CARBCOMN

Green Paper on Compression Dominant Carbon Curing Concrete Structures

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1 Executive Summary

The impact of climate change is becoming increasingly apparent, and so the construction sector cannot afford to lag behind in implementing adjustments through innovative technologies. The innovation we want to put forward in this paper is the development of compression dominant carbon curing concrete structures.

We will first outline the current bottlenecks within the concrete construction sector and elucidate the highlighted technology. We will then share our vision on how this innovative technology, which is also the focus of the ongoing CARBCOMN project, can contribute towards a greener construction sector and why we are convinced that compression dominant carbon curing concrete structures will enable a breakthrough.

With this Green Paper, we aim not only to inform the reader but also to encourage critical reflection. To this end, we have made several statements and would like to hear your opinion on them via an online form. This will enable us to incorporate your feedback into our further developments within the CARBCOMN project. Towards the end of the project, we intend to publish an updated version of this Green Paper reflecting on how your feedback influenced our research goals.

2 This Green Paper

2.1 Setting the scene

Greenhouse gas (GHG) emissions from material extraction, manufacturing of construction products, as well as construction and renovation of buildings are estimated at 5-12% of total national GHG emissions [1]. When comparing different construction materials, the environmental footprint of concrete per material unit volume is amongst the best [2]. However, being used that widely all over the world, concrete is one of the most relevant construction materials in terms of carbon footprint and raw material usage [3].

The cement and concrete industry was the first sector to monitor and publish its CO_2 emissions [4]. These numbers immediately proved that huge amounts of GHG are emitted during concrete production, mainly because of the high calcination temperatures needed to produce clinker (about 40%) and to decarbonize limestone (about 60%) (see Figure 1). Electricity used by the sector contributes further to CO_2 emissions.

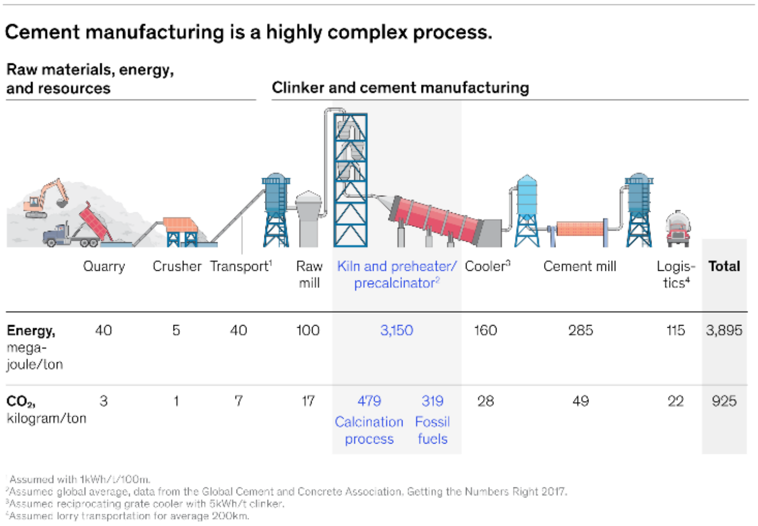

Figure 1. Cement manufacturing process and related CO_2 emissions [5].

In total, cement manufacturing amounts to about 8% of global CO_2 emissions [6]. Also, 1m^3 of concrete requires 2,6 tons of construction materials, so that concrete construction accounts for about 50% of all material extracted for [7]. The upside of these observations is that when improving the environmental impact of concrete, significant gains can be made in terms of reducing carbon dioxide emissions and using less primary raw materials [2]. Because of this, climate-neutral concretes and applications are a global research theme of high interest.

Over the past three decades, the cement and concrete industry has made some initial progress and reduced its emissions proportionately by around a fifth, predominantly by clinker substitution and fuel side measures [4] (Figure 2.A). However, during the current decade, we definitely need to accelerate our CO_2 reductions in the concrete construction sector (i) through lowered emissions upon clinker production by alternative fuel use, (ii) by savings in cement and binders through alternatives to Portland clinker cement, (iii) by optimisation of concrete production in terms of binder utilisation, (iv) through decarbonisation of electricity, (v) through natural uptake of CO_2 by concrete, also called recarbonation, (vi) by more efficient design and construction and (vii) through the currently less significant, being a new lever, carbon capture, utilization and storage [4].

However, none of the currently used concepts result in a full net-zero-carbon impact, because they bring partial and mostly fragmented solutions that cannot stand up to the technical demands of Architecture, Engineering and Construction (AEC). Moreover, as could be seen in Figure 2.B, the potential contribution of ‘Efficiency in design & construction’ and ‘Carbon capture and utilisation/storage (CCUS)’ to achieve net zero CO_2 emissions by 2050 is very significant and should deserve more attention. We should therefore invest now in these required breakthrough technologies and innovations, to further reduce CO_2 emissions in the next decades. Focusing on compression dominant carbon curing concrete structures, being the main topic of this Green Paper, is thus of utmost importance.

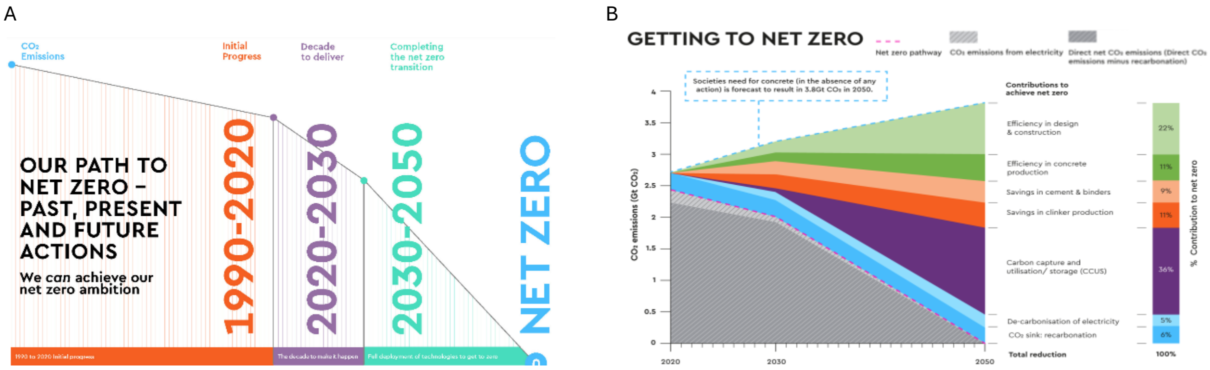

Figure 2. (A) Path towards net-zero CO_2 emissions [4] (B) Getting towards a net zero concrete construction sector [8].

2.2 Ambition of this Green Paper

The intention of this Green Paper is to stimulate discussion on the topic of compression dominant carbon curing concrete structures as one of the key pathways to move towards a net zero concrete construction sector. The objective is not only to communicate towards, but also to consult potential stakeholders to identify key concerns, incorporate diverse perspectives and create consensus on prior research goals. In addition, reaching out to potential stakeholders now, the moment we need to put more focus on 'Efficiency in design & construction' through compression dominant structures and 'Carbon capture and utilisation/storage (CCUS)' through carbon curing concrete structures, is deemed to be very beneficial in order to identify opportunities for innovation, risk mitigation and value creation.

2.3 The CARBCOMN technology explained

Carbon-negative or nearly carbon-negative technologies play a crucial role in mitigating climate change by their ambition in removing more carbon dioxide from the atmosphere than they release. These technologies are essential to achieve net-zero emissions and to limit global warming. They encompass a range of approaches, including both nature-based solutions and engineered solutions. To end up with a net-zero CO_2 emission by 2050 in the cement and concrete construction sector, as highlighted in Section 2.1, more focus needs to be put on the investment in technologies and innovations related to 'Efficiency in design & construction' and 'Carbon capture and utilisation/storage (CCUS)'. An interesting breakthrough solution we want to put forward and discuss in this Green Paper is the development of compression dominant carbon curing concrete structures, which is also the focus of the recently initiated research initiative CARBCOMN. In this EIC (European Innovation Council) Pathfinder project [9], compression dominant structures are an excellent example of design efficiency and carbon curing of concrete is ideally conceived as an ultra-low-carbon technology, as carbon sequestration is used to harden the concrete.

SOME KEY TERMS EXPLAINED (part 1)

Compression dominant structures are a broad classification, encompassing essentially any load bearing structural system that induces a compression dominant stress state via simple (e.g. column) or more complex funicular (e.g. arches, domes) geometries or through combination with normal forces naturally present (e.g. dead loads) or additionally introduced via prestressing (e.g. pre- or post-tensioning). The latter could be obtained using traditional prestressing techniques or using shape memory alloys. Shape memory alloys (SMAs) are metallic alloys that can be deformed at one temperature and then return to their original shape when heated.

Carbon sequestration or carbon mineralization is the chemical reaction which occurs when a carbonatable mineral powder is exposed to carbon dioxide. The carbon dioxide becomes a solid material. Applied to concrete, the term **carbon curing concrete** is used when CO_2 (potentially captured during cement production) is injected into the concrete to accelerate the curing process and 'lock-in' CO_2 into the end product. In that way, the latter becomes carbon-negative or decarbonized. Current low-carbon cement technologies can sequester up to 5% of CO_2, with the potential of 30%.

The CARBCOMN technology (Figure 3) focuses on the development of an ultra-low-carbon concrete mixture, based on carbon curing, suitable for processing with extrusion-based additive manufacturing or 3D printing and relying on only secondary raw materials to produce discrete blocks out of it and assembling them in innovative structural systems consisting of compression dominant members. Carbon cured concrete is less compatible with traditional steel reinforcement, as it does not have the necessary alkalinity to passivate the steel reinforcement in the concrete. By applying compression dominant structures, either by using funicular shapes (compression-only structural forms) or by installing unbonded post-tensioning, this drawback can be avoided. By segmenting the compression dominant structure, it can be constructed using 3D printed concrete blocks with shapes optimized for design flexibility and efficient material use. This also enables the application of the blocks in structures designed to be deconstructed at the end of their life cycle.

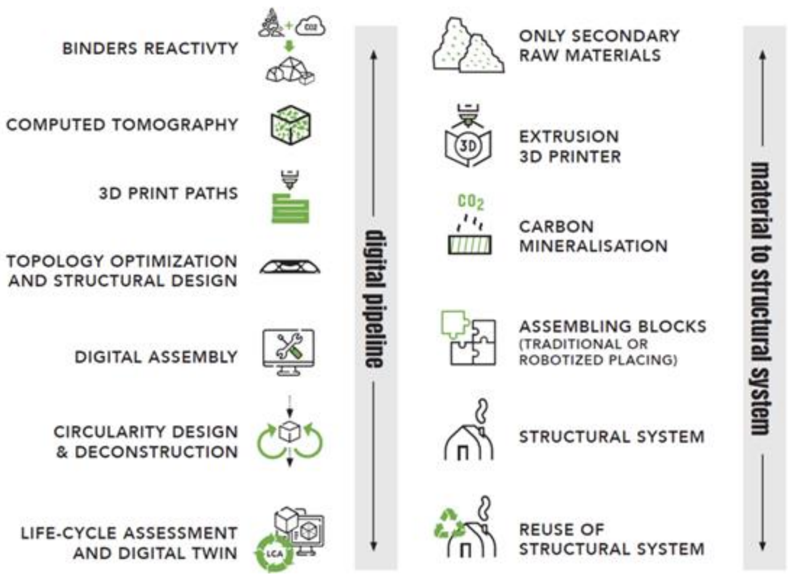

Figure 3. Envisioning decarbonized and deconstructable compression dominant structures through robust design-to-fabrication digital pipeline.

To handle the complex geometries and foster the design and production processes, an innovative digital pipeline (Figure 3) will be developed to define the reactivity of the binders, unravel the microstructure development and related porosity through computed tomography, decide on the structural design through topology optimization and slice the obtained geometries into multiple layers so an optimal print path can be defined. Next to all the latter, also the assembly process, the design for circularity and deconstruction will be digitized together with the life-cycle assessment.

SOME KEY TERMS EXPLAINED (part 2)

Circularity and **deconstructability** are core principles in sustainable construction, promoting resource efficiency and waste reduction. Circularity focuses on keeping materials in use at their highest value for as long as possible, while deconstructability (or design for deconstruction) involves designing buildings with the intent of easy disassembly for material reuse. These principles are crucial for minimizing environmental impact and maximizing resource utilization in the built environment.

Extrusion-based additive manufacturing or **3D printing** of concrete is an advanced digital construction technology that automates layer-by-layer extrusion of concrete, enabling precise, scalable, and waste-efficient building solutions.

Topology optimization is a mathematical method that algorithmically determines the most efficient material distribution within a given design space for a given set of loads, boundary conditions and constraints to achieve a specific goal, such as maximizing stiffness or minimizing weight. This iterative process removes material from areas that do not bear significant loads, resulting in an optimized and often complex final geometry that meets performance requirements.

A **Life Cycle Assessment** (LCA) is a comprehensive methodology that evaluates the environmental impacts of a product, process, or service throughout its entire life cycle, from raw material extraction to disposal. It involves defining the study's goal, quantifying inputs and outputs (like energy, materials, and emissions) in the inventory analysis, assessing the potential environmental impacts in the impact assessment phase, and interpreting these results to make informed decisions and improvements. The goal is to identify environmental "hot spots" and guide eco-design for reduced environmental footprints.

A **digital twin** is set of adaptive models that emulate the behaviour of a physical system in a virtual system getting real time data to update itself along its life cycle. The digital twin replicates the physical system to predict failures and opportunities for changing, to prescribe real time actions for optimizing and/or mitigating unexpected events observing and evaluating the operating profile system [10].

2.4 The CARBCOMN project

Developing the CARBCOMN technology will be the main priority of the CARBCOMN project ‘Carbon-negative compression dominant structures for decarbonized and deconstructable concrete buildings’ in the coming years. The CARBCOMN project is a research initiative launched under the Horizon Europe EIC (European Innovation Council) Pathfinder challenge ‘Digitalization for a Novel Triad of Design, Fabrication, and Materials’. CARBCOMN contributes to this challenge by developing innovative 3D printed ultra-low-carbon concrete and segmental construction practices that align with global sustainability goals (see Figure 2.B and the technology explanation in Section 2.3).

The project will do this by combining (i) carbon-negative concrete through carbon mineralisation, (ii) zero primary raw materials for making the concrete, (iii) compression dominant structures that are immune for rebar corrosion and become intrinsically more durable, (iv) extrusion-based 3D printing of geometrical shapes that drastically reduce material consumption, (v) discretised blocks that allow deconstruction and reuse of entire structures, (vi) shape memory alloys to improve system redundancy, and (vii) life cycle assessment (LCA) integration in form optimised structural designs of these decarbonised and deconstructable concrete load-bearing elements. This combination of features requires a new digital AEC design paradigm as it cannot be achieved with the current design and fabrication methodologies for reinforced and prestressed concrete structures.

To realize all these ambitions, CARBCOMN brings together a consortium of 5 leading research institutions (Ghent University, Technical University Darmstadt, University of Patras, ETH Zürich, EMPA) and 6 industry partners (TESIS, Orbix, incremental3d, Mario Cucinella Architects, re-fer and Zaha Hadid Architects) across Europe.

CARBCOMN directly tackles the main objective of the AEC challenge, by providing professionals and industry with a novel digitally driven and LCA supported design-to-fabrication technique for load-bearing concrete structures to reduce the GHG emissions related to the construction sector, in an unprecedented way. More specifically, a new construction system is formulated, which is based on advanced fabrication of carbon-negative materials to achieve at least carbon-neutral conditions at the construction level, to allow the AEC to adopt a decarbonized and deconstructable system instead of the traditional cast-in-situ moment-resisting frame system currently mainstream in the field of reinforced concrete construction.

3 Vision

The CARBCOMN concept implies a radical change in how constructions are built. A mindset ‘strength through geometry’ is put forward, compared to current design practices in reinforced concrete that are more material driven. Recollecting shapes and experiences from the past architectural knowledge, it relies on the use of modern digital fabrication tools and computational design platforms to realise structures which: are made of a carbon-negative material, employ the minimal quantity of materials and are constructed by using dry-joint unreinforced blocks assembled into deconstructable compression dominant structures. CARBCOMN is unique in combining these 3 aspects, to drastically lower the global warming potential.

3.1 Is carbon-negative concrete possible?

One solution to obtain carbon-negative concrete is through carbon mineralisation, the technology which is also applied within CARBCOMN. This technology is based on the application of a Portland cement free mixture of carbonatable secondary raw materials, such as fine powder of stainless-steel slags, that is cured through exposure to CO_2 in a carbonation curing chamber [11–14]. Although these materials are nowadays introduced on the market [15], they can be only used for producing simple applications, such as paver blocks [16] or hollow bricks in artificial masonry constructions [17] and produced through relatively traditional processes (e.g. moulding and pressing). Although having a sufficiently high compressive strength, this carbon-negative concrete is regarded not suitable for load-bearing concrete structures, because of not being compatible with traditional steel reinforcement that is susceptible to carbonation-induced corrosion.

Other studies, with the aim to formulate carbon-neutral (net-zero) or even carbon-negative concrete [18], but not investigated within CARBCOMN, are quite often still in a germinal stage. They are based on exploiting various chemical reactions or physical phenomena (e.g. concrete with seawater-derived magnesium feedstocks [19], silane-modified recycled powders [20], washout water and biochar [21] or even natural enzymes [22]) with the aim to unleash the carbon capture process.

Assuring that carbon-negative concrete could be applied in load-bearing concrete structures, can be tackled through digitalisation in design-to-fabrication. By doing so, we make the internal material structure more receptive to the carbonation process, we avoid massive elements that are hard to carbonate and avoid internal steel rebars that are the main cause of deterioration through carbonation-induced or other forms of corrosion. In addition, we could use extrusion-based 3D printing to realise structural geometries with high surface-to-volume ratio (for further improvement of the carbonation process) and precise stereotomy (to suit as building block within the assembled compression dominant structure).

3.2 How to reduce material consumption?

As already mentioned before, concrete is the most used construction material and even the most used material on earth after water. A slight reduction in concrete consumption may thus have an enormous effect on its environmental impact.

This need for reduced concrete consumption has acted as a driver to focus on topology optimization. Topology optimization is a technique which is used in concrete design to minimize material use by placing material only where it's needed to carry loads. By taking an iterative procedure, structurally inefficient areas are progressively removed until the design is refined to a desirable state. Due to the free forms that naturally occur, the result is often difficult to manufacture. For that reason, the result emerging from topology optimization is often fine-tuned for manufacturability. Here, 3D printing opens a lot of opportunities as this allows to create complex shapes without the need for expensive formwork. The design freedom enabled by additive manufacturing is thus very well compatible with the concept of topology optimization, whose geometrical complexity generally limits its application using traditional manufacturing methods [23]. It is thus only through the combination of both technologies that the material reduction, where topology optimization is aiming for, could also be realized in practice.

Another approach which could be followed to reduce material consumption is to come up with deconstructable building systems [24] whose members can be reused. In this respect it is important to use 'dry joints' (no fillers or adhesives). Two CARBCOMN partners have already cooperated in developing a deconstructable flat-slab concept [25]. One partner is working further on deconstructable recycled aggregate concrete systems. Such discretised and deconstructable structural systems remain yet unexplored from a decarbonized building perspective and face the challenge of a shift in engineering thinking from material induced structural ductility to system redundancy.

Further to the above aspects, it makes sense to also act on less usage of primary raw construction materials, when making new structures based on the CARBCOMN technology for the first time. In this respect, carbon curing technology is ideally suited to apply by-products from other industries, in the form of mineral powders that have high carbonation potential. As such carbon curing concrete based on secondary materials has been proven feasible, also for mixes that need to be 3D printed, as part of the CARBCOMN project results. A critical reflection can be made here that if the CARBCOMN technology would become largely popular in construction, most likely not sufficient secondary material feedstock with high carbonation potential might be available, so that still primary minerals might be required as well. However, for the current state of development and expected use, the carbon curing concrete can be largely based on secondary material feedstock.

3.3 Are unreinforced compression dominant structures the future?

The potential of compression dominant structures has already been explored before. At the one hand through funicular discretised compression-only structures characterised by superior structural efficiency with respect to the widely adopted moment-resisting frame systems mainstream in today's practice, because of the geometry-induced compression-dominant stress state [26]. On the other hand through post-tensioned segmental members with mechanics-induced compression-dominant stress state, especially realised by adopting an innovative post-tensioning system based on the use of iron-based shape-memory alloys (Fe-SMA) [27]. While for common extrusion-based 3D printed cementitious materials [28], the intrusion of reinforcement faces a serious production issue that is hard to overcome, for compression dominant structures, the need to place reinforcement does not exist and could lead to a breakthrough in this field.

The use of SMA post-tensioning represents a highly innovative solution to realize structural systems by assembling discrete elements. Their suitability for real engineering structures was recently proven, mainly in the context of retrofitting existing RC members [29]. Industrial production of a low-cost iron-based SMA (Fe-SMA) was scaled up to more than 50 tons. Leading material suppliers in Europe (such as Sika and Hilti) have shown interest in these alloys and have participated in the execution of real demonstrative retrofitting projects [30]. Recently, the SMA technology was also explored for discrete helicoidal stair steps. In CARBCOMN, Fe-SMA bars will be used for the first time to join and post-tension the discretized carbon-negative blocks. The SMA post-tensioning will facilitate the activation of the structure after the assembly of the parts. The tensioning is achieved by 'resistive heating', also referred to as 'self-prestressing' given this easy prestressing method. Furthermore, thanks to their high level of ductility (owing failure strain above 30 %), they will bring ductility (and increased robustness) to the system, e.g. when horizontal actions are significant like in the case of earthquake-prone area.

3.4 Why is the CARBCOMN technology disruptive compared to current practice?

Reinforced concrete structures generally consist of moment-resisting frames or reinforced concrete slabs supported by beams, which implies that the concrete should be cracked to work properly and that a significant amount of steel reinforcement is required. From a conceptual design point of view, concrete is thus not employed in the most congenial and efficient way, which results in large cross-sections to resist bending, and a significant environmental impact for concrete structures.

Measures currently under investigation to reduce the GHG emission associated with reinforced concrete structures mainly act at the material level, as they either propose concrete mixture compositions with recycled constituents and alternative binders or figure out the possibility to replace the use of concrete with other supposedly more sustainable materials, such as timber or bamboo. All these measures lead to an "incremental" innovation, which is limited by the actual availability of those alternative materials. Moreover, if the bending-based structural logic stays the same, improving the concrete mixture composition does not affect circularity since the rebars embedded in the concrete will be difficult to remove, the material volume will stay the same, and disassembly will remain challenging.

In contrast to current efforts to reduce GHG emissions from the concrete sector, the CARBCOMN technology will act on both, the material level, the fabrication level and the design level. The disruptive innovation of the CARBCOMN system will be achieved along various technological breakthroughs as further detailed below. All together they result in a major conceptual change and new design paradigm about how structural systems are meant to work.

Current practices in concrete construction	**Breakthroughs targeted by CARBCOMN**
Carbon mineralisation only works for elements of limited size (such as paver blocks) manufactured with a vibrating press for relatively dry concrete mixtures with large open porosity and such mixtures cannot be used for extrusion-based 3D printing.	On the one hand the CARBCOMN technology focuses on the design of discrete blocks tailored in geometry and properties to introduce carbon-negative concrete in load-bearing elements and on the other hand extrudable mix designs that have a fast reaction into green concrete strength while allowing for high CO_2 sequestration through their porous layered structure.
Mix designs for 3D printable concrete only exist for traditional Portland cement-based concrete and all require a relatively high binder content (almost twice the content of conventional ready-mix concrete).	The CARBCOMN technology develops a digital pipeline-based mix design method for cement free carbon-negative concrete with CO_2 sequestration capabilities, which is free of primary raw materials, LCA-based and designed for extrusion-based 3D printing.
Traditional steel strands and cables are applied at on-site or precast factory implementations for prestressed members and SMA only recently demonstrated options but mainly for retrofitting existing reinforced concrete members.	The CARBCOMN technology applies SMA post-tensioning to create digitally fabricated compression dominant structures composed of discrete blocks.
Circular concrete is achieved through crushing and recycling construction and demolition waste.	The CARBCOMN technology focuses on circular load-bearing structures composed of extruded

Re-use of load-bearing elements is almost non-existing in practice, because of material uncertainties, lack of performance and costly voluminous storage.	discrete blocks that are designed for deconstruction and re-use.
Topology optimisation of structures is limited by traditional casting technologies, available formwork and/or construction site limitations, and might require complex formworks or complex concrete mixtures with a high cement content and a high carbon footprint. Moreover, funicular structures have been explored for new structures, but not yet for retrofitting the load-carrying capacity of existing reinforced concrete members.	The CARBCOMN technology will bring savings up to 50-70% in material demand by combining compression dominant structural design principles with topology optimisation of the discretised components. In addition, funicular systems will be employed to both new or existing load-bearing reinforced concrete structures with a minimized environmental impact.
Structural strength and stability of reinforced concrete frame structures (or similar flexural dominant reinforced concrete members) are based on concrete cracking and yielding of internal steel reinforcement and standards specify minimum reinforcement ratios that lead to durability issues through rebar corrosion.	The CARBCOMN construction system consists of discrete blocks assembled in compression dominant structures, following historic unreinforced masonry structural principles. This ensures low stress and no need for rebars, preventing material degradation, and allowing for more durable construction.
Digital tools are limited and fragmented in the procedure to design low carbon structures. In addition, LCA is determined at the end of the design process with little possibilities to reconsider the carbon footprint. Moreover, digital design and structural tools are not prescribed and not lined-up to an integrated or more holistic approach to cover the advanced digital process from material level up to structural level. Complex BIM approaches are upcoming but lack a clear connection to LCA, carbon assessment loops and topology design for material optimization.	The CARBCOMN technology focuses on digital tools that are an inherent part of the digital pipeline to design low carbon-neutral load-bearing structures made of extruded compression blocks, starting with an LCA. Moreover, a fully integrated digital-pipeline approach for material-objects-joints-structural system with an LCA feedback loop between the multiple disciplines (carbon-negative concrete, discretization of structural objects, no internal reinforcement, topology optimized compression dominant structures) will be developed.

4 Triggering debate on the CARBCOMN technology

To stimulate readers of this Green Paper to critically think about and to trigger the debate on the potential of the CARBCOMN technology, we like to posit some statements here. We do not only want the reader of this Green Paper to read and reflect on these statements, but we also want them to come to action and share their opinion (on the below statements) with us through the electronic form which is shared in Section 6.

The cement industry is a top source of CO_2 emissions so it should cut of its emissions by urgent adoption of new technologies.

Concrete construction should lose share to more sustainable alterative materials, such as timber or bamboo.

Focusing on energy efficiency and alternative fuels of cement kilns will not be sufficient as decarbonization levers.

Limited availability of clinker substitutes will hinder their potential as decarbonization levers.

Isolation and collection of CO_2 from industrial emissions followed by recycling for further industrial use or underground storage is the way to move forward.

Digital technology supports the cement and/or concrete industry decarbonization efforts and contributes to its growth challenge.

Just as automakers increasingly view their role as providing mobility, not just making cars, cement and/or concrete companies could likewise be in the business of providing construction solutions.

The role of regulations and economic incentives in promoting sustainable construction materials is underestimated.

Lacking availability and knowledge gaps are more hindering to move towards the use of sustainable materials that the acceptance among architects and builders.

There is a need for more consistent policies to support sustainable construction practices as highlighted by the disparity in incentives.

5 Need for Compression Dominant Carbon Curing Concrete Structures

The global concrete market [31] size is expected to expand at a rate of 6%, reaching 820 billion € by 2026, addressing the urgent need for productivity, sustainability and competitiveness increase, as offered by the CARBCOMN technology. In the following sections, the economic, social and environmental impact is discussed that compression dominant carbon curing concrete structures might have, also reflecting on policy and regulatory considerations.

5.1 Economic impact

In reference to main actors in AEC (including material providers, designers, contractors, end-of-life specialists) CARBCOMN is expected to contribute to upgrading an industry that currently lags behind in digitalisation, making it more appealing in the job market and intellectually rewarding. Key exploitable results in CARBCOMN will bring economic opportunities in terms of (i) multi-functional modelling through digital tools that integrate design, fabrication and materials, (ii) carbon sequestration, (iii) resource efficiency, (iv) compression dominant structural systems, (v) form optimisation of discrete blocks composed into topology optimized systems, (vi) extrusion-based 3D printing of building blocks, (vii) new architectural and engineering designs considering amongst other compression dominant force-flow, deconstructability, systems over material redundancy and life cycle analysis. Moreover, SMA post-tensioning for compression dominant structures, being a new product, will enlarge the market for emerging SMA solutions. Overall, compression dominant structures composed of dry-joint discrete blocks are a disruptive structural system, for which its introduction will create new market opportunities.

Today, the concrete sector is digitalizing its processes, with the precast sector taking the lead, based on traditional reinforced and prestressed concrete engineering designs with a limited productivity increase compared to other sectors that implemented a fully digital revolution (such as car manufacturing). CARBCOMN proposes a boost in the digital revolution in the concrete sector by driving building solutions that are fundamentally different from current practice, are mostly counterintuitive for trained AEC engineers, but provide a huge leap forward in terms of intrinsic deconstructability.

Instead of using traditional engineering methods only based on the stress levels in the material and associated labour-intensive construction processes, CARBCOMN aims to use historical unreinforced masonry structural principles based on equilibrium and geometry to make a disruptive use of modern and novel materials such as carbon-negative circular concrete, digital fabrication tools among which extrusion-based 3D printing of building blocks, computational design platforms to manage discrete shape forming combined with topology optimization at system level and LCA-driven designs for circularity being CO_2 as raw material, 100% secondary materials, geometries and load systems requiring less materials and deconstructability for reuse. It is intended that the performance-based design framework will have the ability to reach 45% to 70% (depending on type and purpose of the elements) of material reduction compared to traditional load-bearing concrete designs [32]. These technological innovations, further integrated in a design-to-fabrication digital pipeline, will push forward economic activities in the construction sector to match challenges of digital transformation and to facilitate stakeholders to use the CARBCOMN concept and promote market entry.

5.2 Social and environmental impact

The AEC industry lays the foundation for basic needs and is in a crucial position to have a large impact on GHG emissions, resources efficiency and waste production. The environmental impact of the AEC industry can be significantly reduced by proactively acting on the following three levers [5]: opting for lower carbon materials, reducing material and resource consumption, and extending the durability and lifetime of single components or the entire building. The CARBCOMN technology acts on all these three levers and could therefore have a significant social and environmental impact.

The highly innovative construction system is based on a sustainable and environmentally safe valorisation of non-critical raw materials. The technology really aims for the use of 0% primary raw materials such as recycled materials (e.g. recycled concrete aggregates) and by-products derived from other industrial processes (e.g. metallurgic slags and incineration ashes), and even waste CO_2. The CO_2 sequestration capability of the newly developed carbon-negative concrete should allow to raise the current storage level of 5 kg CO_2/ton [33] to 10 kg CO_2/ton of concrete.

The system is designed for full recycling/reuse, by using dry-assembled blocks in demountable and reusable structural systems and by discrete blocks without embedded reinforcement that allow high quality recycling and have a lifetime allowing at least 2 reuse cycles (~150-year service life). A full LCA of the proposed CARBCOMN solution will demonstrate the overall superiority with respect to the current state of practice, further to the LCA being part of the feedback loop in the digital pipeline.

Development of compression dominant carbon curing concrete structures will contribute to multiple European Green Deal objectives:

- Substituting traditional, highly polluting cement-based technologies with advanced, cleaner alternatives will contribute to the transition towards sustainable materials and promote innovation in clean technology.

- Using discrete blocks that can be disassembled, allowing to enable products that are repairable, recyclable, and reusable for a longer lifespan.
- Employable for replacing, renovating and reusing the existing built stock, an important step towards more renovated and energy-efficient buildings will be taken.
- The development aligns with the strategic visions of industry, who are actively committed to advancing a greener and more circular construction sector.

As the proposed technological solution is significantly driven by digital methodologies, which open the construction sector, this will result in more future-proof jobs. Where jobs in construction are often restricted to male workers, digitalization in construction appeals to highly qualified jobs, also for women, that will be fully inclusive.

Impact also extends to the New European Bauhaus objectives because this newly proposed construction system is (i) enriching, as the mostly organic shapes of compression dominant structures will recall art and culture; (ii) sustainable, because at least a carbon-neutral construction system is targeted that further facilitates circularity through reuse; and (iii) inclusive, as the research endeavour has to be imprinted to a constructive exchange across disciplines (spanning from materials technology, over architectural design to civil engineering, also including environmental engineering, computer science and robotics).

5.3 Policy and Regulatory Considerations

The proposed solution will be consistently conceived within the standards currently in force for concrete construction in Europe [34]. Although a complete standardization of the research outcome cannot be obtained at this phase of its development, preliminary activities such as interactions with standardization and certification entities are planned to be started near the end of the project implementation. In addition, the basis will also be set for the European Technical Assessment (ETA) of the newly developed carbon-negative concrete-like material [35].

The adoption of new construction materials is often hampered by the conservativeness and risk adverseness of the construction sector. Moreover, adoption of sustainable practices remains limited because of the lack of demand for green construction and insufficient government pressure. This Green Paper is an initiative to increase the awareness and education among the public and private sectors about the benefits of green construction and as such facilitate adoption by the AEC sector. It is further intended to foster an active dialogue with AEC companies and to seek for their feedback to identify key concerns, incorporate diverse perspectives and create consensus on prior project goals. Resulting, near the end of the project an updated Green Paper will be launched where, furthermore, the possibility of replacing the purchase logic with rental ones will be evaluated, hypothesizing the implementation of a business model 'Structure-as-a-service".

Through the establishment of a matrix of application scenarios, comprehensive design solutions will be made clear, that define the integration modalities between compression dominant carbon curing concrete components and the various building systems required to meet high standards of energy efficiency, thermal performance, and architectural quality. These solutions will be analysed in relation to existing regulatory frameworks, enabling alignment with EU directives on sustainable construction, energy performance of buildings, and circular economy principles. This analysis will also identify relevant building typologies, intended uses, and the corresponding stakeholders and beneficiaries - facilitating targeted policy support, regulatory adaptation, and market uptake of the developed technologies.

6 Call for action

This Green Paper was compiled at the start of the CARBCOMN project to disseminate the objectives of the consortium to the wider community and to ask for feedback on our intentions. The aim is that we could take this feedback into account when setting our priority research lines and looking ahead toward implementation of the CARBCOMN technology into practice. We would therefore like to invite critical readers to share their opinion with us through the following electronic form: https://carbcomn.ugent.be/index.php/resources/green-paper

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