Is de-carbonising the construction industry possible?

An overview of advances in materials and processes

By Dr. Jutta LAUF

Content

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Cement, a key product for construction, is by mass the largest manufactured product on Earth. Combined with water and mineral aggregates it forms cement-based materials (e.g., concrete and mortar), the second most used substance in the world after water. Cement based building materials are energy and cost efficient[1], but the globally large scale usage ($4.6 * 10^{12}$ tons in 2015)[1] led to 3% of globally emitted carbon dioxide (CO_2) in 2020[2]. Additional advantages are the wide availability of the raw materials, a sufficient long period of time before settling and its longevity. All these properties make it a versatile material, which is used in many of NATO's infrastructures (Figure 1).

Figure 1: NATO headquarter in Brussel, Blvd Leopold III, 1110 Brussels, Belgium. It was constructed as a "Green building" mainly from concrete. Generally the "green" credentials are related to the operation of the building, not its construction.[3; 4]

The traditional form of cement is the so-called ordinary Portland cement (OPC). The production process requires grinding and calcining (heating to high temperature of approx. 1450 °C) a mixture mainly consisting of limestone and clay. The resulting intermediate material - known as clinker - is ground to a fine powder with 3–5% gypsum added to form OPC. The production of OPC generates on average 842kg CO_2 per ton of clinker. Fossil fuel combustion is responsible for less than

40% of total CO_2 emissions, while limestone ($CaCO_3$) decomposition during calcination to calcium oxide (CaO) is responsible for the remainder.[1; 5]

In essence, CO_2 emissions from clinker production is a mixture of both, an unavoidable chemical reaction, and the heating process to start the chemical reaction. Therefore, increasing the energy efficiency of clinker production is not sufficient to significantly reduce emissions. Carbon capture technologies are necessary to achieve this goal. Significant reductions in CO_2 emissions are also possible after clinker production along the entire construction value chain by reducing the amount of clinker in cement, reducing the amount of cement in concrete and mortar, applying the lowest possible construction norms, prolonging the service live of constructions, recycling the materials after de-construction as well as by decarbonising transport process and power consumption (Figure 2).[1, 5; 6]

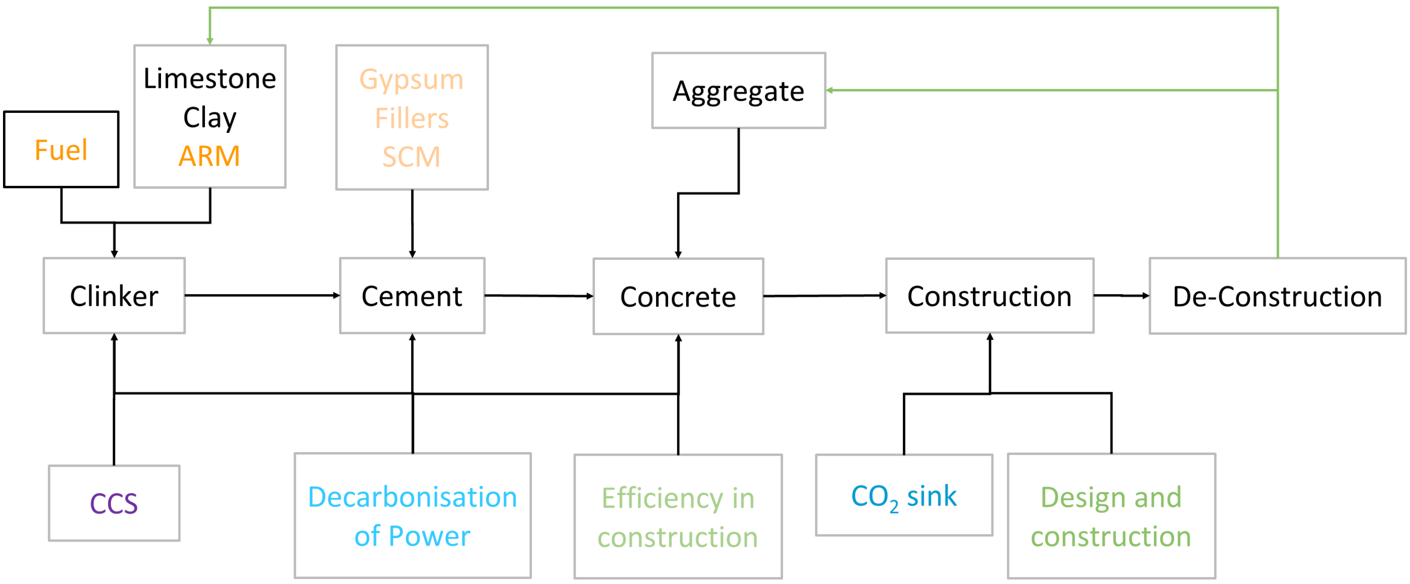

Figure 2: Simplified value chain of cementitious products and points of intervention for reducing the carbon dioxide footprint. Above the value chain raw materials are shown, below the respective concepts. ARM = alternative raw materials. CCS = carbon capture and storage, CO_2 = Carbon dioxide, SCM = supplementary cementitious materials. Colours correspond to the colours used by the GCCA roadmap in Figure 3.

The Global Cement and Concrete Association (GCCA) has issued a roadmap in October of 2021 to decarbonize the value chain of the construction industry by 2050 (cradle to grave). The measure with the highest CO_2 reduction potential (36%) is carbon capture and storage/utilization (CCS/CCU), followed by design optimization of structures and recycling of demolition waste (22%). The reduction potentials during the physical production steps are clinker (11%), cement (9%) and concrete production (11%). The re-carbonation of concrete in finished structures can contribute only 6% (Figure 3).[6] CCS/CCU technologies are usually more expensive than the implementation of "CO_2 avoiding" technologies and are therefore preferred because they keep cement and cementitious materials cheap.[1]

In the following chapters, we discuss a selection of measures (according to the value chain shown in Figure 2), their scientific background, related challenges as well as already developed new businesses models. The colour code of the following headlines corresponds with the colours used in the GCCA roadmap.[6]

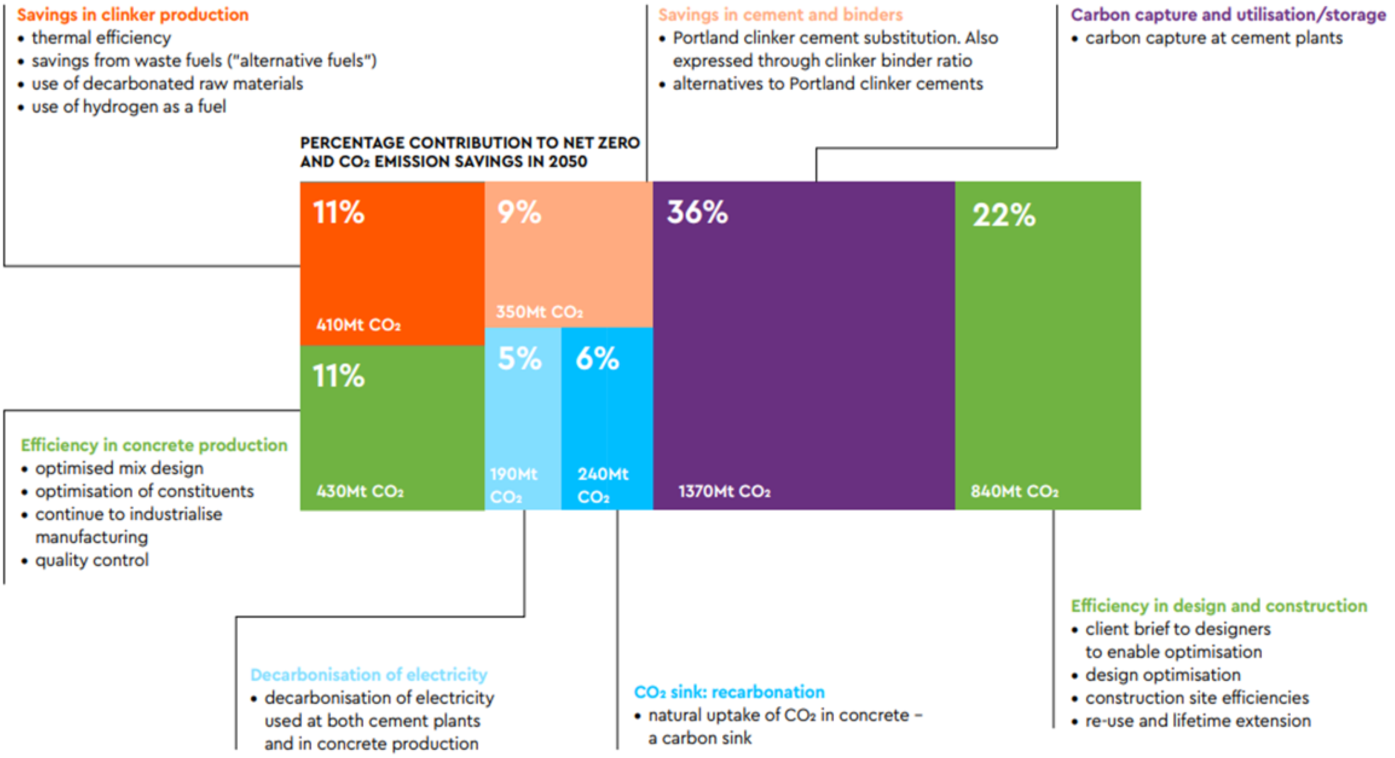

Figure 3: The Global Cement and Concrete Association's (GCCA) plan for reaching a net zero CO_2 emission industry by 2050.[6]

Clinker production and precast building element

Energy demand and fuels

Major efforts to increase energy efficiency began after the energy crisis of the 1970's. It is unlikely that there will be significant gains in best available technology in clinker production, rather than a progressive upgrade of old technology. Modern cement kilns are very flexible machines, which allow the cement industry to change fuels relatively simply. They may change from one type of fuel to another and use any type of fuel which is high in energy, e.g., fossil fuels, biomass or waste.[1] The carbon dioxide reduction potential resides in the increased usage of waste as fuel and in the decarburization of electricity used in clinker and in cement production.[6]

Alternative raw materials for clinker production

The CO_2 emissions from the chemical reaction of CaO formation can be reduced by several means. Clinkers with lower amounts of $CaCO_3$ in the raw mix will result in cements with lower CO_2-emssions from the chemical reaction as well as from fuel consumption. The properties of the resulting cement are altered and such a product is for specialized niche markets only.[1]

Magnesium oxide (MgO) based clinkers use globally abundant ultramafic rocks instead of limestone. These rocks have the inherent capacity to capture CO_2, which results in a truly carbon-negative clinker. Yet, no viable energy-efficient industrial manufacturing process has been developed. This area merits further research.[1]

Newly developed special calcium silicate clinkers made specifically for carbonation curing instead of water curing with mature precast products are available since several years (Solidia, USA).[7] These products are no more expensive than OPC. CO_2 emissions from heating and from the calcination reaction are lower than in OPC. These clinkers can only be cured rapidly in a controlled atmosphere of almost pure CO_2. This requires some modification of the concrete curing chambers typically used for precast products. If the CO_2 for curing is procured from carbon capture facilities, a net zero cement is produced.[1; 7]

The US start-up company Sublime Systems has created an electrochemical CaO production from $CaCO_3$. With renewable power used, no CO_2 is emitted through energy usage while the CO_2 originating from the chemical reaction will be captured with carbon capture technologies. This combination will create a CO_2-free clinker. Further research is needed to develop this technology.[8]

Carbon capture and storage or use

Carbon capture and storage or use is the main strategy to reduce CO_2 emissions of the industry. CCS is still not sufficient proven for large-scale use. CCU may produce commodity chemicals or fuels. However, this technology is a long way from being economically viable at present. Another possibility is the mineral capture of CO_2 which has the potential to permanently capture significant volumes of CO_2 globally to make useful construction products. Solida cements[7] are an example of this approach. Regardless of the technological challenges, CCS and CCU would significantly increase cement production cost.[1] CCS/CCU technologies are described in more detail in previous issues of the journal "Energy Highlights".[9; 10]

Cement

OPC contains >90% Portland cement clinker and gypsum. A well-established strategy for the reduction of energy demand is the substitution of clinker with supplementary cementitious materials (SCM) and fillers. SCM are amorphous Silicon und Aluminium rich substances of various origins. Fillers are normally inactive unburnt limestones. The most common clinker substitutes are by-products from other industries, e.g., granulated blast furnace slag (GBFS), fly ash (FA), natural pozzolans, calcined clays or limestone. The usage of these SCM has levelled off as their availability is modest compared to the demand of the cement industry with the exception of calcined clays. The raw products of calcinated clays are readily available from the waste of the porcelain industry. Limestone fillers are also widely available.[1]

Concrete production and use

The OPC consists of more than 90% clinker (clinker factor > 0.90). The reduction of the clinker content to 60% seems possible. However, realizing this level of clinker substitution will require increased research and education efforts, particularly with users.[1] The concept of easy to use "general purpose" cement is built in in most of modern concrete standards. This leads to the application of unnecessary high cement contents in at least 75% of all concrete types used. High cement contents are only be needed in a certain subsection of steel reinforced structures. If cements standard would clearly designate a specific category for use with steel reinforced concrete, such cements would almost certainly sell at a premium price. Low cement content products could sell for a lower price, encouraging their use in non-steel reinforced applications.[1]

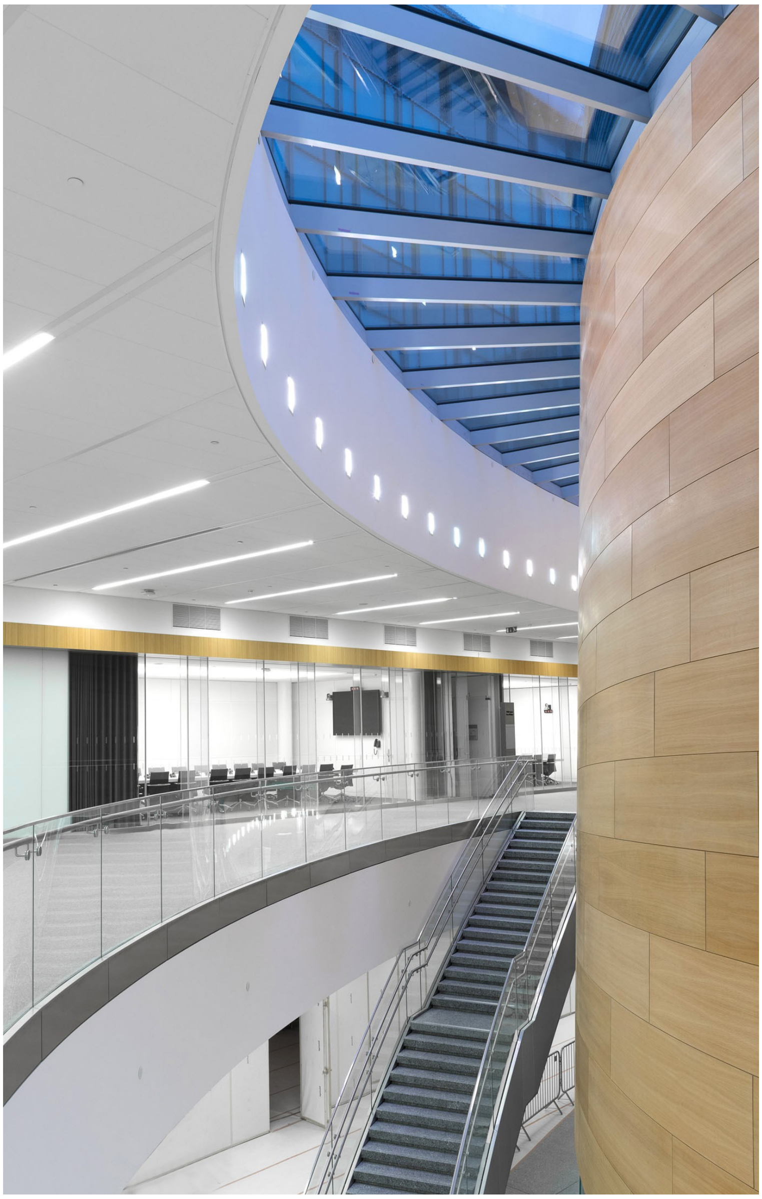

Figure 4: Interior of NATO's headquarters.[4]

One of the many appeals of cement is its longevity, hardiness, and its simplicity of use. The decisions and skills of the user in formulation cement-based mixtures determine the amount of cement used for a given application. In general, untrained personnel use mostly bagged cement and tend to use more cement than necessary. Industrial clients mostly prefer bulk delivery and tend not to overdose cement. The market of bagged cement is a rough estimate of inefficient use of cement.[1] The education of small scale individual users may be the key to reducing CO_2 emissions from overdosing, although it may be a difficult task to fulfil.

Construction

Many structures use concrete of a higher strength than needed for the design, which amounts to a waste of materials.[11; 12] This problem can only be solved by a deep integration of all party involved in construction, e.g., architects, structural and civil engineers as well as construction companies.

The CO_2 footprint of a construction is profoundly influenced by its service life. Although the amount of cement used for repairing degraded structures is rather small, every effort for improving the durability of structures should be taken.[1]

Cement based materials are typically expected to have a service life of at least several decades. Fifty years is standard, although often the expectation is for much longer. The overwhelming majority of problems of concrete durability (probably >90%) are related to steel reinforcement corrosion, which is related mostly to chloride ingress, and less commonly to carbonation. Only a very small proportion of cement use is at risk, because only about 25% of cement use is in reinforced concrete. Of this only a tiny fraction is exposed to conditions posing durability risks.

Figure 5: View on the main entrance of NATO's headquarters.[4]

De-Construction

Significant efforts have been made in recent years to recycle concrete and other cement-based waste. Concrete contains approx. 70% aggregates and approx. 30% hydrated cement. Recovering aggregates will reduce the stress on virgin aggregates and reduce demolition waste going to land fill. Although important in themselves, these measures do not significantly reduce the CO_2 footprint, as the production and transportation of virgin aggregates accounts to less than 10% of cement production.[1]

Crucial to the production of high quality recycled aggregates is the removal of the cement (paste) which is attached to the aggregate's surface. These technologies are energy intensive and improvements are intensively researched.[13] Recycling also results in a high amount of CaO rich fines, which may be recycled as raw materials for clinker production and thus reduce the chemically related CO_2 emissions from clinker production.[1] Circular economy in the building sector is possible, as demonstrated by the price winning ReConcrete-360° initiative of the German cement producer HeidelbergCement AG. Aggregates and hydrated cement are retrieved from demolition waste[14] and are used in the production of EcoCrete®. This commercially viable product shows an up to 66% reduced CO_2 footprint – including all parts of the production value chain - compared to current standards of the industry.[15]

The multi-university program UK FIRES has developed a new cementitious material derived completely from recycled materials. Demolition waste was crushed and separated to aggregate and cement powder, which was used instead of lime-flux in steel recycling. During the melting process the flux forms a floating slag on the hot steel. After tapping off the steel, the slag is cooled rapidly and ground into a powder, which is virtually identical to clinker. Further research and development is currently underway.[16]

Transport

Technologies for the de-carbonisation of the transport of raw materials, cement, concrete, pre-cast element and demolition waste are currently not available on an industrial scale. Prototypes for e.g., hydrogen, methanol and ammonia ships are under construction as well as fuel cell trucks.[9; 10] Although, pilot projects are currently developing.

The Norwegian shipping company Egil Ulvan Rederi AS[17] is currently building a bulk carrier with a hydrogen combustion engine and additional rotor sails with an expected commission in 2024. The price winning vessel *With Orca*[18] is planned to enter into a long-term transport service contract sailing both, the German cement producer HeidelbergerCement AG19 (aggregates) and the Norwegian agribusiness Felleskjøpet Agri[20] (grain) and by this reducing empty sailing.

Government

The mitigation potential of each of the technologies discussed will depend on its success in the market. For this to happen, the authorities have to create new and binding norms and standards for segmented markets on the cement, concrete and construction level.

Governments are among the largest consumers of cement-based materials, especially when investing in infrastructure. Therefore, the use of public purchase power can be decisive in accelerating market penetration.[1] A successful example of purchasing power is the development and implementation of a customized low-carbon concrete for one of Meta's (USA) data centres in the USA with the support of artificial intelligence at Cornell University (USA).[21] Although similar mixtures as the implemented in the data centre are in use in Europe since several decades[22], it is a proof of concept in terms of the usage of AI, the willingness of the authorities to authorize a new product and the purchasing power of customers.

More involvement of governments is needed in providing research funding, influencing educational policies for civil engineers and architects, and promoting environmental awareness. The construction industry itself is confident that it can decarbonise until 2050.[6] The main measure will be CCS/CCU, which is the costliest technology of all. Cheaper alternatives are welcomed, mainly to keep concrete the low-cost building material that it was in the past. The selection of research results, business initiatives and governmental responsibilities described in this article demonstrate both, the progress already made and the efforts to be made to reach this goal and to build a net carbon free future in construction.

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