October 2023

The future of **sustainable construction:** innovative materials

Part 1
Pathways to sustainable concrete

LEONARD
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hello tomorrow

FAHRONI – ENVATO

Forewords & Acknowledgements

In the light of the escalating climate crisis, the urgency for meticulous diligence, proactive approaches, and heightened awareness in our construction endeavours has never been more paramount. At Leonard's, the foresight and innovation platform of the VINCI group, our purpose is to foster this very awareness. Our mission is to navigate present, imminent, and rising transformations, ensuring that communities are ready to meet both contemporary and emerging challenges. Established in 2017, Leonard has continuously been at the forefront of the debate about the evolution of cities and infrastructure. Therefore, it seems only fitting that we delve deeper into one of the most foundational materials in human history – concrete. From the majestic edifices of ancient Rome to the towering skyscrapers defining our modern skyline, concrete has been a linchpin of architectural milestones. Yet, as we stand at a pivotal juncture where environmental responsibility is not just preferable but indispensable, our journey must be guided by both reflection and radical innovation.

It is imperative to remember that the guidelines governing concrete construction—encompassing material selection, execution, and design—were not established overnight. They have been set after decades of experience and some trial-and-error phases. Nowadays, society is asking for guaranteed safety in every domain and the introduction of new construction materials is not possible unless the reliability of corresponding structures is justified. Fortunately, we don't need any longer extended feedback over decades of use for providing such justification because concrete is more and more understood as far as durability and structural behaviour are concerned, and it can be assessed on these topics through relatively short-term laboratory testing. Anyhow, the newer construction materials incorporated into concrete are different from traditional material, the longer is the time needed for a correct and reliable assessment of possible applications, especially when structural applications are targeted. Due to the great complexity of the material, the evolution of concrete solutions towards decarbonisation is more likely to be gradual than driven by breakthrough solutions.

We would like to thank warmly CEMEX Ventures, NOVA by Saint-Gobain, Saint-Gobain and Zacua Ventures together with professionals from VINCI for their help. The advice and expertise provided by all the interviewed professionals have been of the utmost importance during the writing and assessment of the content of this report. We would also like to thank the members of the committee for the revision and valuable feedback for this project. Finally, this report would not have been possible without Hello Tomorrow. Thank you for supporting Leonard in proving that science and technology have the potential to build together a better future.

Julien Villalongue
Managing Director, Leonard

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Executive summary

As our global society strives towards a sustainable future, the construction industry grapples with **a twofold imperative: the ever-increasing need for housing, coupled with the pressing need to dramatically reduce its ecological footprint.** As one of the planet's largest economic ecosystems, the construction industry shoulders a profound responsibility in the pursuit of global sustainability objectives. Indeed, in 2021, **building operations alone assumed** a substantial role in the global energy landscape, accounting for a share of **30% of the world's final energy consumption and 27% of the total emissions emanating from the energy sector.**[1]

Cement: Tackling construction's most polluting material with deep technologies

The journey towards decarbonisation spans the entire spectrum of activities of the construction industry, enveloping everything from the initial design, extraction, and manufacturing of building materials to the construction process itself. **Along the value chain, cement production emerges as a central driver propelling global emissions.** As the bedrock of modern construction, it accounts for 7–8% of worldwide CO_2 emissions[2], chiefly due to the energy-intensive characteristics of its manufacturing. **In this context, achieving rapid decarbonisation within the concrete industry hinges on reimagining the methods of production.** Such strategy encounters multifaceted challenges that necessitate the critical involvement and support of deep technologies.

In a concerted effort to foster awareness and deepen comprehension regarding the future landscape of cement within the construction industry, Leonard & Hello Tomorrow shaped an analysis encompassing innovative strategies for future concrete usage and production.

New concrete admixtures for a greener future

Concrete dominates as the go-to material in the building industry, accounting for 60% of usage on average, overshadowing any other construction materials. However, this material carries a heavy environmental burden, with a staggering 90 to 95% of its carbon footprint attributed to cement, and with clinker production being a primary culprit[3]. In response to this environmental challenge, **three key levers are being explored today: reducing the clinker-to-cement ratio, exploring alternative binders, and applying carbon sequestration techniques to concrete factories.**

The first two strategies share a common principle: they involve adjusting current component proportions and altering the components of concrete to incorporate greener alternatives, primarily targeting the energy-intensive and emission-heavy phases of production. The methods for producing low-carbon concrete have a long history, yet their application remains somewhat limited to specific use cases. In the short term, this approach not only seems to be the most financially pragmatic but also benefits from a certain level of industry-wide familiarity and acceptance. Nevertheless, it's unlikely to spur a full-scale revolution since prevailing regulations still mandate a 50% clinker proportion[4] in the material coupled with the inherent challenges surrounding the substitution of certain materials.

Decarbonating the cement industry at source

While greener concrete solutions are emerging, the real revolution lies in on-site carbon sequestration and achieving a closed production cycle by recycling emitted carbon. A significant 67% of cement production emissions can be attributed to the chemical reactions involved[2], rendering CO_2 capture a promising approach to curbing the environmental footprint of the concrete industry. Nevertheless, despite ambitious 2030 projections, only a handful of factories have adopted carbon sequestration technologies, frequently facing financial and thus scalability challenges. CO_2 recycling, for its part, driven by deep-tech innovations like waste fossilisation and carbonation curing, holds promise for transforming concrete utilisation practices.

Deploying breakthrough technologies to meet 2050 climate targets

For the industry to truly achieve transformative change, prescriber must prioritise more aggressively sustainable technologies. Regulations also have a pivotal role in this transition. Updated regulatory frameworks that incentivise or even mandate the adoption of these breakthrough technologies can not only fast-track the industry's journey towards sustainability but also provide a clear and level playing field for all stakeholders. It is an imperative that both industry leaders and regulatory authorities recognise the gravity of the situation and work in tandem to overhaul outdated practices and standards. As of today, while some are currently distant from achieving practical applications in construction, primarily due to extended duration required for compliance with safety regulations, numerous initiatives have garnered the attention and interest of industrial players.

Beyond concrete: A sneak peek into volume two

Achieving tangible emissions reduction within the construction sector demands exploring innovative techniques further from the cement industry. These entail materials that can either provide sustainable alternatives to concrete or bring novel properties to reimagine the built environment. To comprehensively explore the decarbonisation strategies from all its angles, this report includes a second chapter delving further into material science and the new avenues these deep technologies will unveil.

OUR APPROACH

The industry's transition towards net-zero CO_2 emissions constitutes what is arguably the most challenging transformation in its history. Thus, critical decarbonisation levers have been identified to help bring the industry towards net zero (Exhibit 1). **In the present report, we will focus on aspects directly related to construction processes and practices.** Although the significance of energy efficiency and alternative fuels in the broader decarbonisation discourse is undeniable, they are currently at a more advanced development stage, being pioneered by other industries. Furthermore, they will need to be used in combination with the described sustainable materials in order for the construction industry to reach its decarbonation goals.

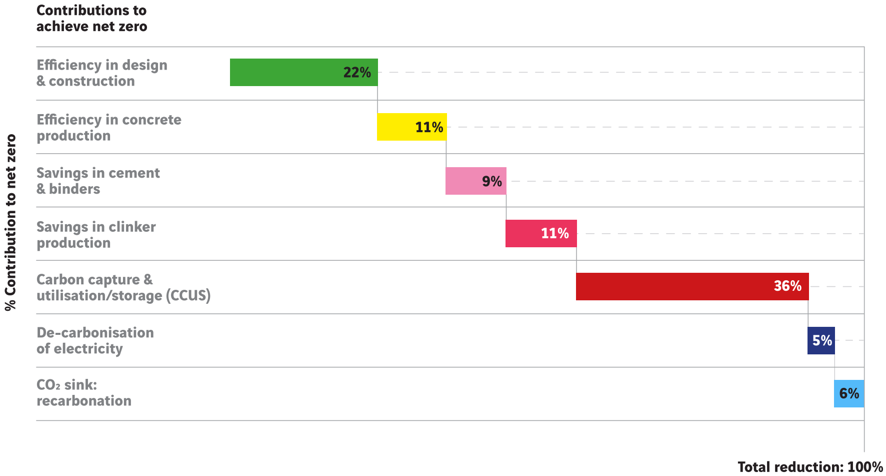


EXHIBIT 1: THE NET ZERO PATHWAY – GCCA

Guided by this framework, our aim has been to study how, through the utilisation of the most promising technologies, each step of the value chain (Exhibit 2) could be enhanced in terms of sustainability. **Certain stages of the value chain are more energy and emissions intensive** than others, and require greater efforts to implement sustainable strategies. For that reason, many solutions are specifically focused on these stages. This is the case of the **extraction of raw materials and manufacturing of products, which represent 65 to 85% of the global embodied carbon emissions** of the entire value chain. Notably, operational emissions at the use and maintenance phase are also of big impact, cumulating 8 to 15% of the global embodied CO_2.[5]

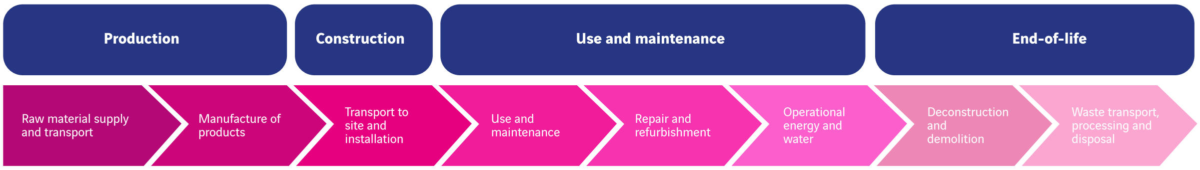


EXHIBIT 2: CONSTRUCTION VALUE CHAIN

This report encompasses an analysis of the construction value chain, considering every step from the production of its materials to the end-of-life of the buildings. **To do so, we have considered the value chain as a fixed framework of distinct stages – production, construction, use and maintenance, and end-of-life.** Each of these has its own set of internal stages, processes, and intricacies, all working in tandem to bring a project to fruition. **It must be noted that, even if compelling strategies in construction and end-of-life steps do exist, this analysis primarily revolves around advanced, material-centric, deep technologies.** Consequently, construction, transportation, and deconstruction processes are acknowledged solely as part of the studied technologies, and not as independent operations.

TOBIAS WEINHOLD – UNSPLASH

Sustainability grid

As we delve into the intricacies of sustainable technologies in the vast landscape of the construction industry, it becomes vital to formulate an organised, systematic evaluative approach. For this purpose, we have conceptualised a comprehensive sustainability grid, designed to rate a multitude of technologies on various sustainability parameters. It revolves around three pivotal sectors, each of which comprises three distinct levels of interest, painting a rich, multi-dimensional portrait of sustainability in construction, bringing to light the technicalities of it.

Before we delve deeper into the facets of each domain, it is worth noting that our sustainability grid incorporates a specific rating system. This allows for a quantitative and qualitative evaluation of each category, affording us a comprehensive perspective on the sustainability of the material sourcing, construction processes, and end-of-life considerations. Each category is assessed on a scale of one to four.

#1 Material sourcing

Material sourcing and transport

Minimising the rarity and transportation of materials required.
By balancing the need for imported, heavy or rare compounds within the material, construction projects can significantly reduce their environmental footprint and contribute to more sustainable practices.

Reuse of existing materials

Reusing materials from demolished or deconstructed buildings, as well as repurposing items that would otherwise be discarded.
With the reuse of material, construction projects can significantly reduce waste, minimise the need for new materials, and lower their overall environmental impact.

Upcycling

Reducing waste and promoting a circular economy.
Upcycling strategies reduce the ecological footprint of construction projects while fostering inventive and sustainable solutions.

●○○○

Materials are primarily imported or rare, non-renewable, and non-recyclable. No consideration is given to reuse or upcycling of existing materials.

●●○○

Some common/local and renewable materials are used, but reliance on imported or rare materials is still significant. Minimal reuse and upcycling of existing materials.

●●●○

Most materials are locally sourced and/or renewable, with a strong focus on reusing and upcycling existing materials when possible.

●●●●

All materials are locally sourced, renewable, and/or recyclable, with a comprehensive approach to reusing and upcycling materials throughout the project.

#2 Construction and operation

Energy efficiency for production

Optimising design, using energy-efficient materials, and employing technologies to minimise energy consumption and non-renewable sources.
To further improve energy efficiency, techniques should be successful in reducing energy usage during the construction process.

Water efficiency for production

Using water-efficient fixtures and appliances, collecting rainwater for reuse, and implementing water-saving landscaping techniques.

●○○○

No energy or water efficiency measures are implemented, and environmental impact is not considered during construction.

●●○○

Some energy and water efficiency measures are used, but overall consumption is still high and not relying on renewable energies. Environmental impact is minimally considered.

●●●○

Energy and water efficiency are prioritised through building design, technology, and material choices, but the sources are not renewable yet. Some measures are taken to minimise the environmental impact.

Efficient water use helps preserve this valuable resource and reduces the overall environmental impact of the project.

Environmental risk management

Minimising site disturbance, protecting natural habitats and ecosystems, and implementing erosion control measures.
Selecting eco-friendly materials and incorporating green building techniques can improve the environmental quality of the construction process to avoid the spread of volatile compounds.

●●●●

Fully optimised for energy and water efficiency, using innovative designs and renewable sources. Environmental impact is minimised through eco-friendly materials and responsible construction practices.

●○○○

The building design does not consider extended lifespan or resilience to changing conditions. No efforts are made to facilitate material recovery at the end of life.

●●○○

Includes some elements of resilience and extended lifespan but lacks comprehensive strategies. Some efforts are made to enable material recovery at the end of life.

●●●○

Prioritises resilience and extends lifespan through careful material choice and flexible design. The end-of-life plan facilitates significant material recovery.

●●●●

Designed for maximum resilience and lifespan, with adaptable spaces and durable materials. At the end of life, the building is completely de-constructible for material recovery and recycling.

#3
Extended resilience and life cycle potential

Extended life cycle

Entails designing and constructing buildings to have a longer-than-usual lifespan, reducing the frequency of demolition and new construction.
By using durable materials, flexible design principles that can adapt to changing needs over time, and regular maintenance to keep the building in good condition.

Recycling potential

The ability to recycle materials at the end of a building's life and design for easy disassembly.
By maximising the recycling potential of a structure, waste can be reduced and resources conserved. An example of this would be recycling concrete debris into aggregate for new concrete mix or melting down metal components for reformation.

Part 1: **Pathways to sustainable concrete**

MAX VAN DEN OETELAAR – UNSPLASH

Pathways to sustainable concrete

Cement, A Key Building Block of Concrete

Concrete has become, in a matter of decades, the backbone of modern infrastructure, relying on one critical ingredient – cement. This binding agent has woven itself into the very fabric of civilisation, ranking as **the world's second-most consumed resource after water.** Due to its exceptional availability and mechanical properties concrete enables the construction of our entire built environment from homes to skyscrapers, roads to dams. With an ever-increasing demand, global cement production surged to an astounding volume of approximately 4.1 billion tonnes in the year 2022. Given these data and following the upward industry trend in past years, the International Energy Agency (IEA), in their Reference Technology Scenario (RTS), has forecasted a 12% boost in global cement production by 2050.[6]

This Voracious Appetite for Cement Poses a Sustainability Dilemma

The cement industry plays a substantial role in CO_2 emissions, responsible for approximately 8% of global human-made emissions, equivalent to a staggering 2.9 gigatonnes of CO_2 per year.[2] Roughly 60% of these emissions result from mineral decomposition (from $CaCO_3$ to CaO), while the remaining portion arises from fuel combustion. As production continues to rise, a projected 4% increase in direct CO_2 emissions is anticipated before mid-century.[6]

As a result, to align with the sustainability goals set forth in the 2-degree Celsius (°C) Scenario (2DS), the cement industry **must achieve a significant 24% reduction in global direct CO_2 emissions from current levels by 2050.**[6] An urgent imperative compels us to re-evaluate and revolutionise the entire value chain to harmonise with environmental considerations. This transformation demands rapid progress in CO_2 emission reduction strategies, a corresponding regulatory framework, public-private collaboration, sustainable financing mechanisms, and societal acceptance.

The trail forward is clear with pathways under development

Over the recent decades, significant headway has been made in embracing novel technologies to tackle increasing environmental concerns and demand for sustainability. Making the future of construction isn't solely about diminishing emissions, but also involved in developing materials and technologies capable of reversing the environmental damage already inflicted.

To catalyse pioneering advancements in the evolution of deep tech within the cement industry, two parallel approaches must be explored. The following approaches forge synergies amongst various facets to optimise the reduction of the environmental impact:

- **Altering the composition of cement and clinker to mitigate emissions, particularly during the most energy-intensive phase of concrete production.**
- **Altering the composition of concrete, by using supplementary cementitious materials and reducing cement content.**
- **Reducing the carbon footprint of the cement manufacturing process itself.**

1.1

REDUCING THE CLINKER-TO-CEMENT RATIO

"The largest challenge for producing cement with near zero emissions is to address the process CO_2 emissions from calcination."

International Energy Agency (IEA) Energy Technology Perspectives 2023

Cement production – the (very) basics

1 Extract limestone from quarries
Identify a location with a rich deposit of limestone, a principal ingredient of cement.

2 Crush the limestone
Extracted raw materials are crushed into smaller pieces and then pre-homogenised to ensure a uniform mix.

3 Grinding and homogenisation
Further ground into a fine powder known as 'raw meal'. Then homogenised to facilitate consistent burning in the kiln.

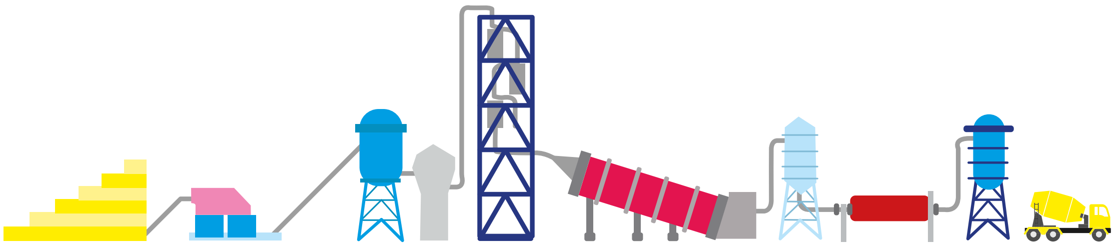
4 Preheating and calcination
Preheated and fed into a pre-calcinator and then into a rotary kiln for calcination. Heated to about 1450 degrees Celsius, which triggers a series of chemical reactions that convert the raw meal into clinker.

5 Clinker cooling and storage
The clinker produced in the kiln is rapidly cooled to preserve its properties and then stored.

6 Last grinding
Clinker is then milled into a fine powder, and a small amount of gypsum is added to control the setting properties of the newly produced cement.

Cement manufacturing is a highly complex process

Raw materials, energy, and resources | **Clinker and cement manufacturing**



	Quarry	Crusher	Transport	Raw mill	Kiln and preheater/ precalcinator	Cooler	Cement mill	Logistics	Total
Energy, mega-joule/ton	40	5	40	100	3,150	160	285	115	3,895
CO_2 kilogram/ton	3	1	7	17	479 Calcination process; 319 Fossil fuels	28	49	22	925

EXHIBIT 3: MANUFACTURING PROCESS OF CEMENT – LAYING THE FOUNDATION FOR ZERO-CARBON CEMENT

Cement primarily serves as the adhesive that cohesively binds the constituent elements of concrete – specifically, sand and aggregates. Functioning as **a hydraulic binder, cement solidifies upon the addition of water**, thereby allowing it to set and harden independently of environmental conditions. As there is a direct correlation between the high CO_2 emissions and the volume of clinker utilised in cement production, it is **worthwhile to find ways to reduce that ratio in cement.** The volume of Portland clinker that can be displaced depends on the substitute material type, and the strength required for the particular concrete application, as it influences the final product's properties. While some substitutes could improve the strength and durability of concrete, it's crucial to maintain the quality and consistency of the output to meet the required standards.

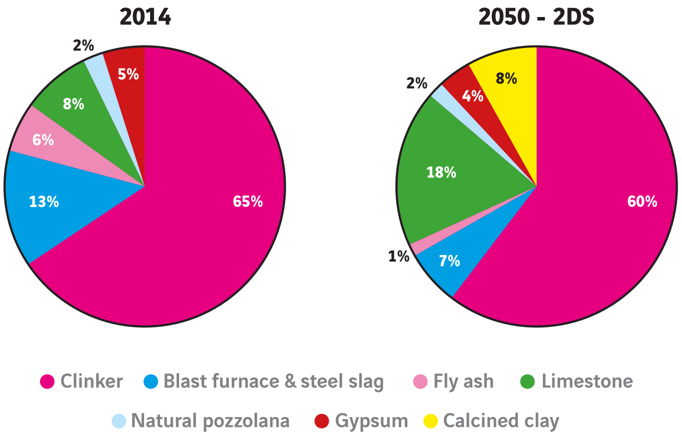


EXHIBIT 4: CEMENT COMPOSITION ESTIMATES ARE PROVIDED AS SHARES OF CEMENT PRODUCTION ON A MASS BASIS – IEA

Traditional concrete is known for its resilience to variations in mixing ratios, allowing for a rough mix that still attains the desired attributes. These substitutes are called supplementary cementitious materials, and represented in 2014 0.35 on a global mass basis of the mix with clinker. China was the lowest region at 0.58 of clinker versus a 0.82 in Eurasia. By 2050 it is projected that the use of these materials will increase and thereby reduce the global ratio to 0.60 (Exhibit 4). Only this outcome would **lead to a 30% decrease in the CO_2 intensity of the cement process over that period**.[6]

Portland Cement

Portland cement is the most common type of cement and a basic ingredient of concrete, mortar, and many plasters. British engineer Joseph Aspdin first patented Portland cement in 1824, and it was named after the natural stone from the Isle of Portland due to its colour and quality similarities. It typically consists of 95% clinker and 5% gypsum.

An overview of some supplementary cementitious materials (SCMs)

Addition of SCMs is amongst the most well-established technologies and has been in use for a long time. Some SCMs (Exhibit 5), such as fly ash or furnace slag, were previously preferred for their cost effectiveness and technical benefit as low heat development and high chemical resistance before their sustainability advantages were recognised, leading to broader acceptance amongst consumers and stakeholders. As most plants already possess the necessary infrastructure, **this technology can be easily implemented**, typically not requiring substantial investment in new equipment or significant changes to the existing manufacturing process.[7]

Using SCMs in concrete provides several key benefits. They improve the workability and pumpability of concrete due to their finer particle size compared to cement. The additional formation of calcium silicate hydrate results in higher concrete strength when SCMs are used. Such concrete also has lower permeability and improved resistance to water penetration thanks to enhanced particle packing. Finally, it increases the durability of concrete, providing better protection against sulfate attack, alkali silica reaction, and chloride ingress. SCMs are often less expensive than Portland cement, lowering material costs.

Supplementary cementitious materials (SCMs)				
Filler		Active nonpozzolanic addition	Active pozzolanic addition	
Natural	Artificial	Artificial	Natural	Artificial
Limestone	Marble powder	Granulated blast furnace slag	Pumice	Siliceous fly ash
	Concrete powder	Burnt shale	Tuff	Metakaolin
		Calcareous fly ash	Diatomaceous earth	Silica fume
			Opaline rock	Agroforestry waste
			Moler	Mixed waste from construction & demolition
			Gaize	Paper sludge
			Clays	Calcined clay
				Glass powder

EXHIBIT 5: TYPES OF SUPPLEMENTARY CEMENTITIOUS MATERIALS – ECOCEM

Most common used SCMs

Portland-limestone cement (PLC), it is a promising substitute for clinker in cement production. Cement with limestone needs less water, improving concrete workability. While it requires finer grinding than PC, it is more grindable than clinker. Typically, limestone content in this cement is 25–35%, but can be increased up to 50% with advanced methods.[7] Currently, limestone-based cement accounts for 25–30% of global production, expected to reach 48% by 2050.[8]

Fly Ash, a coal combustion by-product, is captured from coal-fired furnace flue gases. It can be siliceous or calcareous and has pozzolanic properties. Siliceous fly ash reacts with calcium hydroxide from clinker hydration, boosting strength. Though cement with fly ash has slower initial strength than regular Portland Cement, it requires less water, offers better workability, and has superior long-term strength and durability, including resistance to sulphate attack.[7]

Calcined Clay, it has been used in cement production since the 1930s. Its use can reduce early compressive strength due to slower reaction kinetics than clinker. Recent progress has revealed optimised combinations of calcined clay and ground limestone as cement constituents, potentially enabling up to 50% clinker displacement without affecting cement properties.[7]

Slag, ground granulated blast furnace slag (GGBFS) is created by rapidly quenching molten slag produced during iron making. This granulated material is subsequently ground into a fine powder and exhibits hydraulic properties when mixed with water. Sometimes referred to as slag cement, concrete produced with GGBFS usually displays superior compressive strengths, improved durability, and reduced permeability compared to Portland cement concrete.[8]

Silica Fume, also called microsilica, silica fume is a pozzolan by-product from reducing high-purity quartz with coal in electric arc furnaces. It's extremely fine and comes in both solid and liquid forms. Handling requires strict safety precautions. It's used in concrete needing high strength or high impermeability.[8]

Rice Husk Ash, rice production results in large amounts of rice husk, traditionally used as fuel, producing about 7.4 million tonnes of Rice Husk Ash (RHA) yearly, an environmental concern. The silica-rich RHA has been identified as a potential partial substitute for cement in concrete, improving its strength. Using up to 10% RHA with steel fibres maintains strength, but exceeding 15% decreases concrete performance.[9]

An availability depending on human activities and geography

The replacement rate of SCMs for clinker was typically constrained to approximately 40%. This limitation was primarily due to the observed decline in the structural integrity of concrete as the usage of SCMs increases.[4] **Nowadays, High-Filler Cements with around 20% of clinker are now proven.[3]**

However, a **significant hurdle** in reducing clinker through the use of SCMs is the **restricted and fluctuating availability of these alternative materials across regions and, more importantly, their long-term availability**. With intensifying decarbonisation efforts in the steel and energy sectors, the availability of these materials is expected to decrease, thereby driving up costs. Moreover, cement cannot be completely substituted with SCMs, implying that despite being more easily deployable, it cannot entirely eliminate the considerable CO_2 emissions from production.[6]

This reality becomes even more pressing given the increasing demand for cement. Between 2015 and 2020, the global clinker-to-cement ratio substantially increased, rising by an average of 1.6% annually to reach an estimated 0.72 in 2020. This increase was the primary catalyst behind the upsurge in the direct CO_2 intensity of cement production during this period. Conversely, the Net Zero Scenario predicts a consistent decrease in the clinker-to-cement ratio at a rate of 1.0% per year, resulting in a global average of 0.65 by 2030, attributable to the heightened use of blended cement and clinker substitutes.[8]

As we look ahead, the relevance of clinker replacements made from universally available materials, such as calcined clay amalgamated with limestone, is set to increase. **This anticipated change is in line with the expected decrease in the availability of industrial by-products currently used as substitutes,** like fly ash from coal power plants and ground granulated blast furnace slag from the steel industry, due to decarbonisation efforts in other sectors. Last, the geographical disparity not only poses logistical challenges but also escalates the costs associated with transporting these materials to construction hubs.

Examples in the field

BRIMSTONE

OAKLAND, USA
–

$60M RAISED TOTAL (SERIES A)
–

N/A
–

TRL 6–7
–

The Brimstone Process™ is a breakthrough in cement production, making carbon-negative Portland Cement with carbon-free calcium silicate rock instead of limestone. Calcium silicate is a hundred times more abundant than limestone, and being calcium-free, it eliminates process emissions from the start.
The process produces two core products used in concrete: ordinary Portland Cement and supplementary cementitious materials (SCM). Chemically and physically identical to conventional Portland Cement. The resulting cement is chemically and physically identical to conventional Portland Cement.

FORTERA

Low CO_2 Cement Inspired By Nature

CAMPBELL, USA
–

$55,6M (SERIES B)
–

WORLDWIDE
–

TRL 9
–

Fortera has developed a technology that captures CO_2 emissions and utilises them in the production of low-carbon concrete. The company has patented a process to produce a cementitious material from limestone that absorbs carbon dioxide rather than emitting it. For every tonne of Fortera cement used, almost half a tonne of CO_2 is permanently stored in the built environment.

exegy

PARIS, FRANCE
–

N/A
–

WORLDWIDE
–

TRL 9
–

Exegy is a complete construction solution which aims to generalise the use of low-carbon concrete on construction sites using optimised technical and environmental solutions at efficient prices. They offer low-carbon concrete of up to 70% CO_2 reduction with equivalent performance to its regular counterpart. They also provide adapted construction methodologies from conception to execution and accompany the construction team to facilitate the adoption of these new materials.

LEGEND

HEADQUARTERS
–

FUNDING
–

TERRITORIAL REACH
–

TECHNOLOGY READINESS LEVEL
–

1.2

ALTERNATIVE BINDERS FOR CONCRETE

"The best lower carbon concrete is the concrete that we do not use. This is the importance of sobriety".

Bruno Paul-Dauphin
Director of EXEGY

Alternative binders for concrete

The Roman Empire propelled the use of concrete into the limelight. Some of its most renowned architectural structures, such as the Roman Pantheon, the world's largest unreinforced concrete dome, and the Colosseum, remain standing after two millennia. These edifices are the proof of the robustness and longevity of concrete. Despite the disparity in composition between the cement utilised then and now, the fundamental concept remains the same. Nowadays, Portland cement derived from clinker, has gained prominence as the most prevalent type of cement.

Concrete, as a construction material, comprises cement, water, and aggregates such as sand, gravel, or crushed stone, often augmented by a small quantity of admixtures. The precise mix proportions and type of aggregate used depend on the intended use of the concrete. Mixing this proportion enable the versatility of concrete. Indeed it can be used almost everywhere ranging from housing and shelter provisions to facilitating clean water and sanitation, transport, and commercial infrastructure.

The different steps to make a good concrete

1 **Gather all materials**
The fundamental ingredients for making concrete are Portland cement, sand (also known as fine aggregate), gravel (coarse aggregate), and water. The usual proportion is 1 part cement, 2 parts sand, 3 parts gravel, and a small amount of water.

2 **Mixing**
Begin by dry mixing the cement, sand, and gravel together until the mixture is uniform, then gradually add water while continuing to mix. The aim is to get a thick, paste-like consistency that holds its shape, yet is workable. Too much water weakens the final concrete, while too little will make it unworkable.

3 **Pouring and curing**
Pour the mixed concrete, ensuring that it is packed down well to remove any air pockets. Once it's set, it needs to be left to cure. Curing is a hydration process that continues for several days, and keeping the concrete moist during this period is critical to achieving maximum strength.

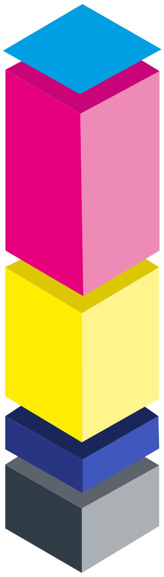


EXHIBIT 6: CONSTITUTENT PARTS OF CEMENT – ECOCEM

Alternative binders in construction today

Whilst conventional Portland Cement (PC) continues to be the primary choice in concrete production, **the industry is actively exploring innovative binders that have the potential to reduce both process and energy-related CO_2 emissions.** The core ingredients of standard PC are two calcium silicate minerals: alite, which catalyses early strength gain, and belite, which facilitates strength development at a later stage. In conventional PC, alite is typically present in larger quantities than belite.

Owing to alite's high calcium content, it requires **the use of substantial amounts of calcium-rich materials like limestone in the raw mix.** Throughout clinker production, these materials are subjected to high temperatures leading to decomposition, subsequently releasing calcium and carbon dioxide (CO_2). The calcium helps the formation of the two essential calcium silicate minerals, while the CO_2 is expelled through the flue gas.

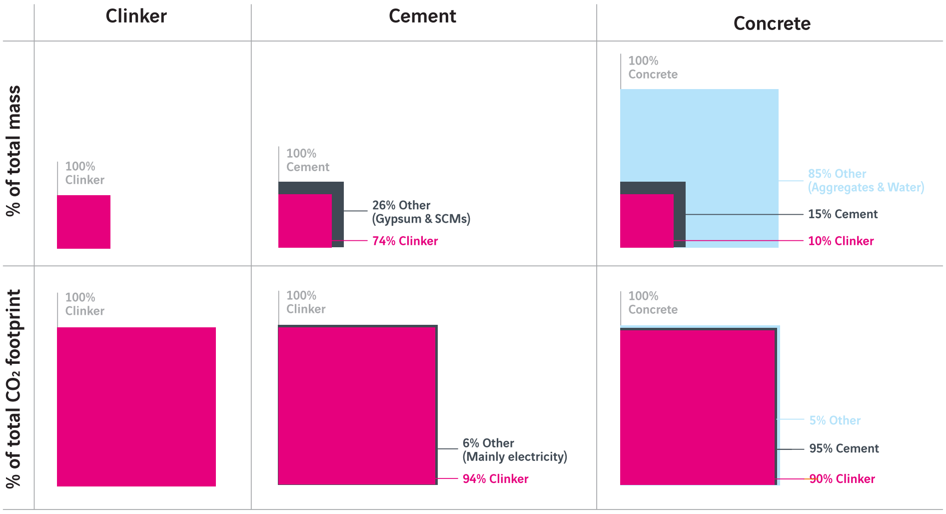


EXHIBIT 7: MASS OF CLINKER, CEMENT, AND CONCRETE, RELATED TO TOTAL FOOTPRINT – ECOCEM

As stated previously the CO_2 releases resulting from this process constitute a huge part of the total outputs attributed to the cement (Exhibit 7). In the first part, the focus was on trying to reduce the quantity of traditional clinker into the mixture. But another strategy is possible to reduce emissions, it is investigating in developing alternative binders that generate lower or zero process emissions during manufacture.[9] The properties of these alternative binders vary considerably from one to the other. **Some retain certain parallels with conventional PC, centring around calcium silicates as key to the hardening process,** but with modifications like the reduction or complete removal of high calcium alite content. This diminishes the quantity of limestone needed in the raw mix, and subsequently the volume of CO_2 released during the process. **Others take a different route, employing disparate chemistries or deviating from the energy-intensive, high-temperature clinkerisation process** inherent in PC production.

The maturity of new binding materials is also disparate. While some have a track record extending back decades and are commercially utilised, albeit not extensively, others are nascent developments or require further scrutiny to reach their full potential. One of the more intriguing concepts in alternative binders is those that harden through carbonation (i.e. see chapter on carbon negative processes), such as cement based on wollastonite, rather than hydration, as is the case with conventional Portland clinker. These essentially absorb the CO_2 emitted during their creation as they set and harden in concrete, culminating in a low-carbon or even carbon-neutral building material.

Some promising alternative binders to Portland Cement

Each alternative binder comes with its unique set of challenges. While it might not be feasible to completely replace conventional Portland cement, **any reduction in its use will inevitably help in lowering the carbon footprint of the industry as a whole.** Therefore, the continued development of these alternatives, even for niche applications, is pivotal to the long-term sustainability of the cement and concrete industry.

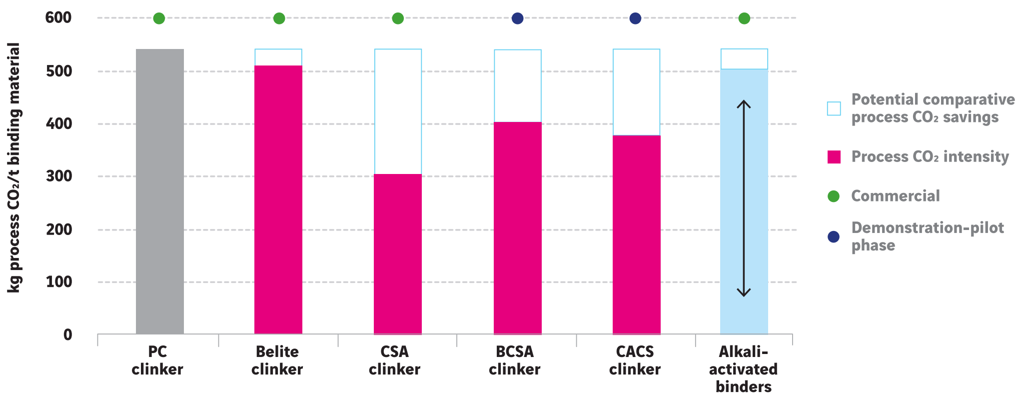


EXHIBIT 8: PROCESS CO_2 EMISSIONS GENERATION INTENSITY FOR CEMENT BINDING MATERIALS – IEA

As the sector is actively exploring and commercialising alternative cement binding materials that deviate from the conventional (PC) clinker formulation. These alternatives, which may use different raw materials or modified material mixes, are part of the industry's strategic initiative to mitigate the environmental implications of process-induced CO_2 emissions. These new methodologies range from commercially available to currently undergoing rigorous testing and developmental stages.

Belite clinker

Belite clinker, characterised by its minimal alite content and a belite proportion of between **40% to 90%, provides an attractive environmental benefit: a reduction of approximately 6% in the process CO_2** intensity of clinker.[10] A lower combustion temperature for belite clinker compared to Portland Cement (PC) clinker results in less fuel consumption and thermal energy savings of approximately 10%. However, belite is much more solid, and this results in a 5% increase in electricity consumption during the grinding process.[10] Despite the successful laboratory-scale production of belite cements at lower temperatures (600–900°C), market adoption remains low, largely due to their significantly reduced early-strength properties. China has been a pioneer in belite cement production, with its first successful application seen in the Three Gorges Hydropower Project.[10]

Calcium sulphoaluminate (CSA) clinker

Ye'elimite-rich clinker, a fundamental ingredient of CSA cements, has the benefit of reducing CO_2 emissions directly associated with the manufacturing process. A commercially produced CSA clinker, for instance, records a notable 44% reduction in process CO_2 intensity when compared to conventional PC (Exhibit 8). In addition, **CSA clinkers are recognised for their rapid strength development and being less prone to drying-shrinkage cracking, enhancing their structural robustness.**[10] Having been in commercial production for over three decades, primarily in China, the current annual output stands at approximately 2 Mt/yr.[6]

Belite calcium sulphoaluminate (BCSA)

Research is currently being carried out into clinker production, with the aim of mitigating the high material costs associated with CSA clinkers, while concurrently delivering a lower CO_2 footprint for standard concrete applications. This objective is primarily achieved by increasing the proportion of belite in the mixture and introducing alumino-ferrite to CSA clinkers, therefore offering a process CO_2 intensity that is 20–30% lower than that of Portland Cement.[10] Moreover, **BCSA clinkers can be synthesised using lower sintering temperatures, thereby requiring 30–50% less electrical power for grinding due to their increased friability.**[7] However, they have yet to reach commercial production, and specific standards for these clinker types are currently lacking, with the exception of the BCSA compositions that comply with Chinese regulations for CSA clinkers. It should be noted that this form of cement has the potential for commercial applications within Europe for specific, well-defined uses. Nonetheless, these applications would require local technical approval before implementation.[7]

Carbonation of calcium silicates (CACS)

Cement formulated on the carbonation of calcium silicates has the unique ability to sequester CO_2 during the curing process. Hence, despite being derived from raw materials akin to those in Portland Cement clinker, these varieties of cement can effectively achieve a net zero in terms of process emissions. This is achieved through the reabsorption of emissions that takes place during the curing process, meaning the primary source of carbon dioxide when manufacturing CACS clinkers is attributed to energy consumption in the kiln. The curing process itself occurs in an environment of relatively pure CO_2 at atmospheric pressure, with controlled ventilation, temperature, and humidity levels.

The application of CACS cement, however, is limited to precast products, and they should not have an overly large cross-section in order to guarantee sufficient curing. In contrast to conventional PC practices, the fuel mix for CACS may be more restrictive, requiring lower sulphur levels in the fuel and potential limitations on waste utilisation. Furthermore, they were not designed to protect traditional steel reinforcement from corrosion, consequently restricting their usage to non-reinforced products or those reinforced with non-steel materials such as glass-fibre-reinforced panels.[10]

Why zoom in on Alkali-activated Binders?

The significant environmental advantages posed by alkali-activated binders make them an exciting prospect. Unlike traditional Portland cement, they utilise industrial waste materials, thereby reducing carbon emissions and promoting a circular economy. **The variability can be extreme, with potential CO_2 and energy savings ranging from a remarkable 97% to a mere 10%, depending on specific factors.**[6]

Sustainability check

Material sourcing ● ● ● ●

It is made of solid waste from urbanisation and other activities.

Construction and operational ● ● ●

The process is less energy-intensive than conventional Portland Cement

Extended resilience and life cycle potential ● ●

The product has not yet been widely used, in order to predict its management at the end-of-life, but has the potential to be recycled according to its raw materials.

Alkali-activated Binders

Alkali-activated binders, often referred to geopolymers, are a class of materials that use a source of alumina and silica (like fly ash or slag) combined with an alkaline activator to create a binder. They can significantly reduce CO_2 emissions by up to 90% compared to Portland cement (PC).[11] These binders form a strong, durable material that is resistant to many common forms of chemical attack, making them an attractive alternative for many applications.

The history of alkali-activated materials in commercial use dates back to the 1970s in Ukraine, where activated blast furnace slag was first utilised. This development was built upon research conducted in the 1940s and 1950s. Since then, the array of precursor materials has expanded to include fly and bottom ashes from coal-powered power stations, calcined clays, natural pozzolans, iron-rich clays, non-ferrous slags, clay-heavy sludges from water treatment processes, red mud, and ashes from agricultural waste.[12]

EXHIBIT 9: ALKALI-ACTIVATED BINDER PROCESS

Alkali-activated binders are created through the reaction of an aluminosilicate (the precursor) with an alkali activator. The ability of these binders to mitigate CO_2 emissions is contingent on the carbon emitted during the creation of the alkali activators. These binders utilise materials akin to those found in blended Portland cement to reduce the clinker-to-cement ratio, originating either from natural sources or industrial ones. Therefore, their availability is largely region-dependent and is projected to decrease in the future for materials such as slag or fly ash. The diverse nature of the mix compounds the complexity of the process, indicating the need for rigorous technical assessment to ensure the quality and performance of the resulting binder.

What makes it special?

Alkali-activated slag (AAS) is earning a solid reputation within the field of alkali-activated materials (AAM) and is becoming increasingly popular in the construction industry. The primary reason for this notoriety is its potential for energy reduction when utilised as a binder in place of Portland cement.[13]

Putting the energy efficiency of AAS into perspective: **the production of one tonne of slag requires approximately 1300 MJ of energy and results in a mere 0.07 tonne of CO_2 emissions.** In stark contrast, the manufacture of an equivalent amount of PC demands 5000 MJ of energy while generating a full tonne of CO_2.[13] The potential for significant energy savings and drastic reductions in carbon emissions makes AAS a game changer in the quest for sustainable construction practices.

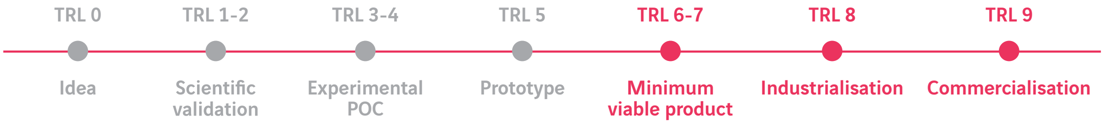
The adoption of alkali-activated binders (AABs) helps the industry manage waste more effectively, as these binders often use aluminosilicate precursors derived from waste materials, thereby preventing potential environmental contamination from improper disposal.

From an economic perspective, these formerly valueless waste materials, when used as binders can replace PC – the most expensive component of traditional concrete. This transformation is a win for both environment and budget.

Utilisation of AABs can help meet the future demand for building materials. Current research indicates that natural deposits used for PC are being overexploited. By adopting AABs, we can conserve these raw materials while still meeting the robust demand for construction binders. Hence, the shift towards AABs signifies a promising evolution in sustainable construction practices.[11]

Maturity of the tech

Alkali-activated binders are currently between MVP and commercialisation:



AABs, despite their wide variety, present a promising avenue for the future of cement concrete. They have the potential to reduce the reliance on Portland cement, thereby contributing to a noticeable reduction in CO_2.[14]

From a technical perspective, rigorous research has confirmed the performance of these binders. However, their commercial application currently remains confined to niche, nonstructural areas. This can be primarily attributed to the absence of exhaustive regulatory standards and guidelines, which tends to foster uncertainty amongst potential users. This highlights the need for the establishment of comprehensive standards that not only ensure performance quality, but also instil confidence within the industry about the use of alkali-activated binders.[7]

Some cement is already commercially available, but primarily used in non-structural applications. An example is Vertua Ultra Zero developed by CEMEX in Switzerland. Others are at earlier stages of development.[15]

Key roadblocks to overcome

PROPERTIES

–

Properties

Properties of alkali-activated binders strongly depend on the starting material properties, so quality control will be an overriding problem in practice. The durability of the concrete has yet to be demonstrated

Optimisation of synthesis process

The wide variety of aluminosilicate precursors available for AAB synthesis makes it difficult to establish general rules for producing binders with the desired properties. The type and concentration of alkaline solutions and the reactivity of aluminosilicate precursors need to be optimised.[16]

Curing methods

One of the challenges in the broader application of AABs is the curing method employed. AABs based on glassy aluminosilicates (e.g. fly ash) typically require specific curing methods to achieve the desired performance.[17]

SCALING UP

–

Cost

The large-scale production of alkali-activated concrete requires substantial quantities of these activators. However, their production at such a scale may not be economically viable at present, potentially driving up the cost of AAB concrete. Solutions to reduce production costs or develop affordable alternatives are critical to make AABs a viable option for the construction industry.

Supply Chain control

The lack of control over the supply chain of source materials, such as fly ash and blast furnace slag, is a barrier to the adoption of AABs. An understanding of market dynamics and the industry value chain is required to push AABs into the well established and conservative construction market.[18]

Standardisation and regulatory acceptance

The development and utilisation of locally available materials as precursors to alkali-activated binders require the establishment of guidelines, standards, and regulatory acceptance for their production and use in the industry.[19]

Operational safety

Handling alkali-activated materials often involves working under highly alkaline conditions, potentially endangering workers' health and safety.

Examples in the field

TERRA CO2

GOLDEN, USA
–

$61M RAISED TOTAL (SERIES A)
–

N/A
–

TRL 6–7
–

Terra CO_2 uses widely available silicate-based raw materials which are amongst the most abundant materials on Earth. Their plants are located on or near existing aggregate mine sites that are broadly found across large urban centres, reducing transportation costs and leveraging existing infrastructure. This eliminates the need to permit new mines for sourcing raw material as well as the expense of having to transport raw materials across long distances. By using their proprietary, patent-protected, low-carbon and low NOx reactor, Terra CO_2 mills its feedstocks and vitrifies them into a glassy powder suitable for blending in cement products.

Sublime Systems

RACINE, USA
–

$3,5 M TOTAL FUNDING
–

N/A
–

TRL 6–7
–

Sublime Systems utilises electrophoresis to extract materials from waste streams, including used concrete, offering a unique solution for recycling and repurposing construction waste. Even impure calcium sources can be processed, separating calcium derivatives from silica, thereby enhancing resource efficiency. Moreover, they convert limestone into lime at room temperature, eliminating the need for energy and fossil fuel-intensive kilns typically used in cement manufacturing. Their strategy, which relies on renewable energy, aims to provide a complete carbon-neutral solution.

Materrup
Fournisseur de construction responsable

SAINT-GEOURS-DE-MAREMNE, FRANCE
–

N/A
–

EUROPE
–

TRL 8–9
–

MATERRUP, an industrial startup with green tech and deep tech accreditation, is a provider of low carbon concrete products. The company leverages crosslinked clay cement technology and manufactures low carbon clay cement. Additionally, it also provides project management assistance for construction projects. Crosslinked Clay Cement® is a breakthrough technological platform that allows the production of customised raw clay cement containing up to 70% uncalcined raw clay. Materrup produces and supplies a type 42.5 cement, based on the performance framework for composite cement in standard NF EN 197-1.

LEGEND

HEADQUARTERS –

FUNDING –

TERRITORIAL REACH –

TECHNOLOGY READINESS LEVEL –

Alternative constituents that are not binders

In some instances, the challenge doesn't stem from the lack of clinker, but instead from the need to identify substitutes or partial replacements for traditional aggregates such as sand and gravel. This has sparked considerable interest in the exploration of innovative solutions that could be applied to various construction projects, further underscoring the industry's commitment to advancing sustainable practices.

Replacing 100% sand/gravel with solid waste

The MASUKO additive is an innovative solution for managing solid waste. This additive allows a wide range of non-reusable materials including polystyrene, rubber, and car parts, to be incorporated into a unique product called Waste Light Concrete (WLC). This material aligns perfectly with the European Union's Green Agreement and offers a scalable solution using traditional concrete mixing methods.

By substituting 100% of the sand and gravel in concrete mixtures with mixed solid waste, MASUKO helps reduce the environmental impact associated with mining and landfilling. The WLC product is lightweight yet durable, with a compressive strength of 3–12 MPa and fire-resistant properties. It's designed to be endlessly reusable, simply by shredding and remixing, thus diminishing the future need for extracting new natural resources and reducing transportation-related environmental damage.

MASUKO PRODUCT

For example, using this technology, a kilometre of a standard two-lane highway could recycle 4,000 tonnes of otherwise non-recyclable solid waste. It can accommodate waste types that typically end up in landfills, accounting for about 30–40% of total solid waste. Moreover, WLC is potentially 10% cheaper than conventional light concrete and could have 20% higher durability. This makes it a cost-effective recycling method that requires zero initial investment, a game changer in sustainable construction.[20]

World's first house made with nappy-blended concrete

Researchers from the University of Kitakyushu, Japan, have discovered that shredded disposable nappies can substitute between 9% and 40% of the sand in concrete formulation without compromising its structural integrity. Given that diapers accounts for a significant portion of non-recyclable waste, and cement production contributes to about 7% of global greenhouse-gas emissions while consuming 50 billion tonnes of sand annually, this is a noteworthy development.

WORLD'S FIRST HOUSE MADE WITH NAPPY-BLENDED CONCRETE – MUHAMMAD ARIEF IRFAN

Demonstrating practical applications, a house in Indonesia was built using this nappy-infused concrete. It showcased how this approach can not only help redirect waste from landfills but also contribute to the creation of cost-effective housing in economically disadvantaged communities. The idea was conceived by Siswanti Zuraida, a civil engineer at the university, while lecturing at the Bandung Science Technology Institute near Jakarta. The rapid population growth in low- and middle-income countries like Indonesia means an increased usage of disposable diapers and demand for affordable accommodation, making such innovations both environmentally and financially beneficial.[21]

1.3
CARBON-SEQUESTRATION

"A breakthrough in carbone dioxide reductions will come in the longer term, together with those shorter-term solutions that require reshaping the manufacturing process of concrete."

Margarita de la Peña Virgós
LatAm Investment Lead
at Zacua Ventures

The essentials of carbon-sequestration

1 **Climate impact mitigation**
By sequestering CO_2, it is prevented from reaching the atmosphere, thereby reducing the emissions contributing to climate change.

2 **Creation of carbon sinks**
Using novel technologies, buildings can effectively store carbon for their entire lifespan, reducing their overall carbon footprint.

3 **Reach for carbon negative**
Effectively deployed, carbon sequestration can create carbon negative operations. A significant step beyond simply reducing or neutralising carbon emissions.

Carbon sequestration can occur naturally or can be technologically facilitated, and both approaches are critical in our global efforts to combat climate change.

Natural carbon sequestration occurs through the known process of photosynthesis in plants, where they absorb carbon dioxide from the atmosphere, convert it into biomass, and store it in their tissues. Furthermore, **CO_2 is also naturally locked in geological formations through the process known as mineral weathering.** In this phenomenon, CO_2 captured in rainwater as carbonic acid, interacts with and dissolves basic rocks and minerals. These minerals generally consist of silicate, calcium, and magnesium, with olivine being a prime example. As a result of this reaction, various compounds like bicarbonate and calcium ions are formed, which gradually seep into the oceans. Within marine ecosystems, organisms consume these compounds and convert them into a stable calcium carbonate, a major component of their shells and skeletons. Simultaneously, the chemical reactions free up the hydrogen and oxygen in water, further drawing down CO_2 from the atmosphere. As these marine organisms perish, their calcium carbonate-rich remains descend to the ocean floor, contributing to the formation of layers of limestone and similar rock types, and effectively absorbing and storing carbon for hundreds of millions of years.[22]

An insufficient natural phenomenon

However, **given the scale of CO_2 emissions, natural sequestration alone is insufficient to balance the greenhouse gases that human activities produce.** For instance, the natural weathering mechanism is able to sequester at least half a billion metric tonnes of CO_2 annually, but human activities are relentlessly emitting over 35 billion tonnes of CO_2 every year, far exceeding the planet's natural carbon recycling capacity.[22]

The knowledge on natural carbon-sequestration processes and the need for more intensive carbon removal from the atmosphere has led to the development of **man-made sequestration techniques.** These methods involve capturing **CO_2 directly from large point sources like power plants,** which are significant contributors to atmospheric CO_2. The captured CO_2 is then compressed and injected deep underground into geological formations for long-term storage. These formations often include depleted oil or gas fields, unmendable coal seams, or deep saline aquifer formations. Moreover, CO_2 can also be further utilised by injecting it into construction materials.

An emerging business arena

Carbon capture, utilisation, and storage (CCUS) technologies are currently employed in approximately 35 commercial complexes worldwide, encompassing industrial processes, fuel transformations, and power generation. However, there are still 259 premises to date that have not yet deployed CCUS applications. **The running facilities that are now in use boast a collective yearly capture potential of nearly 45 million tonnes of CO_2.**[23]

In the coming years, annual CO_2 capture capacity is expected to witness significant growth. Project developers have set an ambitious target to have over **200 new sites operational by 2030, forecast to result in the sequestration of more than 220 million tonnes of carbon dioxide annually.** However, as of June 2022, only around 10 commercial capture projects under development had reached the final investment decision stage. This slower progress can be attributed to the fact that higher capture rates require larger equipment, more process steps, and increased energy consumption per tonne of CO_2 captured, leading to higher unit costs. Therefore, despite the progress made, the pace of CCUS deployment still falls significantly short of the benchmarks set in the Net Zero Scenario.[23]

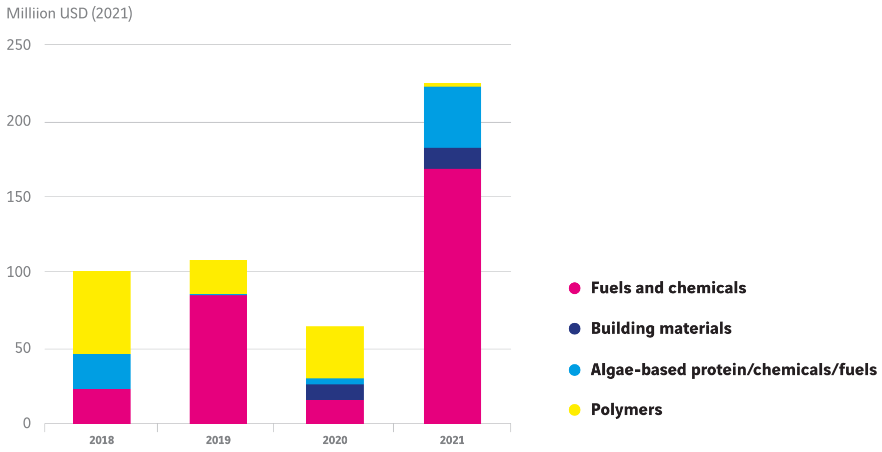


EXHIBIT 10: VENTURE CAPITAL INVESTMENTS IN CCU STARTUPS, 2018–2021 – IEA

Nonetheless, the future of CCUS technologies appears promising, as the interest in their implementation continues to emerge. This is evidenced by the **growing amount of private and public funding being directed towards companies in this field.** Specifically, the pursuit of corporate objectives and targets related to low-emission fuels and materials has driven a major rise in the use of CO_2 for sustainable aviation fuels and building materials. Over the past decade, global venture capital investments dedicated to startups focused on CO_2 operation have surpassed an impressive total of nearly USD 1 billion.[23]

Governments have also demonstrated their commitment to advancing carbon dioxide utilisation by allocating resources and making future pledges towards its implementation. Notably, **in 2021, the UK administration announced a funding package of GBP 180 million** exclusively aimed at supporting the design and construction of sustainable jet-fuel plants within the country. Additionally, authorities in Canada, Japan, the United Kingdom, the United States, and the European Commission have actively provided substantial engagement for research, development, and deployment efforts in CO_2 exploitation.[23]

Carbon sequestering in construction today

CCUS technologies can capture more than 90% of CO_2 outputs from power plants and industrial facilities.[24] However, their deployment in the construction industry is still limited, with an investment representing 6% of the total investment in CCUS startups. Therefore, to achieve a significant reduction of CO_2 by 2030, and culminate in net zero by 2050, the industry needs to accelerate the adoption of technologies. Moreover, stakeholders should also implement a combination of strategies to address both embodied and operational emissions.

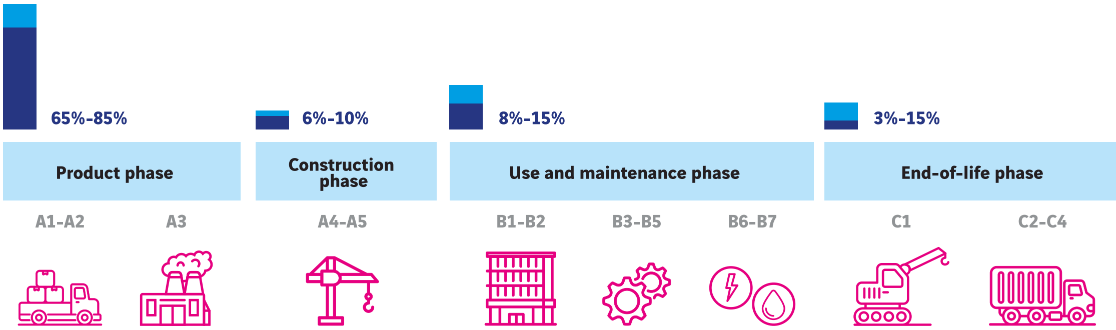


EXHIBIT 11: EMBODIED CARBON EMISSIONS DURING THE DIFFERENT PHASES OF LIFE CYCLE ASSESSMENT – RMI

Embodied carbon emissions, also known as upfront carbon, **depict the greenhouse gases released during the manufacture, transportation, installation of building materials, and demolition stages in the construction sector.** The importance of this metric is escalating, as it can comprise a considerable percentage of an edifice's total life cycle. This prominence is particularly noticeable as the operational energy efficiency of structures improves.

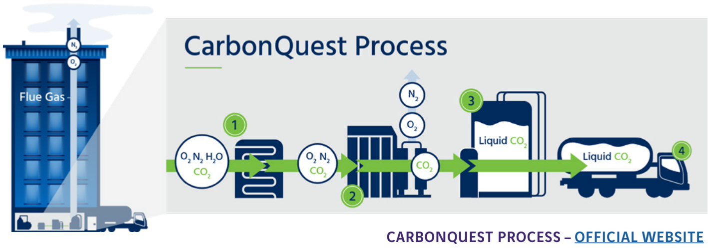
Indeed, it is noteworthy that **the production phase accounts for more than two thirds of a building's emissions.** This fact underscores why a significant portion of the effort in developing new technologies is aimed at the supply, extraction and fabrication of raw materials. With the possibility to store carbon, there is the **potential to reduce the footprint of concrete to zero in the coming decades.**[25] For instance, carbonation is a technique that involves both capturing and incorporating CO_2 into concrete during the manufacturing process. Also, bio-based construction materials store carbon that has been previously sequestered by forests and plants through photosynthesis. Some examples of these are hemp, bamboo, straw and timber, and can be utilised in various domains as insulation, cladding, and structural components to diminish the embodied carbon in a project.

Nevertheless, it is important to note that **CO_2 utilisation does not automatically lead to emissions reduction.** The climate benefits associated with any specific CO_2 usage depend on several factors. These include the origin of the carbon dioxide, whether it's derived from natural, fossil, biogenic or air-captured sources, and the product or service that the CO_2-based product is replacing. Furthermore, there are other significant factors beyond the intensity of the energy used that play a crucial role. Variables such as the length of time the CO_2 is stored within the product, and the size of the market for that specific use are to be considered. For instance, when dealing with CO_2 used in fuels and chemical intermediates, the use of low-carbon energy sources becomes especially vital given the high energy demands of these processes.

Innovative carbon-sequestering solutions

As we previously highlighted, the lion's share of embodied carbon emissions emanates from the production phase, but despite these other stages contributing a relatively smaller percentage to the total emissions, when considered at a global scale, these 'smaller' percentages translate into significant carbon volumes. The few startups described below are working to curtail emissions all along the life cycle of the building, rather than focusing on production.

Capturing CO_2 from building operations



CARBONQUEST PROCESS – OFFICIAL WEBSITE

CarbonQuest is elevating standard carbon capture and sequestration solutions, combining trusted technologies with an innovative, expert approach to point source carbon capture at commercial and residential buildings. Through their cost-effective, modular technology, they are able to deliver an impactful yet widely accessible emission reduction solution that promotes stronger and healthier communities.

This carbon capture technology is safe, cost-effective, and can eliminate up to 70–85% of a building's net CO_2 emissions, depending on customer requirements.

Enhanced weathering to permanently remove CO_2 from the atmosphere

Silicate has developed a low-temperature conversion process to transform silica-containing materials like glass and sand, often derived from surplus concrete, into a weathering agent. When the weathering agent reacts with soil carbonic acid, it forms bicarbonate and calcite, effectively pulling CO_2 from the atmosphere and mineralising it into the geosphere. This process is also beneficial for agricultural practices; when spread on soils, the weathering agent can replace ground limestone as a soil pH amendment, providing dual benefits of carbon sequestration and soil health improvement.

SILICATE – OFFICIAL WEBSITE

Decarbonising supply chains through carbon negative fillers

MADE OF AIR PRODUCT – OFFICIAL WEBSITE

At Made of Air, they are taking carbon dioxide from the air, and permanently storing it in manufactured goods that replace fossil-based plastics or high-emission materials. They supercharge the work of nature with technology and create carbon-negative compounds from biochar and bioplastics. These are sustainably sourced and utilise biomass waste which would otherwise re-release its temporarily stored CO_2 back into the atmosphere. Building products and consumer goods made from our materials are transformed into engineered carbon sinks.

Carbon-sequestering in construction materials

Recycled Concrete

Recycling construction and demolition (C&D) waste into recycled aggregate (RA) is a globally recognised waste disposal strategy. The surge of natural disasters, along with rapid industrialisation and urbanisation, particularly in developing countries, has led to the generation of massive volumes of C&D waste that should persist for several more decades. **China, for instance, has emerged as the world's largest C&D waste producer, generating around 1.65 and 1.85 billion tonnes in 2016 and 2017, respectively.**[26]

Countries like Germany, Japan, and the Netherlands have demonstrated a commendable recycling rate, repurposing over 80% of their C&D waste. In contrast, the recycling rate in other developed countries hovers around 20–40%. **Alarmingly, the recovery rate in developing countries is almost negligible.** One popular recycling method involves replacing virgin aggregate with recycled aggregate in concrete. However, it's worth noting that this substitution can reduce the concrete's compressive strength by approximately 30–40%.[26]

Hempcrete

Hempcrete is a composite material that combines the inner woody core of hemp plants with lime binders. It is approximately one eighth the weight of concrete and is used where concrete block might be used as an exterior or interior wall. Unlike traditional poured-in-place concrete or concrete block, however; it is nonstructural and must be combined with other frame elements such as wood or steel. This is because typical concrete blocks used in walls have compressive strength values varying between 5 megapascals (MPa) to 20 MPa, but lab-scale hempcrete has only shown a compressive strength of 3 MPa.[27] In a recent study, it was found that hempcrete has the potential to sequester approximately 19 pounds of CO_2 per cubic foot. This sequestration capacity is roughly equivalent to offsetting the annual carbon emissions produced by three refrigerators. That highlights the significant carbon sequestration potential of hempcrete and its positive impact on reducing greenhouse gas emissions.[27]

Builders worldwide are recognising the value of hempcrete as a sustainable construction material. It has been successfully utilised in building projects and renovations across several countries, including France, the United Kingdom, Belgium, Ireland, the Netherlands, Italy, and Australia. Notable examples include the utilisation of hempcrete in the artefact's storage facility of the British Science Museum Group, as well as its application in public housing towers and the restoration of centuries-old stone buildings.[27]

Why zoom in on fossilisation and carbonation curing?

As mentioned, several measures are being researched or even implemented to mitigate significant CO_2 emissions from the construction industry by capturing and utilising the gas. The most developed technologies are industrial-level CO_2 capture in cement industries, such as amine scrubbing, oxy-combustion, direct capture, and calcium looping.[26] However, the aim of this report is to showcase novel developments in construction processes and materials, rather than improvements in manufacturing techniques. Therefore, following on, two promising technologies in the field of CO_2 sequestration at the level of building materials will be further developed.

On the one hand, **the accelerated fossilisation process from the French startup Néolithe** will be analysed. It consists of a unique procedure that converts non-recyclable waste into aggregates that can be used in construction to produce concrete or road subbase. Such a method has the potential to replace conventional waste disposal like incineration or landfill and possesses an intrinsically negative carbon impact of -337 kg CO_2/t.[28]

On the other hand, the method of **introducing carbon dioxide to concrete during its production process, known as carbonation curing**, will also be portrayed. It is a more mature technology than the previous one, but it has not yet been established as a standard in the production of structural cement. Even so, it is showing valuable potential due to its better strength and resistance, in addition to its 20% to 50% estimated CO_2 absorption capacity.[29]

Sustainability check

Material sourcing

The product is made of non-recyclable waste materials.

Construction and operational

Avoids non-recyclable waste to go to landfill or incineration, but water and energy are used.

Extended resilience and life cycle potential

The obtained aggregates can be reused to produce concrete.

Fossilisation of waste by Néolithe

Néolithe is a young industrial startup based in the region Pays de la Loire in France. They have developed a new process based on fossilisation for treating non-recyclable waste as an environmentally sustainable and economically viable alternative to landfill and incineration.[30]

By simulating the transformation process of Cretaceous debris into limestone, this startup has achieved a new process with the potential to revolutionise the treatment of non-recyclable, non-inert and non-hazardous waste materials.Néolithe Accelerated Fossilisation is based on a three-stage process:[28]

The aim of the company is to set up the Fossilizator® directly following the sorting centres whether in household waste communities or industrial plants. Thus, they work as equipment suppliers for their installations.

1 **Waste sorting**

Ordinary industrial waste from deconstruction is sorted and separated into recyclable and non-recyclable materials to obtain sorting rejects for the next stage of the process.
Their Fossilizator® technology is capable of handling a range of non-recyclable waste types like plastics, textiles, wood, plaster, and insulation material. Nevertheless, metals are extracted from the process to be repurposed within their respective industrial sectors.

2 **Fossilisation of waste material**

After being introduced into the Fossilizator®, sorting rejects are shredded to obtain a fine powder waste. Eighty percent of this material is then mixed with 20% of their proprietary low carbon binder and water via an emission-free process. The binder, whose formula is confidential, is essential to ensure the inertia of the waste and give it a coherent mineral structure. Finally, the obtained stone pulp is processed to form the Anthropocite® aggregates.

3 **Construction industry applications**

This new mineral has the same technical and mechanical characteristics as traditional aggregates, the most widely consumed raw material in France, at 450 million tonnes per year. Therefore, Anthropocite® aggregates can be reused in construction to produce concrete or road subbase, for instance.

What makes it special?

Traditional waste disposal methods include recycling, landfilling, incineration, composting amongst others. These methods have various environmental and economic drawbacks, such as the release of greenhouse gases, pollution, and the consumption of valuable land and resources.

NEOLITHE PRODUCT

6%
of global greenhouse gas emissions
are from waste treatment

40 million
tonnes of waste
is landfilled or incinerated every year

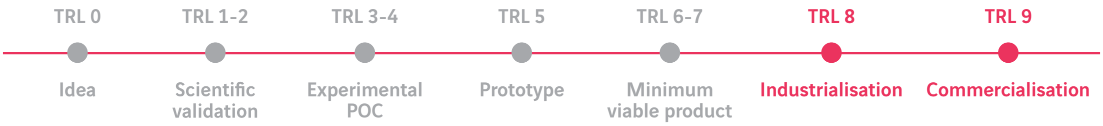
450 million
tonnes of aggregates
are used every year

In contrast, accelerated fossilisation creates a material derived 100% from the recycling of waste, with **an intrinsically negative carbon impact of -337kgCO_2/t.** Also, after obtaining initial approval from the CSTB (the Scientific and Technical Centre for Building) in France, Anthropocite® aggregates are now authorised for use as a substitute for traditional aggregates, **up to a maximum of 10%, in non-structural concrete.** The integration of this novel mineral composition within the mining industry has the potential to contribute to the enhancement of the sector's carbon balance.

Currently, Néolithe aims to extend the uses of this new material to other types of concrete and to higher percentages, with a **short-term objective of 30% substitution of traditional aggregates.**[28]

Maturity of the tech

Néolithe's fossilisation technology is currently between industrialisation and commercialisation:



In May 2022, Néolithe announced **the signature of three pre-orders for the Fossilizator® with major French players** such as Eurovia, Corudo and the Cheval Group. These first installed waste treatment units will have the capacity of 20 tonnes per day and a footprint of 400m^2.[28]

For example, Mat'Ild, a subsidiary of Eurovia (VINCI), is set to install a Fossilizator® at their construction waste sorting centres in the Provence-Alpes-Côte d'Azur region. Subsequently, Eurovia, being a significant producer and consumer of aggregates, will incorporate the **locally produced Anthropocite® aggregates from their own construction projects** within the group.[31]

As previously mentioned, in July 2021, the Technical Evaluation of Products and Materials (ETPM) issued by the CSTB confirmed the high quality of non-structural concrete manufactured using Anthropocite®. This evaluation served as concrete evidence of the successful outcomes achieved and authorised material producers to utilise up to 10% of Anthropocite® as a replacement for conventional aggregates. Thanks to that, the aggregates are now being used for the first time as part of the Empreinte project.

Empreinte is an innovative housing concept focused on low-carbon principles, initiated by the ERB (General Building Company) and carried out by a collaborative group of companies. The primary aim of this initiative is to explore and experiment with new construction methods, thereby paving the way for future housing options. Aligned with Néolithe's commitment to minimising France's carbon footprint through waste management, this sustainable construction initiative plays a crucial role in the development of the Fossilizator® technology.

Key roadblocks to overcome

SCALING UP

–

Regulatory and environmental concerns

Implementing this technology on a large scale may require compliance with various environmental regulations and standards. Ensuring that the process does not have any adverse environmental impacts could be a challenge.

Cost

Despite landfill and incineration being non-compliant with environmental challenges, these methods could still be far cheaper to use than using the novel process.

Market acceptance

Convincing the construction industry and other potential users of the benefits of using Anthropocite® aggregates instead of traditional materials may be difficult. Market acceptance and adoption of this new material will be crucial for the success of Néolithe.

Funding

Néolithe is currently seeking capital to fund its growth and expansion (around $ 100M). Securing sufficient funding and scaling up the technology to meet the demands of the market may be challenging.

Sustainability check

Material sourcing ●●●

CO_2 can be sequestered in the material from the atmosphere or emission sources.

Construction and operational ●●

The moisture curing is avoided; thus less water is used.

Extended resilience and life cycle potential ●

No difference from traditional concrete.

Carbonation curing of concrete

Carbonation curing of concrete involves curing concrete in a high-pressure environment where pure CO_2 is present. In this method, the un-hydrated cement minerals within the concrete react with the CO_2, resulting in the formation of solid carbonate compounds that help solidify the concrete.[29]

Carbonation of concrete refers to the chemical reaction between the hydration products of cement and atmospheric CO_2. This effect occurs naturally when edifices are exposed to the surrounding air, and it is known as weathering or natural carbonation. It is gradual, and it leads to a decrease in the pH value of the structures, which can result in the corrosion of steel reinforcement.[32] However, this **carbonation process can be performed in a controlled environmental condition in a chamber at the early stages of curing and strength gain.** During the process, two of the primary compounds of cement, tri-calcium silicate and di-calcium silicate, and the by-product of hydration, $Ca(OH)_2$, react with the infused CO_2 giving solid calcium carbonates ($CaCO_3$) at ambient temperature.[32]

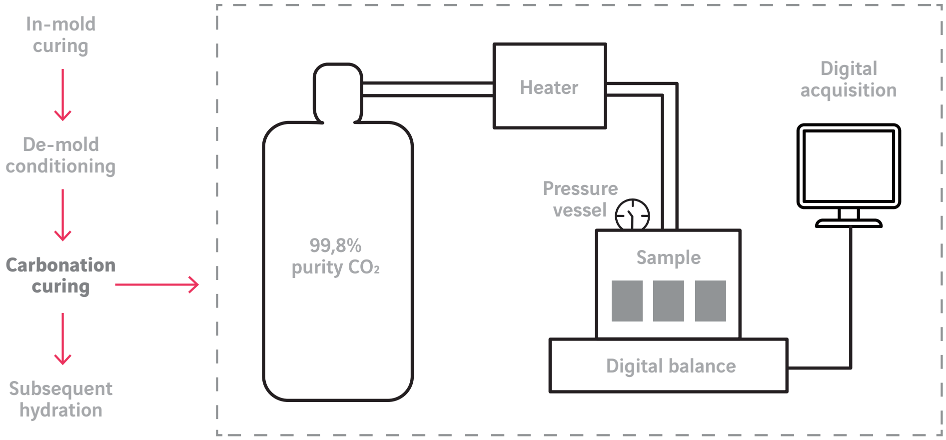


EXHIBIT 11: PROCESS OF CARBONATION CURING

To further improve this process, companies such as CarbonCure and Neustark partner with industrial gas corporations, that capture their CO_2 and transport it to the manufacturing sites. This way, the **CO_2 that would otherwise be emitted to the atmosphere can be reused for manufacturing.**[32,33] In addition, the Swiss company **Neutrask** and others do not work at early stages of production, but, instead, carry out enforced re-carbonation. In this case, the CO_2 **storing technologies are intended to be applied to crushed demolition granules to obtain recycled concrete enriched with CO_2.**[33]

What makes it special?

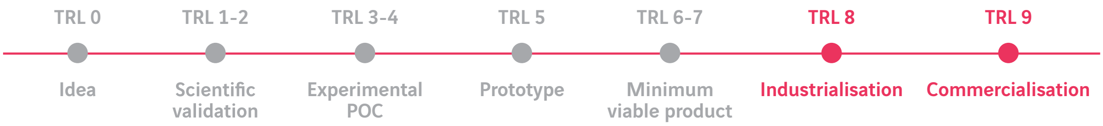
Conventionally cured concrete is referred to as moisture-cured, and it consists of keeping the moist for an extended period to promote proper hydration and strength development. In contrast, **carbonation-cured concrete (CCC) is associated with a greater than 10% increase in compressive strength compared to this method.**[29] To measure its ability to withstand indentation or penetration by a harder material, micro-hardness is used. In this regard, CCC exhibits a 40% increase compared to that of the moisture-cured paste. Moreover, the higher the hardness value of the paste is, the better is the abrasion resistance. Accordingly, CCC has also shown **20% better abrasion resistance than the conventionally cured one.**[29]

To determine the strength and durability of concrete, the pore framework of the material is key. For instance, excessive pore volume and larger pore sizes (between 50 and 100+ nm) can compromise the concrete's ability to withstand external forces, such as compression, tension, or freeze-thaw cycles. In contrast, a well-optimised pore structure with a lower volume of larger pores (below 20 nm and up to 50 nm) can contribute to higher compressive strength and improved resistance to damage. Therefore, **the pore structure is refined after carbonation curing,** adding to the improvement of compressive strength.[29]

On the other hand, the chloride ion is one of the main causes of steel rust. It destroys the passivation film of the steel bar, forms corrosion microcells, accelerates the anode reaction, and thus causes the oxidation of the steel in the concrete. As an advantage, **the anti-chloride ion permeability of carbonation-cured concrete is superior** to that of moisture-cured. This is shown by an electric flux value of 956 Coulombs (C) for the CCC versus a 1389 C of the moisture-cured concrete.[29]

Maturity of the tech

Carbonation-cured concrete is currently between industrialisation and commercialisation:



Research institutions have been working on the conversion of CO_2 to building products, and, in particular, in concrete. For example, CO_2 Concrete, currently the spin-out CarbonBuilt, was a carbon-use technology originally developed at the Laboratory for the Chemistry of Construction Materials (LC2) at the University of California, Los Angeles (UCLA). The platform was able to inject the CO_2 from power plants directly into a curing chamber. The **resulting lab-scale concrete blocks were proven to provide a CO_2 reduction of between 50% to 75% compared to conventional concrete blocks.**[34, 35]

The global market for turning waste CO_2 into building materials has been estimated to have a potential worth of USD 1,3 trillion. Thus, companies in the field are emerging and working to commercialise their approaches. For example, Solidia Technologies is a cement and concrete technology company offering sustainable concrete curing that consumes 240 kg of CO_2. In 2013, they partnered with Lafarge, a world leader in building materials. They have also secured the backing of other high-profile investors and manufacturers, including BASF Venture Capital, Kleiner Perkins Caufield Byers, Bright Capital and BP Ventures.[34, 36, 37]

The first industrial applications for carbon storage through mineral carbonation have been demonstrated in industrial applications beyond the pilot stage. Zirkuilt is a Swiss company that provides CO_2 storage in concrete granules on an industrial scale. Moreover, in May of this year, Solidia Technologies announced the opening of a commercial manufacturing facility for dry-cast concrete by the end of 2024. Even so, although technology for manufacturing carbonation-cured concrete is demonstrated and in use, the application of the resulting material to construction as building blocks has not yet reached the market.[36, 38, 39]

Key roadblocks to overcome

PROPERTIES

–

Low pH

The natural carbonation reaction in concrete is widely recognised for its ability to reduce the pH value, which can potentially lead to steel corrosion. Nonetheless, the effect of carbonation curing on pH has not been widely studied. Research shows that immediately after the completion, the pH of the concrete surface layer (in the range of 0–10 mm in depth within a sample of 10 mm x 10 mm) is less than 9.5, in contrast with 12,1 for moisture-cured concrete. However, after 28 days, the pH value of the carbonated sample increases above 12.0, just like the conventionally cured. This can be attributed to the absence of cement carbonation during the subsequent hydration process, where a greater amount of $Ca(OH)_2$ is generated, increasing the pH value.[32, 29]

Low CO_2 sequestration rate

The rate of CO_2 sequestration remains relatively low, estimated to be around 20% to 50% of the theoretical potential. This limited sequestration rate can be attributed to the challenges associated with CO_2 diffusion into the concrete matrix during the process of carbonation curing. By studying the pH value according to the depth of the sample, it is possible to understand where this latest has occurred. In this sense, research findings have shown that the reaction is confined to the depth range of 0–30 mm within the sample, while its interior showed no signs of carbonation reaction.[29, 40]

SCALING UP

–

Only used for precast concrete

The use of carbonation-cured concrete (CCC) is limited within reinforced concrete construction (RCC) for structural considerations. Further research is needed to clarify if the carbonation process can lead to a reduction in alkalinity and a subsequent increase in the risk of corrosion for the embedded steel reinforcement. If this was the case, it could compromise the structural integrity and long-term durability of the RCC elements. Also, achieving uniform carbonation in large RCC structures, such as foundations, columns, and beams, is challenging due to variations in environmental conditions, concrete thickness, and exposure to moisture. Controlling and monitoring the process becomes more difficult in these scenarios. Instead, CCC is ideal for precast concrete manufacturing where quick turnaround curing times are desired. Moreover, its production often takes place in controlled factory conditions, allowing for better modulation of the process and ensuring uniform carbonation throughout the entire edifice.[32]

Examples in the field

CARBONBUILT
ULTRA-LOW CARBON CONCRETE

LOS ANGELES, USA
–

$10M (SERIES A)
–

N/A
–

TRL 6–7
–

CarbonBuilt developed a process which incorporates CO_2 directly into concrete during the manufacturing phase, transforming it from a greenhouse gas into a valuable raw material. This process not only significantly reduces the carbon footprint of concrete production, but it also leads to the creation of a superior product with similar or better performance characteristics compared to conventional concrete. The company is based on technology developed at the UCLA Carbon XPRIZE team.

ecoLocked

BERLIN, GERMANY
–

$1.78M TOTAL FUNDING
–

N/A
–

TRL 5–6
–

ecoLocked creates biocarbon-based concrete admix materials that are designed to reduce embodied CO_2 and turn the built environment into a carbon sink. The admixtures come with certified recipes customised for a portfolio of concrete applications and integrate seamlessly with existing processes. Besides a significant reduction of direct emissions, ecoLocked materials enhance performance parameters such as the thermal insulation capacity of concrete and thus improve the lifetime energy efficiency of buildings.

concrete 4change

NOTTINGHAM, UNITED KINGDOM
–

$2,2 M TOTAL FUNDING
–

N/A
–

TRL 3–4
–

Concrete4Change (C4C) is developing an award-winning, patented technology that takes CO_2 and permanently locks it into concrete as the safest method for CCUS. C4C technology is already 10 times more efficient than the current market leaders. The sequestration of carbon dioxide results in the strength enhancement of concrete, reducing the amount of cement content required to achieve standard concrete recipes. Both CO_2 sequestration and cement reduction contribute to diminishing concrete's carbon footprint. C4C technology has the potential to mitigate 2 billion tonnes of CO_2 emissions by 2040, the equivalent of total annual EU CO_2 emissions.

LEGEND

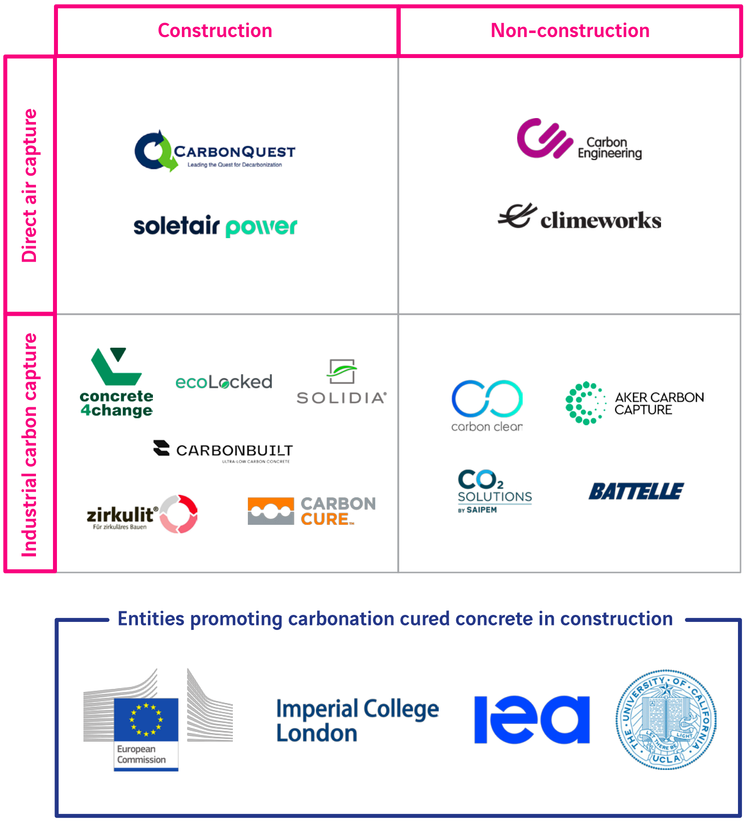
HEADQUARTERS –

FUNDING –

TERRITORIAL REACH –

TECHNOLOGY READINESS LEVEL –

Ecosystem & Actors



When the CO_2 used for carbonation curing is recycled, it can come from two sources: direct air or industrial carbon capture. Direct air capture involves the process of removing CO_2 and other greenhouse gases from the atmosphere.[41] On the other hand, industrial carbon capture entails the extraction of CO_2 from emission sources such as industrial facilities. For both methods, if the collected gas is not used on-site, it can be pressurised and conveyed for diverse applications. As mentioned, this strategy is followed by the companies CarbonCure and Neustark.

Alternatively, if not used to produce concrete, the CO_2 can also be injected and stored into deep geological formations. This is the case of Batelle, a leader in geologic CO_2 storage providing safe and permanent saline storage solutions.[42] Carbonation-cured concrete blocks are promising products that still lack real applications as construction materials. While improving the performance of the building blocks is mainly carried out by the companies, research institutions are more focused on the carbon capture and storage techniques. Specifically, the interest is put on the use of industrial carbon capture technologies on cement plants to produce concrete.

The European Commission is an active actor in the field, pushing the cement industry to commit to climate protection measures. Through the CEMCAP project, they aimed to prepare the ground for a large-scale implementation of industrial CO_2 capture in the cement industry. **For that, amongst other actions, they leveraged to minimum viable products those carbon capture technologies with a targeted capture rate of 90%.**[43]

Future challenges

Having delved into greener concrete production methods, it's evident that further innovative approaches are imperative to attain near-zero emissions in the industry's future. **These encompass deep technologies currently undergoing pilot and demonstration phases, with anticipated deployment in the medium and long term.** At the forefront of these efforts is the installation of carbon capture processes within concrete facilities. Successful implementation of these processes will pave the way for the utilisation of sequestered carbon dioxide in concrete production, thereby closing the sustainability loop.

A not yet attained profitability for capturing carbon

Whilst capturing carbon dioxide at the source of emissions holds great potential, its widespread use is hindered mostly by its costs. Increasingly, emitting polluting gases into the atmosphere is linked to certain economic penalties. For instance, the European Union Emissions Trading System (EU ETS) is a carbon pricing tool designed to lower greenhouse gas emissions by imposing a limit within specific sectors of the economy. However, the current CO_2 cost fluctuates around USD 80/t, and for CCUS facilities to be profitable, such fee should range from USD 80 to USD 130/t. In other words, **carbon capture, utilisation, and storage (CCUS) technologies will be unprofitable for as long as the CO_2 price is lower than the technology costs.**[44]

The industrial sector acknowledges that the current CO_2 quotation does not accurately anticipate the future, and there is a prevalent belief that prices will rise. But there's no consensus on the extent or timing of these increases. For example, different studies mention a too-wide range of CO_2 fee projections, spanning from USD 40 to USD 380/t by the year 2050. These economic uncertainties pose a significant barrier to carbon dioxide mitigation strategies, especially for low-profit sectors like cement. **Therefore, the industry's lack of guidelines or price ranges is slowing down the expansion of CCUS.**[44]

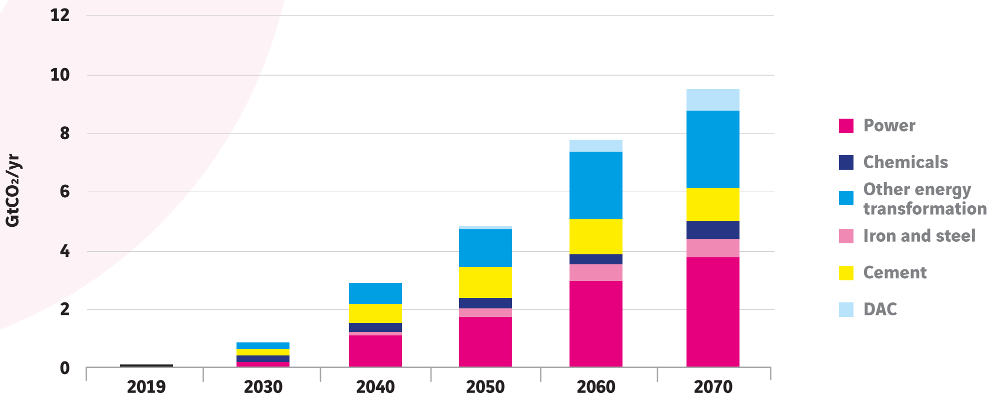


EXHIBIT 12: GROWTH IN GLOBAL CO_2 CAPTURE BY SECTOR, SCENARIO 2019-70 – IEA

Emerging initiatives set to lead the path

Fortunately, several emerging CCUS applications are already being undertaken, even in the absence of an adequate CO_2 price. **Their objective is to raise public awareness and lay the groundwork for future accessibility.** CCUS projects in development are expanding geographically. Beyond North America and Europe, significant strides are being achieved in Asia Pacific and the Middle East. Amongst the diverse technologies known, **chemical absorption and calcium looping are the closest to large-scale commercialisation (TRL 7).** In 2014, Texas saw the launch of the first commercial chemical absorption facility with a 76,488-tonne annual CO_2 capacity, followed by a 50,000-tonne pilot plant in Wuhu, China, in 2018. Similarly, after successful pilot demonstrations of calcium looping technologies, a pre-commercial demonstration plant is slated to begin operations in Italy, and a commercial-scale plant is anticipated in Chinese Taipei by 2025.[6]

A matter of combined effort

Prospective forecasts from the International Energy Agency plan that global net-zero emissions will not be achieved until 2070 by using only CCUS. Accordingly, the calculated CO_2 captured that year would be around 10 Gt (Exhibit 12), with a 10% contribution from the cement sector. These figures do not align with the carbon-neutrality target set for 2050 as outlined in the Paris Agreement. Therefore, to accomplish our endeavour towards sustainable concrete, different solutions must be used in conjunction. That is, alternative cement constituents, being already cost competitive at less than USD 100/t, will be deployed in the short-term, but will continue to be used further on, together with CCUS.[6]

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About us

Leonard is the name of the VINCI Group's foresight platform and fast track for innovative projects, launched in July 2017. Why Leonard? To respond to some of the biggest challenges facing VINCI's businesses: digital revolution, faster innovation cycles and environmental transition. Within a transforming world, Leonard detects new trends, supports innovation and brings together all the players involved in shaping the future of cities and regions.

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Hello Tomorrow is a global initiative that connects deep tech entrepreneurs with businesses and investors, and provides consulting services in strategy and innovation. Over the course of nine editions, the Hello Tomorrow Global Challenge has received 30,000 applications from 132 countries, partnering with universities and research institutions worldwide to identify deep tech solutions that are advancing human and planetary health. Hello Tomorrow then connects these pioneers with industry, investors, researchers, and regulators through international events, consulting services and startup programs to harness the potential of their solutions.

hello-tomorrow.org

TO GO FURTHER

In the first part of the report, the most promising technology trends tackling the production phase of the concrete industry has been assessed.

In part two, an array of novel materials are portrayed, most of which intend to increase the efficiency of the building over its use life, without forgetting about its production and appropriate disposal.

Available here