An innovative compression-dominant structural system for carbon-negative buildings: An overview of EIC Pathfinder project ‘CARBCOMN’

Denis Ayena Lorika[1], Yi Zhang[1], Maximillian Löher[2], Panagiotis Gkournelos[3], Sandro Sanin[4], Lori Zillante[5], Monica Palladino[5], Thinh Nguyen[6], Rosario Lombardi[7], Daniele Florenzano[8], Alessandro Dell’Endice[8], Saim Raza[9], Zohaib Hassan[9], Julien Michels[10], Vishu Bhooshan[11]

[1] *Ghent University, Ghent, Belgium*

[2] *TU Darmstadt, Darmstadt, Germany*

[3] *University of Patras, Patras, Greece*

[4] *Incremental 3D GmbH, Innsbruck, Austria*

[5] *Mario Cucinella Architects srl, Bologna, Italy*

[6] *Orbix Productions, Genk, Belgium*

[7] *TESIS srl, Fisciano (SA), Italy*

[8] *ETH, Zurich, Switzerland*

[9] *Empa, Dubendorf (ZH), Switzerland*

[10] *re-fer AG, Brunnen (SZ), Switzerland*

[11] *Computation & Design Group, Zaha Hadid Architects (ZHA CODE), London, United Kingdom*

Abstract

To address the achievement of net-zero CO_2 emissions, the full life-cycle design philosophy and technological framework of the construction sector require a comprehensive upgrade. EIC-founded project “CARBon-negative COMpression dominant structures for decarbonized and deconstructable CONcrete buildings” (CARBCOMN) proposes an innovative digital building design system encompassing material substitution, structural system optimization, and construction process innovation. It develops novel carbon-negative concrete by partially or entirely replacing conventional raw materials with industrial by-products, coupled with mineral carbonation techniques. 3D concrete printing (3DCP) technology is used to minimise material and enhance the application of structural masonry logic. Compression-dominant structural design through geometry optimization and post-tensioning leverages the high compressive capability of concrete while aligning with the 3DCP process and minimizing the durability issues associated with reinforcement corrosion. The introduced modular, deconstructable structural system not only improves construction efficiency but also aligns with circular economy principles. A comprehensive life cycle assessment (LCA) will be conducted to validate the carbon-negative potential of the proposed system, providing technical support and theoretical foundation for the sustainable transformation of the construction sector. This paper presents the core concepts and preliminary research outcomes of the CARBCOMN project.

1 Introduction

The construction industry faces urgent demands to improve sustainability while addressing enduring labour shortages. These challenges are compounded by the sector’s contribution to global carbon dioxide (CO_2) emissions, necessitating a radical rethinking of how buildings are designed, constructed and decommissioned [1]. Current energy-rooted approaches and material-intensive practices are increasingly misaligned with emerging environmental targets, such as the 2050 net-zero emissions. Consequently, a comprehensive upgrade to the sector’s design philosophy and technological framework is both timely and essential [2]-[4].

In response, the CARBCOMN project – short for 'CARBon-negative COMpression dominant structures for deconstructable CONcrete buildings' purposes an integrated full life-cycle strategy to accelerate the decarbonization of the built environment. Funded by the European Innovation Council (EIC), the project pioneers a digital design system that holistically combines material innovation, structural optimization, and advanced construction technologies [5].

At its core, CARBCOMN aims to develop carbon-negative concrete by substituting conventional concrete constituents with industrial by-products and embedding mineral carbonation to sequester CO_2 within the material matrix. This is complemented by the use of 3D concrete printing (3DCP), a promising fabrication technique that enhances construction precision and aligns well with the digital workflow of the project.

Structurally, the system adopts a compression-dominant design philosophy, leveraging concrete's natural strength under compression while minimizing reliance on steel reinforcement, which is often a source of durability concern, more so in the face of accelerated carbonation [6],[7]. Through geometry optimization and posttensioning, the design achieves high structural efficiency, compatible with 3DCP constraints. Further, the project introduces a modular and deconstructable system that facilitates disassembly and reusability, both of which are key principles in a circular construction economy.

This overview briefly outlines the fundamental concepts and early research methods and outcomes of the CARBCOMN project, with the aim of contributing to a more sustainable automated future in concrete construction.

The early findings presented in this paper form part of the project's commitment to develop carbon-negative mixes using locally sourced by-products and carbonation-curing. As part of a broader technological framework, the project is also investigating discrete compression-dominant structural systems and deriving design strategies informed by masonry principles. Durability performance will be evaluated alongside a life cycle cost analysis incorporating quantified economic and environmental indicators. To enable geometry-specific applications, open-source CAD tools and integrated design-to-fabrication (DTF) workflows will be developed, leading to a set of codifiable design principles for structural components and assemblies. The project culminates in the extrusion-based 3D-printing of carbon negative block geometries, with focus on optimizing boundary conditions for efficient assembly.

2 Experimental program

2.1 Materials

The binder (Carbinox 0–0.25 mm) and sand (Stinox 0–2 mm) derived from stainless steel slag were provided by Orbix. Polycarboxylate superplasticizer, SP (35% solid content, MasterGlenium 51, by BASF) and a hydroxypropyl methylcellulose, VMA (Tylose MOT 60000 YP4 by ShinEtsu) were used to obtain a stable and printable rheology. Tap water was used in all mixing operations. A factorial experimental design of 2 independent variables (aggregates to binder ratio, a/b and water to binder ratio, w/b) was employed, evaluated at 3 levels. The influence of chemical admixtures was assumed to be limited to rheological modification with no significant contribution to strength development. The mix design is summarized in Table 1.

2.2 Methodology

Material constituents were mixed in a planetary mixer at a maximum rotational speed of 285 rpm for 2.5 minutes. The quantity of mixing water was appropriately adjusted to cater for water absorption capacity (3.1%) of the aggregates. Using additives, the mix rheology was optimized to achieve a flow table value of 150 – 170 mm after 25 drops, in accordance with ASTM 1437-20 [8]. The initial mix design was developed through trial and error, targeting extrudability as the primary evaluation criteria. A 2D drill-driven mortar extruder shown in Fig. 1 was used for extrudability tests and subsequent small-scale sample printing from extrudable mixes. Extrudability was defined as: (1) the ability of a mix to be continuously ejected without breaking the plastic nozzle, and (2) its ability to retain geometric stability with minimal deformation upon layer deposition [9],[10]. Specimens consist of four layers, each of 15 mm height, 45 mm width and 200 mm length, were printed. Between 40 to 60 minutes After printing specimens were transferred to a carbonation chamber. Under the scope of this study, carbonation curing was conducted for 7 days under controlled carbonation conditions (CO_2 concentration = 3%, (1 bar), Temperature = 20°C, and relative humidity = 60%. After carbonation curing, the specimens were cut n into standard prisms for flexural and compressive strength tests, in accordance with EN 12390-5 [11] and EN 12390-3 [12] respectively. To account for possible anisotropy due to the layerwise structure, strength measurements were performed by applying the load in two directions, as illustrated in Fig. 2.

Fig. 1 Preparation of small-scale specimens: 2D extrusion of specimens (left), samples in the CO2 chamber (right).

In line with the project's objective to employ compression-dominant geometries, the mix exhibiting the highest compressive strength was selected for the initial block printing trial. The trial-print block was primarily to test the printability of the initial mix. Structural design and optimization of the final blocks for compression dominance is not covered in the scope of this paper. To predict the yield stress evolution of the mix, slow penetration tests were performed at room temperature, using a rheometer (Anton-paar, MCR 102). The peak yield stress was used to estimate the critical printing height, serving as a primary check for printability of the mix for the selected block geometry. The critical printing height, H_{cr} was computed from Eq. (1) [13]. The bulk mix was prepared in a 4-minute cycle and subsequently pumped through a flow rate-controlled pump (Rudolf STROBOT 408) of diameter 25.4 mm. The initial blocks were 3D-printed using a 6-axis robotic arm (ABB IRB 6650) shown in Fig. 3 and were carbon-cured separately under 20% and 3% CO_2 concentrations. In both cases, the temperature and relative humidity were controlled at 20˚C and 60%, respectively.

$$H_{cr} = \frac{\sqrt{3} \times \tau_0}{\rho_m \times g} \tag{1}$$

Where τ_0 is the yield stress of the mix in Pa, ρ_m is the density of the mix, measured as 1882 kg/m^3, and g is acceleration due to gravity, taken as 9.81m/s^2.

Table 1 Mix design for the initial testing program.

Mix	Effective water to binder ratio	Fine Aggregate to binder ratio	SP dosage (% of binder)	VMA dosage (% of binder)
M-0.5_0.25	0.25	0.5	0.8	0.06
M-0.5_0.30	0.30	0.5	0.3	0.06
M-0.5_0.35	0.30	0.5	0.0	0.08
M-0.7_0.25	0.25	0.7	1.0	0.08
M-0.7_0.30	0.30	0.7	0.5	0.08
M-0.7_0.35	0.35	0.7	0.0	0.05
M-1.0_0.25	0.25	1.0	1.8	0.10
M-1.0_0.30	0.30	1.0	1.0	0.10
M-1.0_0.35	0.35	1.0	0.5	0.10

3 Results

From the initial test program, the mix with a/b of 0.5 and w/b of 0.25 exhibited the highest compressive strength (Fig. 4). This performance is attributed to the highly CO_2-reactive binder, which rapidly formed $CaCO_3$ as the binding phase during carbonation [14].

M-0.5_0.25 was selected for the initial block-scale 3D printing trial. Based on the yield stress measurements from slow penetration tests (Fig. 5), the critical printing height reaches 0.74 m (Eq. (1)), which confirms its ability to support the printing height for the compression-dominant geometry proposed for the trial-print. Blocks were successfully printed and retained geometric stability during deposition as shown in Fig. 6. Carbonation curing under 20% CO_2 is currently ongoing to assess improvements in reaction kinetics and mechanical performance relative to the initial curing at 3% CO_2.

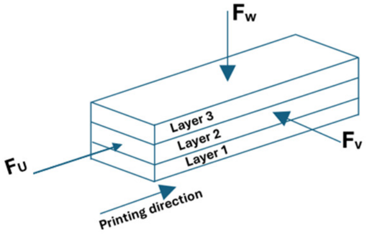

Fig. 2 Loading sign convention of specimens.

Fig. 3 Robotic arm employed for block printing (left).

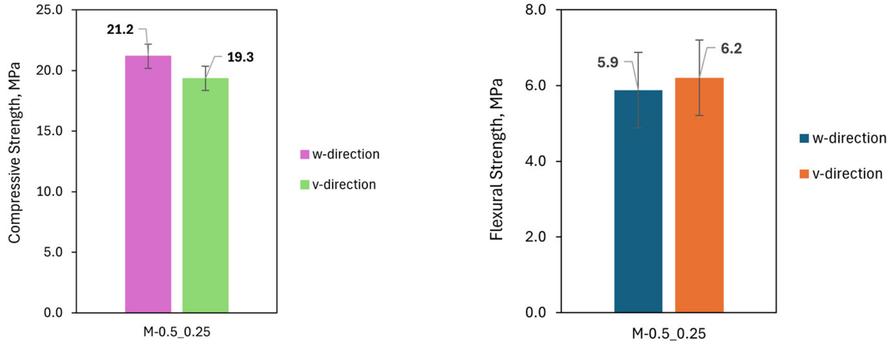

Fig. 4 Mechanical strength results of best performing mix: compressive strength (left), flexural strength (right).

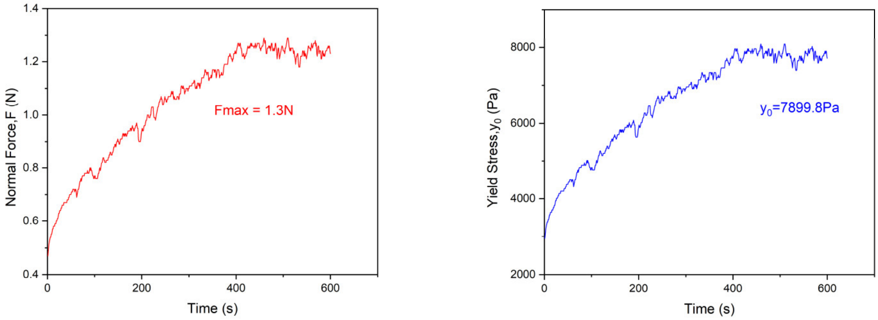

Fig. 5 Strength evolution from slow penetration tests: normal penetration force evolution (left), yield stress evolution (right).

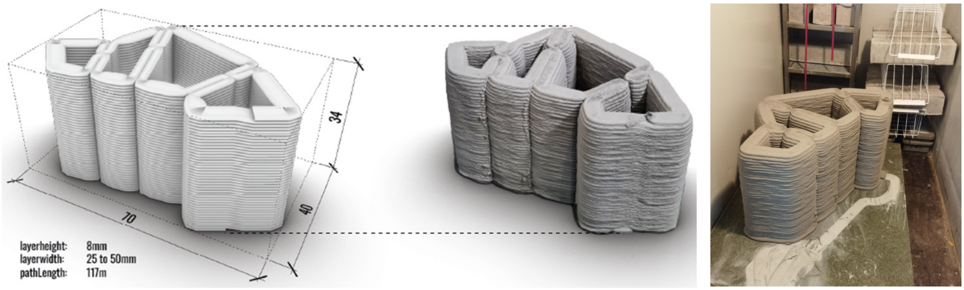

Fig. 6 Proposed trial block geometry (left); printed geometry with optimized mix (middle); printed block in CO_2 chamber (right).

4 Conclusion

The project's early results demonstrate the feasibility of producing 3D printable concrete from 100% secondary constituent materials. The initial mix design exhibits acceptable mechanical performance and print stability, with ongoing carbonation at an elevated CO_2 concentration expected to further enhance CO_2 sequestration and strength development.

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