

Carbon-Negative Pilot

Exploring the application of sustainable carbon-storing construction materials in CMU buildings

by Yao Wang, Mija Hubler, Rakshita Ramesh Bhat, Wil V. Srubar III, Shane Frazier, Loren Burnett, Linfei Li, Ben Stanley, Ryan Dick, and Sean James

In recent decades, the issue of global warming caused by fossil fuel carbon emissions has been a growing concern all over the world. In this context, the possibility of storing carbon in permanent building elements is a remarkable opportunity to reduce our carbon footprint. Ordinary portland cement (OPC) is the primary binder material in conventional concrete and comprises 5 to 9% of global CO₂ emissions.¹ To meet environmental sustainability goals without sacrificing economic viability, interest in OPC alternatives has recently increased.

In partnership with Microsoft Inc., the University of Colorado Boulder's Center for Infrastructure, Energy and Space Testing (CIEST) lab designed, constructed, and tested a special construction system designed to achieve overall carbon negativity. The system comprised a concrete slab supporting an L-shaped wall constructed using concrete masonry units (CMUs). The concrete slab was made of alkali-activated cement containing algae-derived carbon-storing, biogenic limestone from Minus Materials. The wall CMUs were produced by Prometheus Materials. Our team carried out the materials testing to ensure the materials and system met the specified workability (slump and setting time) and mechanical behavior (compressive and flexural strength) requirements, and we provided an embodied carbon estimate of the total system as a pilot demonstration for carbon-negative construction.

Alkali-activated binders have been widely studied and promoted as a sustainable alternative to OPC concrete. Alkali-activated concrete relies on alkaline solutions for activation of aluminosilicate-rich wastes from the industry. Moreover, because the use of alkali-activated binders boosts the recycling of industrial by-products without requiring calcination, life-cycle assessment (LCA) has demonstrated that the global warming potential (GWP) of alkali-activated concrete can be about 70% less than the GWP of OPC concrete.² The addition of algae-derived biogenic limestone from Minus Materials further improves the carbon-storage capacity of alkali-activated slag (AAS) concrete due to the carbon negativity of the limestone filler.

The rapid development and wide application of microbial technology is promoting the birth of innovation in construction materials. Researchers have proposed a novel cement-free living building material (LBM) that leverages desiccated hydrogel to bind sand and microbially induced calcium carbonate precipitation to improve the material strength.^{3,4} These novel LBMs, now being commercialized by Prometheus Materials, offer a low-carbon—and potentially carbon-storing—alternative to traditional CMUs.

Biogenic Limestone

Minus Materials Inc. harvests biogenic limestone from both calcareous microalgae and macroalgae through direct air capture of atmospheric CO₂. The biogenic limestone is dried to suitable water content and stored as a powder.

Biogenic limestone can be used as a direct replacement for quarried limestone in virtually all cement and concrete applications. Primary applications include: 1) using biogenic limestone as a CO₂-storing filler in cementitious materials (for example, Type II portland-limestone cements, alkali-activated slag-limestone cements); and 2) using biogenic limestone as a CO₂-storing raw kiln feed for CO₂-neutral OPC production. No changes are required to existing manufacturing processes within the cement and concrete industry to implement Minus Materials' technology, aside from shifting limestone sources from quarries to Minus Materials' biogenic limestone.

Alkali-Activated Slag Concrete Slab

Ground-granulated blast-furnace slag (GGBS) by Lafarge Cement was used as the binder. Crushed gravels and natural river sand were used as the coarse and fine aggregates, respectively. Powered sodium carbonate (Na₂CO₃), supplied by Fisher Scientific, was used as the activator. Moreover, the slag concrete in this project was mixed with two additives: one was the biogenic limestone supplied by Minus Materials, which acted as a micro-filler to promote a denser and stronger cementitious matrix; the other additive was Helix® 5-25 Micro Rebar® to improve resiliency, ductility, and strength of slag

concrete. Table 1 presents the mass proportions of each ingredient in AAS concrete.

To ensure the workability and mechanical behavior of the AAS concrete met the required design specifications, the CEIST Lab carried out various material tests before wall construction. The AAS concrete achieved a 3 in. (75 mm) slump, and the

Table 1:
Mixture proportions for the AAS concrete used to construct the test slab

Material	Mass, kg/m ³ (lb/yd ³)
GGBS	714 (1203)
Na ₂ CO ₃	15 (25)
Biogenic limestone	179 (302)
Water	380 (641)
Sand	650 (1096)
Coarse aggregate	1200 (2023)
Helix fiber	32 (54)

hardening time was around 40 minutes, which may be extended for a large project through the addition of water reducers. A compressive strength test was conducted on cylinder samples, and the mixture obtained 2500 psi (17 MPa) at 28 days.

Algae-Based Concrete Blocks

By harnessing microalgae to be used as a living building material, Prometheus Materials Inc. produces algae-based CMUs by replacing traditional OPC with biomineralizing microalgae and a proprietary hydrogel binder (Fig. 1). Medium sand was used as the primary aggregate in the block. The algae-based CMU blocks reached a compressive strength of 1200 psi (14 MPa) after curing for 7 days.

CMU Wall Construction

The wall system consisted of an “L” shape 16 x 10 ft (5 x 3 m) CMU wall

constructed on an 8 x 8 ft x 6 in. (2.4 x 2.4 m x 152 mm) AAS concrete slab (Fig. 2). There were eight No. 5 reinforcing bars equally placed along the bottom edge of the wall to connect the masonry wall and the concrete slab. Several wood triangle supports and plywood boards were installed on the wood formwork to resist hydrostatic pressure from freshly placed concrete as well as to avoid the sliding of the wall system during the wall dynamic test. The entire construction process lasted about 1 month, from April 25 to May 27, 2022 (Fig. 3).

Testing program

A structural performance test was conducted on the completed wall system. An MTS hydraulic actuator was used to apply a lateral area load on the CMU wall to assess wind pressure resistance. The test adopted displacement control at 0.5 in./min (13 mm/min). To apply a large surface area load on the CMU wall, a 4 x 7 ft (1.2 x 2.1 m) wood box was used, as shown in Fig. 4, and a steel beam transferred the load from the actuator to the wood box. Beside the MTS embedded sensors, there were three string potentiometers installed at 4, 6, and 8 ft (1.2, 1.8, and 2.4 m), respectively, to measure the wall deflections during the test.



Fig. 1: Biological CMU blocks (photos courtesy of Prometheus Materials, Inc.)

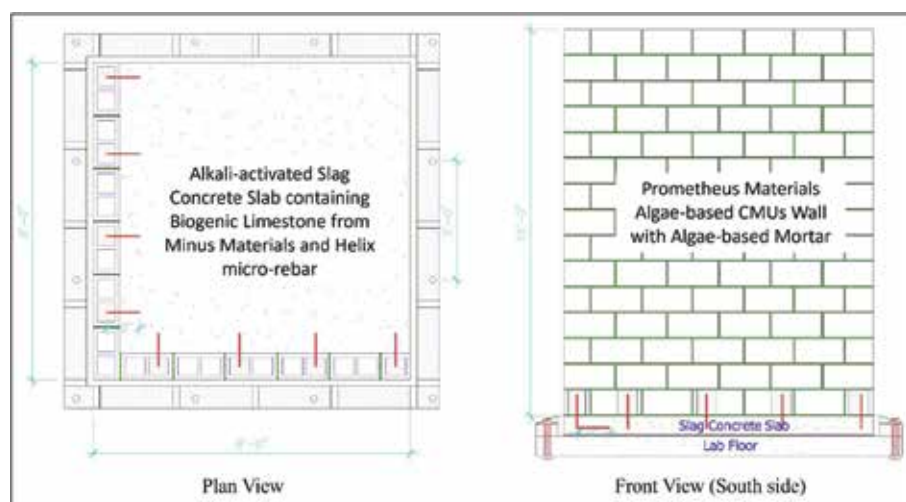


Fig. 2: Plan view and front view of the CMU wall system



Fig. 3: CMU wall construction completion (photo courtesy of CEIST Lab at University of Colorado Boulder)

The entire test lasted 15 minutes, and the wall went through the following stages: intact status, crack initiation, severe crack, and wall failure (Fig. 5). Similarly, the mechanical performance of the wall system also went through the full process of hardening (load rapidly increases with small displacement), softening (displacement increases but load remains constant), and wall failure. The peak load was 4.3 kip (19 kN), which represents the lateral load capacity of this CMU wall, and it meets the specification of engineering safety design. It should be noted that the actual applied area is smaller than the wooden box area because of edge deflection, which results in an actual stress higher than calculated.

Life-Cycle Assessment

Life-cycle assessment (LCA) was conducted, following ISO 14040:2006,⁵ to evaluate the amount of embodied carbon in the AAS biogenic limestone cement concrete and the algae-based CMU wall assembly. The goal of this analysis was to quantify and compare the carbon dioxide equivalent (CO₂e) emissions associated with the production of 1 m³ of various concretes (novel, conventional, and best-in-class incumbents) and 1 m² of various CMU wall assemblies (using novel and conventional CMU blocks). The embodied carbon of the AAS biogenic limestone cement concrete was estimated to be -36.6 kg/m³ (-61.7 lb/yd³), indicating that it can store more CO₂ than is emitted during its manufacture. Further, it exhibited a 113% reduction in embodied carbon compared to OPC concrete (Fig. 6). Opportunities to further increase CO₂ storage in AAS biogenic limestone cement concrete include mixture design optimization for incorporating additional biogenic limestone, minimizing transportation and process emissions, incorporating CO₂-storing fine and coarse aggregate, and CO₂ sequestration due to natural or accelerated carbonation. The algae-based CMU wall assembly had an estimated 96% reduction in embodied carbon emissions compared to a

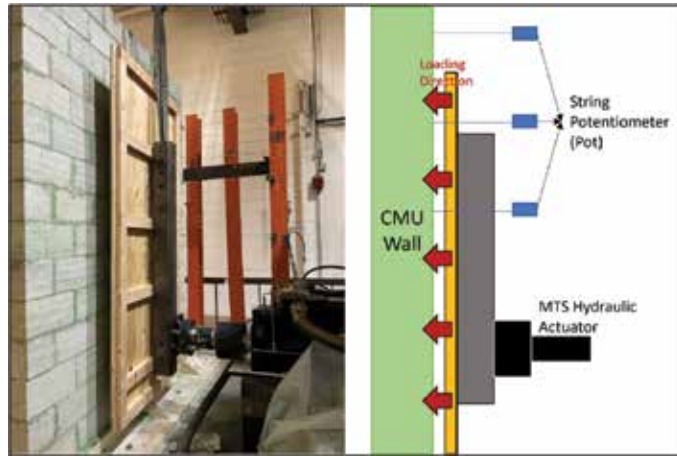


Fig. 4: The CMU wall test setup with a steel beam and a wood box used to apply the load

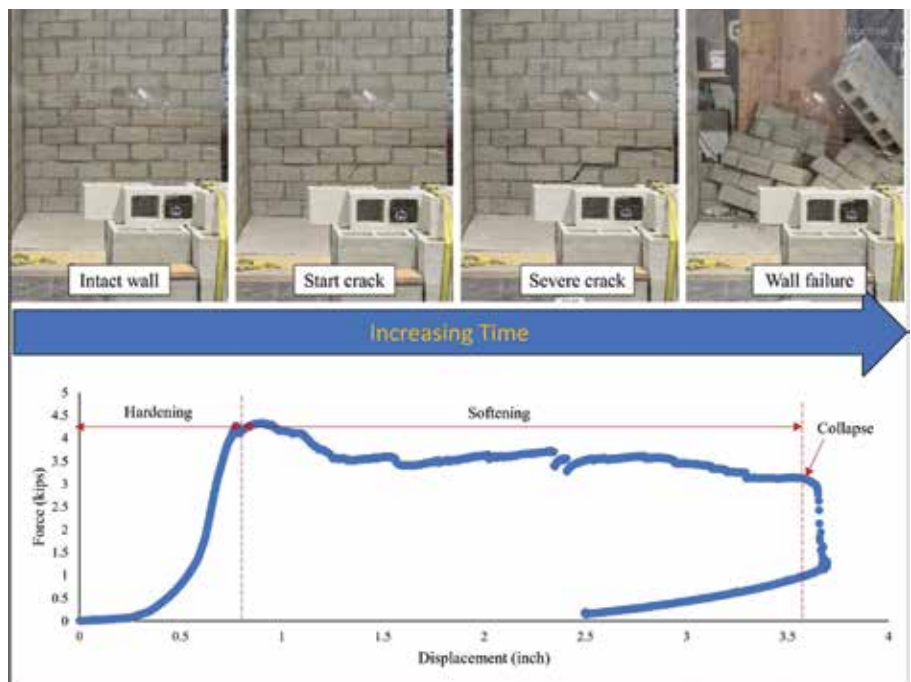


Fig. 5: Wall test stages and experimental measurements (Note: 1 kip = 4.4 kN; 1 in. = 25 mm)

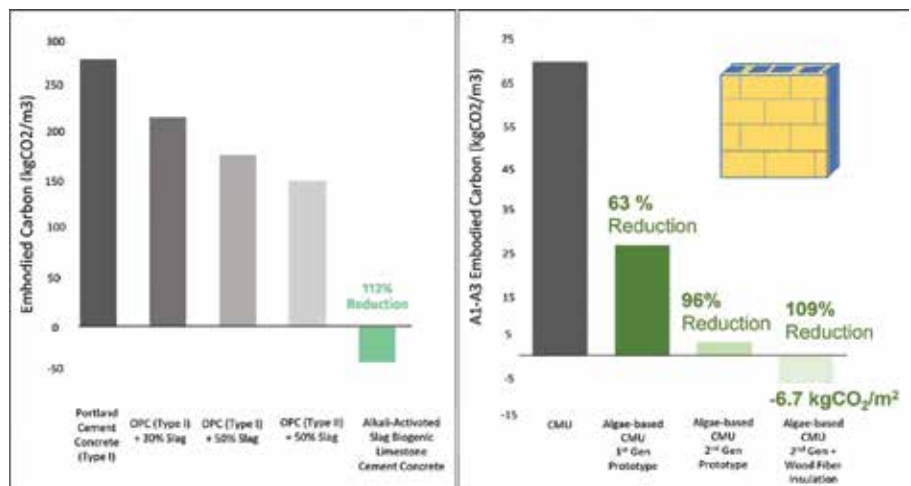


Fig. 6: LCA analysis results for alkali-activated slag biogenic limestone cement concrete and algae-based CMU wall assembly

conventional CMU wall assembly; the reduction could be improved to achieve a 109% reduction if the algae-based CMUs are used in combination with carbon-storing wood-fiber insulation within the wall cavities (Fig. 6).

Conclusions

Based on our research, the following conclusions can be drawn:

- The algae-derived biogenic limestone and algae-based CMUs provide a high impact on reducing embodied carbon emissions. Proper selection and sourcing of materials can minimize—and eliminate—embodied carbon in a CMU wall assembly;
- The tested system incorporated an AAS biogenic limestone cement concrete slab (0.9 m³ [1.2 yd³]) and an algae-based CMU wall with wood-fiber insulation (11.9 m³ [15.5 yd³]). Together, the assembly was estimated to store a net quantity of more than 100 kg (220 lb) CO₂e;
- Opportunities for further increasing the CO₂ storage of the AAS biogenic limestone cement concrete slab include mixture design optimization for incorporating additional biogenic limestone, minimizing transportation and process emissions, incorporating CO₂-storing fine and coarse aggregates, and CO₂ sequestration due to natural or accelerated carbonation; and
- Based on the experimental measurements for wall dynamic testing, the lateral load resistance capacity of the demonstration structure was 1.1 lb/in.² (158.4 lb/ft² [7580 Pa]), which is much higher than the designed pressure of

5.2 lb/ft² (250 Pa). Therefore, the combination of AAS biogenic limestone concrete slab and algae-based CMU wall meets the requirements of 100-year wind load at Seattle, WA, USA, and design specifications of Microsoft data center buildings.

Acknowledgments

The authors would like to thank Microsoft Inc. for financial support and the CIEST Lab at The University of Colorado Boulder for technical support. We sincerely thank Sherri Cook for her involvement in the original LCA work, and Sarah Williams and Danielle Beatty for polishing the entire manuscript. We also like to extend our gratitude to Brad Wham, Benjamin Hewitt, Scott Cusack, Cory Ihnotic, Katherine O'Dell, and the other CIEST Lab staff for their support in this project.

References

1. Nanayakkara, O.; Gunasekara, C.; Sandanayake, M.; Law, D.W.; Nguyen, K.; Xia, J.; and Setunge, S., “Alkali-Activated Slag Concrete Incorporating Recycled Aggregate Concrete: Long-Term Performance and Sustainability Aspect,” *Construction and Building Materials*, V. 271, Feb. 2021.
2. Weil, M.; Dombrowski-Daube, K.; and Buchwald, A., “Life-Cycle Analysis of Geopolymers,” *Geopolymers*, J. Provis and J. Deventer, eds., Woodhead Publishing Ltd., Sawston, UK, 2009, pp. 194-210.
3. Heveran, C.M.; Williams, S.L.; Qiu, J.; Artier, J.; Hubler, M.H.; Cook, S.M.; Cameron, J.C.; and Srubar III, W.V., “Biom mineralization and Successive Regeneration of Engineered Living Building Materials,” *Matter*, V. 2, No. 2, Feb. 2020, pp. 481-494.

MASONRY BUILDING CODE REQUIREMENTS

ACI Offers All Recent Editions of Masonry Building Code Requirements

The American Concrete Institute offers the 2016, 2013, and 2011 editions of Building Code Requirements for Masonry Structures. Available in both print and digital formats.

Learn more at
www.concrete.org



American Concrete Institute
Always advancing



4. Qiu J.; Artier J.; Cook S.; Srubar W.; Cameron J.; and Hubler M., “Engineering Living Building Materials for Enhanced Bacterial Viability and Mechanical Properties,” *IScience*, V. 24, No. 2, Feb. 2021.

5. “ISO 14040:2006: Environmental Management — Life Cycle

Assessment — Principles and Framework,” International Organization for Standardization, Geneva, Switzerland, 2006, 20 pp.

Selected for reader interest by the editors.



Yao Wang is a Postdoctoral Associate at the University of Colorado Boulder, Boulder, CO, USA. He received his MS and PhD both in civil engineering from the University of Colorado Boulder.



Loren Burnett is President and CEO of Prometheus Materials. He is also a serial entrepreneur and founder of six tech companies, four of which were based on tech transfer agreements.



ACI member **Mija Hubler** is an Associate Professor in the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado Boulder. She is a Co-Director of the Center for Infrastructure, Energy and Space Testing (CIEST), as well as a Co-Founder of Prometheus Materials, Inc.



Linfei Li is Director of Product Development at Prometheus Materials, Inc. He received his PhD in civil engineering from the University of Colorado Boulder.



Rakshita Ramesh Bhat is an Assistant Estimator at Adolfsen and Peterson Construction. She received her MS in civil engineering from the University of Colorado Boulder.



Ben Stanley is a Senior Consultant at WSP USA.



Wil V. Srubar III is an Associate Professor in the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado Boulder. He is a Co-Founder of Prometheus Materials, Inc., as well as a Co-Founder of Minus Materials, Inc.



Ryan Dick is a Senior Project Director at WSP USA.



Shane Frazier is a Co-Founder of Minus Materials, Inc. He received his PhD in materials science and engineering from the University of Colorado Boulder.



Sean James is the Director of Datacenter Research at Microsoft.

Copyright of Concrete International is the property of American Concrete Institute and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.