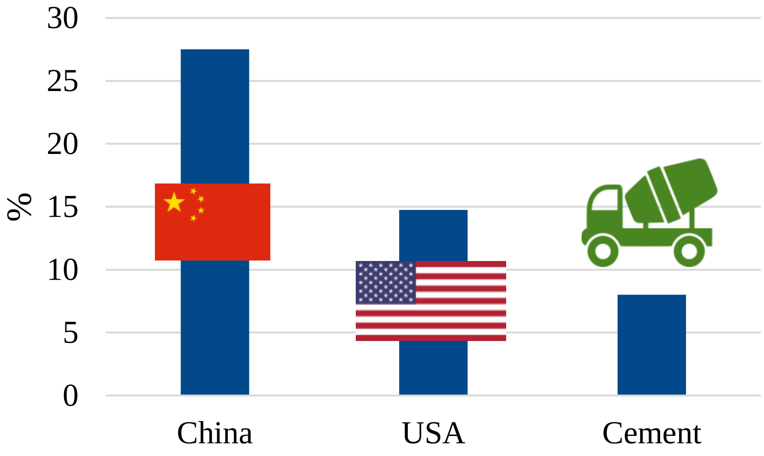
Reducing Emissions in the Cement Industry an Introduction.

Cement, the silent giant

When contemplating Green House Gas (GHG) emissions it's common to think about cars, planes and power plants. However, a huge emitter of CO_2 that's often overlooked, is cement. In 2018 4.1 billion tonnes of cement was produced globally. The IEA estimates cement production will rise between 12%-23% by 2050. Its grossly inefficient production process means the industry was responsible for 2.2 billion tonnes of CO_2 emissions in 2016 which equates to a mammoth 8% of the global total.[1,2] If the cement industry was a country, it would be the third largest emitter of CO_2 in the world after China and the US, see **Figure 1**. If we are to have any hope of meeting the temperature goals set out in the Paris Agreement, global economies need to focus on dramatically reducing emissions in the cement industry, though limited progress has been made to date.

Figure 1 – Largest global CO_2 emitters



Cement is an amazing binding agent that is a basic ingredient of mortar and most grout. However, cement is most famous for the material created when it is mixed with sand, gravel and water – concrete.[3] Wet concrete, the product of mixing these ingredients in a ratio of around 1 : 1.5 : 3 : 0.45 respectively, can be cast in almost any shape. Once hardened it becomes a structural and load bearing construction material used more than any other in the world.

Our toxic dependence on cement doesn't just impact emissions. In addition to its impact on global heating, the cement industry uses around a tenth of the world's industrial water, or 3 trillion liters per year. This amount of water would fill a 1,000,000 Olympic swimming pools annually. Furthermore, the acquisition of sand can be catastrophic – destroying so many of the world's beaches and river courses that this form of mining is now increasingly run by organised crime gangs.

Finally, the least researched, impact of concrete, is that it destroys natural infrastructure without replacing the ecological functions we depends on for fertilisation, pollination, flood control, oxygen production and water purification.

However, many engineers argue that there is no viable alternative. Steel, asphalt and plasterboard remain more energy intensive than concrete and the world's forests are already being depleted at an alarming rate even without further demand for timber. The world was unlikely to reach "peak concrete" as the raw materials are virtually limitless and will be in demand for as long as we build roads, bridges and anything else that needs a foundation.

Therefore, countries, companies and research must focus on what we can do to reduce the overall environmental impact of a material that is such a vital prerequisite for human development.

Current Cement Production

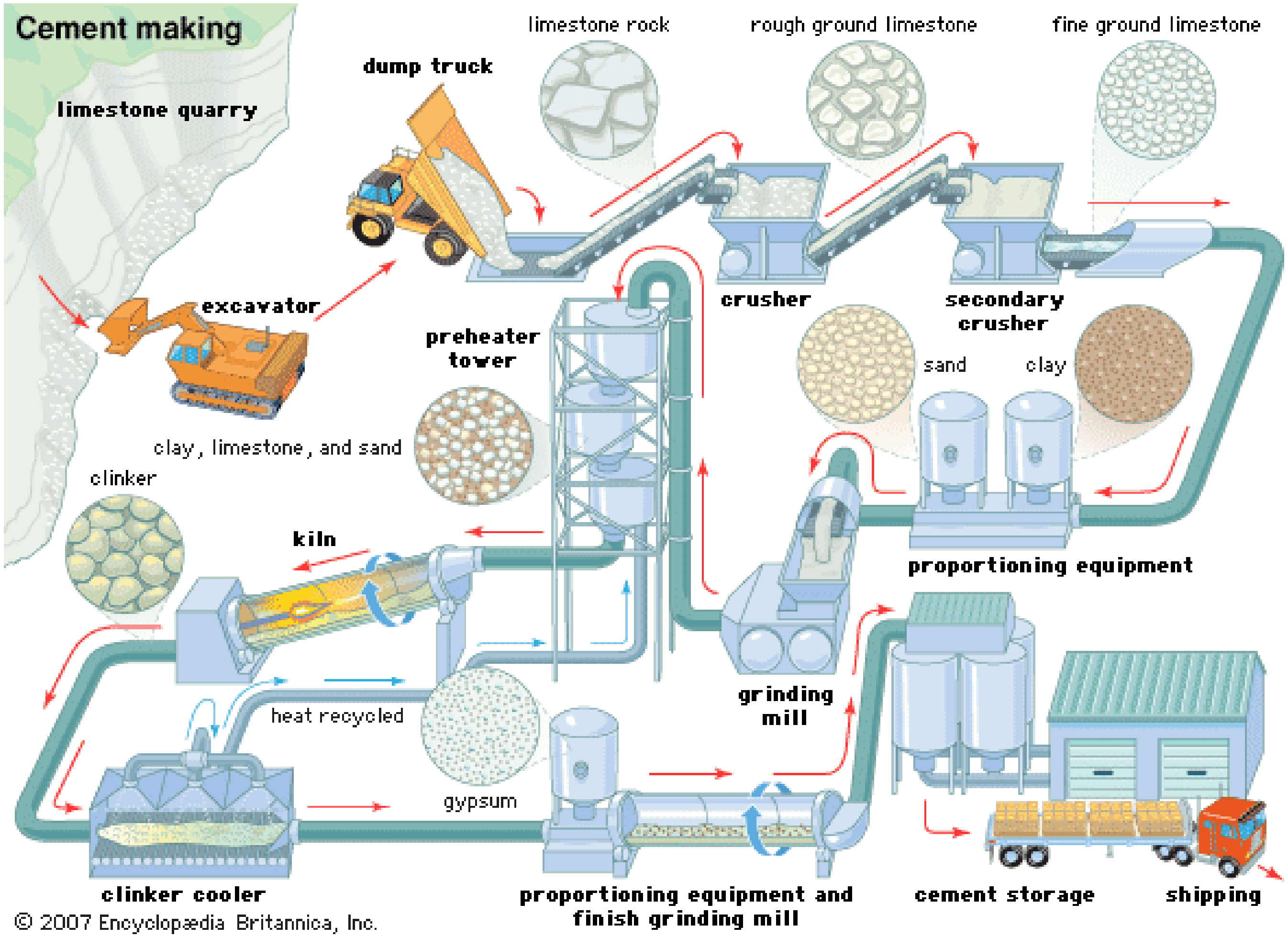


Figure 2 – Full process of cement production

Current Cement Production

Portland cement, by far the most common cement used globally, is used in 98% of concrete produced. It is made by the following process, depicted in **Figures 2 and 3**:

1. Limestone and clay are quarried, crushed and ground before mixing with other materials - such as iron ore/ash.
2. This mixture is then fed into a large, rotating, cylindrical kiln and heated to about 1,450 °C.
3. At these elevated temperatures, the chemical process of calcination splits calcium carbonate into calcium oxide and CO_2. Chemical reaction shown in **Equation 1**.
4. **Equation 2** shows how the intermediate oxide reacts with silicon oxide to form calcium silicates, or *clinker*.
5. The clinker is cooled, mixed with gypsum and ground into a powder.

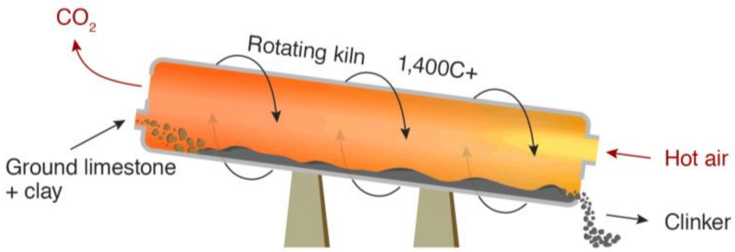


Figure 3 - Kiln process of cement production [5]

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

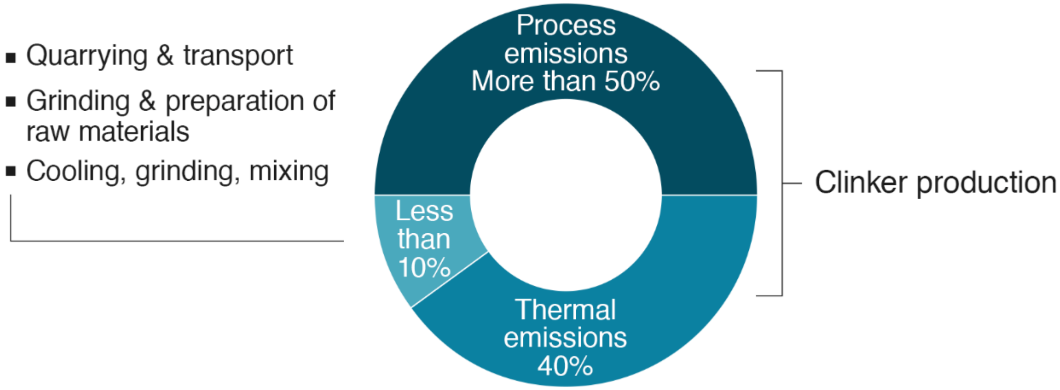
Equation 1

$$3CaO + SiO_2 \rightarrow Ca_3SiO_5 = \textit{Clinker}$$

Equation 2

Cement manufacturing releases CO_2 in the atmosphere both directly, during step **3**. and indirectly as a result of the energy used to heat the reaction, in step **2**. As shown in **Figure 4** up to 60% of the emissions is from the chemical calcination process, and up to 40% from burning fuel to achieve the elevated kiln temperature. The remaining allocation is somewhat variable and outside the scope of this report. [4]

Figure 4 - Kiln process of cement production [5]



Reducing Environmental Impact

Green cement

To increase the environmental sustainability of the sector there are several methods that can be implemented. To date, research efforts have largely been concerned with mimicking traditional clinker-based cement rather than on radically altering the mix of raw materials used. Key areas of research into green cement include the following:

Reducing calcination temperatures – Up to 40% of the cement's total emissions are derived from the energy used to heat the kiln to temperatures that facilitate clinker synthesis. Innovative challenger companies have proposed alternative ingredient ratios and manufacturing methods that greatly reduce the temperature required for reaction.

More sustainable thermal energy – Classically kiln heating has been achieved through combustion of coal which is an inefficient fuel source and very dirty. Many developed producing nations are focusing on transitioning to cleaner heat sources, such as biomass, as well as moving to newer, more efficient equipment.

Geopolymer cement – adding more environmentally friendly, often waste, components that dilute the proportion of standard calcium silicate clinker can dramatically improver overall sustainability. Geopolymer cements substitute calcium silicates for aluminosilicate precursors. Common sources include:

- **Fly-ash**, a by-product of coal-fired electric generating plants that can strengthen concrete, improve its workability, reduce the water required for hydration and reduce its shrinkage. Conversely, it can be slower to gain its increased strength and may experience lower freeze/thaw performance. Availability in a coal-less future is also a key concern;[6]
- **Slag**, or blast furnace slag, is an another industrial by-product, making it a cheap additive. The end concrete product is less chemically reactive than standard product, making it more corrosion resistant with increased durability and the fine slag particles give a smoother finish. Similar to fly-ash the product takes longer to get to full strength.[7]

Other clinker substitutes – Aside from geopolymers other clinker substitutes are continually researched and at present fall into 3 broad categories: Alkali Activated Binders that glue materials when mixed with Alkali; Hydraulic Binders (like Ordinary Portland Cement) that bind inputs when mixed with water and Carbonatable which harden when reacted with CO_2. Clinker substitution can be deployed relatively cheaply today, as many don't require large investments in new equipment or changes in fuel sources. However, availability of resources is a key consideration. [8]

Carbon Capture, Usage and Storage (CCUS) – Emission from the calcination process in cement kilns, which accounts for > 50 % of cement's overall total, could be captured and then stored or used. Current commercial deployment of CCUS is limited but there has been innovation in recent years that could bring the technology out of the demonstration stage. Without the implementation of an efficient price/tax on cement emissions, companies have little incentive to implement given its current expense.

Reducing Environmental Impact (2)

Green concrete

Other, indirect methods can be implemented to processes and materials downstream from cement that improve the sustainability of the wider industry:

- **Novel cements –** Direct replacements of Ordinary Portland Cement (OPC) can reduce emissions by up to 90% but so far the majority have failed to achieve commercial viability. [9]
- **Reduction of water use –** Though not effecting emissions reporting, water usage hugely impacts the local environmental. Some alternative cements reduce the overall amount of water required by curing the product with CO_2 rather than H_2O.
- **Recycled aggregate concrete** – utilising alternative aggregate inputs, such as repurposed waste concrete, can reduces costs and landfill while preventing depletion of additional natural resources. The crushed concrete also absorbs CO_2 further reducing the overall impact. However, the product can only be used in certain applications because of a broad downgrading in quality, increase its water absorption and decrease its compressive strength as well as its workability. [10]

Figure 5 shows the emissions reduction potential for some of the key solutions discussed above. However, the most effective reduction methods are also the most expensive the least developed. Furthermore, no one solution will fit all required use cases. Each will need to be deployed in tandem, wherever possible and at scale to meet the decarbonisation challenge.

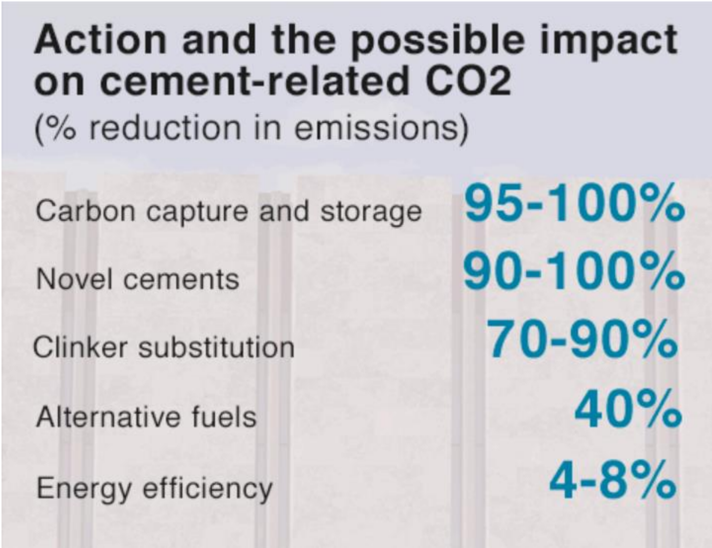


Figure 5 – Emission reduction potential [9]

Carbon taxing cement

Globally there are currently at least 70 carbon tax schemes in operation covering 20% of all manmade emissions. Some, like those imposed in Norway, Sweden and Finland, are straight taxes; others, including California, the EU, China and South Korea, are emission-trading schemes which issue permits for industries to pollute. Regions and nations that do not operate a carbon tax scheme constitute the majority of the remaining 80% of global emissions. However, further to this, each scheme does not cover all greenhouse gas (GHG) emissions (e.g. the EU covers 45% of their total). A significant portion of the remainder is made up of exemptions, gifted to certain industries on the grounds of retaining regional/national competition or to prevent *carbon leakage*.

Carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies and carbon taxes, businesses were to transfer production to other countries with laxer emission constraints which could lead to an increase in their total emissions. The cement industry is an example of such a sector.[11] For this reason, since the initiation of the EU-ETS, the cement industry has received free *emission allowances* for its emissions production which have, perversely, resulted in a large revenue windfall for some of the biggest polluters in the industry.

However, recent studies indicate that the risk of carbon leakage in such *carbon intensive products* as cement isn't as high as once conceived. Furthermore there is a general consensus in the EU that we aren't on track to meet our required emissions reduction targets. As a result, the pace at which *emission allowances* are reduced is increasing. From 2021 onwards emissions allowances will decline at 2.2% per year and expect to terminate by 2030.[12] This will have a large impact on the industry in the medium to long term as firms that currently have no economic incentive to reduce the environmental impact of their cement will have to invest in greener cements to avoid paying for *emission allowances*, the price of which have surged in recent years, see **Figure 6**.

It is certainly possible that the cement industry will have to pay for the environmental cost of their product in the shorter term or before 2030. For example, in the absence of a global carbon tax, the European Commission president has pledged to introduce an EU-wide carbon border tax. Such a tax would apply a levy to goods coming into the EU, so that the price of imports from non-EU countries includes a CO_2 cost equivalent to that imposed by the EU. The implementation of such a tax would negate any requirement for free emission allowances and force previous recipients along with all importers to pay a carbon tax on cement produced.

Outside of the EU, the US congress are currently debating whether to adopt a *carbon dividend* that would be funded by a carbon tax on domestic production and imports of *carbon intensive products*. Other markets that have recently implemented a carbon tax on cement include Vietnam and South Africa.

Into the next decade and beyond rising carbon prices on emissions from cement production will be inescapable. They will put significant pressure on revenues and force companies into more sustainable practices.

Figure 6 – EU Emission Allowance (EUR) [13]

Economics of green cement

Today, much of the cement industry does not pay the real cost for the CO_2 they produce and most buyers aren't willing to pay the premium that often exists for green cement over standard materials. Thus, the global green cement market is currently driven by progressive corporate responsibility, linked to public awareness about the industry's detrimental effect on the environment. However, relative to meeting our Sustainable Development Goals (SDGs), not enough of the private sector fall into this category and standard practices prevail.

Accordingly, until the realisation of a significant tax on the production of Ordinary Portland Cement (OPC), green cement must create its own economic justification to buyers. Fortunately, in addition to releasing less CO_2 into the atmosphere, green cements can: provide better, more diverse functionality; require less energy and fewer natural materials in production and be produced in a shorter timeframe. A combination of these factors is swinging the balance of green cement for ever more users and use cases.

Benefits of new green cements

Many new entrants championing sustainable products maintain increased strength, quality and durability of the end product. Concrete's heterogeneous nature often means that non cement additives can improve its performance which can be attractive when high durability and strength to volume ratios are important.

The standard curing method for OPC derived concrete involves maintaining adequate moister and temperature levels to aid the chemical hydration of the cement and water. This results in the formation of various chemicals that set and harden the concrete. This process can take up to two weeks depending on the product and has a regulatory minimum of seven days for many structural products. Certain green cement entrants cure their product with CO_2 which, in addition to sequestering emissions, can cut the curing process down to 24 hours. [14]

Adding CO_2 during curing contributes to making the end product stronger and more durable, increasing its value.

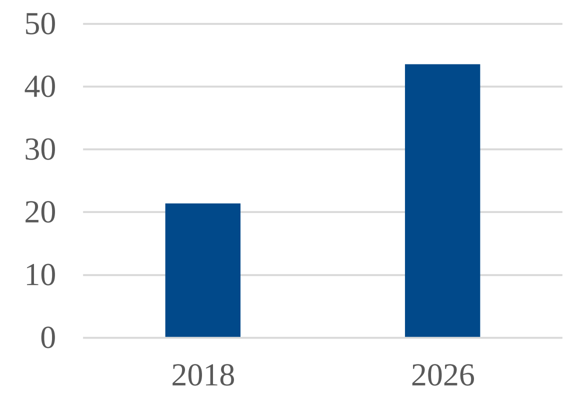


Figure 7 - The Global Green Cement Market (m USD)

The mammoth amount of thermal energy, ordinarily required to enable calcination in OPC, is responsible for the largest portion of its production costs. In the long term, as the green cement industry benefits from economies of scale, this efficiency will bring down green cement prices. Similarly, many new cements minimise the requirement for other expensive raw materials used in the production which will again reduce costs.

An amalgamation of these factors meant that in 2018 the green cement market was valued at $21.4 billion and is expected to reach $43.6 billion by 2026, see **Figure 7**. [15] Over the next decade and beyond, progressively more stringent environment regulations, tax conditions, subsidies and grants for green materials production are expected to massively boost the growth of this fledgling market.

Opportunities and Competition

The cement sector is dominated by a small number of major producers who are reluctant to experiment or change their business model. Most large producers don't currently maintain centralised research efforts which creates an opportunity for new entrants and technologies. While there has been much R&D in this area, only some of the products analysed have been commercialised and none have been applied at scale. Some of the more developed and better know green cement/concrete challengers are below:

Commercialised

US based **Solidia**, founded in 2008, is perhaps the most well known and well funded name in the industry, partly as a result of its partnership with major incumbent LafargeHolcim and other significant VC investment. To date, they have raised $27m over three funding rounds. Their product uses a different ratio of chemical inputs that requires significantly less thermal energy to produce a calcium silicate clinker. The cement produced is then cured (carbonated) in the presence of the waste CO_2 instead of water. The combination garners a carbon reduction of up to 70% compared to ordinary concrete. The equipment/chambers required for the CO_2 curing means Solidia currently only sells ready made products such as bricks, paves and slabs but claims that they cost less than existing alternatives.

CarbonCure, founded in 2007**,** has raised over $10m from VC investment. Their concrete product, currently on sale in the US, includes standard cement mixed with two geopolymer binders: slag and fly ash. What makes their process unique is the ability to inject liquid CO_2 into the wet concrete mix which reacts with calcium ions and water from cement to form calcium carbonate which becomes permanently embedded in the concrete. This is a key benefit over competitors as it means that, in addition to pre-made products that are cured in a CO_2 chamber, they can offer a ready mix product that constitutes the bulk of the market. Expensive complications associated with sourcing and handling liquid CO_2 on site restrict the range of users. At the same time the source of CO_2 isn't directly from cement production but transported from other industrial emitters and their own studies put total concrete emission reductions at only 4.6%.[16]

Demonstration Phase

Blue planet are a California start up that have filed hundred's of patents since 2012 but had minimal institutional funding until their Dec 2019 partnership with Kamine Development Corporation ("KDC") which is intended to scale their technology. They, too utilise captured CO_2 from industrial emitters but use it to synthesise limestone which can then be used as an aggregate substitute without changing the other inputs, such as cement. They market themselves as *carbon negative concrete* but if you include the emissions of the cement production they net a 48% reduction in the overall process. They currently have one successful pilot, a boarding area on San Francisco airport.

Opportunities and Competition (2)

Pilot Phase

Celitement is a spin off from German university, KIT, founded in 2016. Their product creates 50% less CO_2 than Ordinary Portland Cement (OPC) by using a low carbonate clinker and calcium silicates that are pre-hydrated. This product can be bagged, shipped and, most importantly, used like OPC. It is still cured with water so there is no need for changes to existing infrastructure. However, they are yet to use the product in the real world.

bioMASON, founded North Carolina in 2012, employs naturally occurring bacteria as an alternative binder to make concrete bricks with no CO_2 emissions. They've raised bioMASON has rasied $2 million in capital, another $3.4 million in debt and recently launched another $18m equity round.

Canada's **CarbiCrete**, founded in 2016, uses an industrial waste, steel-slag, based geopolymer as an alternative to OPC cures/ carbonated the concrete with CO_2, further reducing emissions. They've raise upwards of $5.1m to date.

CO_2Concrete, a spin-off from UCLA, are finalists in the Carbon XPRIZE, the winner of which will receive $20m. There technology is similar to Blue Planet, using CO_2 from power plants to produce solid mineral carbonates to be used in concrete.

Calera's secretive operation secured over $45m in funding in 2008 including $20m from the US government. Their technology uses CO_2 to make Calcium Carbonate which can be used to replace a portion of OPC and claims emissions reductions of 60%. However, after repeated disappointments, it shifted to focusing on specialized calcium carbonate for niche applications, such as wallboards.

Others, like banah in the UK and Zeobond in Australia, are focused on using industrial by-products to create so-called other geopolymer substitutes.

Standards / Regulation

Unparalleled global proliferation of cement and concrete in the construction industry combined with an extreme requirement for structural strength means both materials are heavily regulated. They follow strict standards about the production process as well as the physical properties of the end product. Green cement and green concrete, utilise new materials and processes which may not fall under existing regulation while regulators can be slow to adopt new technologies. Additionally, regulations designed to prevent anti-competitive behaviour create barriers to greater industry cooperation.

If more sustainable materials are to be adopted in any form, their development needs to be matched with accreditation to existing standards and companies must work with regulatory bodies to create relevant new rules. However, adding to or changing regulation takes significant time, capital and influence. Instead of prescriptive codes and standards that require concrete be made a certain way, challenger companies are advocating a transition to more performance based criteria that will spur innovation. Progress is slow and regulation remains a key bottleneck for the budding industry.

One tool green producers are using is leveraging independent researchers, such as universities, to test the structural attributes and capabilities. In the short term, this data allows companies to prove to buyers and regulators that their materials match or exceed exiting benchmarks.

Due to their relatively simple regulatory standards, the first green products entering the market are bricks, blocks and pavers. However this excludes the ready mixed concrete market which makes up three quarters of the total.

Conclusion

In conclusion, in such an enormous market, ruled by a handful of major producers wary of changing their existing business models, an absence of strong green policies has yet to incentivise significant adoption of greener technologies to date. The construction industry is understandably cautious about ‘novel building materials’ but, as we transition towards a global tax on carbon, the requirement for an economical and structurally viable green alternative to cement will become a necessity. It will revolutionise the industry.

The winners of this revolution will be those that can offer a product that fits as seamlessly as possible into expensive existing infrastructure. The industry is screaming out for a green, ready mixed concrete that can be cured either using today’s methods or require minimal new technology spend. This would open up 75% of the market for the few companies that have so far managed to commercialise blocks and slabs.

Larger US companies like Solidia and CarbonCure are making headway but they have a distance to go before capturing even a small share of the market. The sector’s widespread conservativism is a key hurdle but partnering with large, familiar names can be one way to breach that mental barrier. Generally the industry’s attitude is ‘see it to believe it’ so testing and real world case studies are also important when trying to convince commercial clients.

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