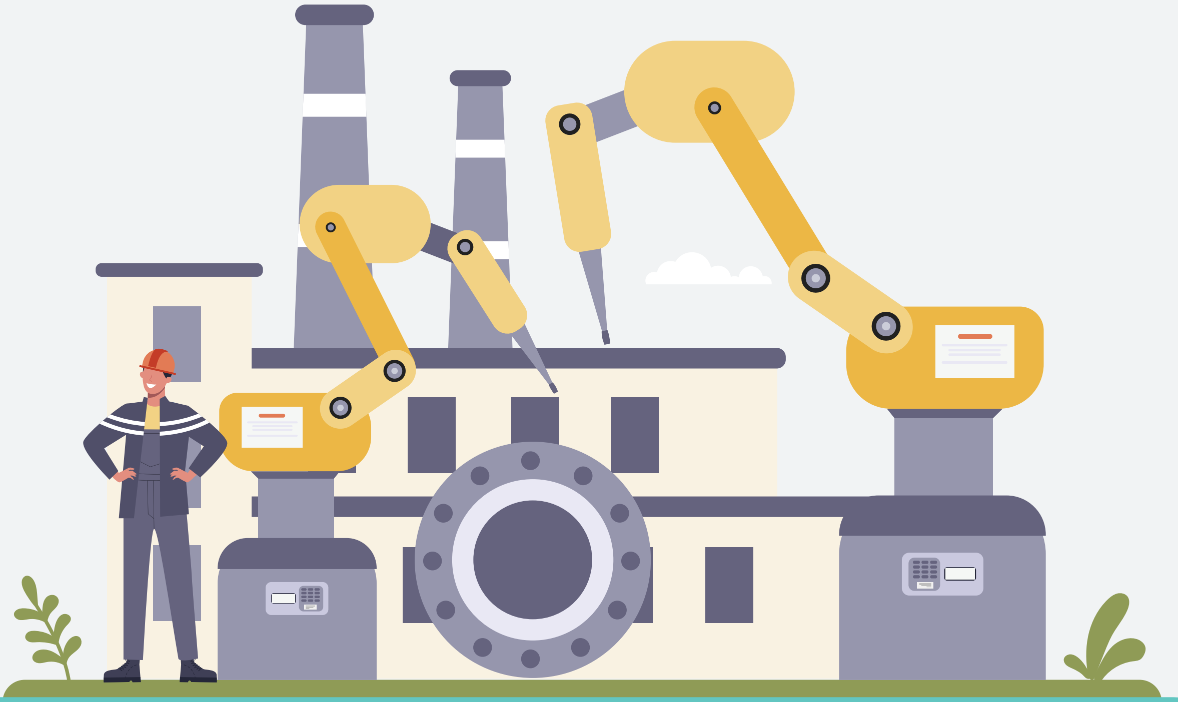


Figure 2

CONCLUSIONS

The transition of the cement industry towards net zero presents a significant challenge for sustainability, but also unlocks a vast array of opportunities for innovation, market expansion, and economic growth by enabling the development and adoption of new low-carbon technologies, materials, and business models, potentially positioning companies as leaders in the green construction market.



Powering the shift: Electrification and the redesign of cement's thermal core

Joonas Rauramo, CEO
Coolbrook

Cement is the backbone of our cities—but the process of producing it is structurally tied to carbon. The cement industry is responsible for around 2.3 billion tons of CO_2 emissions each year—over 8% of total CO_2 emissions—a figure that continues to rise in tandem with global construction demand. The vast majority of these emissions stem from two key elements of cement production: the calcination of limestone, and the use of fossil fuels to reach the high temperatures required for calcination and clinker formation.

Yet for the first time, the process is being meaningfully re-evaluated. Electrification technologies capable of delivering ultra-high temperature process heat—powered entirely by renewable electricity—are moving from pilot lines into full-scale deployment. A technically and economically viable route to decarbonizing cement at its thermal core is now available.

This isn't a tweak at the margins. It's a foundational redesign of how the industry generates heat—and with it, how it produces value in a low-carbon future.

THE THERMAL BARRIER: A HARD LIMIT ON CONVENTIONAL DECARBONIZATION

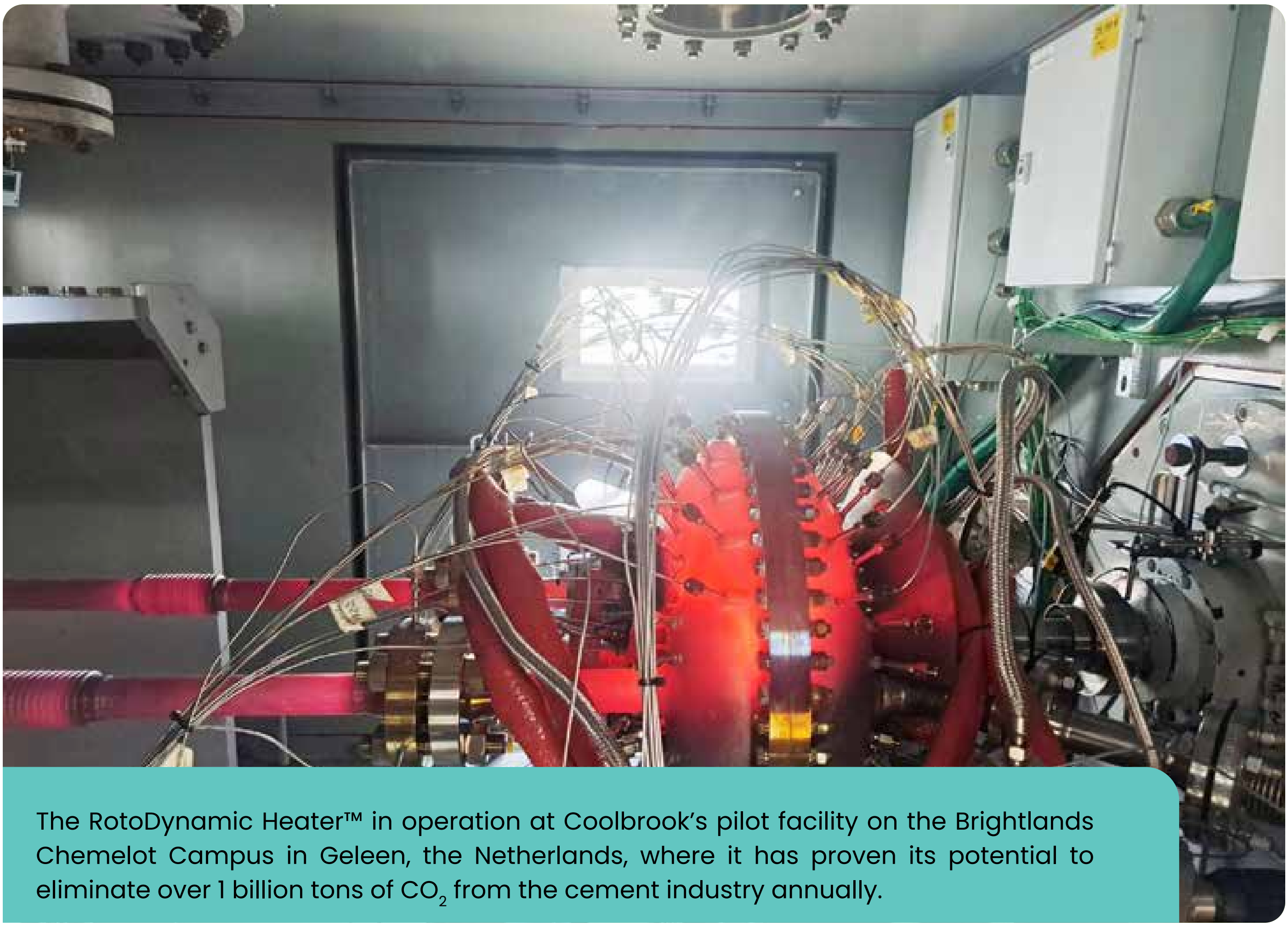
Cement production emits CO_2 in two interlocking ways. Firstly, it comes, from the calcination process itself—when limestone ($CaCO_3$) is converted into lime (CaO), releasing CO_2 as a by-product. Then secondly, from the combustion of fossil fuels, needed to generate the high temperatures required for calcination and clinker production in kilns and precalciners.

These combustion emissions, while often treated as separate from process emissions, are in fact deeply linked. The temperature profile, heating dynamics, and emissions footprint of the entire system is defined by how thermal energy is delivered.

While carbon capture, fuel switching, and material innovation all have roles to play, none address the root thermal paradigm. This is where electrification offers an entirely different model—one that eliminates combustion, reshapes the emissions profile, and introduces new levels of efficiency and control.

DIRECT ELECTRIC HEAT: A TECHNICAL BREAKTHROUGH FOR CEMENT

At the center of this shift is Coolbrook's proprietary RotoDynamic Heater™ (RDH™) technology—a direct electric heating system designed specifically for ultra-high temperature industrial processes. Unlike resistive or induction heating, Coolbrook's RDH™ uses a unique rotor-stator mechanism to impart kinetic energy directly into process gas flows, achieving uniform volumetric heating up to 1,700°C, in milliseconds.



The RotoDynamic Heater™ in operation at Coolbrook's pilot facility on the Brightlands Chemelot Campus in Geleen, the Netherlands, where it has proven its potential to eliminate over 1 billion tons of CO_2 from the cement industry annually.

This non-combustion approach offers several critical advantages for cement production:

- **High thermal efficiency (up to 95%)** that rivals the best fossil-based systems without their emissions profile
- **Zero direct emissions from combustion**, with no formation of thermal NO_x or SOx
- Instantaneous control, allowing for precise tuning of heat delivery across process stages
- **Compact, modular design**, enabling retrofits into existing kiln systems without fundamental redesigns

Crucially, RDH™ can operate in hybrid mode—alongside traditional, fossil fuel burners—allowing for phased electrification and process continuity during integration. Its flexible configuration supports deployment across a range of plant types and process stages.

Use cases in cement manufacturing processes include:

- **Cement grinding:** Fossil-free drying and processing of slag and other constituents using electric heat
- **Calcination:** Full electric pre-calciner replacement, enabling CO_2 separation at source and simplifying carbon capture and storage (CCS) integration
- **Clinker burning:** Supplementary or full heat

replacement in rotary kilns

- **Drying of AFR and Pre-combustion of AFR:** before feeding to the calciner to improve the pyro process operating efficiency
- **Material drying:** Electrified preheating of limestone, clays, and alternative fuels upstream of the kiln
- **White cement production:** Reduction of fossil fuel use by up to 50% with a corresponding increase in throughput

The system also enhances waste heat recovery options and simplifies flue gas cleaning, offering a cleaner exhaust profile with fewer inert gases and particulates.

SYSTEM ECONOMICS AND INTEGRATION STRATEGY

As energy transition continues, its economic logic also becomes increasingly compelling. Renewable electricity is now competitive to conventional energy source across many regions, and its long-term price trajectory is far more stable than fossil alternatives. At the same time, carbon pricing and compliance costs are rising, driving manufacturers toward more future-proof thermal systems.

Hydrogen, though often proposed as an alternative, remains fundamentally mismatched for cement kilns. It is a strongly reducing gas, unsuitable for the oxidizing environment required in clinker formation. It also exhibits low energy efficiency—typically only up to 60% compared to +90% with direct electrification—and currently at far higher costs per delivered MWh than electricity.

RDH™ systems avoid these limitations entirely. They can be deployed in a modular format, integrated incrementally, and paired with on-site renewable generation or grid-supplied green electricity. The result is a heat delivery system that is not only cleaner but also more responsive, maintainable, and economically efficient.

Industry leaders including CEMEX, UltraTech Cement, and Adani-owned Ambuja Cements are already working with Coolbrook to bring RDH™ into real-world cement facilities. These partnerships are testing the system across various plant layouts, material compositions, and operating conditions—demonstrating its robustness and adaptability under industrial loads.

A REDEFINED HEAT SYSTEM FOR A REDEFINED INDUSTRY

For decades, the cement industry has focused on optimizing around a fixed thermal model: combustion. But in a carbon-constrained world, this model is reaching its limits—both environmentally and economically. Electrification isn't simply the substitution of an energy source. It enables a new way to think about heat: faster, cleaner, more flexible, and integrated with digital control systems. This approach unlocks not just emissions reductions, but also broader performance gains—shorter ramp-up times, real-time thermal modulation, reduced maintenance windows, and lower total cost of ownership over time.

Electrification, powered by technologies like the RotoDynamic Heater™, is not an aspirational endpoint, it is a practical, deployable solution that aligns with the cement industry's engineering requirements and business imperatives. And as grid infrastructure evolves and policy support for clean heat accelerates, the case for implementation will only strengthen.

CEMENT'S THERMAL FUTURE IS ELECTRIC

The cement industry does not need to wait for a breakthrough to begin its transformation. The technology exists and the integration pathways are clear. The opportunity—for emissions reduction, cost optimization, and long-term industrial resilience—is real.

By investing in electrified heat systems today, manufacturers can position themselves at the forefront of a global shift, and turn the heat that once defined their emissions into the very mechanism of their sustainability and survival.

KHD Pyro Process: Technological Advancements In Cooling Solutions

Ashok Kumar Dembla, President & Managing Director;
Anurag Johari, Asst Vice President;
Deepti Varshney, General Manager
Humboldt Wedag India Private Limited

PRELUDE

Energy efficiency has become a crucial focus in today's world, emphasizing the importance of conserving energy and promoting clean energy solutions. It plays a significant role in addressing climate change by regulating emissions that affect the global average temperature. The benefits of energy efficiency are vast, including the reduction of greenhouse gas emissions from both direct sources, like fossil fuel consumption and combustion, and indirect sources, such as electricity generation. The increasing emissions pose a significant challenge in combating climate change, necessitating urgent action.

Energy efficiency is a vital yet often overlooked method to reduce the greenhouse gas emissions driving the climate crisis, paving the way for a more sustainable future. Both large and small manufacturing and industrial sectors contribute significantly to GHG emissions. Enhancing efficiency through improved practices, advanced technology, and innovative materials can lower emissions, save energy, reduce waste, and cut costs.

Decarbonizing the global energy system is essential to prevent future increases in global temperatures. The primary motivation for decarbonization is the urgent need to mitigate climate change. Industries like cement and concrete production release greenhouse gas emissions, particularly CO2, intrinsically as a part of their production process.. By reducing emissions from these sectors, we can make substantial progress in addressing the global climate crisis. Decarbonization aligns with international agreements and targets, such as the Paris Agreement, which aims to limit global temperature rise and combat the adverse effects of climate change.

A brief analysis of impact of energy saving technologies on CO2 reduction states that approximately 6 kg CO2/t of cement can be reduced upon deployment of high efficiency cooler. In this stake KHD has done various successful modification to improve the efficiency of KHD cooler which are summarised in coming section.

HIGHLY DEVELOPED CLINKER COOLER PARTS FOR LATEST GENERATION COOLER PFC^2

To increase efficiency and plant availability and to reduce maintenance costs at the same time, KHD Humboldt Wedag has developed the PYROFLOOR® cooler two decades ago. As this third-generation clinker cooler, affecting the efficiency of a cement plant it has a wide impact on the thermal and electrical consumption of the produced product.

Even though the first transition of a KHD PYROFLOOR® cooler (PFC) towards the PYROFLOOR2® (PFC^2) has already been achieved, an improvement of PFC^2 clinker cooler parts is still an ongoing process.

In the following sections, experiences are discussed with existing clinker cooler parts and its evolution into the latest new PYROFLOOR2® parts. This offers even higher state of process efficiencies, maintainability and reliability of a clinker cooler.

COOLER CASSETTES DESIGN FACTORS

The basic concept of a walking floor cooler design is the modular setup of the movable grate. In PFC, part of this is the aeration cassette which has to ensure:

- Preventing fall through (leakage) of fine clinker particles for keeping the the undergrate compartment need and clean.
- Generating as less as possible pressure loss for reducing the power consumption and investment cost of cooling air fans.
- Avoiding any relative movement between clinker particles and metallic surfaces for less wear (providing autogenous protection).

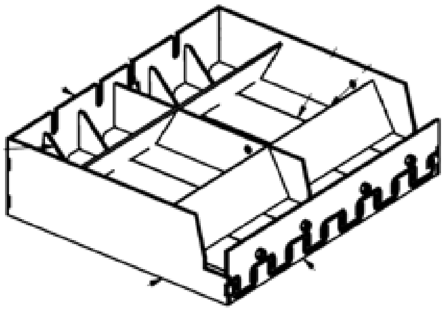
The marked is further demanding a very low pressure loss therefore the KHD´s engineers were targeting optimized cassette design to reduce pressure loss. Following features were implemented:

- Aeration slots design optimized for reduced pressure loss.
- Perpendicular to the direction of clinker flow.
- Maintains the USP of autogenous wear protection.
- Shall be installed using adapter frames on the existing top modules (ready for modification projects).

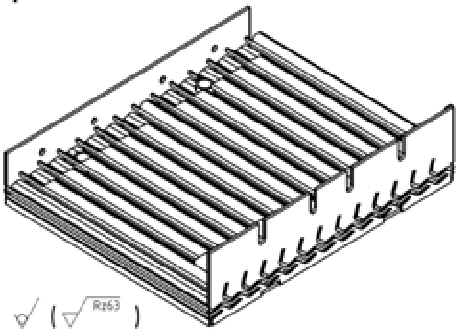
In the following slides the existing PFC^2 aeration cassettes and the new developed optimized cassettes so called “Opti Cassettes” are shown.

Design Features PFC Cassettes

PFC^2 Aeration Cassette



Optimized Aeration Cassette



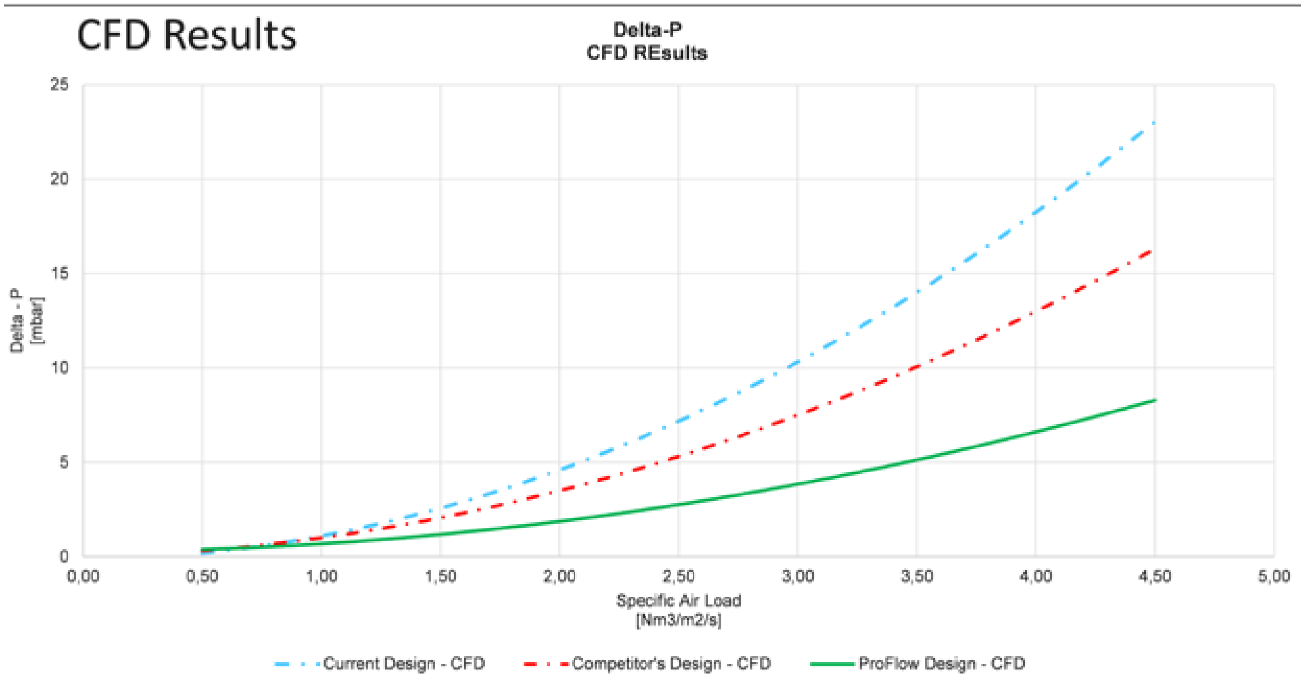
PFC^2		
System Dimension	0,6 mm X 0,66 mm	0,396 mm^2
Aeration slots	12	
Slot Gap	8 mm	
Open Area	0,0564 mm^2	14 %

Optimized Cass.		
System Dimension	0,6 mm X 0,66 mm	0,396 mm^2
Aeration slots	13	
Slot Gap	6 mm	
Open Area	0,0459 mm^2	11,5 %

CFD MODELLING

For evaluating the benefits of the new design features the original cassettes and competitors design was taken as a benchmark for CFD modelling. In the following pictures the simulation of the velocity is patterned. Also, as a result of CFD analysis the pressure loss at different specific air loads as Nm³/m²s are shown in a graph.

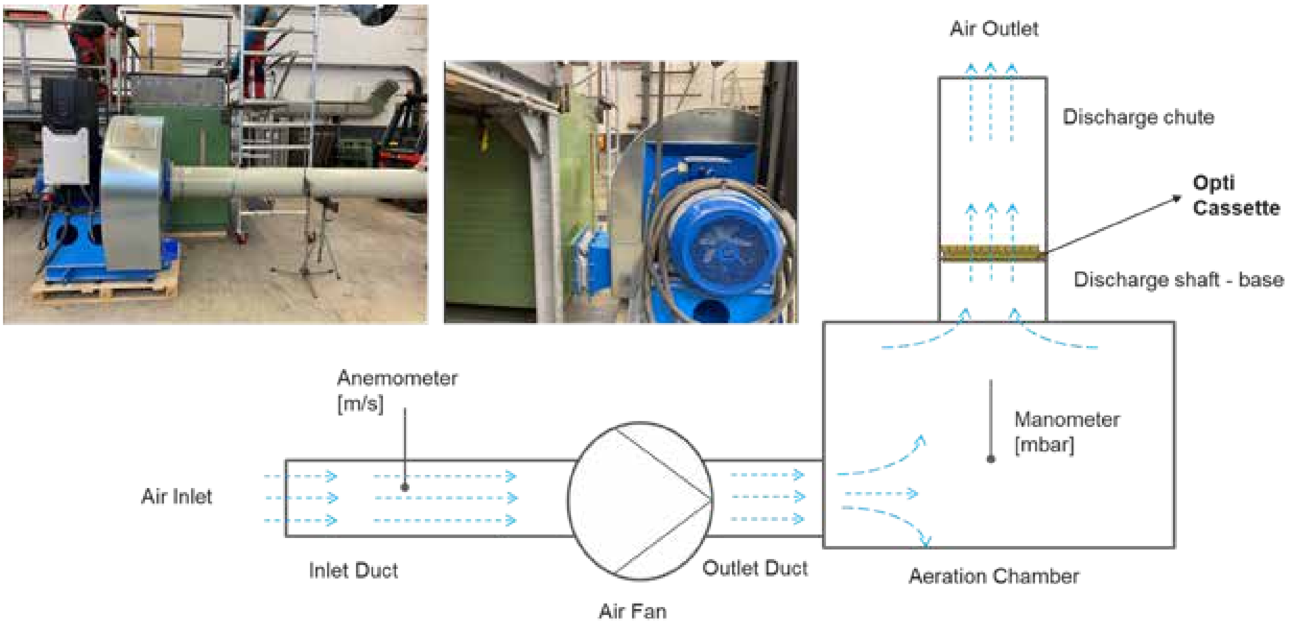
CFD Results of 3rd generation clinker cooler



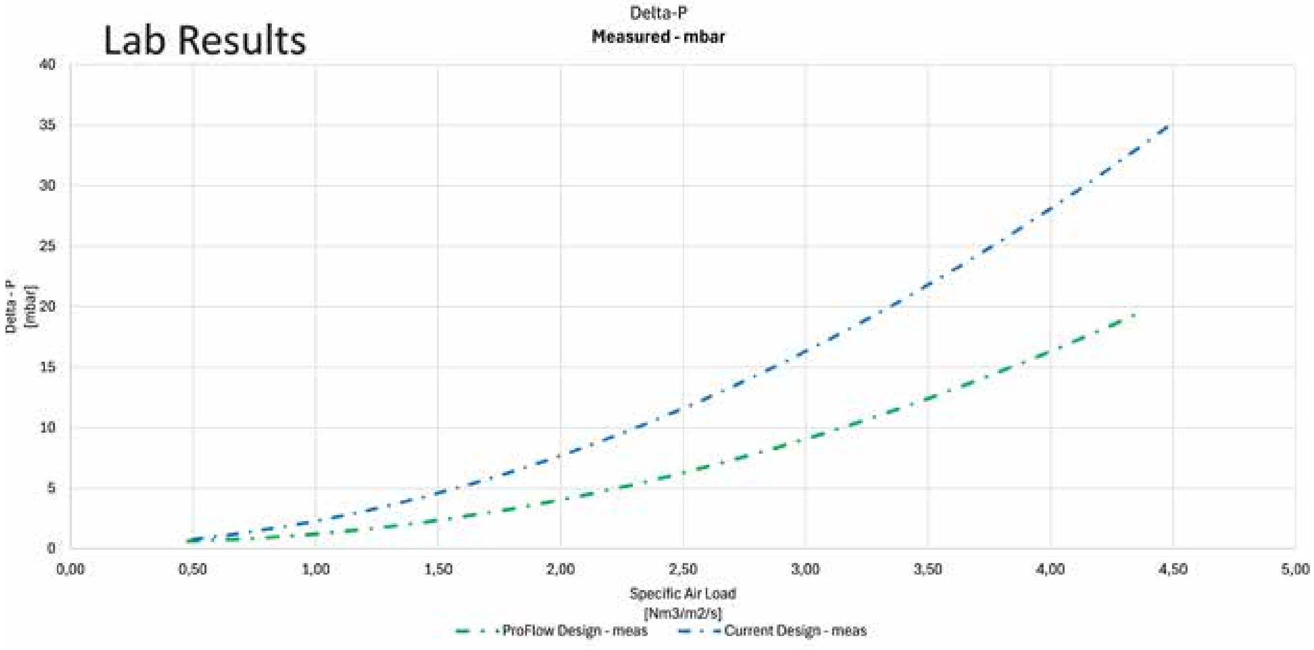
LABORATORY TEST

Before implementing the new cassette design in the field, a validation of the CFD modelling results was done. In the following pictures, the test facility for cassette testing is shown. Pictures of fan and cassette setup as well as a general flow sheet of the test facility are attached.

Laboratory test setup for PFC cassettes



Laboratory test results of PFC cassettes

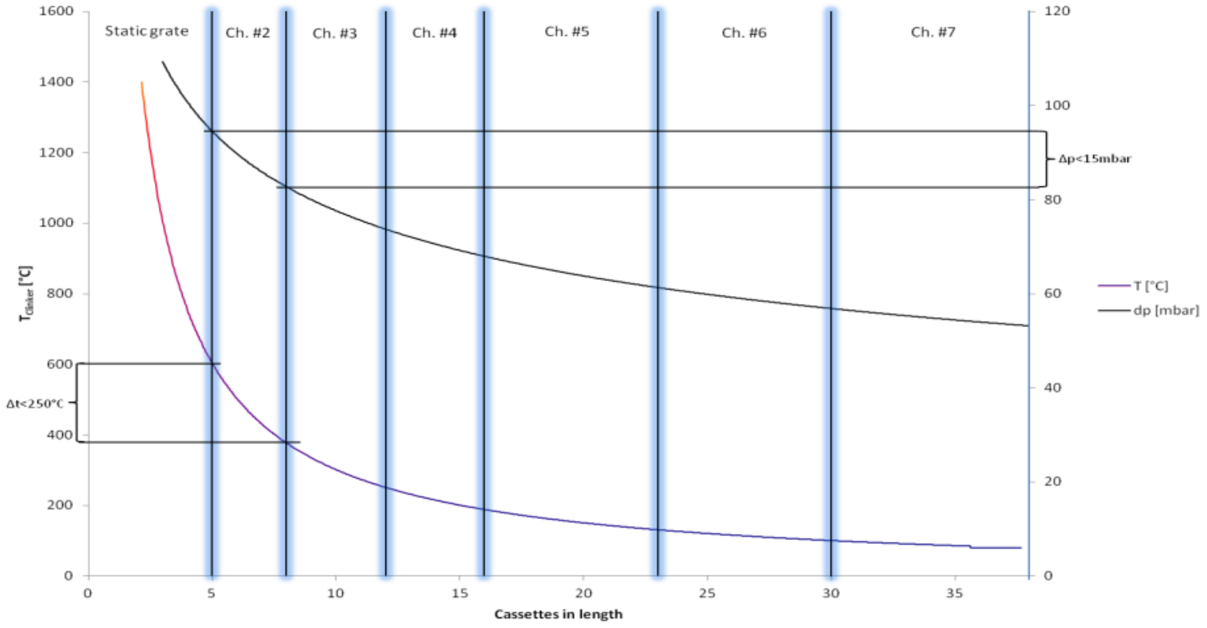


A clear reduction of pressure loss can be seen. CFD results and Measured results have similar trend. However, measured pressure loss is higher than the CFD. In the range 0.5 to 2.0 Nm³/m²/s there is ca. 45 % reduced pressure loss as compared to current PFC² Cassette.

COOLER STATIC GRATE DESIGN FACTORS

Keeping the heat within the kiln line is the mayor requirement of a static grate. A rapid cooling ensures a higher state of heat recuperation. In the following graph, an optimized temperature profile and a standard pressure profile of a PFC is shown.

Laboratory test results of PFC cassettes



The new static grate design was optimized from 12.5° to have an increased inclination of 15° and eliminated steps on the surface to enable 'sliding' movement of clinker from static grate on to the moving lanes. Quick & smooth transition of clinker from static grate to moving lanes. No upward step where plates meet. It allows sliding down of clinker pile on static grate which gives a benefit in "Snowman" reduction. The optimized slot gap ensures better aerodynamic at entry point. Resulting in less pressure loss.

OPERATIONAL UPSHOTS: -

After successful implementation of new design static grate in several project the so called PYROSTATIC is now KHD´s standard in all their coolers. It is implemented not just in their PFC-products but also in their second generation PYROSTEP coolers. It also can be retrofitted to any cooler in the market.

Case study; Plant

With a focus on increased clinker cooling on the static grate, a modification on the static grate of PYROFLOOR® cooler installed in a Romanian plant owned by Holcim. A clear business case was:

- Reduce pressure drop across the static grate plates.
- Optimize the design to allow clinker to 'slide' better from the static grate on to the moving lanes.
- Increase of heat recuperation for higher thermal efficiency.
- Increase of secondary air temperature for higher alternative fuel substitution (ignition temperature for main-burner and calciner fuel).

As a result of this project the following table was conducted with process values.

PYROSTEP® Cooler	Units of measurement		Before Up-grade	After Up-grade	Comment
		Guarantees	Zero Test	Performance Test	
Type of upgrade			Old Static Grate	PYROSTATIC® Retrofit	
Clinker Throughput	t/d	4674	4080	4704	+15%
AF Rate	%	60	50	64	+16%
Cooling Air amount	Nm^3/kgcli	< 2,00; > 1,75	1.56	1.85	OK
Chamber Pressure Static Grate	mbar		97	70	
Power Consumption (static grate fans)	kWh/tcli		1,85	0,90	-0.57
Clinker outlet temperature	°C	130	169	76	OK
Total heat consumption	kcal/kg		884	876	- 8 kcal/kg

CONCLUSION

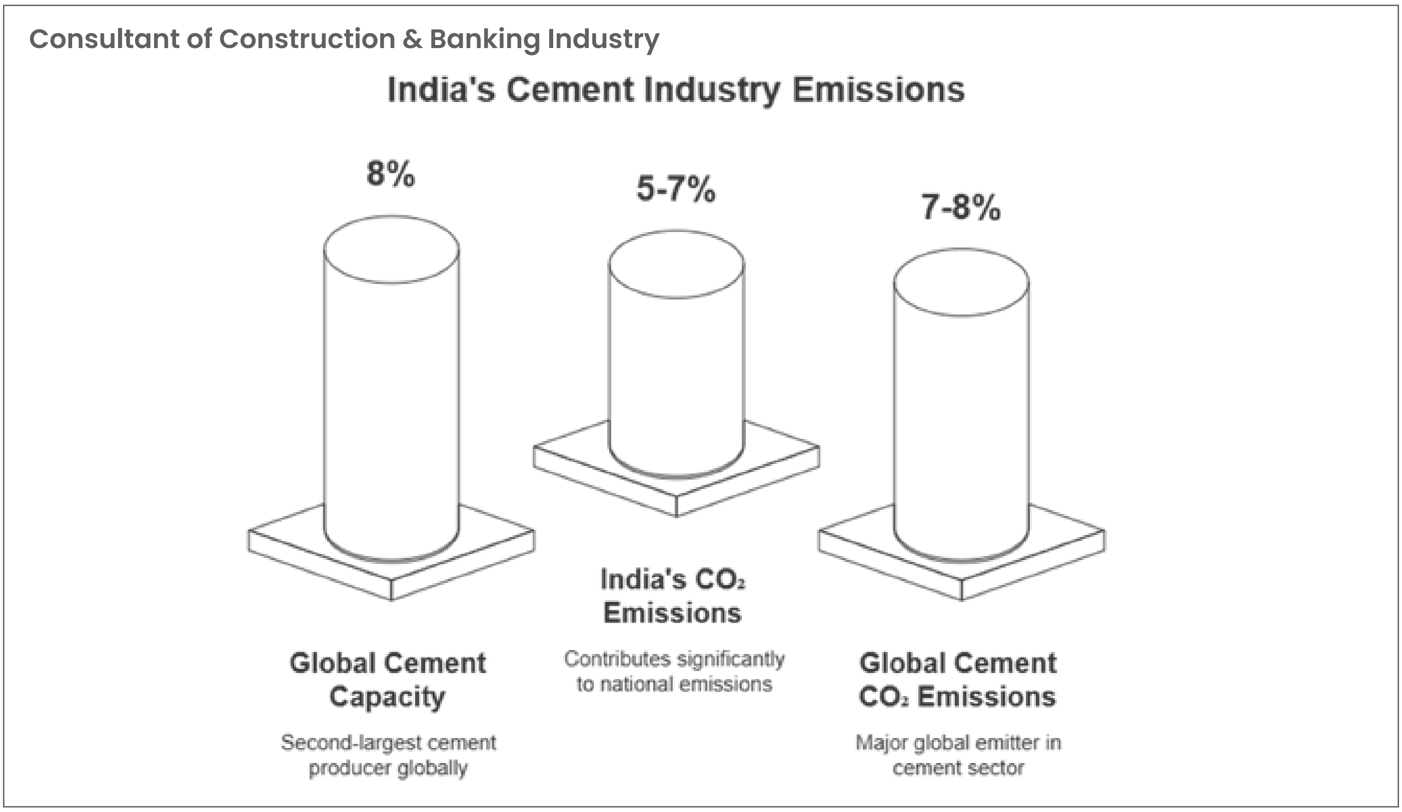
Launching a new product is always an exciting challenge, especially in times where development cycles become increasingly shorter. With now more than 15 years of operation experience, the PFC cooler was improved continuously.

Weak points have been critically analyzed and goal-directed solutions been introduced.

With the new cooler cassettes and new static grate design KHD is answering the questions how to optimize a state-of-the-art cooler. The focus is not just mechanical but also process related. A higher recuperation leading in a reduced thermal input of a plant. A reduced pressure loss for the cooling air fans leading in reduced electrical power consumption. By this KHD Humboldt Wedag with its strong entity Humboldt Wedag India as one of the major architects for engineering and machinery for the cement industry is participating actively in developing and providing solutions for sustainable growth of the industry with moving forward in green steps on the path of lower GHG emissions for low carbon road map initiative taken by all the major cement producers globally.

Cement 2030: Breakthrough Technologies Reshaping a Net-Zero Future

Dr(Prof) Mainak Ghosal
Consultant of Construction & Banking Industry

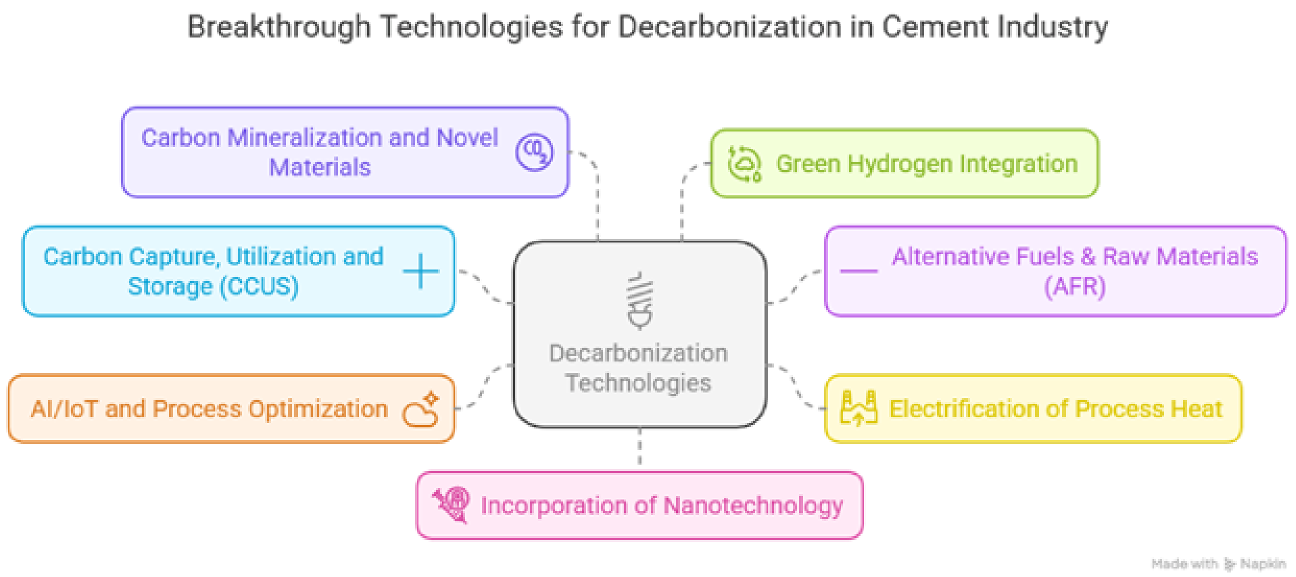


India is the second-largest cement producer in the world, with around 8% of the total installed capacity. In 2019–20, it manufactured cement amounting to approximately 334 million tonnes. Though critical to infrastructure, the cement industry is often called a "hard-to-abate" sector: it is responsible for approximately 5–7% of India's CO_2 emissions (global cement accounts for ~7–8% of CO_2) and releases approximately 0.68 t CO_2 per tonne of cement[IEA, 2023]. Decreasing this footprint is essential if India is to achieve its 2030 climate goals (45% emissions intensity reduction by 2030 and net-zero by 2070).

CURRENT EMISSIONS FOOTPRINT

Cement production releases CO_2 both through the burning of fossil fuels and the calcination of limestone (releasing CO_2). In 2020 the industry's emissions intensity was approximately 0.68 tCO_2per tonne of cement. With increasing demand (per-capita consumption is increasing), overall emissions are expected to rise unless decarbonization picks up pace. The government-industry action plan aims for reducing intensity to 0.56 t CO_2/t by 2030. India's per-capita cement consumption (~280 kg per capita) is still below the world average (560 kg/ capita), suggesting additional potential for growth – but this only makes taking action sooner more necessary.

BREAKTHROUGH TECHNOLOGIES FOR DECARBONIZATION



CARBON CAPTURE, UTILIZATION AND STORAGE (CCUS)

CCUS is crucial for cement: models indicate that even with maximum energy efficiency and fuel switching, cement cannot achieve net-zero without process CO_2 capture[Global CCS Institute, 2024]. India's decarbonisation roadmap (NITI Aayog) lists CCUS as one of the "levers" and expects CCUS to contribute a significant share of the sector's emissions reductions to net-zero. CCUS includes capturing CO_2 from kiln flue gases and either storing it permanently underground (geological sequestration) or utilizing it to produce products (CCU).

Several Indian companies are spearheading CCUS solutions. To illustrate, Dalmia Cement has made proposals (through a 2019 MoU) for a 500,000 t/yr capture facility, and CCU projects by L&T/JSW. CCUS, however, is energy- and capital-intensive and India is as yet formulating regulatory frameworks to support it. Significantly, the revised Energy Conservation Act (2022) and the new Carbon Credit Trading Scheme (CCTS) offer economic incentives to CCUS (projects can accrue tradable carbon credits), but they also stress the importance of legal clarity regarding CO_2 storage. Strong governmental backing – i.e., carbon credit incentives, a carbon-capture finance company, will be necessary in order to rally the $30+ billion necessary for big CCUS in heavy industry.

ALTERNATIVE FUELS & RAW MATERIALS (AFR) AND CLINKER SUBSTITUTION

Substituting coal and petroleum-based fuels with alternative raw materials and fuels (AFR) can reduce fossil CO_2. In India these are biomass (like rice husk, bagasse, plantation waste), industrial wastes (used tyres, solvents, sludge), and municipal refuse-derived fuel (RDF). The use of fly ash, slag, and other by-products as part-cement replacements in the kiln or blended cement is also included. Research into belite-rich clinker phases and alternative binders like calcium sulfoaluminate (CSA) cements shows potential to fundamentally alter the emissions profile [WBCSD, 2023].

Adoption is incremental but progress is being made. For example, UltraTech Cement only uses alternative fuels for ~5.2% of fuel requirements. India's plan predicts this could go up to 35% by 2070. Some firms have established in-between targets – an industry publication mentions a target of ~10% AFR by 2025–26 (including biomass and waste) to cut the use of coal. Similarly, substitution of clinker is on a large scale: blended cements such as Portland Pozzolana Cement (PPC, with fly ash) and Portland Slag Cement (PSC) are ubiquitous, and newer forms such as Portland Limestone Cement (PLC) and Limestone Calcined Clay Cement (LC3) are being launched [EPFL, 2022]. As per the roadmap, clinker factor is to decline from 0.75 (2020) to 0.56 by 2070 through blends – i.e., much less limestone must be calcined. Some plants today already co-process wastes and byproducts, but economic limitations keep them from being widely used: blended cements compare with standard cement on price, and fly ash could become less available as coal plants go offline.

ELECTRIFICATION OF PROCESS HEAT

Cement kilns historically fire coal or petcoke at ~1500 °C. Electric heating provides an opportunity to decarbonize if the power is renewable. New technology is on the horizon: electric arc calciners, plasma or microwave heating, and electric RotoDynamic Heaters to substitute fuel-fired burners.

Indian producers are testing such systems. Late in 2023 Dalmia Cement joined with Sweden's SaltX to trial a fuel-free electric arc calciner at its Rajgangpur (Odisha) factory. UltraTech Cement has signed an agreement with Finland's Coolbrook to commission a RotoDynamic Heater (RDH) at one of its plants, to employ clean electric heat for firing and drying. JSW Cement will also employ Coolbrook's RDH at its Vijayanagar plant (Karnataka) to heat its slag-cement process. These pilots intend to end fossil fuel burning in kiln processes, but hurdles exist: electric kilns have enormous power requirements and are as clean as the grid or local renewables. Still, if ramped up, electrified kilns could sharply reduce emissions, as 100% renewably-powered heat would end stack CO_2 (aside from the intrinsic calcination CO_2).

AI/IOT AND PROCESS OPTIMIZATION

Digital technologies are making process control smarter. Cement plants are adding IoT sensors and employing AI/ML to track and optimize operations: from accurate fuel feeding and preheater temperature control to predictive maintenance of kiln fans and mill drives. Industry analysis observes that AI can deliver energy savings by optimizing raw mix, kiln zones, and minimizing fuel variability. In reality, plants with sophisticated control systems (e.g. model predictive controllers) have achieved noticeable reductions in energy. With "Industry 4.0" solutions expanding, Indian cement companies are deploying sensors and data analysis to drive out efficiencies and cut time down. In the long run, these software systems will be supplemented by hardware improvements, to make thermal and electrical consumption more efficient with little extra emissions.

CARBON MINERALIZATION AND NOVEL MATERIALS

Aside from engineered CCUS, carbon mineralization is an emerging field. Geological research indicates that India's vast basalt basins would be able to store CO_2 safely underground through conversion into stable minerals. Industry is also investigating ex-situ carbonates in the near term: e.g., injecting CO_2 into fresh concrete (e.g., in "carbon cure" technologies) or introducing cement additives that uptake CO_2 as calcium carbonate. Carbonated concrete research in India is in its infancy, but worldwide it holds promise.

At the same time, bio-based products (such as biomass pyrolysis biochar) are being experimented with as partial cement substitutes, which sequester biogenic carbon within the concrete. Certain start-ups globally (e.g. CarbonCure, CarbonBuilt) are working on methods to supply CO_2 to cementitious mixtures. In India, they are largely at the laboratory phase, but interest is increasing in making cement go from a carbon source to a carbon sink, even at the periphery.

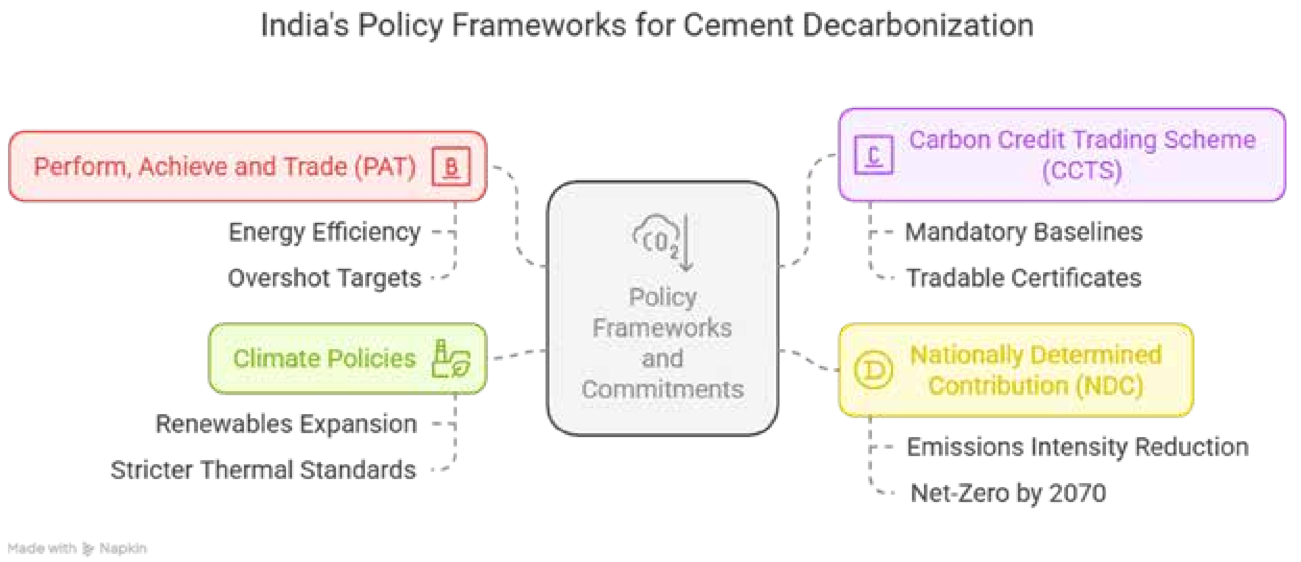
GREEN HYDROGEN INTEGRATION

Green hydrogen (made from renewables) provides another option: it can be used as a carbon-free fuel, or even chemical reactant in cement manufacture. Experiments elsewhere have injected H_2 into kilns (with oxygen) or employed it to produce hydrogen-based precursors (such as so-called "green" clinker). In India, pilot projects remain scarce, but firms and research organizations are looking into mixing hydrogen with coal or employing it to manufacture synthetic lime precursors. High cost and the absence of infrastructure are hurdles, but by 2030 demonstration-scale applications of H_2 in cement kilns or upstream operations (e.g. hydrogen calcinations of calcium carbonate) can be anticipated.

INCORPORATION OF NANOTECHNOLOGY

The use of nanotechnology is revolutionizing material science in the cement sector. Nano-silica additives, for instance, increase the mechanical strength and sustainability of concrete while decreasing the amount of cement needed (ScienceDirect, 2023). Nanoparticles may also be used to create intelligent, self-healing concretes and optimize carbonation processes, directly supporting CO_2 sequestration. In addition, nano-designed membranes may radically enhance carbon capture systems by selectively filtering CO_2 molecules more efficiently.

POLICY FRAMEWORKS AND COMMITMENTS

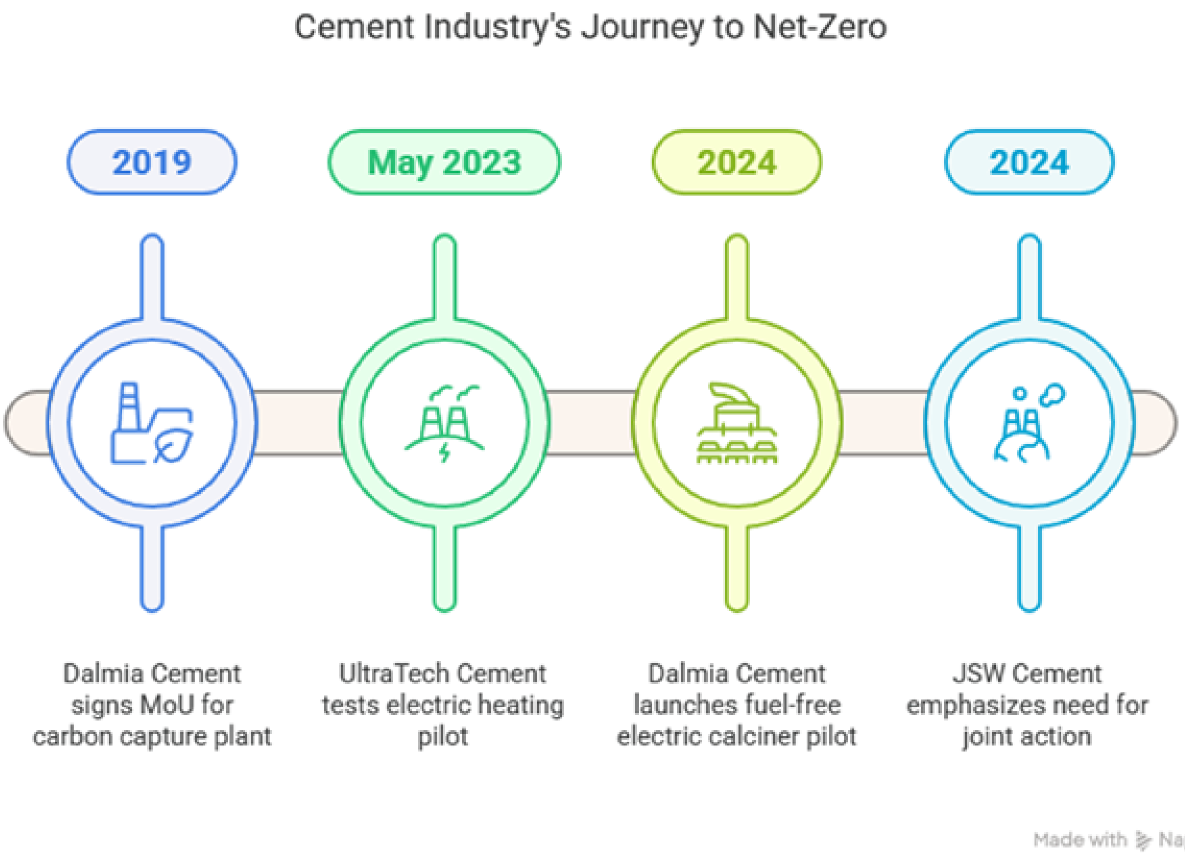


India's policy landscape is changing fast to facilitate cement decarbonization. The Perform, Achieve and Trade (PAT) program has been focusing on cement for energy efficiency for a long time. Cement companies have even exceeded their PAT targets: for instance, in Cycles I and II the industry achieved 81.6% and 48.6% more than its mandated savings respectively. These gains in efficiency provide a solid platform. Drawing on PAT, India modified the Energy Conservation Act (2022) to establish a Carbon Credit Trading Scheme (CCTS). In mid-2024, regulations for this intensity framework were released in their final form. The CCTS places compulsory CO_2 emissions intensity baselines (tCO_2 /tonne output) on nine industries – including the cement industry – and permits those below their targets to earn tradable Carbon Credit Certificates. This actually puts a price on CO_2 at the industry level and should encourage more sustainable practices.

Internationally, India's updated Nationally Determined Contribution (NDC) (2022) pledges a 45% decrease in emissions intensity (base year 2005) by 2030 and net-zero by 2070. Significantly, the NDC does not specifically refer to CCUS as yet, but the industry roadmap (GCCA/TERI) aligns with the 2070 net-zero commitment and even includes an interim target for 2047 (Indian independence centenary). The roadmap prioritizes "built environment" interventions such as optimal use of concrete and sustainable procurement, and it calls for policy interventions – e.g., CCUS subsidies or tax credits, investments in infrastructure, and public works-led demand creation for low-carbon cement.

Moreover, India's climate measures – ranging from increasing renewables (corporate RE100 commitments) to more stringent thermal plant standards – indirectly contribute to cement. The industry is also connected to wider initiatives (e.g. Extended Producer Responsibility for solid waste, potentially redirecting waste streams into cement co-processing).

INDUSTRY CASE STUDIES



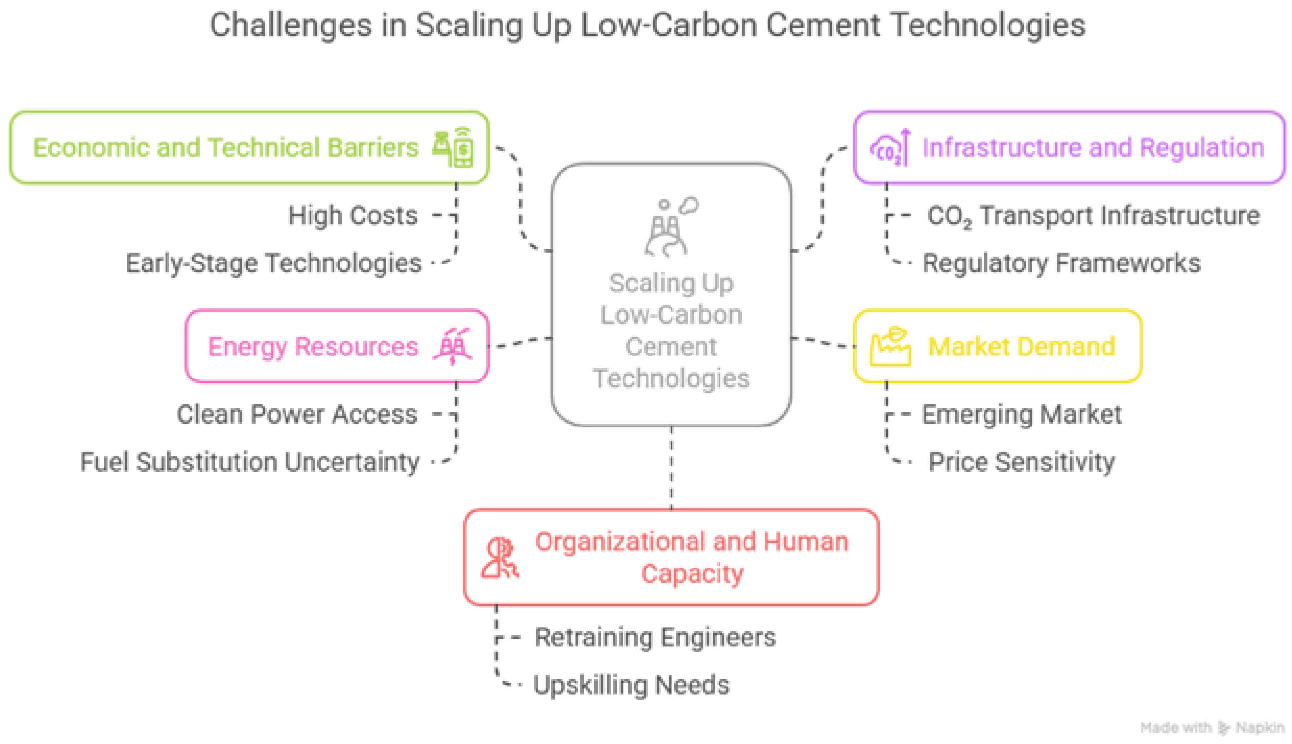
- UltraTech Cement (India's leading cement manufacturer) has been the first to try many initiatives. It has enormously expanded waste co-processing: as of 2023 approximately 5.2% of fuel was sourced from "alternative fuels and wastes" (biomass, sewage sludge, RDF, etc.). UltraTech is also exploring electric heating – in May 2023 it launched a trial of Coolbrook's RotoDynamic Heater, using renewable electricity instead of kiln fuel, for drying alternative fuel feed. Additionally, UltraTech is scaling up waste-heat recovery systems and pledged to 100% renewable electricity (RE100).

- Dalmia Cement (Bharat) has ambitious goals and partnerships. It is planning to be carbon-negative by 2040. In 2019 it signed an MoU to construct a 500 kt/yr carbon capture facility with Carbon Clean Solutions. Recently, Dalmia partnered with SaltX (Sweden) to commission a fuel-free electric calciner pilot in 2024, one of the first in-India demonstrations of an all-electric kiln process. Dalmia is also expanding its utilization of industrial byproducts (ash and slag) as clinker substitutes.

- JSW Cement is adopting new technologies. It is partnering with Coolbrook to fit an electric RotoDynamic Heater at its Vijayanagar slag grinding facility to cut down fuel-based CO_2 JSW has invested in co-processing (utilization of steelmaking industry wastes and biomass) as well as the development of CCS technologies (with research collaborations). In 2024 JSW's chair reinforced that government-business "joint dedicated action" would be required if India is to achieve its 2070 net-zero target.

- Other groups are also adopting new sustainable practices. For instance, Ambuja Cement (Holcim Group) aims for 60% of its energy to come from renewables by 2027, and several mid-scale groups (such as Nuvoco, Orient Cement, etc.) engage in national pilots for green cement. Together, these case studies reveal an industry that is trying things out: changing fuels, piloting CCUS, embracing digital solutions and establishing internal targets on par with global roadmaps.

CHALLENGES AND ROADMAP TO 2030



While there has been such progress, large-scale-up continues to be challenging. The major challenges are:

- Economic and Technical Barriers: Most low-carbon technologies are still expensive. CCUS projects have significant capital and operating expenses, and there is not much commercial experience in cement. Electrified kilns and hydrogen systems are in their initial stages and demand enormous electricity (or H_2 inputs. Even blended cements and Alternative Fuel Replacement (AFR) may suffer supply-chain difficulties (e.g., consistent availability of waste fuel or SCMs) and need investment in new processing lines. Indian cement producers point out that alternative fuels and blended cement introduction has been "limited due to economic constraints.".

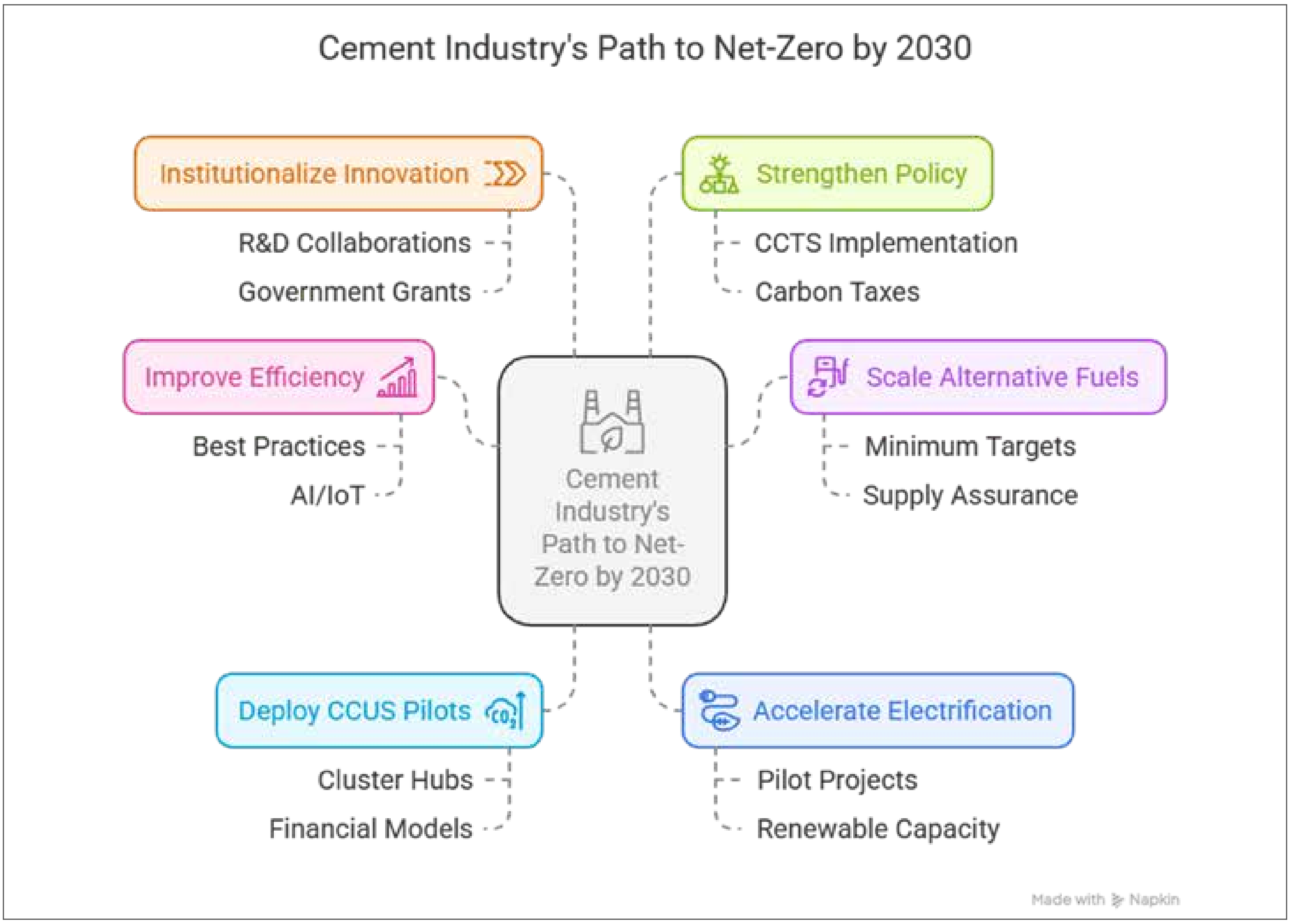
- Infrastructure and Regulation: There is currently no large-scale CO_2 transportation and storage infrastructure in India, and regulation over CO_2 pipes and reservoirs is in infancy. Although there is a market pull offered by the new CCTS, there is still required legal certainty (e.g., rules of liability for CO_2storage). In the same manner, sound biomass or industrial waste supply chains to be used as fuels need to be established and would require alignment with agriculture and waste industries.

- Market Demand: Demand for "green cement" is still just developing. Cement margins have historically been low, and end-users (builders, contractors) have been sensitive to price. Without incentives or mandates (e.g. government buying low-carbon concrete, or awarding "green points" for low-CO_2 material), firms might not be able to pass on the cost to consumers.

- Energy Sources: India's grid is greening, but cement factories will use more electricity if they electrify heat. Having access to clean power is essential. In addition, thermal coal itself is consumed in other industries; its future price and carbon tax prospects make fuel substitution strategies uncertain.

- Organizational and Human Capacity: The shift involves retraining engineers, employing experts (in CO_2 technology, AI analytics, etc.), and dismantling organizational silos. Cement companies are already establishing in-house R&D or innovation cells, but mass up skilling is necessary.

Roadmap to 2030: To meet its intermediate targets, India's cement industry must rapidly deepen deployment of proven measures and bring emerging ones into play. Key actions include:



Aggressively enhance efficiency: New rounds of PAT and energy audits should incentivize plants to implement best practices (high-efficiency preheaters, state-of-the-art coolers, variable-speed drives, WHRS) and AI/IoT for ongoing optimization. Already, energy savings are substantial; by 2030 the industry should solidify an intensity of 0.56 tCO_2/t (2020 target).

• Scale up alternative fuels and clinker blends: The government may stipulate minimum AFR share targets (e.g. 10–15% by 2030) and for reducing clinker factor. This entails ensuring supply – e.g. incentivizing RDF manufacture or pelletizing biomass – and revising standards for blended cements. Wastes such as PET-based PFAs (plastic fuel alternatives) and biomass briquettes may be mainstreamed.

• Build CCUS pilots and hubs: India should have at least one big (>=0.5 Mt/yr) cement CCUS demonstration by 2030. Industry and government can agree on cluster hubs (e.g. Andhra Pradesh or Gujarat) where several plants are coupled with shared capture and transport infrastructure. Carbon bonds, green banks, mentioned in policy reports, could finance these pilots. At the same time, regulatory actions (completion of CO_2 pipeline regulations, resolution of storage ownership issues) need to be taken.

• Advance process electrification: From pilots, cement companies should make pilot projects in the second half of this decade to electrify at least part of their heat (e.g. second kiln line or a clinkering stage). Up scaling renewable electricity capacity (wind/solar + storage) will be required to drive it. Hybrids (bio-coal burners supplemented with electric additives) can bridge the transition.

• Institutionalize innovation: Continue to fund R&D partnerships (TERI, IITs, Innovandi) to advance upcoming solutions (carbon cures, LC3, new binders) to commercial readiness. Government tenders or grants for Concrete Breakthrough projects (as initiated at COP28) may target low-carbon cement recipes and digital platforms.

• Strengthen policy and market signals: Have CCTS implemented with open baselines and comprehensive GHG coverage. Utilize green public infrastructure (bridges, metro, housing) to make low-CO_2 cement specifying. Impose carbon taxes or differential excise (as some nations already do) in order to make emissions costs evident.

CONCLUSION

India's cement sector is on the cusp of revolutionary change. Reaching net-zero emissions by 2050—or sooner—will rely on a harmonious deployment of game-changing technologies: from CCUS and novel clinkers to electrification, hydrogen fuel, nanotechnology, and digitalization. Fast scale-up of pilot projects, facilitated by the CCTS framework and national programs such as the Green Hydrogen Mission, will be essential.

The industry needs to adopt innovation not just to satisfy regulatory requirements but also to achieve competitive edges in a more climate-aware global economy. Cement 2030 sees an industry where old high-emission methods are replaced by intelligent, cleaner, and more sustainable technologies—reshaping the future of infrastructure for generations to come.

By combining these measures, the industry can take its emissions curve sharply downward by 2030, and develop capacity and lower costs for the deeper 2050–2070 transition. India's aspiration to "leapfrog" to cutting-edge cement technologies will need industry leadership as well as policy support. The evidence is clear: technology pathways (CCUS, AFR, electrification, digitalization) are available and being piloted in India; the task left now is scaling them quickly and sustainably.

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Decarbonisation Journey at JSW Nandyal Cement Works

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The cement industry is classified as a "hard-to-abate" sector due to the significant challenges involved in reducing its carbon emissions. It accounts for approximately 6-7% of global greenhouse gas (GHG) emissions. The primary source of emissions in cement production is process emissions, which contribute 55-60% of the total emissions. During the calcination process, limestone, the key raw material, is heated to produce clinker—the primary component of cement. This chemical reaction releases a substantial amount of CO2 as limestone (calcium carbonate) breaks down into calcium oxide and CO2. These emissions are intrinsic to the process, making them difficult to mitigate.

Another key contributor to emissions is fuel emissions, accounting for around 25-30% of the total emissions. This is generated when coal is burned to reach the high temperatures required (over 1,400°C) for clinker production. Additionally, power and transport emissions contribute approximately 10-15% of the overall emissions.

Indian cement companies, including JSW Cement, are actively exploring various strategies to reduce their emissions. JSW Cement, in particular, has demonstrated significant progress in sustainable growth. Over the past decade, the company has increased its production capacity by four times, while simultaneously reducing its emission intensity by more than 50%. This achievement is largely attributed to various decarbonisation initiatives, many of which have been implemented at the Nandyal Cement Works. This article highlights all the initiatives and practices which are being undertaken at this unit.

ABOUT NANDYAL CEMENT WORKS

JSW Cement's Nandyal plant is a state-of-the-art cement production unit located at Bilakalaguduru village near Kurnool District, Andhra Pradesh. The plant is recognized for its environmental friendliness and is one of the most energy-efficient cement plants in India. The plant has an annual production capacity of approximately 2.2 million tons of clinker and 4.8 million tons of cement. Key features of the plant include:

- The use of Blast Furnace Slag as a raw material, which reduces the consumption of limestone and consequently lowers emission intensity.
- Combi-Comflex technology, making Nandyal the first cement plant in India to adopt this technology for enhanced efficiency and reduced emissions.
- Multiple systems designed to control air and dust pollution.
- An automatic packing and truck loading system that minimizes air pollution.
- The consumption of half the amount of limestone required by conventional cement plants.
- Utilization of slag as a raw material, thereby reducing pollution and wastage.

LOW CARBON PRODUCT PORTFOLIO

Since Nandyal uses significant amount of BF slag in its process, it produces a variety of low-carbon cement products, including:

- Portland Slag Cement (PSC), a mix of Blast Furnace Slag and Ordinary Portland Cement (OPC).
- Ground Granulated Blast Furnace Slag (GGBS).
- Ordinary Portland Cement (OPC) in 43 and 53 grades.

RENEWABLE AND CLEAN ENERGY INITIATIVES

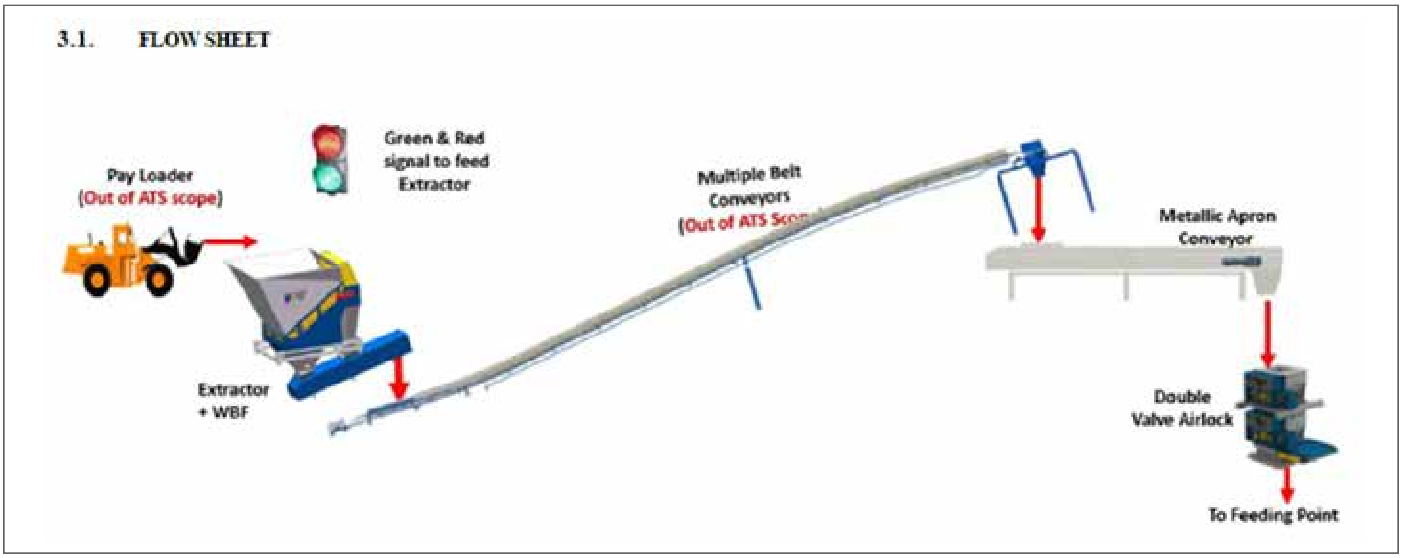
JSW Cement is committed to decarbonizing its operations by investing in renewable energy sources. At the Nandyal plant, solar power contributes significantly to reducing the plant's carbon footprint. The plant has secured power from a 15.5 MW solar plant, which, along with the Waste Heat Recovery System (WHRS), meets approximately 42% of the plant's power requirements.

The Waste Heat Recovery Plant was installed and commissioned in June 2023, generating approximately 78 GWh of electricity without any breakdowns or stoppages.

What makes its WHRS noteworthy is an in-house water harvesting system has also been along with WHRS. This system captures condensate water from air conditioners and stores it in a common reservoir. The system currently collects approximately 200 litres of water per day, which is used for non-potable purposes like washing hands and faces. Since its installation in June 2024, the system has harvested around 60,000 litres of water.

ALTERNATIVE FUEL RESOURCES (AFR)

Nandyal Cement Works has been actively involved in co-processing waste for the past six years. The plant gradually upgraded its Alternative Fuel and Raw Materials (AFR) feeding system, which resulted in a significant increase in the Thermal Substitution Rate (TSR) from approximately 4% to 18% over five years. This initiative contributes to the reduction of fossil fuel consumption and further lowers the plant's carbon footprint.



Pre-processing & Storage

- 60X60 AFR storage shead with preprocessing shreadder system inside the shed.
- Water proof and chemical proof flooring
- Fire and flame proof electricle fittings and Lighting.
- Fire hydrant system
- Provision for EOT grab hoist of max 5 M3 capacity.
- Belt conveyors
- Screen, magnetic seperator

Co-processing system: Soild

- Extractor/Hop feeder of 40 TPH
- Weight Bridge Feeder of 40 TPH
- Above both at the feeding point replacing the Screw feeder and the steep conveyor
- All existing belt conveyors capacity 40TPH
- Metallic apron conveyor 40 TPH
- Heavy duty double flap valve/gate 40 TPH
- Heavy duty slide gate below doubble flap valve

Co-processing system: Liquid

- Capacity: 6 KL/hr
- Storage -50 KL
- Quality deviations minimized ,50 KL tank helped to achieve uniform quality of PH,Chlorides and NCV .
- Fire and flame froof electricle fittings and Lighting.Fire hydrant system

RDF /MSW

Solid Hzardous waste

Multilayer Plastic

Liquid Organic waste

Paper Mill waste

The unit co-processes different types of wastes including liquid solvents, biomass waste, plastic waste/RDF waste, multi-layer plastics in its kilns. It has increased its TSR from ~4% in 2021-22 to 17.7 % in 2024-25.

EV TRANSITION

In its efforts to reduce CO2 emission not just in operations but its value chain also, in 2023, Nandyal undertook a pilot of Electric Vehicles (EV trucks) trials for its logistics operations. JSW Cement is one of the few cement companies to begin EV trials in logistics. This pilot project has been initiated by integrating 5 EV Trucks on the route of its manufacturing operations in Andhra Pradesh and Karnataka. From this pilot project, it has avoided more than 150 tonnes of carbon emissions which is equivalent to the amount of CO2 absorbed annually by 6,000 trees.

In conclusion, JSW Cement's Nandyal Cement Works serves as a prime example of sustainable practices in the cement industry. Through a combination of technological advancements, renewable energy adoption, and waste management initiatives, the plant has made significant strides in its decarbonisation journey, demonstrating that substantial emissions reductions are possible even in the hard-to-abate cement sector.

Implementing the upcoming Carbon Credit Trading Scheme in Limestone Mining

Bhanu Prakash Bhatnagar, Head Mining & Geology
Ambuja Cement Limited

PREAMBLE

India has officially crossed a historic milestone in its climate journey. With the Ministry of Environment, Forest and Climate Change (MoEFCC) notifying the Greenhouse Gas Emission Intensity (GEI) Targets 2025 under the India Carbon Credit Trading Scheme 2023, the country is laying the foundation for a fully functional, domestic carbon market.

The Carbon Credit Trading Scheme (CCTS) is a market-based mechanism that aims to reduce greenhouse gas emissions by allowing the buying and selling of carbon credits. In other words, CCTS is a critical policy framework for reducing carbon dioxide (CO_2) emissions from any industrial process. The CCTS framework allows trading of emission certificates, which in process fundamentally provide market incentives to reduce carbon dioxide. In the context of limestone mining associated with the Cement Industry, it aims to incentivize emission reductions to help this industry. CCTS creates a market-based mechanism where industries can trade carbon credits, effectively putting a price on their greenhouse gas (GHG) emissions. During limestone mining, this means that if a company reduces its emissions below a set target, it can generate carbon credit that it can then sell to other companies that need to meet their emission targets.

INDIAN SCENARIO FOR CARBON MARKET:

India's industrial sector is the backbone of its economic growth—contributing over 25% of GDP and employing millions. However, it is also a significant source of greenhouse gas (GHG) emissions, primarily from steel, cement, chemicals, and power generation. To meet its Net Zero 2070 target, industrial decarbonization in India is not just important—it's urgent. India has pledged at

COP26 to reduce carbon emissions intensity of GDP by 45% by 2030 and to source 50% of power from renewables.

India's Carbon Credit Trading Scheme (CCTS) is a domestic emissions trading scheme (ETS) that plays a crucial role in meeting India's Nationally Determined Contributions (NDC) and net-zero targets. Understanding the India Carbon Credit Trading Scheme 2023. This market-based mechanism is designed to align with India's Net Zero by 2070 commitment while promoting industrial innovation and global competitiveness. The India Carbon Credit Trading Scheme 2023 (CCTS) was introduced to regulate and reduce carbon emissions across major industries by assigning specific Greenhouse Gas Emission Intensity (GEI) Targets to individual entities. The following sectors account for the majority of India's industrial emissions:

- Steel – 12% of total GHG emissions
- Cement – 8% (due to process emissions and energy use)
- Chemical and Fertilizer – High energy intensity and methane leaks
- Textiles & Manufacturing – Significant use of coal-based power

These sectors depend heavily on fossil fuels and lack energy efficiency, making decarbonization complex but essential. These industries can meet these targets either by:

- Reducing their own emissions through clean technologies, or
- Purchasing carbon credits from compliant businesses via the Indian Carbon Market (ICM).

The following notified sectors are affected by CCTS 2023:

- Aluminium manufacturers.
- Cement producers
- White Cement brands
- Refineries
- Portland Pozzolana Cement (PPC) and other cement categories.
- Grinding units and ultra-low emissions plants.

Over 130+ industrial giants are now accountable for their emission intensity per ton of equivalent production. The success of the India Carbon Credit Trading Scheme 2023 will depend on:

- Industry cooperation.
- Transparent governance.
- Policy adaptability.

When implemented efficiently, it could be India's most significant step yet toward a green industrial revolution, with alignment of India's Net Zero Ambitions with larger climate goals:

- Net Zero by 2070.
- Renewable energy target: 500 GW by 2030.
- Hydrogen Mission: Scaling green hydrogen production.

CEMENT INDUSTRY

- Alternative fuels like biomass and RDF (Refuse Derived Fuel)
- Clinker substitution using fly ash, slag
- Carbon capture and storage (CCS) pilot programs
- Role of Green Hydrogen - India is pushing ahead with its National Green Hydrogen Mission, aiming to make it a $12 billion industry by 2030. Heavy industries like steel and cement are expected to be early adopters, replacing coal-based energy with renewable-powered hydrogen.

KEY STAKEHOLDERS FOR CCTS IMPLEMENTATION IN INDIA:

- **Ministry of Power:** Oversees the regulatory framework of CCTS.
- **Bureau of Energy Efficiency (BEE):** Administers CCTS.
- **Obligated Entities:** Industries (e.g., cement, power) required to comply with emission reduction targets.
- **Non-Obligated Entities:** Businesses and individuals who can participate in the voluntary carbon market.
- **Indian Carbon Market (ICM):** The platform for trading carbon credits.

CCTS IN THE MINING SECTOR: The mining sector is energy-intensive and a significant source of CO_2 emissions. Implementing CCTS in this sector involves several strategies:

- Capture Technologies: Utilizing pre-combustion, post-combustion, and oxy-fuel combustion technologies to capture CO_2 emissions from mining operations and processing plants.

- Energy Efficiency: Enhancing energy efficiency in mining operations to reduce overall CO_2 emissions.
- Renewable Energy Integration: Incorporating renewable energy sources, such as solar and wind, to power mining operations, thereby reducing reliance on fossil fuels.
- Geological Storage: Storing captured CO_2 in geological formations, such as depleted mines or deep saline aquifers, to prevent it from entering the atmosphere.

IMPLEMENTING CCTS FOR LIMESTONE MINING:

- The cement industry, which uses limestone as a key raw material, is one of the sectors targeted by CCTS.
- Limestone mining activities contribute to GHG emissions, particularly through fossil fuel combustion and the mining process itself.
- CCTS provides a market-based mechanism for limestone mining companies to reduce their emissions and potentially generate carbon credits.
- This can incentivize companies to adopt cleaner mining practices, such as using renewable energy sources, improving energy efficiency in mining operations, and exploring technologies for capturing and storing emissions.

THE FOLLOWING PROCESS CAN BE FOLLOWED IN A MINE FOR CCTS –

SETTING EMISSION TARGETS:

The government or regulatory body sets Greenhouse Gas Emission Intensity (GEI) targets for mining companies. GEI refers to the amount of GHGs emitted per unit of output (e.g., tonnes of ore).

COMPLIANCE MECHANISMS:

CCTS includes a compliance mechanism, where obligated entities (like Limestone mining companies) are given emission reduction targets. These targets are usually expressed as GHG emission intensity (GHG emissions per unit of output).

Mining companies can achieve compliance with these targets in two ways:

- **Reducing their own emissions:** This involves investing in clean technologies, improving energy efficiency, and adopting sustainable mining practices.
- **Purchasing carbon credit:** If a mining company emits more than its allocated limit, it can purchase carbon credits from companies that have emitted less than their allocated limit.
- **Offset Mechanism:** The offset mechanism allows entities (including limestone mining companies) to voluntarily participate in the market by reducing or removing GHG emissions. This can lead to the creation of carbon credit that can be traded.

INDIAN CARBON MARKET (ICM):

The ICM is the platform where carbon credits are bought, sold, and traded. It provides a unified framework for transparent and efficient carbon trading.

Process flow of CCTS for limestone mining:

- **Target Setting:** The Ministry of Environment, Forest and Climate Change (MoEFCC) sets GHG emission intensity targets for obligated entities in the limestone mining sector. Obligated entities in the mining sector are required to comply with prescribed GHG emission intensity targets. This can be achieved by either reducing emissions or purchasing carbon credits.
- **Compliance:** Limestone mining companies must comply with these targets in each compliance cycle. Mining companies that reduce their emissions below the prescribed targets can generate and sell carbon credits. Conversely, companies that exceed their targets can purchase carbon credits from other entities to comply with the regulations.
- **Monitoring and Reporting:** Companies must monitor and report their GHG emissions. Mining companies participating in the CCTS will need to establish monitoring plans, submit periodic reports, and measure their emissions within defined boundaries. Accredited agencies will verify the reported data to ensure accuracy and adherence to standards.
- **Credit Generation:** If a company reduces its emissions below its target, it can generate carbon credit.
- **Trading:** These carbon credits can then be traded on the Indian Carbon Market (ICM).

- **Sectoral Scope and Methodologies:** The CCTS framework, according to the Bureau of Energy Efficiency, will identify the sectoral scope and develop methodologies for calculating GHG emissions and generating carbon credits. This ensures that the CCTS is effectively implemented and that carbon credits represent real, measurable, and additional GHG emission reductions.
- **Penalties for Non-Compliance:** Mining Companies that fail to meet their emission intensity targets and cannot purchase sufficient carbon credit may face penalties, which could include financial charges or other sanctions.
- **Deepening the Carbon Market:** The CCTS can help deepen the Indian carbon credit market by allowing non-obligated entities to voluntarily purchase carbon credits and by enabling Indian entities to register decarbonization projects and generate carbon credits.

Mining companies can reduce their GHG emissions by adopting various strategies, including:

- **Energy Efficiency:** Implementing energy-efficient technologies and processes, such as optimizing energy consumption in mining operations and using renewable energy sources.
- **Process Optimization:** Utilizing digital tools like AI to optimize mining processes, reduce waste, and improve energy efficiency.
- **Waste Management:** Minimizing waste generation and implementing waste management practices, such as recycling and reuse of waste mining.
- **Carbon Capture, Utilization, and Storage (CCUS):** Implementing CCUS technologies to capture and store carbon dioxide emissions from mining operations.

BENEFITS OF CCTS FOR LIMESTONE MINING:

CCTS can help Limestone mining companies achieve their climate goals, reduce their carbon footprint, and potentially create new revenue streams by selling carbon credits.

- **Incentive for Emission Reduction:** CCTS creates a market-based incentive for companies to reduce their emissions. Companies that exceed their emission targets can purchase carbon credits from companies that have reduced their emissions below their targets, effectively incentivizing emission reductions. CCTS provides a strong financial incentive for mining companies to reduce their emissions and invest in clean technologies.
- **Flexibility and Cost-Effectiveness:** The carbon credit trading mechanism allows companies to find the most cost-effective way to meet their emission targets.
- **Sustainable Development:** CCTS promotes sustainable development in the mining sector by encouraging the adoption of environmentally friendly practices.
- **Meeting Climate Commitments:** By participating in CCTS, mining companies can contribute to India's climate goals and align with the Paris Agreement.

CHALLENGES IN IMPLEMENTING CCTS IN LIMESTONE MINING

- India's Carbon Credit Trading Scheme 2023:

- **Uneven Industry Readiness:** Not all mining sites are equally equipped to meet these emission targets. Small and mid-sized mines & their respective companies may struggle to upgrade technology or shift to renewable energy, unlike major conglomerates.
- **Transparency and Verification:** The credibility of the carbon credit system relies on robust Monitoring, Reporting, and Verification (MRV) protocols. We must think for blockchain-based or AI-powered verification systems to avoid fraudulent trading, similar to systems used by Verra and Gold Standard globally.
- **Policy Flexibility and Feedback Loops:** The Ministry of Environment, Forest and Climate Change has invited public feedback on the policy. It remains to be seen whether the framework will evolve to accommodate emerging sectors like green hydrogen, EV manufacturing, and circular economy solutions.

CONCLUSION:

Industrial decarbonization in India is no longer a choice—it's a strategic necessity. As India moves toward becoming a $5 trillion economy, its success must be low-carbon, inclusive, and resilient. By embracing clean technologies, enabling policies, and stakeholder collaboration, India can become a global leader in green industrialization.

CCTS is a vital technology for reducing CO_2

emissions in the mining and cement sectors. By adopting CCTS technologies and practices, these industries can significantly contribute to global climate goals and sustainable development. The regulatory frameworks and compliance mechanisms in place, particularly in India, provide a structured approach to achieving these reductions.

The notification of GEI targets under the India Carbon Credit Trading Scheme 2023 is more than just a policy move — it is a blueprint for how India plans to decouple economic growth from carbon emissions. With this bold step, the nation aims to balance industrial competitiveness with environmental responsibility, all while unlocking new opportunities for green jobs, tech innovation, and international investment. Ultimately, the success of CCTS will hinge on continued innovation, effective governance, and widespread stakeholder engagement. Realizing the full potential of CCTS will require concerted efforts across government, industry, and civil society to innovate, invest, and uphold rigorous environmental standards.

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