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 CO_2 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 CO_2. 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 CO_2-storing filler in cementitious materials (for example, Type IL portland-limestone cements, alkali-activated slag-limestone cements); and 2) using biogenic limestone as a CO_2-storing raw kiln feed for CO_2-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 (Na_2CO_3), 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 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.

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

Material	Mass, kg/m³ (lb/yd³)
GGBS	714 (1203)
Na_2CO_3	15 (25)
Biogenic limestone	179 (302)
Water	380 (641)
Sand	650 (1096)
Coarse aggregate	1200 (2023)
Helix fiber	32 (54)

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.)*

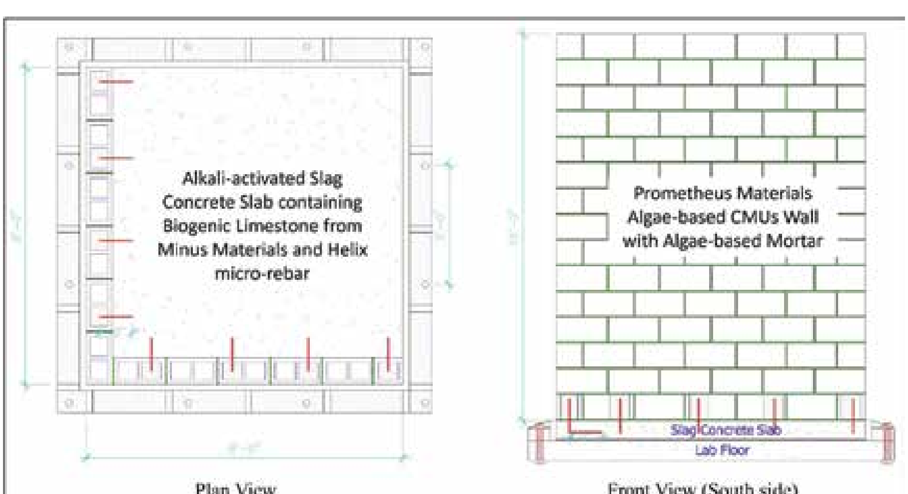


Fig. 2: Plan view and front view of the CMU wall system

Fig. 3: CMU wall construction completion *(photo courtesy of CIEST 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 (CO_2e) emissions associated with the production of 1 m^3 of various concretes (novel, conventional, and best-in-class incumbents) and 1 m^2 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/m^3 (−61.7 lb/yd^3), indicating that it can store more CO_2 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 CO_2 storage in AAS biogenic limestone cement concrete include mixture design optimization for incorporating additional biogenic limestone, minimizing transportation and process emissions, incorporating CO_2-storing fine and coarse aggregate, and CO_2 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

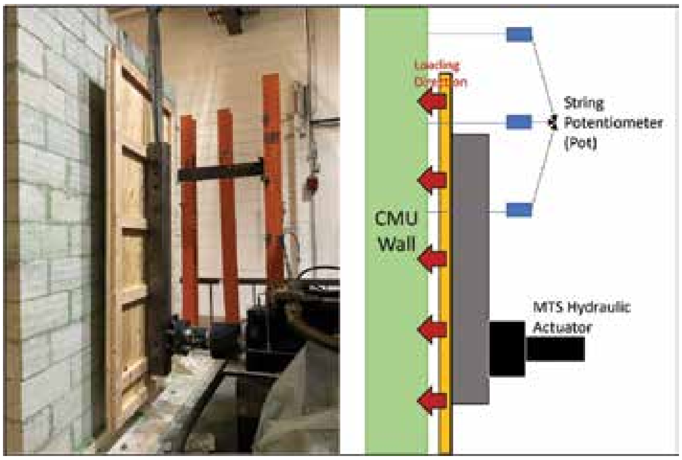


Fig. 4: The CMU wall test setup with a steel beam and a wood box used to apply the load

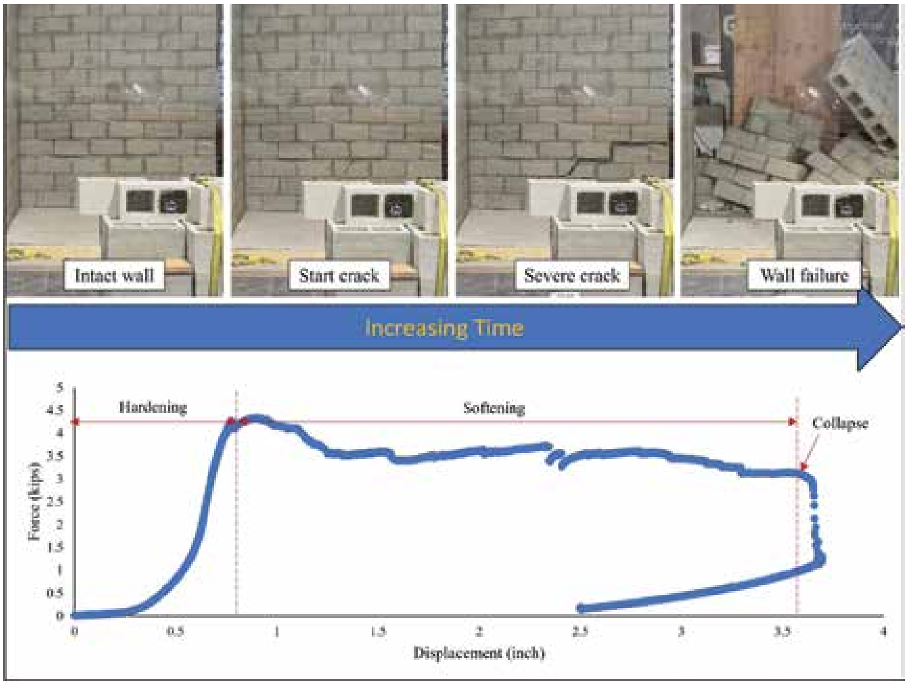


Fig. 5: Wall test stages and experimental measurements (Note: 1 kip = 4.4 kN; 1 in. = 25 mm)

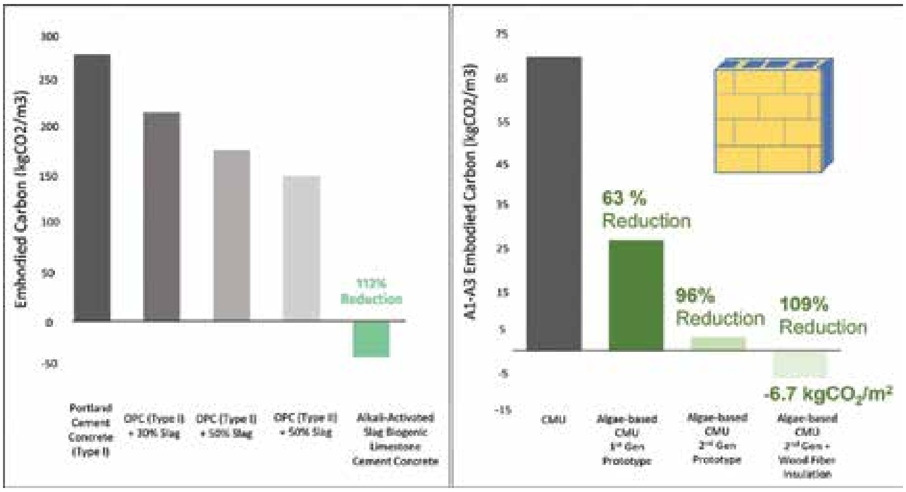


Fig. 6: LCA analysis results for alkali-activated slag biogenic limestone cement concrete and algae-based CMU wall assembly

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 m^3 [1.2 yd^3]) and an algae-based CMU wall with wood-fiber insulation (11.9 m^3 [15.5 yd^3]). Together, the assembly was estimated to store a net quantity of more than 100 kg (220 lb) CO_2e;
- Opportunities for further increasing the CO_2 storage of the AAS biogenic limestone cement concrete slab include mixture design optimization for incorporating additional biogenic limestone, minimizing transportation and process emissions, incorporating CO_2-storing fine and coarse aggregates, and CO_2 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/ft^2 [7580 Pa]), which is much higher than the designed pressure of 5.2 lb/ft^2 (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.

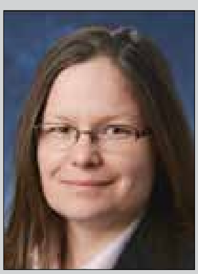
3. Heveran, C.M.; Williams, S.L.; Qiu, J.; Artier, J.; Hubler, M.H.; Cook, S.M.; Cameron, J.C.; and Srubar III, W.V., "Biomineralization and Successive Regeneration of Engineered Living Building Materials," *Matter*, V. 2, No. 2, Feb. 2020, pp. 481-494.

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.

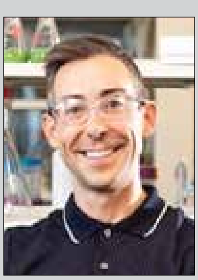
Selected for reader interest by the editors.

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.



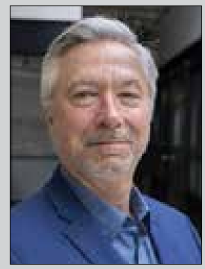
ACI member **Mija Hubler** is an Associate Professor in the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado Boulder. She is a Co-Director of the Center for Infrastructure, Energy and Space Testing (CIEST), as well as a Co-Founder of Prometheus Materials,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

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

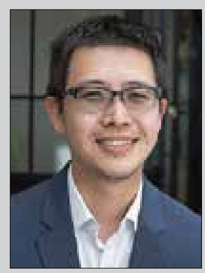


Wil V. Srubar III is an Associate Professor in the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado Boulder. He is a Co-Founder of Prometheus Materials, Inc., as well as a Co-Founder of Minus Materials, Inc.

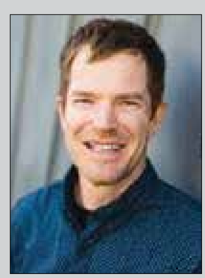
Shane Frazier is a Co-Founder of Minus Materials, Inc. He received his PhD in materials science and engineering from the University of Colorado Boulder.



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.



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



Ben Stanley is a Senior Consultant at WSP USA.

Ryan Dick is a Senior Project Director at WSP USA.

Sean James is the Director of Datacenter Research at Microsoft.

Losa de concreto de escoria activada con álcalis que contiene caliza biogénica de Minus Materials y microbarras helicoidales

Muros de UMC a base de algas con mortero a base de algas de Prometheus Materials

Losa de Concreto de Escoria
Piso de Laboratorio

Vista en Planta

Vista Frontal (Lado Sur)

Fig. 2: Vista en planta y frontal del sistema de muros de UMC.

Muro de UMC

Construcción

El sistema de muros consistía en un muro de UMC en forma de “L” de 5 x 3 m (16 x 10 pies) construido sobre una losa de concreto de EAA de 2.4 x 2.4 m x 152 mm (8 x 8 pies x 6 pulg.) (Fig. 2). Había ocho barras de refuerzo del #5 distribuidas equitativamente a lo largo del borde inferior del muro para conectar el muro de mampostería y la losa de concreto. En la cimbra de madera se instalaron varios soportes triangulares y tableros contrachapados de madera para resistir la presión hidrostática del concreto recién colocado, así como para evitar el deslizamiento del sistema de muros durante la prueba dinámica de los mismos. Todo el proceso de construcción duró aproximadamente 1 mes, del 25 de abril al 27 de mayo de 2022 (Fig. 3).

Programa de pruebas

Se realizó una prueba de desempeño estructural en el sistema de muro terminado. Se utilizó un actuador hidráulico MTS para aplicar una carga lateral en el área del muro de UMC con el fin de evaluar la resistencia de este a la presión del viento. La prueba utilizó un control de desplazamiento de 13 mm/min (0.5 pulg./min). Para aplicar una carga sobre una amplia superficie en la pared de la UMC, se utilizó una caja de madera de 1.2 x 2.1 m (4 x 7 pies), como se muestra en la Fig. 4, y una viga de acero transfirió la carga desde el actuador a la caja de madera. Además de los sensores MTS embebidos, también se instalaron tres potenciómetros de cuerda a 1.2, 1.8 y 2.4 m (4, 6 y 8 pies), respectivamente, para medir las deflexiones del muro durante la prueba.

Fig. 3: Finalización de la construcción del muro de UMC (foto cortesía del laboratorio CIEST de la Universidad de Colorado Boulder).

El ensayo completo duró 15 minutos, y el muro pasó por las siguientes etapas: estado intacto, inicio de la grieta, grieta grave y fallo del muro (Fig. 5). Del mismo modo, el comportamiento mecánico del sistema de muros también pasó por el proceso completo de endurecimiento (la carga aumenta rápidamente con un desplazamiento pequeño), reblandecimiento (el desplazamiento aumenta, pero la carga permanece constante) y fallo del muro. La carga máxima fue de 4.3 kip (19 kN), lo que representa la capacidad de carga lateral de este muro de UMC, y cumple la especificación de diseño de seguridad de ingeniería. Se debe considerar que el área real aplicada es menor que el área de la caja de madera debido a la deflexión de los bordes, lo que resulta en un esfuerzo real mayor que el calculado.

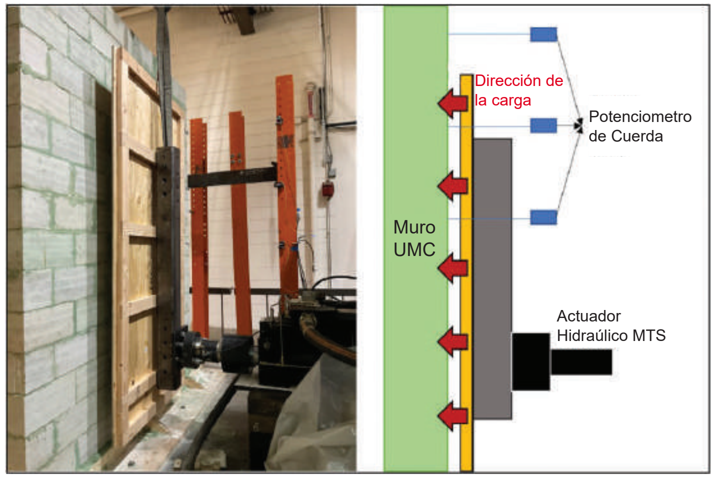


Fig. 4: Montaje del ensayo de un muro UMC con una viga de acero y un cajón de madera para aplicar la carga.

Evaluación del ciclo de vida

Se llevó a cabo una evaluación del ciclo de vida (ECV), siguiendo la norma ISO 14040:2006[5], para evaluar la cantidad de carbono incorporado en el concreto de cemento de caliza biogénica de EAA y en el ensamblaje del muro de UMC a base de algas. El objetivo de este análisis era cuantificar y comparar las emisiones de dióxido de carbono equivalente (CO_2e) asociadas a la producción de 1 m^3 de distintos concretos (nuevos, convencionales y los mejores de su clase) y 1 m^2 de distintos ensambles de muros de UMC (utilizando bloques de UMC nuevos y convencionales). El carbono incorporado del concreto de cemento de caliza biogénica de EAA se estimó en -36.6 kg/m^3 (-61.7 lb/yd^3), lo que indica que puede almacenar más CO_2 del que se emite durante su fabricación. Además, mostró una reducción del 113% del carbono incorporado en comparación con el concreto de CPO (Fig. 6). Las oportunidades para aumentar aún más el almacenamiento de CO_2 en el concreto de cemento de caliza biogénica con EAA incluyen la optimización del diseño de mezcla para incorporar caliza biogénica adicional, minimizar el transporte y las emisiones del proceso, incorporar agregados finos y gruesos que almacenen CO_2, y la captura de CO_2 gracias a la carbonatación natural o acelerada. Se estima que las emisiones de carbono del conjunto de muros de UMC a base de algas se redujeron en un 96% en comparación con un conjunto de muros de UMC convencional; la reducción podría mejorarse hasta alcanzar una disminución del 109% si las UMC a base de algas se utilizaran en combinación con un aislamiento de fibra de madera que almacenara carbono dentro de las cavidades de los muros (Fig. 6).

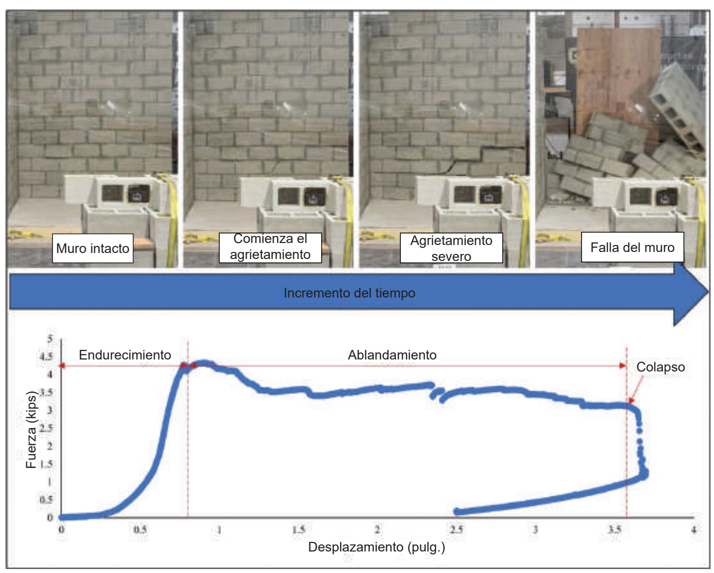


Fig. 5: Etapas del ensayo de muros y mediciones experimentales (Nota: 1 kip = 4.4 kN; 1 pulg. = 25 mm).

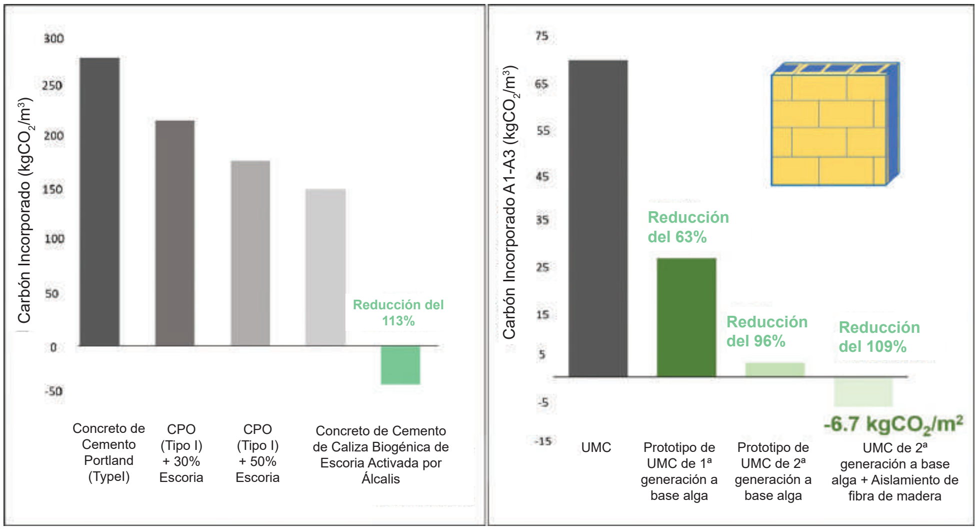


Fig. 6: Resultados del análisis de la ECV del concreto de cemento de caliza biogénica de escoria activada con álcali y del conjunto de muros de UMC a base de algas

Conclusiones

De nuestra investigación se desprenden las siguientes conclusiones:

- La caliza biogénica procedente de algas y las UMC a base de algas tienen un gran impacto en la reducción de las emisiones de carbono incorporadas. La selección y el abastecimiento adecuados de los materiales pueden minimizar -y eliminar- el carbono incorporado en un ensamble de muros de UMC;
- En el sistema ensayado se incorporó una losa de concreto de cemento de caliza biogénica de EAA (0.9 m^3 [1.2 yd^3]) y un muro de UMC a base de algas con aislamiento de fibra de madera (11.9 m^3 [15.5 yd^3]). Se estima que, en total, el conjunto almacena una cantidad neta de más de 100 kg (220 lb) de CO_2e;
- Las oportunidades para aumentar aún más el almacenamiento de CO_2 de la losa de concreto de cemento de caliza biogénica de EAA incluyen la optimización del diseño de mezcla para incorporar caliza biogénica adicional, minimizar el transporte y las emisiones del proceso, incorporar agregados finos y gruesos que almacenen CO_2, y el secuestro de CO_2 debido a la carbonatación natural o acelerada; y
- Según las mediciones experimentales de las pruebas dinámicas del muro, la capacidad de resistencia a la carga lateral de la estructura experimental fue de 1.1 lb/$pulg.^2$ (158.4 lb/pie^2 [7580 Pa]), cifra muy superior a la presión de diseño de 5.2 lb/pie^2 (250 Pa). Por lo tanto, la combinación de la losa de concreto de caliza biogénica de EAA y el muro de UMC a base de algas cumple con los requisitos de carga de viento de 100 años en Seattle, WA, EE.UU., y las especificaciones de diseño del Centro de Datos de Edificios de Microsoft.

Agradecimientos

Los autores desean dar las gracias a Microsoft Inc. por su apoyo financiero y al laboratorio CIEST de la Universidad de Colorado Boulder por su apoyo técnico. Agradecemos sinceramente a Sherri Cook su participación en el trabajo original de ECV, y a Sarah Williams y Danielle Beatty por pulir todo el manuscrito. También queremos expresar nuestra gratitud a Brad Wham, Benjamin Hewitt, Scott Cusack, Cory Ihnotic, Katherine O'Dell y el resto del personal del laboratorio CIEST por su apoyo en este proyecto.

Referencias

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., “Biomineralization and Successive Regeneration of Engineered Living Building Materials,” Matter, V. 2, No. 2, Feb. 2020, pp. 481-494.
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.

Yao Wang es asociado posdoctoral en la Universidad de Colorado Boulder, Boulder, CO, EE UU. Es licenciado y doctor en Ingeniería Civil por la Universidad de Colorado Boulder.

Loren Burnett es Presidente y Consejero Delegado de Prometheus Materials. También es emprendedor serial y fundador de seis empresas tecnológicas, cuatro de las cuales se crearon a partir de acuerdos de transferencia de tecnología.

Mija Hubler, miembro de ACI, es profesora asociada del Departamento de Ingeniería Civil, Ambiental y Arquitectura de la Universidad de Colorado Boulder. Es codirectora del Centro de Pruebas de Infraestructuras, Energía y Espacio (CIEST), así como cofundadora de Prometheus Materials, Inc.

Linfei Li es Director de Desarrollo de Productos de Prometheus Materials, Inc. Se doctoró en Ingeniería Civil por la Universidad de Colorado Boulder.

Rakshita Ramesh Bhat es ayudante de presupuesto en Adolfson and Peterson Construction. Es licenciada en Ingeniería Civil por la Universidad de Colorado Boulder.

Ben Stanley es Consultor Senior en WSP USA.

Wil V. Srubar III es profesor asociado del Departamento de Ingeniería Civil, Ambiental y Arquitectura de la Universidad de Colorado Boulder. Es cofundador de Prometheus Materials, Inc. así como cofundador de Minus Materials, Inc.

Ryan Dick es Director Senior de Proyectos en WSP USA.

Shane Shane es cofundador de Minus Materials, Inc. Obtuvo su doctorado en ciencia e ingeniería de materiales en la Universidad de Colorado Boulder.

Sean James es Director de Investigación del Centro de Datos de Microsoft.

La traducción de este artículo correspondió al Capítulo Noreste de México.

Título: Prueba Piloto de Carbono-Negativo

Traductora:
Lic. Iliana Margarita Garza Gutiérrez

Revisor Técnico:
Dr. Jorge Maurilio Rivera Torres