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The Cement Industry can Achieve Greener Concrete and Curb Emissions Through Carbon Capture and Other Innovations Despite the Challenges

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Abstract: Cement production is a major source of global CO2 emissions, accounting for roughly 8%. A significant portion, up to 70%, stems from the chemical process of calcining calcium carbonate (CaCO3) into lime (CaO) to produce clinker, the primary component of cement. Fossil fuels used in blending, crushing, heating, and grinding clinker also contribute to emissions. While renewable energy is growing, decarbonizing the cement industry poses a considerable challenge. Achieving net zero in this sector, balancing emissions with removal or offsetting, is crucial for limiting global warming to 1.5°C and mitigating severe climate change impacts (Bhatia et al. 2024). This paper ultimately emphasizes the scopes and opportunities of cement industry in shaping a sustainable one. Net zero means balancing the amount of greenhouse gases released with the same amount stored or offset so that the temperature has no effect at all & we need to maintain the same during cement manufacturing.

Keywords: *Clinker, Bricks, Concrete, Limestone, Fossil Fuels, Kiln, Carbon Capture and Storage (CCS), CCUS (Carbon Capture, Utilization and Storage), Portland-Limestone Cement (PLC), Fly Ash, Green Concrete, Nano-Silica, Graphene, De-Carbonized, Epoxy Cements, Sublime, Nu-Rock, Rock Weathering.*

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I. INTRODUCTION

Traditional brick production involves baking clay and water mixtures at extreme temperatures, typically between 1,000 to 1,200 °C (1,832 to 2,192 °F). This energy-intensive process relies on fossil fuels, leading to significant carbon dioxide emissions. Note that both the brick and cement manufacturing also consume substantial volumes of water. A study indicates that manufacturing a single ton of ordinary Portland cement requires up to 680 liters of water. This process also involves significant clay mining, causing land degradation, soil erosion, and biodiversity loss. Researchers propose that replacing 35% of Portland cement with silica could render the concrete (A building material made from a mixture of broken stone or gravel, sand, cement, and water, which can be spread or poured into moulds and forms a mass resembling stone on hardening) carbon-neutral. Increasing silica content to 75% would make the cement carbon-negative. (Brahambhatt et al. 2024).

Concrete and cement production are major contributors to carbon dioxide emissions, driving air pollution, global warming and posing significant risks to human and environmental health. With concrete being the second most-used material globally (after water), and cement it's the crucial ingredient, over 30 billion tons are used yearly, and this demand continues to grow with infrastructure projects. (Kullman et al. 2023).

Limestone, cement's main ingredient, transforms into calcium oxide and releases CO2 when heated to approximately 900°C. This calcium oxide is then combined with silica and alumina and heated to 1,500°C to form cement clinker, the binding component. Beyond CO2 from limestone conversion, the fossil fuels used to provide the intense heat for calcium oxide's chemical transformation also release substantial CO2. In total, one ton of cement typically generates 0.8 to 0.9 tons of CO2, accounting for roughly 8% of global anthropogenic CO2 emissions and about 25% of all industrial carbon emissions.

Decarbonizing cement manufacturing is challenging, largely because its standard chemical process inherently releases CO2. The difficulty lies in the lack of affordable and scalable high-temperature alternatives for the necessary chemical reactions. Portland cement is the most widely used cement, foundational for concrete, mortar, stucco, and certain grouts. While cement companies have significantly improved plant energy efficiency, the CO2 from calcium carbonate decomposition remains. Manufacturing and construction industries prefer traditional cement and concrete for their reliable properties and cost-effective, high-volume production for infrastructure, ensuring their continued material of choice status (Gomez et al. 2022).

- *Background:*

Numerous nations have recently pledged substantial cuts to carbon emissions, aiming for 'net zero' in the near future. This goal is rapidly gaining traction as a vital measure to combat climate change and its devastating impacts. Net zero signifies that any ongoing emissions are fully offset by an equal amount of carbon removed from the atmosphere. If we continue to pump out the emissions that cause climate change, however, temperatures will continue to rise well beyond 1.5, to levels that threaten the lives and livelihoods of people everywhere. This is why a growing number of countries are making commitments to achieve carbon neutrality, or "net zero" emissions within the next few decades. It's a big task, requiring ambitious actions starting right now. Net zero by 2050 is the goal. But countries also need to demonstrate how they will get there. Efforts to reach net-zero must be complemented with adaptation and resilience measures, and the mobilization of climate financing for developing countries (News UN, 2 December 2020). C40 is a network where the world's megacities unite to combat climate change. It enables cities to collaborate, share knowledge, and implement meaningful, measurable, and sustainable climate actions. ICLEI, originally established in 1990 as the International Council for Local Environmental Initiatives, is now known as Local Governments for Sustainability. Its mission is to support cities, towns, and regions in tackling complex issues like rapid urbanization, climate change, ecosystem degradation, and inequity. (Banerjee et al. Press Release, DNCC & DSCC, 2024).

Concrete is inescapable. As the world's second-most used material, it forms our roads, the foundations of our homes, and often the walls of our workplaces. However, this widespread use comes at a significant environmental cost: concrete production, particularly cement manufacturing, is a major contributor to carbon dioxide emissions. Cement, a crucial ingredient, is the second-largest industrial CO2 emitter globally, accounting for around 7-8% of total carbon emissions. Reducing these emissions is challenging because most of the carbon is released during the fundamental process of heating limestone, clay, and sand at extremely high temperatures in a kiln to create "clinker," which is then ground into cement.

II. MATERIALS AND METHODS

Cement manufacturing raw materials are clay, limestone, gypsum, fly ash and water etc. But the whole process is powered by Fossil fuels. Cement, a highly emissions-intensive material, currently accounts for approximately 8% of global carbon emissions, with carbon dioxide being a constant byproduct. While alternative "geo-polymer" binders exist, their widespread use is hampered by a lack of scalable raw materials. Ground Granulated Blast-furnace Slag (GGBS), a steel production by-product, is already fully consumed as a cement substitute. However, the raw materials for other sustainable binders – industrial carbon dioxide and abundant global reserves of olivine (magnesium iron silicate) – are readily available. Furthermore, if industrial CO2 supply decreases in the future, affordable direct air capture could serve as an alternative, drawing CO2 directly from the atmosphere.

A key benefit of this technology is how easily it integrates into existing concrete production. It won't require major changes to current practices, which means faster implementation. We can blend the silica with Portland cement right on-site, just like any other supplementary cementitious material (SCM). Below are the developing and deploying technologies and methods that maintain Carbon balances during cement manufacturing in order to shaping the environmental sustainability at large.

- *Recently Developed, Long-Life Low Carbon Concrete Replaces Roughly 80% of its Cement Content with Coal Ash:*

Researchers have innovated a "green concrete" that doubles the recycled coal ash content compared to existing low-carbon concrete. This new material halves the required cement and even outlasts conventional Portland cement concrete. This development is particularly significant given the vast global supply of coal ash, with power stations generating approximately 1.2 billion tons annually. It's a staggering figure and it's also a safe bet that will remain abundant long time into the renewable energy transition stage. Hence, it's an enormous potential material resource and low-carbon concrete manufacturers have been using it as a cement substitute and typically replaces up to 40% of the

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cement. In an environmental sense, this kills two birds with one stone, making use of a massive waste product while cutting down on cement which by itself accounts for around 8% of all global carbon emissions.

Here, the researchers used a mixture of low calcium fly ash, with 18% hydrated lime and 3% nano-silica as strengthening agents, then poured some concrete and started testing its mechanical properties (Figure 1). As a result, High-Volume Fly Ash (HFVA-80) concrete demonstrated a compressive strength increase from 22 to 71 MPa between days 7 and 450. It achieved flexural strengths of 2.7-8.7 MPa, splitting tensile strengths of 1.6–5.0 MPa and an elastic modulus of 28.9–37.0 GPa. It came through regular Portland cement over time when exposed to acids and Sulphates for two years (Blain et al. 2024).

Fig 1 Eraring Power Station is Dwarfed by its Enormous Ash Dam, Australia

- *Cement Industry is Turning to Carbon Capture to Curb Emissions:*

Below Figure 2 shows carbon capture equipment being installed at Heidelberg's cement plant in Brevik, Norway. This project is slated to be operational in 2024, aiming to capture 400,000 tons of CO2 annually (Duhatschek et al. 2023).

Fig 2 Cement Plant in Brevik, Norway, Consisting of Carbon Capture Technology

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Two of the world's leading cement manufacturers, Heidelberg and Lafarge, are well underway in their efforts to integrate carbon capture technology into their operations. Heidelberg alone has outlined nine carbon capture and storage projects (Figure 3) across North America, Europe, and the U.K., with the initial two anticipated to become operational in Edmonton and Brevik, Norway.

Fig 3 A Visual Rendering Depicts Heidelberg's Full-Scale Carbon Capture Plant in Edmonton, Projected to be Operational by Late 2026.

The Brevik plant is projected to capture approximately 400,000 tons of CO2 annually, representing about 50% of its total emissions. In comparison, Heidelberg's Edmonton plant is expected to achieve a significantly higher capture rate of 95% of its emissions.

Fig 4 The Lafarge Cement Plant in Richmond, B.C., Plans to Repurpose its Captured Carbon into Synthetic Hydrocarbons for Plastics, Lubricants, and Cosmetics

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Lafarge announced a new phase where captured carbon (Figure 4) will be used to produce synthetic hydrocarbons for plastics, lubricants, and cosmetics. This demonstrates the concrete and cement industry's multi-pronged approach to net-zero, not solely relying on carbon capture. The Cement Association of Canada notes companies are also phasing out coal and coke, increasing alternative fuel use, and reducing clinker. Despite limitations, the association emphasizes that Carbon Capture and Storage (CCS) remains the sole technology for eliminating process emissions. Combined with bioenergy, clean fuels, and carbon uptake, CCS could lead to carbon-negative concrete.

➢ *Making Concrete in More Environmentally Friendly:*

As the world's most used material, concrete is ingrained in our daily lives, from sidewalks to buildings. However, it's expected to contribute 12% of global greenhouse gas emissions by 2060 which is currently responsible for as much as eight per cent of emissions. But there's a measure to make concrete greener by reducing its carbon footprint. The Global Cement and Concrete Association has promised carbon-neutral concrete by 2050 (Ross et al. 2021).

Let's break it down. Concrete consists of water, aggregate (rock, sand or gravel) and cement, a grey powder that binds it all together. To manufacture cement, we first heat ground limestone, clay and sand at extremely high temperatures in a kiln, this technically forms clinker, which is then ground into cement. There are two reasons why manufacturing cement releases a lot of carbon. One is the combustion of fossil fuels typically used to heat the kiln, and the chemical reaction that releases carbon stored in limestone. Reducing the carbon currently used to fire the kilns is already in progress. Almost all cement producers in Canada use some portion of lower-carbon fuel, such as waste biomass, which is mostly wood left over from things like construction and demolition. The CAC (Cement Association of Canada) estimates these could help reduce emissions by a third, and that the future could mean more biomass as well as natural gas and hydrogen. The industry is also finding ways of changing the composition of cement that it's less carbon-intensive. Portland-limestone cement (PLC) is an example which is a blended cement that uses un-calcified limestone that can reduce C02 emissions by 10 per cent.

Supplementary materials are also being used to reduce carbon. Fly ash, a waste product of coal combustion, can replace some of the cement and companies like Lafarge, Canada are using it. Fly ash currently makes up between 15 and 60 per cent of some cement mixtures and can reduce emissions by proportionate amounts. Slag, a waste product from steelmaking, can replace cement as well. There's also a move to capture carbon at the point of production. There's also a way to recycle existing concrete. It can be used in place of natural aggregates like sand and gravel to lessen concrete's environmental impact and divert it from landfill. The results of a five-year study found it's as durable and strong as conventional concrete.

➢ *Magic Dust! Graphene Addition During Concrete Manufacturing:*

We're aware that the cement industry is a substantial driver of global greenhouse gas emissions, responsible for at least 8% of the total. This makes it a disproportionately large polluter compared to other industrial sectors like iron and steel or oil and gas manufacturing. (Rowlatt et al. 2024). Accordingly, the construction of modern buildings as well as urban infrastructure consumes roughly 8% of the carbon dioxide (CO_2) emissions eventually. Ultimately, concrete's substantial environmental impact highlights the critical need for the construction industry to quickly adopt and extensively use lower-carbon alternatives. This imperative is amplified by global population growth, urban expansion, and improving living standards, which fuel demand. Worldwide, concrete consumption now reaches about 30 billion tons annually - a 300% rise from 40 years ago, exceeds than that of materials such as steel or wood. (Linganna Girish, May21, 2024).

India fortunately consumes far less cement per person than the global average, with figures around 250-270 kg compared to 500-550 kg worldwide. However, China's per capita cement consumption is exceptionally high, typically between 1,750 kg and 1,850 kg, making it the global leader.

➢ *Manufacturing Procedure of Complete Concrete:*

Concrete production begins by mixing sand, gravel, cement, and water, then pouring this mixture into molds. Cement manufacturing itself is a complex process: raw materials like limestone and clay are crushed, then heated to over 1,400°C in a kiln, typically using fossil fuels that cause significant pollution. This heating induces chemical reactions, transforming the materials into clinker—small, hard, spherical particles essential for cement's binding properties. Once cooled, clinker is ground into a fine powder and mixed with gypsum and other additives to create cement. Cement acts as the crucial binding agent in concrete, providing essential durability and strength for construction projects worldwide. A significant chemical reaction during clinker formation is the transformation of limestone ($CaCO_3$) into calcium silicate (Ca_2SiO_4), which is not only vital but also releases approximately 600 kg of CO_2 per ton of cement, contributing to environmental concerns. (Figure 5).

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Fig 5 The Cement Industry is a Major Contributor to Global Greenhouse Gas Emissions.

To lessen concrete production's environmental impact, cement manufacturers, researchers, and engineers are actively exploring ways to reduce clinker use. One key strategy involves replacing a portion of clinker with supplementary cementitious materials (SCMs), such as industrial by-products like fly ash and blast furnace slag. However, the primary challenge is that SCMs often lack clinker's strong binding properties, potentially leading to reduced cement performance.

➢ *Cement Strength Improvement:*

In recent years, Researchers have made a breakthrough, discovering how to incorporate graphene into concrete. This innovation not only enhances the material's strength and water resistance but also, more significantly, allows for a reduction in concrete use by up to 50%.

➢ *Definition of Graphene:*

Graphene is an incredibly strong, carbon-atom material arranged in a honeycomb pattern, resembling a stretched-out, incredibly thin sheet of pencil graphite. It's intensely powerful yet incredibly light, an amazing conductor of electricity and heat, and 200 times stronger than steel. Moreover, graphene is flexible, bending without breaking. These remarkable properties make it a promising material for numerous exciting applications across manufacturing industries.

➢ *Usage of Graphene to Resolve Clinker Issue:*

Since its discovery, graphene has been a focus for scientists exploring its potential to enhance concrete properties. A significant breakthrough occurred in 2014 when researchers devised a method to mix minuscule amounts of graphene with water, overcoming its inherent hydrophobicity. This innovation paved the way for graphene's application in concrete. By incorporating just 0.03% graphene into cement, scientists developed a new type of concrete exhibiting remarkable strength, both in terms of compressive and flexural properties. These impressive lab results confirmed graphene's transformative impact, 'magic dust' to concrete, where even a tiny amount dramatically improves its strength.

➢ *Breakthrough in Manufacturing could Slash Emissions from Cement:*

Scientists recently announced a breakthrough in recycling cement from demolished concrete. Cement, the world's most common building material, is a significant source of planet-warming CO2 emissions due to its production process. Recycling cement would drastically cut its carbon footprint. Furthermore, researchers propose that utilizing electric furnaces powered by renewable energy (wind, solar) would eliminate greenhouse gas emissions entirely during cement production. And that would be a great deal (Figure 6). Remember, cement forms the foundation of the modern economy both literally and metaphorically (Rowlatt et al. 2024).

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Fig 6 Scientists Hope to Clean up Cement Making

This is what binds the sand and aggregate in concrete altogether and we know concrete is the most widely used material on the planet after water. It is also a major driver of climate change. But the problem is the material's uniquely polluting chemistry. It is made by heating limestone to up 1600 degree Celsius in giant kilns powered by fossil fuels right now. Beyond direct emissions, the heat used to extract carbon dioxide from limestone in cement production also contributes significantly to pollution. Combined, these processes yield approximately one ton of CO2 for every ton of cement. Scientists have now discovered a novel, cleaner method to circumvent these emissions. This approach involves reactivating used cement through re-exposure to high temperatures – a well-established chemical process already scaled in cement kilns. The key innovation is demonstrating this can be achieved by utilizing waste heat from other heavy industries, such as steel recycling. When we recycle steel, we add chemicals that float on the surface of the molten metal to prevent it reacting with the air itself and creating impurities (Figure 7). This is known as slag actually. Scientists spotted the composition of used cement is almost exactly the same as this slag used in electric arc furnaces.

Fig 7 Flames Emerge from the Top of an Arc Furnace as the Material that will form the Slag is Added to the Molten Steel

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The reactivation of old cement at high temperatures in furnaces has been successfully demonstrated. Crucially, the use of electric arc furnaces allows for powering the entire cement production process with renewable energy, leading to complete decarbonization. This 'electric cement' is also projected to be more economical to produce, as it harnesses what is essentially waste heat from heavy industries like steel recycling. Such a process could be universally adopted, potentially slashing global cement-related emissions.

➤ *Scientists can Make Zero Emission Cement:*

According to recent researchers there were a step closer to solving one of the trickiest problems in tackling climate change in regards to concrete; i.e., how to keep making cement despite its enormous carbon footprint. First, engineers from Britain's University of Cambridge have shown that cement can be recycled without the same steep cost to the environment as making it from the scratches. Ideally cement binds concrete together but the whitish powder is highly carbon-intensive to produce, generating more than triple of the emissions of global air travel. Demand for concrete is already the most widely used construction material on Earth. But the notoriously polluting industry has struggled to produce it in a less harmful way to the climate and human. The team at Cambridge believes that it has a solution, pioneering a method that tweaks an existing process for steel manufacturing to produce recycled cement without the associated CO2 pollution to air. To produce cement, the basic ingredients concrete & limestone must be fired in kilns at very high temperatures usually achieved by burning fossil fuels like coal. On top of that, limestone produces significant additional CO2 when heated (Perry et al. 2024).

The cement industry alone accounts for nearly eight percent of human-caused CO2 emissions, more than any country except China and the United States. According to industry figures 14 billion cubic meters of concrete are cast every year and more still will be needed as economies and cities growing in the future world (Figure 8). The International Energy Agency says that if emissions from the cement industry continue to increase, a pledge of carbon neutrality by 2050 will almost certainly remain out of scope. Many efforts to produce low-carbon or so-called "green cement" are too expensive or difficult to deploy at scale till now by relying on unproven technologies or don't come near zero emissions yet.

Fig 8 Some 14 Billion Cubic Meters of Concrete are Cast Every Year Around the Globe, According to Industry Figures.

The Cambridge researchers devised an ingenious solution by re-imagining a critical step in the established steel recycling industry, which employs electric furnaces. They cleverly replaced a key ingredient in this process with old cement salvaged from demolished buildings. This not only avoids waste but also yields recycled cement ready for concrete, effectively circumventing the carbon-intensive superheating of limestone in kilns. Without such circular economy innovations, achieving the Paris Agreement's crucial 2050 net-zero CO2 targets would be impossible given concrete's current production methods.

➤ *Carbon Free Cement is Now a Step Closer for the Researchers:*

Groundbreaking advancements are drastically reducing emissions from concrete, the world's most destructive material. Only water is more widely used globally. This universal grey substance is fundamental to human civilization, forming everything from our homes and hospitals to vital infrastructure like airports, dams, and underground networks for transport and utilities. The modern world as we know it would be unimaginable without concrete. Beyond its recognized environmental toll, concrete is often deemed the most destructive material on Earth (Figure 9). Its detrimental effects extend beyond simply burying fertile soil, obstructing rivers, and suffocating habitats. Acting as a rigid second skin, it also desensitizes us to the natural world beyond our urban environments. Crucially, its significant carbon emissions during production are a major concern. (Winkless et al. 2024).

Fig 9 While 'Concrete' and 'Cement' are Frequently Conflated, it's Cement Production that Accounts for the Bulk of Emissions

It is evident that concrete production contributes significantly to global CO_2 emissions, ranging from 7% to 10%. The primary culprit in these emissions is Portland cement, a foundational ingredient in modern concrete. Its manufacturing process involves pulverizing and carefully proportioning limestone, silica, alumina, and iron. This blend then undergoes high-temperature heating in kilns, reaching up to 1650 °C (~3000 °F), which results in CO_2 liberation from the limestone and the formation of clinker. The cooled clinker is subsequently ground and combined with a small quantity of gypsum. The result is Portland cement, a fine powder that serves as concrete's 'glue. This is also the primary focus for decarbonization efforts, which seek to modify its carbon-intensive chemistry without compromising performance. Beyond cement, concrete's other two main components significantly impact the environment. Most of its volume comes from aggregates of sand, gravel, or crushed stone excavated from mines and about 7% is water. Small amounts of other additives can also fine-tune the mixture. The hydration process then begins - cement powder and water react, hardening and binding the aggregates and additives into the familiar, tough, rock-like mass. This hardening continues for years, making the concrete stronger as it ages, at least for a positive duration.

➢ *New Crack-Resistant Cement Material is Inspired by Environment:*

A new cement composite material, significantly more crack-resistant and flexible than conventional concrete, has been developed by researchers. (Rolls et al. 2024).

- *The Special Formulation:*

The genesis of this innovative cement composite was an unexpected one – nacre/mother of pearl, the material found in oyster and abalone shells. Researchers explained that, microscopically, nacre is composed of hexagonal tablets of a hard mineral called aragonite, held together by a soft biopolymer. The aragonite tablets primarily provide nacre's strength, while the biopolymer enhances its flexibility and crack resistance. Under stress, these aragonite tablets slide, enabling the nacre to effectively disperse energy and preserve its structural integrity, resulting in a material that is both strong and remarkably resilient.

- *Building a Tougher Cement:*

Drawing inspiration from nacre's exceptional properties, the research team aimed to develop a cement composite mirroring its structure. They achieved this using common construction materials: Portland cement paste and a minimal amount of polymer. The team fabricated multilayered small beams, alternating sheets of cement paste with thin layers of polyvinyl siloxane, a highly stretchable polymer. To assess crack resistance and fracture toughness, these beams underwent a notched three-point bending test. Three types of beams were produced:

- ✓ One incorporating alternating layers of cement paste sheets and thin polymer films.
- ✓ Another featuring hexagonal grooves laser-engraved into the cement paste sheets.
- ✓ A third comprising entirely separated hexagonal cement tablets linked by a polymer layer, mimicking the aragonite-biopolymer arrangement in nacre.

- *Outstanding Results which is 17-Times More Crack-Resistant:*

The experiments clearly showed that the nacre-imitating beams, those with completely separated hexagonal tablets – yielded the most impressive results. These beams achieved 19 times greater ductility and 17 times more fracture toughness, all while maintaining nearly the same strength as a solid cement paste beam.

- *A New Frontier in Cement-Based Construction:*

While these findings stem from lab conditions and require further research for field application, their potential impact on the construction industry is immense. Researchers are now investigating whether these improvements in fracture toughness and ductility extend to other ceramic materials beyond cement paste, including concrete.

- *Nature-Inspired Crack-Resistant Cement:*

In essence, this research unlocks vast potential for developing stronger, safer, and more durable construction materials. By emulating nacre's intricate design, the team has engineered a cement composite with dramatically improved crack resistance and flexibility. As further research explores this bio-inspired approach, the construction industry anticipates a new era of resilient and sustainable materials.

- *Architects Construct with World's First Concrete Capable of Absorbing Air Pollution:*

The design transpires into blocks arranged in a gradient-like pattern. One small concrete block, one giant leap for sustainable living. Imagine a home that not only provides shelter but actively helps clean the air. That's exactly what a new house. Thanks to the world's first carbon-absorbing concrete. This innovative building material, called CO2-SUICOM, was used to create the block walls of the mountain resort home, located about 70 minutes from Tokyo. By literally sucking planet-heating carbon gas out of the atmosphere, this pollution-eating concrete could be a game-changer for sustainable construction, according to the researchers (Sattler et al. 2024).

Developed by a consortium of Japanese companies, CO2-SUICOM is a revolutionary concrete that achieves carbon neutrality. It works by replacing some cement with industrial waste and incorporating carbon-absorbing materials, enabling it to sequester atmospheric CO2 during production. This innovation is significant, as cement manufacturing currently accounts for approximately 8% of global carbon emissions. Crucially, CO2-SUICOM matches the strength of conventional concrete, allowing builders to adopt it without compromising quality. Widespread adoption of such carbon-absorbing materials promises substantial reductions in construction-related pollution, marking a significant stride towards sustainable building and stylish, eco-friendly homes.

- *A Novel Application for Discarded Concrete Hints at a Carbon Capture Revolution:*

Scientists have discovered a groundbreaking method for sequestering greenhouse gases using construction waste, with key highlights including:

- ✓ Accelerated Rock Weathering: While natural rock weathering slowly sequesters carbon as calcium carbonate in oceans, an Irish startup aims to dramatically speed this up.
- ✓ Concrete-Enhanced Agriculture: Their counterintuitive technique involves spreading 1-millimeter waste concrete bits across agricultural fields.
- ✓ Dual Benefits: This method has already demonstrated increased bicarbonate formation and improved soil conditions. (Orf et al. 2024).

Spreading waste concrete on agricultural fields presents a unique win-win solution. Ireland-based startup Silicate proposes this counter-intuitive technique can both capture carbon and boost crop yields, all without harmful side effects. While trees are widely recognized for their carbon sequestration, Earth possesses other, less heralded, natural processes that remove this greenhouse gas from the atmosphere. Among these processes is rock weathering, where rain erodes rocks, releasing elements such as calcium and magnesium. These elements then react with atmospheric CO2 to form new rocks like calcium carbonate and limestone, thereby sequestering CO2.

The underlying science is surprisingly straightforward. Concrete production involves heating calcium carbonate (limestone) to create calcium oxide (lime), which then mixes with aggregate to form concrete. Once this lime reacts with atmospheric CO2, bicarbonate ions are trapped in the soil. These ions eventually wash into the ocean, where they remain for approximately 80,000 years before potentially reforming as calcium carbonate. While this process is far too slow with solid concrete to combat rapid global warming, Silicate aims to drastically accelerate it by crushing concrete into 1-millimeter pieces. Fortunately, waste concrete is abundant worldwide.

While the precise amount of carbon removed remains unquantified by researchers, New Scientist reports that fields treated with Silicate's concrete dust exhibited elevated bicarbonate levels. An Irish study on oats further showed a 35% increase in seed mass in concrete-treated fields, attributed to concrete's carbon capture and soil pH amendment properties. Though rock weathering offers significant carbon sequestration potential, potentially surpassing trees (which release stored carbon upon death),

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and its downstream effects are not fully understood. Moreover, even with all other natural sequestration methods, enhanced rock weathering alone cannot offset humanity's entire CO2 budget. While Silicate's process offers a dual benefit—combating climate change and repurposing waste concrete—the fundamental solution to planetary warming remains the elimination of CO2 emissions at their source.

➢ *New Outstanding Innovation "True Zero Carbon" Cement uses Electrolysis During Manufacturing, not Furnaces:*

Sublime (Figure 10) Cement declares that they are ready to start escalating the "world's cleanest cement," which meets industry routine standards. They were dependent on room-temperature electrolyzers instead of fossil-fueled furnaces and used a variety of zero-carbon input materials during manufacturing (Blain et al. 2023). Traditionally, concrete manufacturing processes result in a ton of CO2 against each & every ton of cement produced. This figure is around 4.1 billion tons globally, just in the year of 2022 which is more than half of that in China alone. We know, Cement is a massive contributor to climate change. But MIT spinout Sublime Systems in 2020. They simply replaced the kiln with an electrolyzer that can make cement at an ambient temperature from a variety of calcium sources. This process also eliminates emissions from limestone. It creates a novel electrochemical approach indeed in manufacturing cement "true zero carbon" instead of "net zero carbon" or "carbon-sequestering". Note that it can totally eliminate carbon emissions at both the operational stages where they usually arise during the process.

Fig 10 Sublime's Carbon-Neutral (or Near-Neutral) Cement Manufacturing Breakthrough

• *Some Highlights of Cement Developing Procedure are as Follows:*

Sublime has developed a revolutionary, energy-efficient cement production method that stands out for its ultra-low carbon footprint and operation at room temperature, requiring no combustion or electric heating. The core steps involve:

✓ Splitting water to produce hydrogen and oxygen.
✓ Reacting a calcium-containing mineral with an acidic byproduct to create dissolved calcium.
✓ Combining these calcium ions with a base to form calcium hydroxide (builder's lime), a crucial component for traditional cement manufacturing.

Sublime's innovation further refines this process by isolating the oxygen and CO2 gas streams, no longer producing hydrogen as a side product. Crucially, even though CO2 is still generated, it's released in a pure, cold, and pre-compressed form, significantly simplifying and lowering the energy cost of capture and storage compared to conventional methods. This flexible process can utilize diverse, low-cost feedstocks, including low-grade limestone. Sublime boldly claims their technology is the sole fossil-fuel-free, scalable, and direct substitute for conventional cement in concrete worldwide.

➢ *Sublime, an Exemplary Reference of Achieving a Key Certification Goal for True Carbon Zero Cement Manufacturing:*

Sublime has announced a significant milestone: their cement product now meets the ASTM C1157 (Figure 11) standard. This industry benchmark, established in 1992, sets rigorous performance criteria, including strength, durability, shrinkage, water retention, air content, setting time, density, early stiffening, and cracking. Achieving this means Sublime Cement is now compliant with Major American and international building codes, opening doors for widespread use. This is particularly noteworthy as many parts of the cement industry still rely on older standards from 1940 and 1967, which are less comprehensive in performance requirements and specifically mandate Portland cement, necessitating energy-intensive 1,400 °C furnaces. (Blain et al. 2023).

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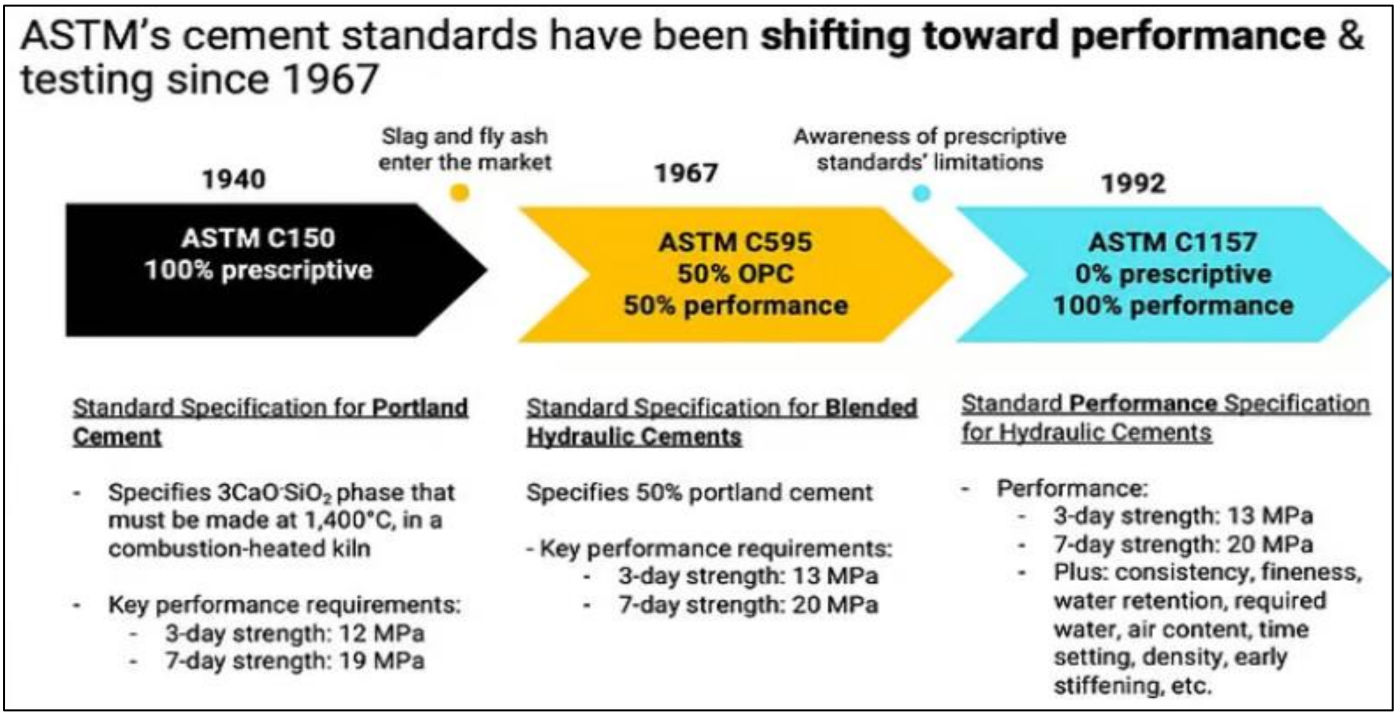

Fig 11 ASTM C1157 Standard for Cement Qualification

➢ *How to Make Profitable and Pricing of True Carbon Zero Cement [17]:*

Sublime envisions its technology making a tangible impact on global carbon emissions as early as 2023, a key part of their long-range vision. They foresee that within the next 8 to 10 years, as their process scales and matures, they will reach a point where their cement can be produced at a comparable cost to conventional Portland cement. Crucially, they believe their pricing will ultimately undercut the cost of traditional cement when factoring in the additional expenses of carbon capture.

➢ *Rice Bran Instead of Cement in Concrete Construction:*

Ideally 7 to 10 percent of carbon is released in cement production worldwide. On the other hand, if rice husk is left, it does not rot easily. As a result, the environment is damaged. Recently, CUET Bangladesh research team have obtained excellent results by burning rice husk in a controlled manner to collect 'nano silica' from it and use it as an alternative to cement. Hopefully the results of this research will be beneficial for our environment, country and the people of the world. This new innovation of using rice husk cement is applauded. This type of research is pivotal for the country's progress. (Correspondent CUET, 2024).

➢ *Plastics into Bricks:*

Plastic pollution is a pervasive global crisis, impacting ecosystems, wildlife, and human health from the deepest oceans to the highest peaks. With discarded plastic taking up to 500 years to decompose and only nine percent of the world's plastic waste being recycled, the need for solutions is critical. Kenya is actively addressing this challenge by repurposing discarded plastic. Every week, they recycle 10 to 25 metric tons of plastic waste, which is then combined with sand and molded into paving bricks. This initiative primarily utilizes mechanical recycling, a more cost-effective method for developing economies, as opposed to chemical recycling which converts plastic into oil (Ward et al., 2023). There are several stages:

The creation of these paving blocks begins with pre-processing, which involves sourcing and collecting plastic waste. This waste then undergoes cleaning, shredding, and separation by plastic type. Next is the processing stage, where the prepared plastic waste is mixed with sand and glass, with color additives possible at this point. A hydraulic press molds this mixture into various shapes and sizes. Finally, the molded blocks are transferred to a cooling bath to reach room temperature. Once cooled, these blocks are ready for installation, offering a significant advantage: they are stronger and more economical than traditional concrete paving.

➢ *Plastic-Waste Bricks: 5% More Energy-Efficient:*

Traditional brick manufacturing (business-as-usual) is a significant environmental concern, generating harmful emissions like carbon dioxide, sulfur dioxide, and chlorine, while also depleting natural resources, especially clay (Kazmer et al., 2024). In response, researchers have developed an ingenious new brick that substitutes clay with glass waste and trash ash. This innovation offers multiple benefits: it diverts waste from landfills, provides improved insulation, and lowers manufacturing costs. This breakthrough has the potential to dramatically reduce the air pollution caused by the estimated 1.5 billion hand-molded bricks produced globally each year in coal-fired kilns. Such kilns, according to the Climate & Clean Air Coalition, contribute a staggering 20% of the world's soot pollution, with severe consequences for human health, agriculture, and the climate. Annually, approximately 1.4 trillion bricks are utilized in construction worldwide. (Figure 12).

Fig 12 Energy-Efficient Bricks from Plastic Waste

These new bricks provide a dual benefit: replacing clay with 20% solid waste ash and 15% glass refuse allows for a 20% drop in kiln temperatures, yielding immediate cost savings. Furthermore, their enhanced insulation can reduce household energy bills by 5%. The technique is particularly valuable as it utilizes fine glass waste that is otherwise unrecyclable. Such cleaner bricks are fundamental to sustainable, passive building designs, where they are essential for preventing energy loss in well-insulated structures.

- *CO2-Enhanced Concrete:*

CO2 curing offers stronger concrete with less cement than traditional methods, but is generally restricted to precast components due to steel corrosion risks (Owolabi et al., 2024). The CO2 used is permanently sequestered. While its production emissions (0-413 kg CO2) are often lower than conventional concrete (240-420 kg CO2), achieving a net climate benefit depends on various factors; otherwise, it could be worse. Even with 30-50% market penetration by 2040, its total CO2 capture potential is modest (40-70 Mtpa), constrained by low CO2 uptake per ton and limited applicability to the precast market. The technology is mature, with existing users in precast. However, its 1.3-1.5 times higher cost makes it economically viable only under specific conditions, particularly proximity to affordable CO2 sources.

III. DISCUSSION

The Carbon is inherent and it's literally part of the Chemistry. Enter Carbon Capture and Storage (CCS) and its utilization counterpart, CCUS. These technologies, recently gaining significant traction, are increasingly viewed as a vital solution for "hard-to-abate" industries. Sectors like cement, iron, and steel production, where much of the carbon dioxide emissions stem from unavoidable process reactions rather than fuel combustion, are prime examples. Power and fertilizer plants are also turning to this technology. While CCS has geological limitations tied to project locations, the number of ongoing projects is growing as companies seek decarbonization pathways where simpler options are unavailable.

Furthermore, it's crucial to assess the role of Direct Air Capture (DAC) and other Carbon Dioxide Removal (CDR) approaches in achieving net-zero strategies. A clearer understanding and communication of their anticipated contribution will highlight specific technology, policy, and market requirements across nations and regions. For instance, the United Kingdom's Net Zero Strategy projects a need for approximately 80 MtCO2 of technology-based carbon removals by 2050.

Initially, scientists and governments understood that offsetting greenhouse gas emissions was as crucial as reducing them. This opened the carbon offset market for forested developing countries, allowing them to contribute to "carbon neutrality" by accepting payments from Kyoto Protocol-bound industrialized nations to mitigate their emissions cheaply. While the Kyoto Protocol committed industrialized countries to specific GHG cuts, the focus gradually shifted to temperature targets, such as the two-degree warming limit. The ultimate goal became to achieve a balance between human-caused emissions and their removal by sinks by the latter half of this century. This critical equilibrium is universally understood as "net zero." (Morgan et al. 2024).

IV. CHALLENGES AND MORE APPROACHES IN ACHIEVING CEMENT DE-CARBONIZATION

This analysis of American clean cement startups seeks to understand the scale of the problem and the fundamental chemistry of cement, emphasizing why its de-carbonization is crucial. It also offers a preliminary look at selected company approaches. Traditional cement production is inherently carbon-intensive. It starts with abundant, cheap limestone, which, when heated to 900°C in kilns to extract lime (56% yield), releases 44% of its mass as CO_2. This calcination, combined with further energy-intensive clinker formation (Barnard et al., 2024), contributes massively to emissions. Given 60-70% of cement is lime, and 4.1 billion tons of cement are made annually (producing 4.1 billion tons of CO_2 – 8-10% of global emissions), cement is a significant climate issue. If we incorporate electrochemistry, this alarming environmental impact drives the search for new methods, including those leveraging electrochemistry - a process where manipulating charged electrodes and pH can transform materials in ways that almost seem like alchemy. (Figure 13).

Fig 13 AI-Generated Panorama: Circuit-Covered Electric Cement Truck at a Construction Site

Sublime's innovative approach replaces high-heat cement production with an electrochemical process. They electrolyze water into oxygen and hydrogen, then combine this ionic solution with powdered lime-bearing materials (like limestone or recycled concrete). This allows electrochemistry to separate lime from CO_2 without 900°C heat. While overall energy use might not drop due to energy-intensive water electrolysis, the lime precipitates, and the CO_2 emerges pure, cold, and at 10 atmospheres, making it readily capturable. The economic viability of the co-produced hydrogen is still under investigation, as its quantity or location might hinder easy utilization.

The immense scale of cement manufacturing poses a formidable challenge for Sublime's approach. The combined supply of steel slag and recycled concrete would barely cover 10% of global lime requirements, leaving limestone as the only economically viable option for the bulk of production due to its widespread and accessible deposits. Alternative strategies involve using naturally occurring calcium silicates, which are appealing as they lack carbon and thus avoid process CO_2 emissions. While cement manufacturing already creates artificial calcium silicates (alite and belite) by adding specific oxides to lime, sourcing natural calcium silicates is different. Being igneous and metamorphic, these rocks are concentrated in geologically active zones, not broadly distributed like limestone. Critically, their decomposition into lime typically necessitates 50% more heat (around 1,450°C) and generates a substantial amount of silicon dioxide as solid waste.

Epoxy cements face a distinct challenge. While they are petroleum-derived, they are not combusted, and the required quantities are within extractable limits. However, their higher cost presents an obstacle. For those concerned about epoxy's petrochemical origin, it's crucial to remember that the petrochemical industry will endure even as we transition away from burning fossil fuels like gasoline, diesel, and kerosene. Durable petrochemical products, such as epoxies, can indeed be low-carbon, particularly if producers prioritize easily extracted, light, low-sulfur petroleum located near water and electrify their extraction, processing, and refining operations. This shift will also be aided by avoiding energy-intensive crude oils whose economic viability often hinges on producers burning high-emission, low-cost fossil fuels "behind the meter." (Figure 14).

Fig 14 An AI-Generated Panoramic Image of an Electrolysis Cement Plant of the Future, Powered by Wind Turbines.

Alternative solutions were proposed, such as fiberglass-reinforced concrete to eliminate high-carbon steel. However, a major obstacle proved to be the skepticism of cement plant operators towards new electric kiln heating, seen as experimental and met with general resistance to change. Although cement manufacturing is considered a viable target for carbon capture and sequestration (CCS), the scale is daunting: assuming current process efficiencies, it means handling two billion tons of CO2 annually that needs to be captured, purified, multi-stage compressed, piped, and injected into distant underground storage.

V. INNOVATIVE TECHNOLOGY TO TURN PLASTIC WASTE INTO CONCRETE ADDITIVE

This startup is pioneering a sustainable future by converting plastic waste into concrete additives, preventing pollution of landfills and oceans. Their technology is designed to turn any plastic waste into an eco-friendly component for stronger, more durable concrete. The process involves shredding and sorting plastic by density, then melting and mixing it into a mineral-polymer hybrid, which is finally granulated into RESIN8 for concrete mixes (Figure 15). Concrete incorporating RESIN8 is notably stronger, more flexible, and more fire/heat-resistant than regular concrete, while also reducing the need for new material production. (Sattler et al. June 13, 2024).

Fig 15 Concrete Additive from Plastic Waste

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➢ *RESIN8 Background:*

RESIN8 stands out as the sole plastic-waste derived material that not only enhances the performance of structural concrete but also garners acceptance from the construction industry. Concrete applications incorporating RESIN8 surpass the rigorous ASTM standards, which serve as the international benchmark for material performance. Extensive testing of RESIN8 (**Figure 16**) has confirmed its ability to significantly boost compression strength, flexibility, fire resistance, thermal resistance, and acoustic properties. It is versatile enough for use in both structural and non-structural concrete, as well as "poured-in-place" applications. RESIN8 represents both an immediate and long-term eco-friendly solution, transforming plastic industry waste into a valuable raw material for the construction sector, embodying true circularity where the concrete can eventually be recycled. RESIN8 provides comprehensive benefits for sustainable building:

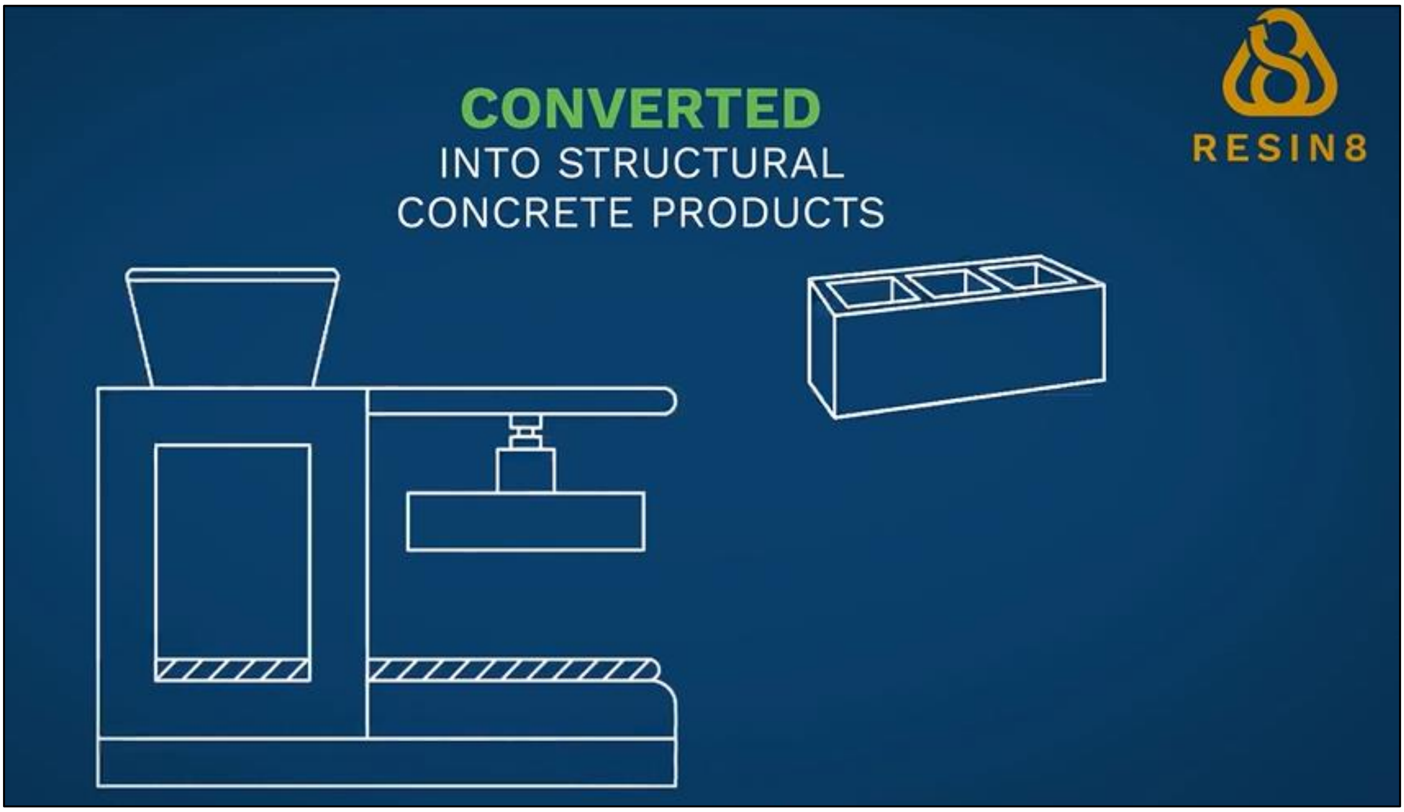

Fig 16 Resin 8 and Converted Concrete Products

- It accepts all plastic waste (Resins 1-7), diverting it from disposal.
- Plastic waste converts into RESIN8, a lightweight "Eco-Aggregate" that meets construction needs and gives plastic a new, extended purpose.
- Its thermal properties make it an effective insulation material, reducing building energy use for improved climate resilience and long-term net-zero support.
- No leaching, abrasion, or micro-plastic release occurs from RESIN8 in concrete.
- As a recycled product, RESIN8 achieves full circularity, being reusable at concrete's end-of-life and having a low embodied energy footprint.

VI. CONCRETE, BANGLADESH PERSPECTIVE CHALLENGES & OPPORTUNITIES

Citing recent environmental damage, Bangladesh's government is phasing out traditional bricks, mandating alternatives for official constructions from 2024 and promoting them to build market demand. These new bricks address infrastructure needs without harming soil or increasing air pollution (Figure 17). The urgency stems from brickfields annually consuming 3,350 million cubic feet of dust and clay (Ochs et al., 2024), severely degrading topsoil, reducing crop yields (40-80%), and slashing farmer incomes (40-70%), threatening food security. Air quality is also a major concern, with Dhaka's kilns alone emitting 1.8 million tons of CO2 and other pollutants. To counter this, traditional kilns are being shut down and replaced with alternative brick production sites. Made from dredged river soil, cement, sand, and iron, these alternatives are half the cost of conventional bricks, protect the environment, and can be used widely in both rural and urban areas, eliminating the need for topsoil.

Fig 17 Challenges Through Bangladesh Perspective

Bangladesh's transition to alternative bricks is part of a larger global trend pushing modern brickmaking technology forward. Innovators worldwide are exploring diverse materials like sugarcane byproducts, invasive algae, and recycled bottles to produce stronger, more sustainable, and more resilient building components. Fortunately, Bangladesh's government finds support for its shift to alternative bricks within the rapidly expanding brickmaking industry. This development is certainly positive news.

VII. CONCLUSION

The cement industry contributes a staggering 25% of the world's CO2 emissions, a figure that includes the carbon released from burning limestone, which is often overlooked in lower estimates (8-9%). Nu-Rock (Figure 18) offers a world-leading, non-cementitious solution: it converts industrial, mining, and domestic waste into "formulated rock." This versatile material can produce superior, green building products like blocks, bricks, pavers, railway sleepers, traffic barriers, seawalls, retaining walls, soil conditioners, aggregates, pipes, and roof tiles, among others.

They developed and tested over the past 34 years, uses a chemical curing process that turns waste products into “formulated rock” that can be shaped into building blocks. These do not deteriorate like traditional Portland cement and are stronger and more durable. Importantly, during the curing process these blocks absorb carbon dioxide to create the lowest embedded energy concrete or cement substitute product in the world. Nu-Rock - a site-remediation company that turns the waste into a product so that it doesn’t cost money to clean up the site, It makes money. It’s a completely different philosophy to those companies that will charge per ton to clean it up. They cost less to manufacture, they’re lighter, more fire-resistant, they have more compressive strength, are salt and acid-resistant, have better thermal and acoustic qualities, and can be shaped into any article we want. The most important thing, though, is that they just got Environmental Product Declaration rating (The international standard for measuring the carbon footprint of all concrete and construction products). They are the first carbon negative masonry product in the world with minus 23.3kg of CO_2 emitted for every 1000 kilograms of product made. Cement emits between 450 and 600kg of CO_2 per 1000kg, and that’s excluding the limestone they burn to make it. But the real beauty of his product is that while traditional concrete requires the quarrying of materials such as sandstone, gravel and aggregates out of the ground at huge cost, there is almost an endless supply of waste material to make the bricks, blocks, pavers and other products using the Nu-Rock manufacturing method (Schlesinger et al. 2024).

Fig 18 Nu-Rock Founder, Maroun Rahme at Mount Piper Power Station with a Non-Cement Building Block Made by Nu-Rock.

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Furthermore, if we replace part of the cement content (40% max.) of concrete with a type of silica created with carbon dioxide, captured directly from factory flues. The carbon capture and storage (CCS) involved to make the replacement material means that more carbon is stored in the concrete than is emitted in its cement production, making it overall carbon-neutral. This approach has the advantage of being the most practical for the immediate future. Once scaled-up and implemented, has the potential to significantly reduce overall carbon emissions from the construction industry. In fact, an outstanding architectural contribution to human development.

➢ *Statement and Declaration:*

The author (s) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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- Faishal Abidein: Formal analysis, Investigation, Supervision, review and editing.

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➢ *Data Availability Statement:*

The datasets generated and analyzed during the current study will be available from the corresponding author upon reasonabl request.

➢ *Ethical Approval:*

- Not applicable

➢ *Consent to Publish:*

Written informed consent for publication from all identifiable individuals whose data or images are presented in this article.

➢ *Consent to Participate:*

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➢ *Clinical Trial Declaration:*

- Not applicable.

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