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Research Article

Keywords: CO₂ Emission, Portland Cement, Carbon Geocrete, Sustainable Construction Materials, Structural Performance

Posted Date: October 28th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11504308/v1>

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Additional Declarations: The authors declare no competing interests.

**Mechanical and Structural Evaluation of Carbon Geocrete
as an Alternative to Portland Cement Concrete**

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ABSTRACT

The construction industry is a significant contributor to global CO₂ emissions, primarily due to the widespread use of ordinary portland cement (OPC) in concrete production. To address this environmental challenge, this study investigates the mechanical and structural performance of a novel geopolymer concrete (GPC) known as carbon geocrete. This material is developed by activating industrial byproducts engineered to sequester atmospheric CO₂, offering a sustainable and cement-free alternative for construction applications. A comprehensive experimental program was carried out to evaluate the mechanical properties of carbon geocrete—including compressive strength, tensile strength, flexural capacity, and bond strength—through both material-level testing and structural testing of reinforced components. The performance of carbon geocrete was systematically compared to that of conventional OPC concrete to assess its feasibility for standard structural use. The results demonstrate that carbon geocrete meets the mechanical and structural performance requirements for potential application in precast and cast-in-place building elements. The tested specimens exhibited adequate strength and durability characteristics, supporting their potential for use as a full replacement for OPC-based concrete. Overall, the findings highlight carbon geocrete as a viable, alternative to conventional cementitious materials, capable of significantly reducing the carbon footprint of concrete construction. Its successful performance at both component and structure scales underscores its promise for future widespread adoption in the construction industry.

Keywords: CO₂ Emission; Portland Cement; Carbon Geocrete; Sustainable Construction Materials; Structural Performance.

INTRODUCTION

Concrete is the most widely used construction material globally due to its high strength, long-term durability, and cost efficiency (Makul, 2020). It is the second most consumed substance on Earth after water, with global production approaching 30 billion tons annually. In the United States, although wood-frame construction predominates in low-rise residential housing, concrete

remains indispensable in numerous residential and multi-family applications. Beyond traditional uses—such as slab-on-grade floors, footings, and basement or foundation walls (Data, 2001; Jellen and Memari, 2019) — concrete is increasingly used in prefabricated wall and floor systems, including insulated concrete forms (ICFs) and precast insulated foundation panels such as Superior Walls systems (ACS, 2025), which provide enhanced energy efficiency, moisture resistance, and long-term structural reliability in residential and light-commercial buildings (Kosmatka et al., 2011).

Furthermore, the growing adoption of 3D concrete printing has introduced new possibilities for rapid, low-cost, and sustainable home construction, with several projects demonstrating its feasibility for single- and multi-family dwellings (Buswell et al., 2018; Wolfs et al., 2019). Collectively, these advancements illustrate that concrete plays a crucial role not only in conventional foundation systems but also in modern residential building envelopes and construction technologies.

Although concrete structures offer exceptional strength and durability, their production imposes substantial environmental burdens, including high energy consumption, elevated greenhouse gas emissions, and depletion of natural resources (Habert et al., 2020). The cement manufacturing process alone accounts for nearly 8% of global anthropogenic CO₂ emissions, mainly due to the calcination of limestone and fossil fuel combustion in kilns.

To address these challenges, researchers have explored incorporating waste-derived materials—such as recycled glass and reclaimed concrete aggregates—as partial replacements in concrete mixtures (Mohajerani et al., 2020; Vishwakarma and Ramachandran, 2018). This approach not only diverts industrial and municipal waste from landfills but also reduces the ecological footprint of construction materials. Consequently, the integration of waste by-products into concrete has gained recognition as a practical and sustainable strategy to address the environmental challenges associated with portland cement production (Gopinath et al., 2020).

Among the most promising waste-derived innovations are alkali-activated binders or geopolymers (GPCs), which replace ordinary portland cement (OPC) entirely with industrial by-products such as fly ash (FA) and ground granulated blast-furnace slag (GGBFS) (Palomo et al., 1999; Provis and Van Deventer, 2014). When activated with alkaline solutions such as sodium hydroxide and sodium silicate, these precursors undergo polymerization to form an amorphous aluminosilicate network distinct from the calcium–silicate–hydrate gel characteristic of OPC systems (Davidovits, 2015; Meyer, 2009). The resulting materials exhibit significant environmental advantages: geopolymer binder production consumes approximately 40% less energy and emits up to 80–90% less CO₂ than conventional cement manufacturing (McLellan et al., 2011; Habert and Ouellet-Plamondon, 2016). The use of these binders therefore offers a dual benefit—reducing carbon emissions and reusing industrial waste materials (Mikulčić et al., 2016). Moreover, geopolymer technology supports the development of low-carbon housing solutions, particularly in regions seeking to combine energy-efficient construction with climate resilience and reduced lifecycle emissions.

Beyond environmental performance, fly ash and slag-based geopolymer concretes have demonstrated mechanical properties comparable to those of OPC concrete. Optimized geopolymer mixes commonly achieve 28-day compressive strengths of 40–60 MPa (Nath and Sarker, 2014), with the inclusion of GGBFS improving early-age strength and enabling ambient curing (Bernal et al., 2012; Ismail et al., 2014). Their tensile and flexural strengths typically range from 3 to 5 MPa and 7 to 9 MPa, respectively—values that align closely with structural-grade OPC concretes (Sarker et al., 2013; Yellaiah et al., 2018). The elastic modulus, typically between 20 and 30 GPa, also remains within the expected range for reinforced concrete design (Thomas and Peethamparan, 2015; Nath and Sarker, 2017). These findings confirm that design relationships used for OPC concrete can be adapted for geopolymer systems with appropriate calibration.

At the structural scale, experimental investigations on reinforced geopolymer concrete beams, columns, and bond behavior have confirmed that GPC members can achieve similar load capacity, stiffness, ductility, and cracking behavior as their OPC counterparts (Shaikh and Vimonsatit, 2015; Nath et al., 2018; Ojha et al., 2023). Studies on residential-scale elements—such as wall panels and slab systems—have also indicated the feasibility of geopolymer concretes for prefabricated housing and modular construction (Ngo et al., 2021). The compatibility of geopolymer mixtures with automated and additive manufacturing techniques strengthens their potential role in next-generation residential construction, particularly in the context of 3D-printed concrete housing (Buswell et al., 2018; Wolfs et al., 2019). In addition to structural reliability, geopolymer concretes exhibit improved fire resistance, lower permeability, and enhanced thermal stability—attributes that are increasingly valued in modern residential building codes emphasizing energy efficiency and resilience (Nath and Sarker, 2015; Kong et al., 2018).

Despite extensive research on fly ash and slag-based geopolymers, most studies focus on material-level properties under controlled conditions, with fewer addressing large-scale reinforced behavior or direct comparison with OPC systems in the context of residential or low-rise building applications. Additionally, only limited studies have investigated geopolymer concretes that actively sequester CO₂ during their production phase. This research gap constrains the practical adoption of cement-free concretes in mainstream housing construction.

The present study addresses this limitation by experimentally evaluating the mechanical and structural behavior of carbon geocrete, a novel geopolymer concrete formulated from carbonated industrial by-products designed to capture and store CO₂. Through comprehensive testing of compressive, tensile, flexural, and bond strength at both material and structural scales, this study benchmarks carbon geocrete against OPC concrete and provides key insights into its suitability for structural and residential construction applications, supporting the transition toward carbon-neutral and carbon-negative building materials for the next generation of sustainable housing.

EXPERIMENTAL PROGRAM

The experimental program was designed to evaluate and compare the mechanical and structural performance of carbon geocrete and OPC concrete through a series of standardized laboratory tests. The study began with a mixture design phase aimed at optimizing the proportions of binders, aggregates, and activators to achieve the desired strength and workability. The OPC mix was proportioned according to conventional design procedures specified in ACI 211 (ACI, 2016), whereas the carbon geocrete mix incorporated geopolymeric binders and alkaline activators derived from industrial by-products to eliminate cement usage and reduce carbon emissions.

Material-level investigations included compressive strength, splitting tensile strength, and flexural tensile strength tests. Structural performance was further evaluated through flexural testing of reinforced beams under center-point loading and bond strength testing to assess the interaction between steel reinforcement and the concrete matrix. This comprehensive program provided a foundation for assessing the feasibility of carbon geocrete as a sustainable alternative to conventional cement-based materials.

Mixture Composition

The carbon geocrete mixture was designed to achieve strength and workability comparable to conventional OPC concrete while completely eliminating portland cement. The mixture proportions were established using a particle packing–based mixture design approach, following the Tarantula Curve concept to optimize aggregate gradation and minimize void content. This method aims to achieve dense packing through a continuous gradation, thereby reducing paste demand while maintaining adequate workability (Funk and Dinger, 2013).

The final carbon geocrete mixture comprised 62% aggregate, 32% paste, and 6% entrained air, yielding a slump of 165 mm—measured in accordance with ASTM C143/C143M (ASTM International, 2023a)—indicating high workability suitable for casting and consolidation. In contrast, the control OPC concrete—proportioned per ACI 211 (ACI, 2016) with a water-to-cement ratio of 0.50—contained 61% aggregate, 32% paste, and 7% entrained air, achieving a slump of 135 mm. Both mixtures were proportioned to attain equivalent 28-day compressive strength, allowing direct performance comparison between the two systems.

In the carbon geocrete mixture, carbonated fly ash (C. FA) served as the primary aluminosilicate precursor and was activated using a blended alkaline solution comprising sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The complete elimination of portland cement substantially reduced CO_2 emissions while preserving sufficient binder reactivity to ensure proper geopolymerization (Morsy et al., 2014). The detailed mixture proportions for both concretes are summarized in Table 1, highlighting the fundamental compositional differences between the geopolymeric and cementitious systems.

Table 1. Mix Proportions for Carbon Geocrete and OPC Concrete.

Material	Carbon Geocrete (kg/m ³)	OPC Concrete (kg/m ³)
Coarse Aggregate #8 (ASTM C33)	943	831
Fine Aggregate (ASTM C33)	691	923
Portland Cement (Type IL)	—	418
Carbonated Fly Ash (C. FA)	395	—
Sodium Silicate (Na ₂ SiO ₃)	97	—
Sodium hydroxide (NaOH)	37	—
Water	91	209

Compressive Strength

The compressive strength test was performed to evaluate the fundamental mechanical performance of carbon geocrete in comparison with OPC concrete. The procedure followed the specifications of ASTM C39/C39M (ASTM International, 2023b), which defines the determination of compressive strength for cylindrical concrete specimens under axial loading. Cylinders were cast, cured, and tested at designated ages to measure their load-carrying capacity and assess the rate of strength development over time. These results provide critical insight into the hydration and geopolymerization kinetics that govern the mechanical behavior of both materials.

For each curing age—7, 14, and 28 days—three cylindrical specimens of both Carbon Geocrete and OPC concrete were prepared and tested. The measured compressive strengths are summarized in Table 2. At the target age of 28 days, both mixtures achieved comparable compressive strengths of approximately 30 MPa. However, the pattern of strength development differed significantly between the two materials. The OPC concrete exhibited rapid early-age strength gain, increasing from 22.5 MPa at 7 days to 27.8 MPa at 14 days, followed by a modest rise approaching its 28-day strength. In contrast, Carbon Geocrete displayed a delayed but more progressive strength evolution—beginning at 4.5 MPa at 7 days, rising to 17.5 MPa at 14 days, and ultimately reaching 30.6 MPa at 28 days.

This distinct trend, illustrated in Figure 1, underscores the fundamentally different binder development mechanisms in cementitious and geopolymeric systems. Whereas OPC concrete derives its early strength primarily from the hydration of clinker phases, the strength of carbon geocrete is governed by a gradual geopolymerization process that continues beyond the initial curing period. The nearly linear increase in compressive strength observed after 14 days suggests continued long-term polymeric network formation, indicating the potential for superior

mechanical performance and enhanced durability of carbon geocrete compared with conventional OPC concrete over extended curing durations.

Table 2. Compressive Strength Results for Carbon Geocrete and OPC Concrete.

Material	Time (Day)	Compressive Strength (MPa)	Std.
Carbon Geocrete	7	4.5	0.1
	14	17.5	0.4
	28	30.6	0.5
OPC Concrete	7	22.5	0.6
	14	27.8	0.5
	28	30.4	0.2

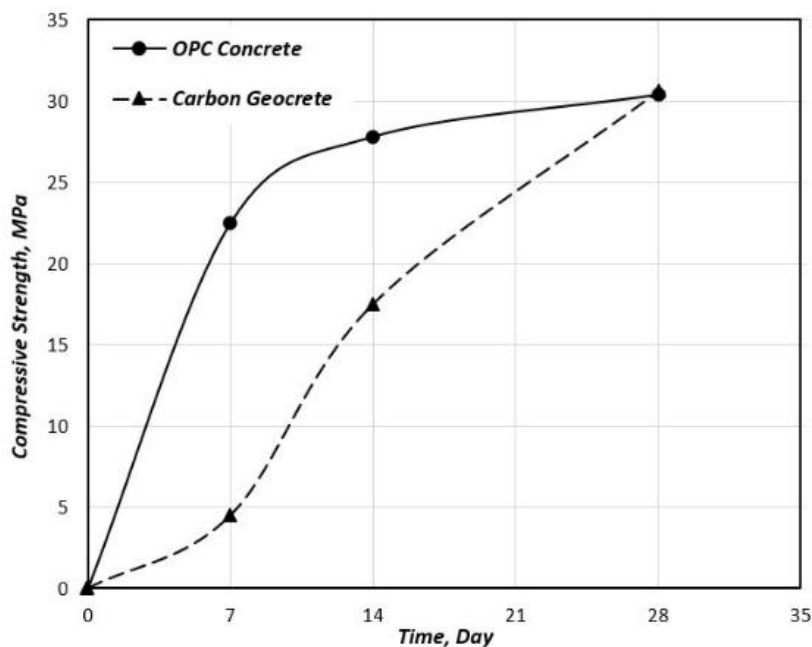


Figure 1. Variation of compressive strength with curing age for carbon geocrete compared with OPC concrete.

Tensile Strength

Tensile strength testing provides essential information about a material's cracking resistance, cohesion, and its ability to transfer stresses between aggregates and binder phases. In this study,

tensile performance was evaluated using two standardized methods: the splitting tensile strength test per ASTM C496/C496M (ASTM International, 2023c) and the flexural tensile strength test per ASTM C78/C78M (ASTM International, 2023d). These tests characterize the indirect and flexural tensile capacities of carbon geocrete and OPC concrete, which are critical for understanding their behavior under cracking and flexural loading in structural applications.

Splitting (or indirect) tensile strength tests were performed on cylindrical specimens following ASTM C496/C496M (ASTM International, 2023c). This test is particularly valuable for estimating the shear resistance of concrete and for determining parameters such as the development length of reinforcement in structural design. Three cylindrical specimens were tested for each material type after 28 days of curing, and the results are presented in Table 3.

Carbon geocrete exhibited an average splitting tensile strength of 3.2 ± 0.1 MPa, slightly higher than that of OPC concrete, which achieved 3.1 ± 0.1 MPa. The results demonstrate that carbon geocrete not only satisfied the requirement of achieving at least 10% of its compressive strength as tensile capacity but also slightly exceeded this threshold, exhibiting higher splitting tensile strength than OPC concrete. These findings confirm that the geopolymeric binder system in carbon geocrete can achieve tensile performance comparable to or exceeding that of conventional cementitious binders, supporting its suitability for structural applications.

Table 3. Splitting Tensile Strength Results for Carbon Geocrete and OPC Concrete.

Material	Specimen	Splitting Tensile Strength (MPa)	Avg. $\pm$ Std.
Carbon Geocrete	CG-1	3.3	3.2 ± 0.1
	CG-2	3.1	
	CG-3	3.0	
OPC Concrete	OPC-1	3.1	3.1 ± 0.1
	OPC-2	3.2	
	OPC-3	2.9	

Flexural tensile strength (or modulus of rupture) tests were conducted on prism specimens according to ASTM C78/C78M (ASTM International, 2023d) to evaluate the tensile capacity of the materials under bending stresses. Three carbon geocrete prisms were tested after 28 days of curing, and the results are summarized in Table 4. For comparison, OPC concrete specimens of the same geometry were tested under identical conditions.

Both carbon geocrete and OPC concrete achieved comparable flexural tensile strengths, with average modulus of rupture of 7.8 ± 0.9 MPa and 7.6 ± 0.8 MPa, respectively. As this test

represents the effective tensile stress developed at the bottom fiber of a beam or a slab under flexural loading, the results confirm that carbon geocrete exhibits flexural tensile performance comparable to or slightly superior to OPC concrete, validating its potential for structural applications where flexural behavior governs performance.

Table 4. Flexural Tensile Strength Test Results for Carbon Geocrete and OPC Concrete.

Material	Specimen	Modulus of Rupture (MPa)	Avg. $\pm$ Std.
Carbon Geocrete	CG-1	8.5	7.8 $\pm$ 0.9
	CG-2	8.4	
	CG-3	6.6	
OPC Concrete	OPC-1	6.8	7.6 $\pm$ 0.8
	OPC-2	7.2	
	OPC-3	8.7	

Flexural Strength

Although no specific standard exists for flexural testing of slender reinforced concrete beams, the present study adopted a center-point loading configuration following the general setup of ASTM C293/C293M (ASTM International, 2023e), which specifies procedures for determining the flexural strength of concrete specimens under center-point loading. In this test, each reinforced beam was simply supported at both ends and subjected to a concentrated load at midspan, allowing for evaluation of the overall moment capacity and flexural behavior of the reinforced members, as illustrated in Figure 2.

Half-scale reinforced concrete beams with dimensions of 50 $\times$ 75 $\times$ 600 mm were prepared using both carbon geocrete and conventional OPC concrete mixtures. Each beam was reinforced with a single #3 longitudinal steel rebar placed at the bottom. The applied midspan load was gradually increased until failure, and the corresponding ultimate moments were calculated based on the measured support span and applied load.

The moment capacities for the reinforced beams are summarized in Table 5, which indicates that the carbon geocrete beams achieved an average moment capacity of 1.5 kN.m, while the OPC concrete beams reached an average of 1.4 kN.m. These results reveal that carbon geocrete reinforced beams provided slightly higher flexural performance than their OPC counterparts, confirming the material's ability to develop effective composite action between the geopolymeric matrix and steel reinforcement. Overall, the flexural testing results demonstrate

that carbon geocrete can serve as a structurally competent and sustainable alternative to OPC concrete in reinforced flexural member.



Figure 2. Center-point loading test on (A) carbon geocrete and (B) OPC concrete slender reinforced beams.

Table 5. Flexural Moment Capacity of Reinforced Carbon Geocrete and OPC Concrete Beams Under Center-Point Loading.

Material	Specimen	Moment Capacity (KN.m)	Avg. $\pm$ Std.
Carbon Geocrete	CG-1	1.73	1.5 $\pm$ 0.2
	CG-2	1.30	
	CG-3	1.55	
OPC Concrete	OPC-1	1.28	1.4 $\pm$ 0.1
	OPC-2	1.57	
	OPC-3	1.46	

Bond Strength

The bond between reinforcing steel and the surrounding concrete is fundamental to the composite action of reinforced concrete members. This bond primarily consists of three mechanisms—chemical adhesion, friction, and mechanical interlocking—each contributing to stress transfer between steel and concrete (Nilson et al., 2010). The relative importance of these mechanisms depends on several factors, including concrete strength, bar surface geometry, casting orientation, bleeding behavior, confining stresses, and the presence of fibers or supplementary materials. Understanding this bond behavior is essential for evaluating the performance and reliability of reinforced concrete systems.

In this study, bond strength was evaluated using the pull-out test in accordance with the principles of ASTM A944 (ASTM International, 2023f), which outlines procedures for determining the bond strength of steel reinforcing bars embedded in concrete beam-end specimens. Each specimen consisted of a #3 steel rebar embedded in a $100 \times 150 \times 300$ mm concrete block prepared from both carbon geocrete and OPC concrete, as illustrated in Figure 3. During testing, a controlled tensile load was applied along the axis of the rebar until bond failure occurred. The maximum pull-out load was recorded and used to calculate the bond strength (u) according to the following equation:

$$u = \frac{P}{\pi d_b L_b}$$

where P is the maximum pull-out load, d_b is the rebar diameter, and L_b is the embedment length. The test system was carefully designed to maintain the applied tensile load parallel to the rebar axis and to prevent yielding of the steel reinforcement, ensuring that the observed failure corresponded to bond failure rather than bar deformation.

The results, summarized in Table 6, indicate that carbon geocrete specimens achieved an average bond strength of 8.1 MPa, while OPC concrete specimens recorded an average of 7.8 MPa. The slightly higher bond strength of carbon geocrete suggests improved adhesion and interfacial interaction between the geopolymeric binder and steel surface.

The findings demonstrate that carbon geocrete provides bond performance comparable to that of OPC concrete, confirming its suitability for reinforced applications such as beam-column joints and lap splice zones.



Figure 3. Bond strength testing on (A) carbon geocrete and (B) OPC concrete specimens conducted in accordance with ASTM A944 (ASTM International, 2023f).

Table 6. Bond Strength for Reinforcing Steel in Carbon Geocrete and OPC Concrete.

Material	Specimen	Bond Strength (MPa)	Avg. $\pm$ Std.
Carbon Geocrete	CG-1	9.5	8.1 $\pm$ 1.0
	CG-2	7.3	
	CG-3	7.6	
OPC Concrete	OPC-1	8.5	7.8 $\pm$ 0.6
	OPC-2	7.1	
	OPC-3	7.9	

CONCLUSION

This study evaluated the mechanical and structural performance of carbon geocrete, a portland-cement-free concrete, compared with conventional OPC concrete through standardized ASTM tests. Results showed that carbon geocrete achieved comparable properties, reaching a 28-day compressive strength of about 30 MPa. While OPC gained strength rapidly through hydration, carbon geocrete exhibited a gradual, continuous increase governed by geopolymerization, indicating superior long-term performance and durability. It also satisfied the expected tensile-to-compressive strength ratio for structural-grade concrete, confirming an effective binder–aggregate interface within the geopolymeric matrix.

At the structural scale, reinforced carbon geocrete beams demonstrated slightly higher flexural capacity than OPC beams, confirming effective composite action with steel reinforcement. Bond strength testing showed improved adhesion between the geopolymeric binder and steel, attributed to refined interfacial chemistry. Collectively, these results validate that carbon geocrete can be effectively used in reinforced concrete elements without compromising mechanical integrity or bond reliability.

Given the widespread use of reinforced concrete in residential and low-rise buildings, these findings have direct implications for sustainable housing. Replacing conventional cement-based concrete with carbon geocrete maintains structural reliability while reducing the embodied carbon footprint of residential and multi-family structures. This cement-free system supports carbon-neutral construction practices and offers a practical path to lower emissions in the built environment.

By eliminating portland cement and utilizing carbonated fly ash as the main binder, carbon geocrete reduces CO₂ emissions while preserving mechanical competence. These results demonstrate that carbon geocrete is a structurally sound and environmentally responsible

alternative to OPC concrete, enabling low-carbon reinforced concrete construction, especially in residential and light-commercial sectors. Its proven performance at both material and structural scales underscores its potential for reducing the carbon footprint of modern buildings.

Furthermore, beyond conventional cast-in-place and precast applications, the geopolymeric binder system of carbon geocrete presents promising opportunities for adaptation to emerging 3D concrete printing technologies through tailored mix design modifications aimed at achieving printability, buildability, and early-age stability, which could be explored in future research.

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