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3D Concrete Printing of Triply Periodic Minimum Surfaces for Enhanced Carbon Capture and Storage

Kun-Hao Yu, Teng Teng, So Hee Nah, Hua Chai, Yefan Zhi, Kun-Yu Wang, Yinding Chi, Peter Psarras, Masoud Akbarzadeh,* and Shu Yang*

Concrete, the world's second most utilized material after water, is responsible for 8% of global greenhouse emissions. Current carbon capturing and storage (CCS) concrete often involves convoluted processes, slow kinetics, limited CO₂ uptake, non-uniform carbonation in structures, and high cost. Efforts to enhance carbon sequestration often rely on increasing porosities, which compromise the mechanical strength of the resulting concrete. The 3D printing of CCS concrete is reported by incorporating diatomaceous earth (DE), a highly accessible biomineral with hierarchical porosity, into triply periodic minimal surface (TPMS) structures. DE enables stable extrusion, high print fidelity, and reduced density, which are crucial for 3D concrete printing. Further, DE facilitates CaCO₃ nucleation within the concrete and mitigates carbonation resistance, achieving a maximum CO₂ absorption of 488.7 gCO₂ per kg cement in 7 days, a 142% increase over conventional concrete. Optimizing TPMS geometry further enhances carbonation efficiency by enabling uniform CO₂ uptake throughout the structure. This geometry refinement reduces material usage by 78% and increases the surface-area-to-volume ratio by 515%, leading to a 30% higher CO₂ uptake while preserving mechanical integrity. The material strategy, together with the optimized concrete printing of TPMS structures, offers a pathway toward scalable and sustainable solutions without undermining concrete's structural functions.

human-made material (≈30 Gt annually),^[2] presents an immense opportunity for longterm CO₂ sequestration.^[3] Recent analyses suggest that replacing conventional concrete with CO2-storing alternatives could sequester carbon at the billion-tonne scale, positioning the built environment as a viable contributor to global decarbonization efforts.^[4] However, the current state of CCSintegrated concrete remains limited by inefficient carbonation kinetics, high energy requirements, and material constraints.^[5] A widely adopted approach to mitigating CO₂ emissions is to partially replace cement with supplementary cementitious materials (SCMs) such as fly ash, silica fume, and alkaline earth minerals,^[6] which could also enhance concrete's mechanical strength through carbonation. However, the degree of carbonation is typically limited to the surface layers, leading to inhomogeneous mechanical properties.^[7] Porous materials have been widely explored to increase CO2 uptake while minimizing energy requirements due to their high surface area.^[8] However, excessive porosity compromises mechanical strength, undermining the core function of concrete as a durable construction material.^[9] Further,

1. Introduction

The urgent need for large-scale carbon removal has prompted growing interest in integrating carbon capture and storage (CCS) into widely used materials.^[1] Concrete, as the most consumed

K.-H. Yu, S. H. Nah, K.-Y. Wang, Y. Chi, S. Yang Department of Materials Science and Engineering University of Pennsylvania 3231 Walnut Street, Philadelphia, PA 19104, USA E-mail: shuyang@seas.upenn.edu

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many of them are not scalable for construction purposes. Thus, a cost-effective, scalable, and structurally viable approach to CO₂-storing concrete is urgently needed.

3D concrete printing offers a transformative pathway by enabling precise geometric control, eliminating the need for

T. Teng, H. Chai, Y. Zhi, M. Akbarzadeh Polyhedral Structures Laboratory Department of Architecture University of Pennsylvania 3401 Grays Ferry Avenue, Philadelphia, PA 19146, USA E-mail: masouda@design.upenn.edu M. Akbarzadeh General Robotic, Automation, Sensing and Perception (GRASP) Lab School of Engineering and Applied Science University of Pennsylvania Philadelphia, PA 19104, USA P. Psarras Department of Chemical and Biomolecular Engineering University of Pennsylvania 220 S. 33rd Street, Philadelphia, PA 19104, USA ADVANCED SCIENCE NEWS ______



Figure 1. Design of the 3D Printable Biomineral-infused Concrete. a to b) Illustrations of a) the bio-inspirations and b) a floor design assembled from 3D printed TPMS carbon-absorbing concrete structures. c) Effect of varying diatomaceous earth (DE)/binder mass ratios on the surface area distribution of the concrete, measured 1 day after being cured in the mold. d) Effect of varying DE/binder mass ratios on the compressive strength of the concrete after being cured in saturated limewater for 28 days, with corresponding water/binder mass ratios. e) Compressive strength of the concrete after being cured in saturated limewater at different time periods with a fixed water/binder mass ratio of 0.87, but with varying binder mass compositions (DE/binder mass ratio = 0.3 and 0, silica fume (SF)/binder mass ratio = 0.3). Error bars in the graph represent the standard deviation of 3 to 5 samples.

formwork, and significantly reducing construction waste.^[10] Unlike conventional cast-in-place methods, 3D concrete printing allows for optimized structural design, enhancing structural integrity, minimized concrete usage, enlarged surface area through programmed porosity gradient, and optimal thermal efficiency.^[11] Recent advances in 3D printing have enabled a wide range of architected materials for CCS applications, in addition to cementitious systems. These include 3D-printed membranebased absorbers, hierarchically porous ceramics, and monolithic supports integrated with metal-organic frameworks (MOFs), which demonstrate enhanced mass transfer performance compared to conventional cast systems.^[12] Among various architected designs, self-supporting triply periodic minimal surface (TPMS) structures, characterized by non-self-intersecting, periodic surfaces with zero mean curvatures,^[11] as manifested in sea stars, plants, and human bones,^[13] have emerged as promising architectures (Figure 1a) that offer heightened structural stability, maximal surface areas, and superior energy absorption.^[14] Recent studies have demonstrated that 3D-printed TPMS structures, either used directly as structured supports in absorber columns or post-functionalized with CO₂-sorbing materials, can further improve capture efficiency and reduce operational cost by increasing accessible surface area, improving interfacial mass transfer, and lowering pressure drop.^[15] However, the intrinsic reliance of concrete on yield stress and thixotropy during continuous 3D printing via layer-by-layer stacking complicates the formation of stable overhang geometries (horizontal offset of the subsequent layers), thereby posing significant obstacles to fully harnessing the advantages of TPMS architectures for sustainable concrete construction.^[16]

Here, we demonstrate 3D printing of CCS concrete in diamond TPMS structures by replacing cement with abundantly available biomineral, diatomaceous earth (DE) of hierarchical porosity, and optimize the design and printing tool path to realize large overhangs. By leveraging the material properties of DE and the geometric design of diamond-based TPMS structures, we achieve uniform CO₂ uptake throughout the bulk, while maintaining structural integrity. DE, derived from remains of fossilized diatom with 80–90% SiO₂, is a naturally abundant porous material with a global production of 2.6 million tons in 2023.^[17] Its hierarchical pore structure (2–100 nm)^[18] (Figure S1, Supporting Information) enhances nutrient absorption, gas exchange, and structural support.^[19] Integration of DE imparts many advantages, including shear-thinning rheology for smooth extrusion, rapid structural recovery for self-supporting prints, water retention and redistribution to mitigate shrinkage-induced cracking during drying, and reduced density that is important to realize TPMS structures in concrete with a large overhang angle, θ , up to 45° (Figure 1b). The TPMS optimization design reduces material usage by 78%, while increasing the surface-area-to-volume ratio by 515%. Meanwhile, gas adsorption analysis confirms that DE exhibits superior CO₂ sorption capacity compared to silica

fume (SF), a commonly used SiO₂-based SCM (Figure S2, Supporting Information). More importantly, through the interactions with CaO hydration products, DE further reduces carbonation resistance and promotes nucleation and growth of CaCO₃ crystals for increased compressive strength. Leveraging both the material benefits of DE and the geometric advantages of TPMS, the 3D-printed CCS concrete structures exhibit a 30% higher CO₂ conversion and a 32% greater CO₂ uptake rate than conventional solid cubes.

2. Results and Discussion

2.1. Design and Characterization of 3D Printable Biomineral-Infused Concrete

The hierarchical porosity of DE (micron-sized pores in the skeleton and nanopores in silica) is anticipated to enhance CO₂ absorption efficiency.^[6a,20] As we systematically increase the DE/binder mass ratio (binder refers to the combined mass of cement and DE), a linear relationship is observed between the reduction of concrete density and the increase in porosity (Figure S3, Supporting Information). Brunauer-Emmett-Teller (BET) analysis further confirms that when the DE/binder ratio exceeds 0.3, pore sizes increase within the 2-10 nm range, leading to a high BET surface area (>11.6 m² g⁻¹) (Figure 1c; Figure S4, Supporting Information). In addition to enhancing porosity, DE serves as a water-retaining scaffold in the concrete ink, allowing for a high water/binder mass ratio without compromising viscosity (Figure 1d; Figure S3a, Supporting Information). Proper water management is critical during 3D printing, as the printed structure is continuously exposed to environmental conditions and the exothermic heat generated by cement hydration, both of which accelerate moisture loss. Hydration reactions occur as tricalcium silicate (3CaO·SiO₂, C₃S) and dicalcium silicate (2CaO·SiO₂, C₂S) react with water to form calcium silicate hydrate (3CaO·SiO₂ ·3H₂O, C-S-H) gel and calcium hydroxide (Ca(OH)₂), which governs mechanical strength development.^[6a] However, a high water/binder ratio typically reduces strength due to excessive pore formation, while a low ratio increases the risk of nozzle clogging. Thus, achieving an optimal DE/binder ratio is necessary to balance printability, hydration kinetics, and mechanical performance.

Based on these considerations, a DE/binder mass ratio of 0.3 is selected as the model composition to optimize CO₂ uptake while maintaining mechanical integrity. At this composition, the 3D-printed concrete achieves a compressive strength of 23.4 \pm 0.12 MPa after 28 days of curing in saturated limewater, comparable to conventional OPC concrete (20-40 MPa)^[20b] (Figure 1e; Figure S5, Supporting Information). To assess the impact of DE's water retention on strength development, two control groups are formulated: one with pure cement as the binder (DE/binder = 0) and another where SF replaced cement SF at an SF/binder ratio of 0.3. Despite all formulations maintaining the same waterto-binder mass ratio (0.87), the cement-only sample exhibited a significantly lower compressive strength of 13.4 ± 0.69 MPa, while the SF-containing sample reached only 8.27 ± 0.11 MPa after 28 days of curing (Figure 1e). This reduction in strength is attributed to excess free water in the mixtures, which leads to large pore volumes after curing and drying. In contrast, the porous framework of DE retains water within the matrix, preventing excessive free water from generating larger pores that compromise structural integrity. This controlled water release mitigates early evaporation and ensures sustained hydration reactions, promoting continuous strength development beyond 28 days. The pozzolanic reaction between DE's silica content and Ca(OH)₂ leads to the formation of additional C-S-H gel, which serves as a secondary binder that further strengthens the material over time. As a result, the DE-enhanced concrete reaches a peak compressive strength of 30.5 ± 0.57 MPa after 90 days, whereas both control samples plateau at 28 days. This prolonged strength gain suggests that the hierarchical porosity of DE facilitates a localized concentration gradient of hydration products, such as Ca²⁺ and SiO₄⁴⁻, enhancing their reaction with free lime and yielding a denser microstructure with superior mechanical properties.

2.2. Mechanical and 3D Printing Performance of Biomineral-Infused Concrete

3D concrete printing is a multifaceted process that needs to consider pumping efficiency, extrusion quality, shape retention, layer stacking ability, and material integrity post-printing and curing (Figure S6, Supporting Information). Concrete printing also involves a complex shear scenario across various printing stages. We subject the fresh concrete inks to varying shear rates to simulate the 3D printing stages. Although both the concrete inks with and without DE demonstrate shearthinning behaviors (Figure S7a, Supporting Information), the DE-infused ink rapidly restores its initial viscosity and yield stress within a second at 100 s⁻¹, ensuring extrusion stability and effective layer stacking (Figure 2a). In contrast, the control ink recovers only 76% (Figure S7b, Supporting Information). We next examine the ink's ability to retain its shape when extruded through nozzles of different diameters. Nozzles larger than 20 mm are commonly used in mid and large-scale robotic concrete printing. DE-infused ink consistently maintains a width/height (b/d) ratio <1.1 across nozzle diameters up to 21 mm, attributed to its lower density $(1,700 \text{ kg/m}^3)$ (Figure 2b,c). The control ink, with a density of 2,100 kg m⁻³, reaches b/d = 1.2 for nozzle diameters above 6.8 mm due to gravity effects.

The load-bearing capacity of the printed concrete ink is important to its stacking height. Once the concrete is deposited, it reaches a stable state, while the hydration reactions continue, gradually increasing its strength over time. To investigate the change in the strength of the concrete ink post-extrusion, we perform micro-indentation onto the freshly printed concrete inks at various time intervals after they are stabilized from the high shear rates. The DE-infused concrete has nearly identical stiffness to the control ink over an hour, despite using less cement and more water (Figure 2d). After setting for 30 min, DE-infused concrete exhibits strain-hardening due to enhancing interparticle cohesion and yield stress^[21] (Figure 2e). Conversely, the concrete without DE exhibits a drastic drop in post-yield strength after reaching its yield point (Figure 2f), making it highly susceptible to catastrophic failure.



Figure 2. Mechanical Performance of DE-Infused Concrete with a DE/Binder Mass Ratio of 0 and 0.3. a) Rheological characterization of the thixotropy behaviors of the fresh concrete ink with DE, involving 3 steps: a low shear rate of 0.1 s^{-1} for 60 s to mimic the initial resting state of the fresh concrete in the hopper, followed by a high shear rate of 100 s^{-1} for 30 s to mimic the shearing and extruding process, and lastly a low shear rate of 0.1 s^{-1} for 60 s to mimic the material resting on the printing stage. b) Width/height (b/d) ratio of the cross-section area of the extruded concrete with and without DE using different-sized printing nozzles. c) The cross-sectional view of the extruded concrete with and without DE using different diameter printing nozzles. d) Elastic modulus of the fresh concrete ink with and without DE at various time intervals after mixing. Inset: The setup for micro-indentation. e) Force-displacement curves of the fresh concrete ink with DE at various time intervals after mixing. f) Force-displacement curves of the fresh concrete ink with SD of 3 to 5 samples.

To assess the layer stacking ability of the DE-infused concrete ink during printing, we conduct a buildability test by continuously printing a single-wall cylinder. The DE-infused concrete sustains stacking up to 111 layers till exhausting the ink, reaching an aspect ratio of 42, while the control ink fails after 43 layers due to uneven drying and high density (Figure 3a; Movie S1, Supporting Information). In fact, the exposed lower layers experience early hydration reactions, leading to shrinkage, cracks, and structural instability (Figure 3b). In contrast, water can migrate through DE's hierarchical porosity, preventing differential drying across printed layers in DE-infused concrete, and retaining moisture in the lower layers for up to 20 h under ambient conditions (Figure 3b,c; Figure S8, Supporting Information). We hypothesize that hydrated products (e.g., Ca^{2+} , SiO₄⁴⁻, and OH⁻) can also migrate along with water between layers, thereby enhancing the interfacial bonding strength of the printed layers. Typically, the interface between layers creates weak points that reduce the mechanical performance of the printed structure. To test this hypothesis, we conduct a threepoint bending test to measure the interfacial bonding strength of the 3D-printed and cast concrete cubes, with and without DE (Figure 3d). The DE-infused, printed concrete exhibits a 178% increase in interfacial strength ratio (vs the cast sample) compared to that printed from the conventional concrete (Figure 3e; Figure **S9**, Supporting Information). We employed cube-shaped samples rather than the standard beams (with a 3:1 span-to-depth ratio) due to the printing limitations of the material without DE, which lacks sufficient buildability to produce slender geometries. As the focus here is on comparing the relative interfacial bonding performance between materials under identical fabrication conditions, the use of cubes provides a consistent basis for comparison.

2.3. Geometrical Design and Optimization of Triply Periodic Minimal Surfaces

Compared with simple geometries such as cylinders with $\theta = 0^{\circ}$, complex highly porous structures with $\theta \ge 45^{\circ}$ for high surfacearea-to-volume ratios are much more delicate and face new challenges, especially when printed in concrete (Figure 1b): extensive support structures are typically required, but removing them could break the brittle concrete prints. Here, we employ a posttension design and optimization strategy^[10,22] that transforms the TPMS geometry into self-supporting, high surface area printable forms, followed by post-slicing overhang analysis to assess printability. To elucidate our design principle, we use the diamond (D) TPMS unit cell as a case study. A surface composed of two-unit cells with a wavelength of 70 mm is thickened by 8 mm to form a printable volume and is sliced at 2.8 mm layer height for overhang analysis (Figure 4a-c). Overhang is defined as the horizontal offset between subsequent layers divided by the layer height (Figure 4d). An overhang value of 1 corresponds to a 45° local inclination, generally acceptable for most 3D printable materials without additional support structures. The cumulative distribution of overhangs shows that the original TPMS structure has 18% of points with overhangs greater than 1, suggesting a high probability of printing failure due to layer collapse (Figure 4e). By scaling the geometry by a factor of 2 in the z-direction, we reduce overhangs above 45° to less than 2% (Figure 4e-g), ensuring sufficient layer contact and enabling successful printing with DE-infused concrete.

Building on this, we design a more complex post-tensioned TPMS concrete beam composed of nine modular units with integrated channels for post-tensioning cables. These continuous channels are aligned with the tensile force requirements of www.advancedsciencenews.com

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Figure 3. 3D Printing and Post-printing Performance of DE-Infused Concrete with a DE/Binder Mass Ratio of 0 and 0.3. a) A 3D-printed single-wall cylinder with and without DE. The zoom-in images show the status of the bottom part of the structure. b) Photos showing a 3D printed cylinder with and without DE after 4 h of printing. c) Illustration of the migration of water and Ca^{2+} ions between printed layers during the water evaporation pathway in the middle part of the DE-infused 3D printed concrete structure. d) Schematics of the 3-point bending test of a 3D printed cube. The cube's coordinates indicate the printing and testing direction. e) The interfacial strength ratio of the 3D printed cubes with and without DE. Error bars show the SD of 3 to 5 samples.

the structure and enable the prefabricated 3D printed concrete units to be assembled after printing. A comprehensive computational methodology of design, optimization, and fabrication of the TPMS concrete beam is presented in the authors' previous work.^[10] A three-step computational pipeline guides the design and optimization process (Figure 4i). First, the Polyhedral Graphic Statics (PGS) form-finding process, involves establishing the geometry of the load paths that minimize the bending moment in the system, setting the base dimensions, and defining the boundary conditions, including the desired loads and support locations. This initial setup serves as a constraint for the system, providing the foundation for further design. A force diagram of graphic statics shows the equilibrium of forces as closed polyhedral cells that are topologically dual to the form diagram represented as a bar-node model. The structural form is derived from the force diagram based on their reciprocal relationship in a process that is called structural form finding. The form of the structure is a network of bars (to carry forces) connected by nodes. The internal flow of forces can be further optimized by manipulating the force diagram.^[23] In Figure 4i, the blue bars indicate compression forces, while the red bars indicate tension forces. By ensuring equilibrium, a range of equilibrated structural forms can be generated, accommodating both tension and compression forces. In the example of a concrete beam design, constant tension forces are maintained in the lower bars of the system. This approach prevents higher stress concentrations at specific points in the beam system and allows for even load distribution. Given the anisotropic nature of concrete, characterized by its high compressive strength but low tensile strength, the constant tension

force determined from graphic statics can be utilized as the posttensioning force for cables running through the beam, ideally producing consistent compression.^[10] Once the bar-node model is established, the desired structure form is defined.

Second, we embed the TPMS into the generated form diagram. We select the D surface because it exhibits high mechanical strength and load-bearing capacity compared to other common TPMS geometries, such as Gyroid (G) and Primitive (P) surfaces, making it suitable for applications requiring robust structural integrity.^[22,24] Besides, the implicit function defining the D surface, $\cos \cos \cos \cos \cos z = \sin \sin \sin \sin \sin \sin z$, inherently contains straight lines.^[25] The linear segments reduce the complexity of the 3D printing process, decreasing the need for support structures and mitigating structural collapse. Additionally, our design requires a continuous force path to integrate posttensioning cables for assembling the 3D printed modules. The straight lines within the D surface facilitate the implementation of these force paths, aligning well with the bar-node model used in the PGS form-finding process. In the TPMS embedding process, geometric transformations of the D surface are performed, including rotation, translation, scaling, and mirroring. The D surface's periodic anticlastic surfaces, defined by the centers of curvature on opposing sides forming a hyperbolic paraboloid, permit the application of mirroring, rotation, and translation without compromising structural integrity.^[10,26] The transformation of the D surface not only aligns the force path but also reduces overhangs, as demonstrated in the single unit of the D surface example in Figure 4h. In addition, the introduction of mirror symmetry in the D surface enhances mechanical performance by

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Figure 4. Overhang Analysis of Diamond Surfaces and Flow Chart of the Steps for Design and Optimization of the Diamond TPMS Concrete Canopy. a) The original D surface with two-unit cells and a wavelength of 70 mm, thickened by 8 mm. b) Sliced original D surface geometry with a layer height of 2.8 mm. c) Overhang analysis of original D surface geometry. d) Definition of the overhang. e) Cumulative distribution of the overhang for the original and scaled D surfaces. f) Scaled D surface, scaled by a factor of 2 in the z-direction. g) Sliced Scaled D surface geometry with a layer height of 2.8 mm. h) Overhang analysis of scaled D surface geometry. i) Step 1: Polyhedral Graphic Statics (PGS) Form-Finding. Base dimensions of the structure are established as the initial input/constraint. Boundary conditions and applied load locations are defined, and a force diagram is generated using a bar-node model. Blue bars indicate compression forces and red bars indicate tension forces. Step 2: Embedding the TPMS into the Form Diagram. The diamond TPMS is embedded into the generated form diagram. Step 3: Volumetric Modeling and Overhang Analysis. Volumetric modeling adds thickness to the designed surfaces, using SDF. The design is segmented into unit cells, and each cell is analyzed for overhangs and 3D printability. j,k) Two 3D printed TPMS-based structures using DE-infused concrete.

deflecting the cracks and regulating the deformation behavior, thus preventing catastrophic failure due to stress concentration.^[27] By leveraging these transformations, we ensure that the TPMS geometry is integrated seamlessly with the desired form diagram, enhancing both the mechanical performance and printability of the final structure. Last, we employ volumetric modeling to add thickness to the designed surfaces, creating a tangible 3D structure. The Signed Distance Function (SDF) is used for this purpose.^[28] An SDF describes a shape by providing the shortest distance from any point in space to the nearest point on the shape's surface. The SDF value is positive for points outside the shape, negative for points

inside, and zero on the surface. This technique allows for precise definition and manipulation of geometric forms, enabling the uniform assignment of thickness to the designed surfaces and the seamless integration of these surfaces into a coherent volumetric model. Following the volumetric modeling of the structure, the design is segmented into nine unit cells. Each unit cell is then analyzed to assess the presence of large overhangs and their suitability for 3D printing, using the same process shown in Figure 4e. This evaluation ensures that the final printed structure is self-supported.

To validate our design strategy, we print two TPMS-based structures using DE-infused concrete with a maximum θ = 45 ° without any support. Figure 3j shows a printed scaled diamond TPMS unit cell with two periodicities, achieving a 66% reduction in material usage and 274% increase in surface area-to-volume ratio compared to the identical bounding box of the smallest rectangular geometry that completely encloses the structure (Figure S10a, Supporting Information). We further print a unit of a posttensioned concrete beam,^[10] resulting in a 78% reduction in material usage and 515% increase in surface area-to-volume ratio compared to its identical bounding box (Figure 4k; Figure S10b, Supporting Information). These results demonstrate how TPMS geometries, integrated with design transformations and overhang optimization, enable the printing of structurally robust, geometrically complex concrete structures with large overhangs (up to 45°) and high surface area, without layer collapse during printing.

2.4. CO₂ Sequestration and Carbonation Mechanism in Biomineral-Infused Concrete

To evaluate the CO₂ sequestration efficiency, we pre-hydrate the concrete with and without DE for 24 h. This process facilitates the release of Ca^{2+} and SiO_4^{2-} from C_3S , C_2S , and $Ca(OH)_2$ into water retained in the pores of DE and concrete mixtures, driven by the ion concentration gradient^[29] (Figure 5a). Limited prehydration could cause CaCO3 to encase the unhydrated cement, hindering the binding effect and limiting the carbonation reactions.^[20a] As seen from the scanning electron microscopy (SEM) images (Figure 5b), after 24 h of prehydration, an acicular Type I C-S-H (needle-like ettringite structure) is formed within the concrete^[30] and on the DE surface. Water retained within the DE pores facilitates the ion migration process, thereby amplifying the ion concentration gradient and promoting interactions between Ca²⁺ and the negatively charged DE. Type I C-S-H and prism-like calcium hydroxide crystals (Ca(OH)₂) are also present randomly in the concrete without DE (Figure S11, Supporting Information). The prehydrated samples are subsequently introduced to a pure CO₂ environment under ambient pressure and 75% relative humidity (RH). High-purity CO₂ accelerates the concrete carbonation rate and increases the degree of carbonation. Thus, it is commonly used in the concrete carbonation process.^[29] Furthermore, high-concentration CO₂ from industrial waste flue gases is readily available. Careful control of RH is essential for optimizing the concrete carbonation reactions; excessive moisture can block the pores and hinder CO₂ diffusion.^[31] The CO₂ adsorption isotherm shows that after 24 h of prehydration, DE-infused concrete achieves higher adsorption of CO₂ compared to concrete without DE (Figure 5g). After 7 days of carbonation, DE surface was cleared up. Instead, stable calcite crystals exhibiting a characteristic rhombohedral morphology are formed in the adjacent regions^[6b,32] (Figure 5c,d; Figures S11 and S12, Supporting Information). The re-emergence of pores on DE leads to a surface area (20.5 m² g⁻¹), 240% higher than that of concrete without DE (8.57 m² g⁻¹), primarily attributed to micropores (pores < 2 nm) (Figure 5h; Figure S13, Supporting Information).

Typically, the carbonation product (CaCO₃) has a higher molar volume than Ca(OH)₂ and C-S-H, resulting in a significant decrease in porosity. However, in this case, the large surface area and increased pore size/pore volume benefit the continuous carbonation process.^[7b,20b] To further understand the mechanism, we compare the carbonated concrete to a control group exposed to an N2 environment, representing continuous curing through hydration (Figure 5E; Figure S11, Supporting Information). SEM images reveal the continuous formation of ettringite clusters^[33] resulting in occluding pores on DE in the concrete after 7 days of curing under N₂ (Figure 5f), and reduction in surface area over time (Figure 3h; Figure S13, Supporting Information). During prehydration, the pozzolanic reaction of DE promotes the early formation of C-S-H around the DE particles.^[34] When set in an N₂ environment, the reaction continues, promoting further formation of C-S-H and occluding the pores on DE. The high surface area of DE allows for numerous sites for nucleation and growth of CaCO₃. In contrast, when exposed to CO₂, CO₂ molecules diffuse into the concrete pores through DE, dissolve in water, and form carbonate ions. Carbonation reaction promotes the dissolution of hydration products and their reactions with the prehydrated products. Meanwhile, mass transport depletes Ca2+ and CO32- ions locally over the DE surface, creating undersaturation, leading to the formation of calcite crystals outside of DE and re-emergence of pores on the DE surface (Figure 5b), in agreement with the literature.[35]

The capacity of CO₂ stored in carbonated concrete is quantified by thermogravimetric analysis (TGA) (Figure 5i; Figure S14, Supporting Information). DE-infused concrete stores up to 488.7 gCO₂ kg_{cement}⁻¹ after 7 days of carbonation, a 142% increase over concrete without DE (Figure 5i; Tables S1 and S2, Supporting Information). This enhanced carbonation efficiency is attributed to DE's ability to mitigate carbonation resistance in concrete^[20b] and the inherent reduction in cement content. To reveal how DE-infused concrete may improve CO2 diffusion, we cast samples with and without DE in 10 cm tubes, exposing only one surface to CO₂ over 7 days. We then drill the tubes stepwise (Figure S15, Supporting Information) and measure CO₂ uptake across depths. While CO₂ uptake, in general, decreases with sample depth, it ceases beyond a depth of 20 mm in the concrete without DE. In contrast, even at depths of 20-30 mm, the DE-infused concrete retained 65% of the CO_2 uptake at its surface layer (0-5 mm) (Figure 5j). Efficient CO₂ diffusion assists the growth of stable calcite, enhancing early strength and durability:[6b,20b] compressive tests consistently show higher strength in CO₂-cured samples compared to N₂-cured ones over the first 96 h (Figure S16, Supporting Information).

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Figure 5. CO_2 Sequestration of DE-Infused Concrete with a DE/Binder Mass Ratio of 0.3. a, c, and e) Schematic illustrations of the possible products and the distribution of Ca^{2+} ion concentration $[Ca^{2+}]$ from concrete with DE after being a) pre-hydrated for 1 day, c) cured in CO_2 , and e) N_2 environments for 7 days, respectively. $[Ca^{2+}]$ sat refers to the saturation concentration of Ca^{2+} ions required for $CaCO_3$ formation. b, d, and f) Scanning electron microscope (SEM) images of the concrete with DE corresponding to a, c, and e. g) CO_2 sorption isotherm of the concrete with and without DE after pre-hydration for 1 day. h) Effect of curing time on BET surface areas of the concrete with and without DE cured in CO_2 and N_2 environments, respectively. i) CO_2 uptake of the concrete after being cured in a CO_2 environment for different durations. j) CO_2 uptake at various depths in concrete after being cured in a sealed plastic tube with one end open in a CO_2 environment for 7 days.

2.5. Carbonation Efficiency of the 3D Printed TPMS Structures

We next assess the contribution of TPMS geometry to CO_2 uptake enhancement beyond the material's effect. A 3D printed diamond TPMS structure and a cast solid cube with the same bounding box volume are placed in a CO_2 chamber for 7 days after 24 h of pre-hydration (**Figure 6**a; Figure S10, Supporting Information). Stepwise sample collection and TGA results show that the TPMS structure achieves CO_2 uptake of 423.7 ± 3.6 g CO_2 kg_{cement}⁻¹ at the surface and 393.2 ± 4.5 g CO_2 kg_{cement}⁻¹ at the core layer (only a 7.2% drop). In contrast, CO_2 uptake in the solid cube drops by 81% from 344.1 ± 8.3 g CO_2 kg_{cement}⁻¹ at the surface to 64.8 ± 2.9 g CO_2 kg_{cement}⁻¹ at the core. Notably, within the same surface depth range (0-10 mm), the TPMS structure exhibits 122% higher CO_2 uptake than the cast cube, attributed to the corrugated surface of the TPMS geometry, which further enhances the surface area for carbonation. Using the maximum CO_2 uptake of DE-infused concrete (Figure 5i) as a reference for 100% uptake efficiency, we estimate total CO_2 uptake based on mass and layer-by-layer analysis. The TPMS structure with a DE/binder mass ratio of 0.3 achieves an uptake efficiency of 85% versus 55% for the cube, highlighting the geometric advantage of a 274% higher surface area-to-volume ratio (Figure 6b).

To explore TPMS structural benefits, we transformed four flat surfaces of a standard ASTM C109 cube into diamond TPMS surfaces and thickened them to form walls. Considering the potential buckling of the thin-walled TPMS structure, we reinforce it by offsetting contour surfaces inward and filling the internal cavities (**Figure 7**a; Figure S17 and Movies S2, S3, Supporting Information). This approach increases material usage but still reduces overall material volume by 11% while achieving a 27% higher

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Figure 6. Carbonation Efficiency of 3D Printed DE-Infused Structures with a DE/Binder Mass Ratio of 0.3. a) CO₂ uptake measured at increasing depths from the surface to the core in both cast cube and 3D printed TPMS structures. b) CO₂ uptake efficiency of the cast cube and 3D printed TPMS structure.

surface-area-to-volume ratio than the bulk cube (Figure S17, Supporting Information). We note in meter-scale floor assemblies, adhesives, rebar, and support structures will be used to enhance the overall strength, which is ongoing. Here, we focus on the material assessment of individual TPMS units.

To assess whether the TPMS surface affects the mechanical performance of the cube, we conduct finite element analysis (FEA) simulations to analyze the stress distribution of both cube structures (Figure 7b) under compression force. FEA results indicate stresses concentrate at the edges and walls of a standard cube, but more at the edge of the TPMS cube due to boundary effects (Figure 7b). The TPMS cube has 11.4% lower stiffness than the solid cube (Figure S17, Supporting Information). To validate this, we perform compression tests on the cast standard solid cubes and 3D printed TPMS cubes (Movie S3, Supporting Information) with the same bounding box dimensions ($5 \times 5 \times 5$ cm according to ASTM C109). The compressive stress-strain curve shows that the 3D printed TPMS cube has 10.5% lower compressive strength than the solid cast cube (Figure 7c), in agreement with the FEA simulation. This could be due to stress concentration on the walls of the structure, as observed in the FEA, and that the testing surface (top surface)

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Figure 7. Structural Performance and Carbonation Efficiency of 3D Printed DE-Infused TPMS Structures with a DE/Binder Mass Ratio of 0.3. a) CAD designs and corresponding photos of the 3D printed specimens of a solid cube and a TPMS cube, respectively. The solid and dashed line represents the bounding box of the structure. b) Finite element analysis (FEA) simulation of the solid cube and the TPMS cube. c) Compressive stress-strain curves for the solid cube and TPMS cube from physical testing. d) Specific strength and specific stiffness of the solid cube and TPMS cube as measured in physical tests. e) Schematic illustration of the CO₂ uptake rate testing using an automated CO₂ flux system. f) CO₂ concentration changes over 60 s in the test chamber containing (i) cast cube with 1 exposed face, (ii) cast cube with 5 exposed faces, and (iii) 3D-printed TPMS cube. The band indicates the error bar range. g) Comparison of CO₂ uptake rate per kg of cement. Error bars show the SD of 3 to 5 samples.

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is not as flat as the cast concrete due to the corrugated printing textures, causing additional stress concentration. We note that the TPMS cube has a smaller volume within the bounding box, resulting in a lower structural density for the TPMS cube (1520.3 kg m⁻³) compared to the solid cube (1700 kg m⁻³). Therefore, the TPMS cube only experiences a 0.02% reduction in its specific strength and a 2.3% reduction in its specific stiffness (strength or stiffness divided by the structural density of the cube) compared to the cast solid cube (Figure 7d). This highlights that the TPMS cube can maintain its structural strength while reducing material usage and increasing the structure's surface area.

Next, we evaluate the geometry effect on CO₂ uptake rate, we continuously measure CO₂ concentration in a closed chamber for 60 s for both cast solid cube and printed TPMS cube under ambient conditions (450-480 ppm CO₂), utilizing an automated CO₂ flux system (Figure 7e; Figure S18, Supporting Information). Over 5 cycles, the cast solid cube with five open surfaces absorbs four times more CO₂ than the single-surface cube (Figure 7f(i,ii)). The non-linear CO₂ uptake versus surface area may result from competition for CO₂ among adjacent surfaces, therefore, reducing the overall absorption efficiency. Nevertheless, the 3D printed TPMS cube demonstrates a further 9% reduction in CO₂ concentration within the observation period compared to the cast cube (Figure 7f(iii)). After normalizing the CO₂ uptake rate by the total cement usage in each structure, the TPMS cube achieves a 32% higher uptake rate than the cast cube (Figure 7g).

3. Conclusion

In this paper, we present a highly sustainable and 3D-printed CCS concrete by replacing cement with naturally abundant biomineral, DE, featuring hierarchical porosity, and the optimal design of self-supported, highly porous diamond TPMS structures. DE provides the necessary rheology for printing intricate TPMS structures, prevents non-uniform dehydration during printing, and enables a maximum CO2 absorption of 488.7 gCO₂ kg_{cement}⁻¹ within 7 days—a 142% increase compared to conventional concrete. Importantly, DE-infused concrete allows for deeper and more uniform carbonation throughout the structure. We further elucidate the role of DE beyond being simply a porous material for carbonation. We show that DE reduces carbonation resistance, allowing the re-emergence of pores for continuous carbonation, and promotes nucleation and growth of CaCO₃ crystals for increased compressive strength. The TPMS design reduces material usage by 78%. Together, the highly porous geometry and the use of DE lead to a 30% improvement in the CO₂ uptake efficiency compared to a solid cube of the same volume. The continuous monitoring of CO₂ concentration changes reveals that the optimized TPMS design improves the CO₂ uptake rate by 32%. Our concrete design outperforms the state-of-the-art OPC-based concrete in carbonation efficiency, approaching the theoretical CO₂ uptake maximum within just 7 days (Figure S19, Tables S3, S4, Supporting Information). Here, through optimized geometry that minimizes material waste, and understanding various roles of highly accessible, nature's products, DE, in concrete 3D printing, we offer insights that will advance

sustainable, scalable, and high-performing next-generation infrastructures.

4. Experimental Section

Material Composition and Preparation: The concrete ink formulation first started with the dry mixing of ASTM C-150 type I Portland cement (Quikrete, USA) and natural diatomaceous Earth (DE) (DiatomaceousEarth.com) at a weight ratio of 7:3 to serve as the binder. The DE used in this study was an uncalcined, naturally occurring material composed primarily of amorphous silica (>95% SiO₂) with less than 5% crystalline silica. It was used as received, without further purification. It was noted that any modification will significantly increase the cost of the concrete. The DE appears as a fine white powder with no detectable odor, a specific gravity of 2.2, a pH range of 7.5-9.0, low water solubility (<1%), and a melting point above 1300 °C. Detailed morphological and pore structure characterizations, including SEM, TEM, and N₂ sorption isotherms, are provided in Figure S1 (Supporting Information). Subsequently, all-purpose sand (Quikrete, USA) was sifted through a No. 20 sieve (ASTM E11 Test Sieve) and dry-mixed with the binder in a 2:1 weight ratio. For enhancing extrudability during 3D printing, hydroxypropyl methylcellulose (HPMC) was incorporated as a viscosity-modifying admixture (VMA) at a concentration of 0.4 wt% relative to the binder. Following the dry material homogenization at medium speed for 2 min using a stainless-steel mixer (KitchenAid Classic Stand mixer), 0.87 wt% of deionized (DI) water corresponding to the binder was introduced into the mixer. The mixing process involved initial low-speed blending for 60 s, followed by medium-speed mixing for 120 s, with intermittent manual scraping to ensure thorough incorporation and prevent material adherence to the sides. Throughout the mixing, the mixer was covered to avoid water loss. The mixed fresh concrete was utilized within 3 min for subsequent 3D printing and characterization. The chemicals were used as purchased without further purifications. In the case of various DE/binder ratio concrete mixtures, the ratios of sand to binder and VMA to binder remained consistent. The water/binder ratio varied based on the DE/binder ratio, determined by the equation: $W_{water} = 0.5 \, * \, W_{cement} \, + \, 1.73 \, * \, W_{DE},$ where W_{water} is the water weight, W_{cement} is the cement weight, and W_{DE} is the DE weight. It was crucial to note that the constants (0.5 and 1.73) may be adjusted based on material sources, with the final values determined through the assessment of mixture extrudability using a 2 mm nozzle syringe. To evaluate the impact of microstructure variations-specifically, the presence or absence of pores-on the mechanical strength of concrete under high water content conditions, DE was replaced with an equivalent weight of ASTM C-1240 silica fume (Sikacrete-950DP, Sika) and all other parameters were kept the same.

Rheological Characterization: The rheological properties of the fresh concrete were tested using a temperature-controlled rheometer (DHR-3, TA Instruments) with a 40-mm-diameter parallel plate. The measurements were carried out at 23 °C with an 8000 μ m gap and began immediately after material preparation. The concrete mixture was pre-sheared at a rate of 100 s⁻¹ for 60 s and then left to rest for 60 s before each test. The thixotropy test included 3 steps. First, the sample was sheared by a constant shear rate of 100 s⁻¹ for 60 s. Second, the sample was sheared by a constant shear rate of 100 s⁻¹ for 60 s. Shear-thinning was evaluated from 0.1 to 150 s⁻¹ within 120 s and then decreased from 150 to 0.1 s⁻¹ in 120 s.

Mechanical Testing: Cubes (5 × 5 × 5 cm, ASTM C109) and cylinders (diameter: 15 mm, height: 30 mm) were used for compressive strength testing. For the compressive strength of the hydrated cured sample, the material was cast in the mold for 24 h at room temperature (23 °C) and then fully immersed in saturated limewater at room temperature (23 °C) until the desired curing age (3, 7, 14, 28, 60, and 90 days). Subsequently, the samples were wiped free of surface water and tested using a mechanical tester (Instron 4206) with a 1 mm min⁻¹ loading rate until failure. For the compressive strength of the carbonated samples, testing occurred immediately after the carbonation process at different carbonation times

(6 h, 1, 2, 3, and 4 days). The interfacial bonding strength of the 3D printed structures was measured through the three-point bending test. 3D printed cubes $(5 \times 5 \times 5 \text{ cm})$ were manufactured with the same printing parameters as outlined in the 3D printing section and were loaded onto a mechanical tester with a supporting span of 4 cm and a loading rate of 1 mm min $^{-1}$, testing until failure. The upper anvil was positioned between two printed layers at the center of the specimen. The force-displacement curve and Young's modulus of the concrete mixture at different setting times were determined by compacting wet concrete in a petri dish (height: 20.3 mm, diameter: 50 mm) and using a round-flat end cylinder indenter with radius R = 0.5 mm loaded onto the Instron mechanical tester to indent the center of the sample by applying force F to a certain indentation depth δ . Young's modulus was calculated as $E = F(1-v^2)/2R\delta$, where v = 0.5 is the Poisson ratio of the fresh concrete. The interfacial strength ratio was defined as the maximum strength of a 3D printed cube under a 3-point bending test divided by the strength of a cast cubic sample of the same size.

Physical Properties: The dry density of materials with various DE/binder mass ratios was determined by drying the samples in a vacuum chamber at 80 °C for 24 h until a constant weight was achieved. The dry density was calculated by dividing the dry mass of the concrete sample by its volume. The porosity of materials with various DE/binder mass ratios was determined by fully immersing the sample in water and sonicating it for 1 h. The sample was then wiped to remove surface water, and the weight was measured. The absorbed water weight was used to calculate the pore volume of the sample, and the porosity was determined by dividing the pore volume by the total volume of the sample.

3D Printing: To conduct printing tests, an in-house-developed desktop concrete 3D printer with a $25 \times 25 \times 25$ cm printing volume was used. The printer adapted a multiple-step extrusion method that was composed of a nozzle with an embedded auger and a 2L syringe-like material hopper. The printer was equipped with two extra stepper motors in addition to the three motors driving the gantry in the XY and Z directions. Of the two additional motors, one controls the auger that was embedded in the nozzle to provide a shear force on the concrete through the spinning to achieve shear-thinning and enhance the extrudability of the concrete; the other stepper motor paired with a 1:20 reducer gearbox and drive a linear piston moving linearly to compress the concrete from the material hopper to nozzle through PVC hose (Figure S6, Supporting Information). The rotational speed, direction, torque, and power supply of both stepper motors were numerically controlled through the programmable logic controller and were set to the same parameters for all the printing described in this paper. All 3D-printed structures in this study were fabricated using a nozzle with a diameter of 4.8 mm. This nozzle size was selected to provide an optimal balance between extrusion stability and printing resolution for both DE and DE-free formulations, ensuring consistent and comparable print quality. The 4.8 mm nozzle also enabled the fabrication of structures with sufficient build height to support interfacial bonding and early-stage drving evaluations.

Printing Characterization: The extrudability and shape retainability of the concrete inks were characterized using the 3D printing system. Various diameters of nozzle heads (2, 4.8, 6.8, 11, 16, and 21 mm) were installed on the printing head to assess whether the fresh concrete could be successfully extruded. The extruded material was printed into a straight line with a layer height 1.2 times that of the nozzle diameter, which prevented the nozzle from squeezing the deposited material. The printed lines from different nozzle sizes were then cured in a humidity chamber (RH > 95%) for 24 h. Subsequently, a sharp blade was used to cut the printed lines at different locations, and a micro-camera combined with the image processing tool (Image]) was employed to measure the width and height of the cut cross-section. The material buildability was characterized by printing a 10 cm diameter cylinder structure with a 4.8 mm line width and a 1.8 mm layer height, continuously printing to 111 layers (equivalent to 200 mm) or until failure.

Carbonation: For the CO₂ sequestration and carbonation mechanism study (Figure 5a–i), cylindrical samples (Diameter: 15 mm, Height: 30 mm) were cast and pre-hydrated at room temperature (23 °C) for 24 h. After demolding, each sample was sealed in a 1-gallon airtight bag. Pure humidified CO₂ was injected into the bag every 6 h at ambient pressure,

and relative humidity was maintained at \approx 75% using a saturated NaCl solution. For control samples, pure humid N₂ was used instead of CO₂. The samples were removed from the carbonation bag after various carbonation times (6 h, 1, 2, 3, 4, 5, 6, and 7 days) and stored immediately in a vacuum desiccator until characterization. For the CO₂ uptake tests at various depths (Figure 5j), samples were cast into 10 cm-long plastic tubes (3 cm diameter) with one surface left open to allow undirectional carbonation (see Figure S15, Supporting Information). After 1 day of pre-hydration, the same 7-day carbonation procedure was applied. For the casted solid cube and 3D-printed TPMS structure (Figure 6), carbonation was performed in a custom-built acrylic chamber under identical conditions (pure humidified CO₂ at 1 atm, RH \approx 75%). Both printed and cast specimens were pre-hydrated for 24 h in >99% RH prior to exposure to CO₂, followed by carbonation for 7 days.

Carbonation Characterization: The quantity of absorbed CO₂ was characterized by a thermogravimetric analyzer (TGA-DSC SDT650, TA Instruments). The material was ground and sifted through a No. 20 sieve (ASTM E11 Test Sieve). \approx 10–20 mg of powder was then loaded into an aluminum pan. The furnace was heated from 30 °C to 1000 °C with a ramp rate of 10 °C min⁻¹ under a constant N₂ flow of 100 mL min⁻¹. The derivative thermogravimetry (DTG) curves were then obtained by taking the first derivative of the weight signal with time and plotting it as a function of the temperature. Powder X-ray diffraction (XRD) diagrams were collected using a Rigaku Smartlab high-resolution diffractometer with Cu Ka radiation ($\lambda = 1.5416$ Å, 30 mA, and 40 kV) with a parallel beam setting in the θ -2 θ geometry. The 2 θ range was screened between 20 and 80° with data points collected every 0.05° (2 θ) using a scan speed of 35 s per step. CO₂ and N₂ adsorption-desorption isotherms were collected using a surface area and porosity analyzer (TriStar II Plus-3030, Micromeritics Inc., USA). CO₂ as the adsorbate was performed at 273 K, and N₂ as the adsorbate was completed at 77 K. Prior to the experiment, samples were degassed at 105 °C for 24 h under vacuum. The adsorption-desorption isotherms were evaluated to give the pore size distribution and cumulative volume based on non-local density functional theory (NLDFT) from the absorption isotherm, as well as Brunauer-Emmett-Teller (BET) surface areas.

Image Analysis: SEM micrographs were collected using environmental scanning electron microscopy (FEI Quanta 600 ESEM). TEM micrographs were collected using a JEOL 1400 microscope operated at 120 kV. The TEM was calibrated using a MAGICAL TEM calibration standard.

Sample Preparation for CO₂ Uptake Measurement at Various Depths: To assess CO₂ uptake at different depths, a stepwise drilling approach was implemented on carbonated concrete samples. A concrete sample was cast in a plastic tube (3 cm in diameter, 10 cm in length) and carbonated for 7 days with only the top surface exposed, with the sides sealed using Parafilm to restrict carbonation to a single surface (Step 1). A 3/16" drill bit was first used to collect powder samples from the target depth (Step 2). To minimize cross-contamination, a 1/2" drill bit was then used to clear the surrounding material at the same depth (Step 3). This process was repeated for deeper layers, alternating between the 3/16" and 1/2" drill bits to ensure precise sampling at each designated depth (Step 4). For comparing CO₂ uptake efficiency between the 3D printed TPMS structure and a solid cast cube with the same bounding volume, both structures underwent a 1-day pre-hydration followed by 7-day carbonation in a CO₂ chamber. For Figure 5j, the sampling depth interval was 5 mm. For Figure 6a, the TPMS structure was sampled at 5 mm intervals, and the solid cube was sampled at 10 mm intervals.

 CO_2 Uptake Rate: The CO_2 uptake rate was measured using an automated long-term chamber with a 20 cm collar (8100-104, LI-COR Biosciences), a multiplexer to link the chamber to the gas analyzers (LI-8150, LI-COR Biosciences), and an automated Soil CO_2 flux system to measure CO_2 concentrations (LI-8100A, LI-COR Biosciences). The 3D-printed and cast samples were stored and cured in a humidity chamber (>95%) with pure humid N₂ filled for 24 h before measuring the CO_2 uptake. The samples were introduced into the testing chamber for 5 cycles. In each cycle, the chamber opened with a 45-s pre-purge of fresh air, then closed for a 1 min observation period to measure CO_2 concentration. The 1 min observation period was selected to allow sufficient time for detecting changes in CO_2 concentration while minimizing excessive CO_2 depletion within



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the chamber. Following the observation period, a 45-s post-purge reset the chamber to ambient CO_2 levels, which was essential for maintaining accuracy and consistency across measurements.

Finite Element Analysis (FEA): In the FEA simulation (Abaqus/Standard), the concrete corresponding to solid and TPMS cubes were modeled as linear elastic, isotropic material with the measured Young's modulus of 3.5 GPa and Poisson's ratio of 0.2. The built geometric were imported into Abaqus CAE as STL files and were meshed to solid quadratic tetrahedral elements (C3D10). A mesh refinement study was conducted to verify the accuracy and convergence of the solution. Static analysis was performed for compression. The minimum time step was set to 10–12 to ensure the accuracy.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

Kun-Hao Yu and Shu Yang have filed a provisional patent.

Author Contributions

K.Y. and S.Y. conceived the idea, designed the research, and interpreted the results. K.Y., T.T., and S.N. conducted the experiments, with T.T. providing technical support for the 3D printer. H.C. designed the diamond TPMS structures and Y.Z. Optimized the toolpath for printing. M.A. supervised the design and printing toolpath optimization. K.W., Y.C., P.P., and M.A. offered technical support for the experiments. K.Y., T.T., H.C., Y.Z., S.N., and S.Y. wrote the manuscript, and all authors contributed to revising the manuscript.

Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the text, including the Methods section, and Supporting Information.

Keywords

3D concrete printing, biominerals, carbon capture and storage, diatomaceous earth, triply periodic minimum surfaces

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