

Green Geopolymer Concrete (GGC)

[Transforming Industrial Waste into a High-Performance, Low-Carbon Construction Material]

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Abstract

The global construction sector faces an urgent challenge: balancing rapid infrastructure development with the need to drastically reduce carbon emissions, resource consumption, and environmental degradation. Ordinary Portland Cement (OPC), the primary binder used in conventional concrete, is responsible for approximately 8% of global CO₂ emissions, making it one of the most carbon-intensive industrial materials in use today.

This article presents **Green Geopolymer Concrete (GGC)** as a scientifically validated, cement-free alternative developed and tested by the **Fujairah Municipality Construction Materials Research Laboratory (CMRL)**. GGC is produced through the alkaline activation of industrial by-products—including fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica-rich volcanic ash, and recycled aggregates—transforming waste materials into a durable, high-performance construction binder.

Comprehensive laboratory experimentation and pilot-scale trials demonstrate that GGC achieves compressive strengths exceeding **60 MPa**, exhibits superior durability under harsh climatic conditions, reduces CO₂ emissions by up to **80%**, and lowers water consumption by approximately **50%** compared to OPC-based concrete. Beyond material performance, this initiative establishes a structured roadmap for large-scale adoption, regulatory integration, and industry implementation within the United Arab Emirates.

Green Geopolymer Concrete represents not merely a material innovation, but a strategic sustainability solution—bridging scientific research, circular-economy principles, and national climate commitments to redefine the future of construction.

1. Introduction

The United Arab Emirates has emerged as one of the world's most dynamic hubs for urban development, driven by sustained infrastructure investment, rapid population growth, and strategic economic diversification. Large-scale transportation networks, residential developments, industrial zones, and public infrastructure projects continue to reshape the built environment across the Emirates. While this accelerated development plays a critical role in national prosperity and global competitiveness, it also places increasing pressure on natural resources, energy consumption, and environmental systems.

Among all construction materials, concrete remains the most widely used due to its versatility, strength, and economic viability. However, the environmental footprint of conventional concrete is dominated by its primary binder—Ordinary Portland Cement (OPC). Cement manufacturing is an energy-intensive process that requires the large-scale extraction of limestone and other raw materials, high-temperature kiln operations, and fossil-fuel combustion. In addition to direct energy use, the chemical calcination of limestone releases substantial amounts of carbon dioxide, making cement production responsible for approximately 8% of global CO₂ emissions. This environmental burden is further compounded by high water consumption and the generation of industrial waste during material production.

As the UAE advances its commitment to climate action through the **UAE Net Zero 2050 Strategy**, the construction sector faces an urgent responsibility to decouple infrastructure growth from carbon emissions and resource depletion. Achieving this transition requires the adoption of innovative, low-carbon construction materials that meet or exceed the performance, durability, and safety standards of conventional systems. The challenge is not only to reduce emissions, but also to ensure that alternative materials are technically robust, economically viable, and suitable for the region's harsh climatic conditions, including high temperatures, salinity, and humidity.

Green Geopolymer Concrete (GGC) directly addresses these challenges by eliminating cement entirely and replacing it with industrial by-products such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica-rich volcanic ash, and recycled aggregates. Through the process of alkaline activation, these materials are transformed into a dense, high-performance binder, effectively converting industrial waste into a valuable construction resource. This approach simultaneously reduces carbon emissions, conserves natural resources, diverts waste from landfills, and supports circular-economy principles.

In this context, Green Geopolymer Concrete is not merely an alternative construction material, but a strategic innovation that aligns environmental responsibility with engineering performance. By integrating scientific research, sustainability objectives, and practical implementation, GGC offers a viable pathway for the UAE to achieve low-carbon infrastructure development while maintaining its ambitious growth trajectory.

2. Scientific Basis of Green Geopolymer Concrete

Green Geopolymer Concrete is founded on the process of **geopolymerization**, a chemical reaction in which aluminosilicate materials dissolve and re-polymerize under alkaline conditions to form a dense, stable, and durable binding matrix.

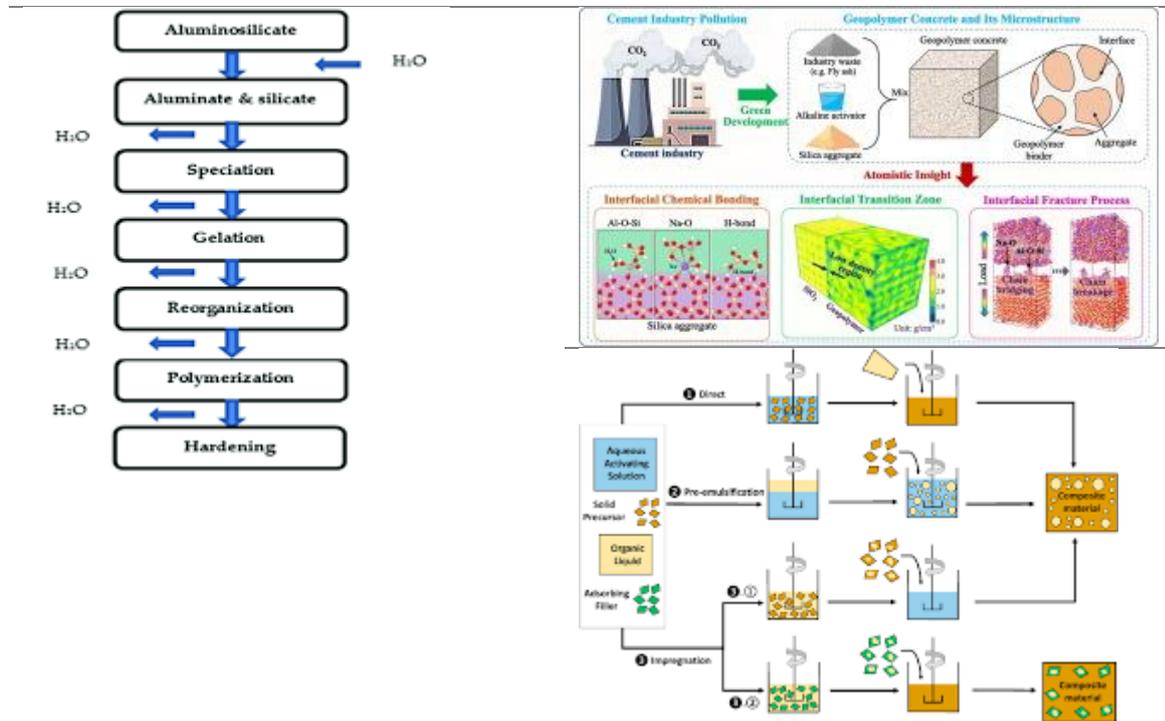


Figure 1: Schematic representation of the geopolymerization process showing alkaline activation of aluminosilicate industrial by-products and formation of a dense geopolymer binder matrix.

2.1 Constituent Materials

The GGC developed at CMRL utilizes locally and regionally available materials, including:

- **Fly Ash** – a silica- and alumina-rich by-product from thermal power generation
- **Ground Granulated Blast Furnace Slag (GGBS)** – a latent hydraulic material from steel manufacturing
- **Silica-rich Volcanic Ash** – naturally abundant in Fujairah’s mountainous geology
- **Recycled Aggregates** – derived from construction and demolition waste
- **Alkaline Activators** – Sodium Hydroxide (NaOH) and Sodium Silicate (Na₂SiO₃)

2.2 Material Advantages

The resulting geopolymer matrix exhibits:

- Low permeability
- High chemical resistance
- Excellent thermal stability
- Reduced shrinkage and micro-cracking

These properties make GGC particularly suitable for the UAE’s high-temperature, high-salinity environment.

3. Environmental and Sustainability Impact

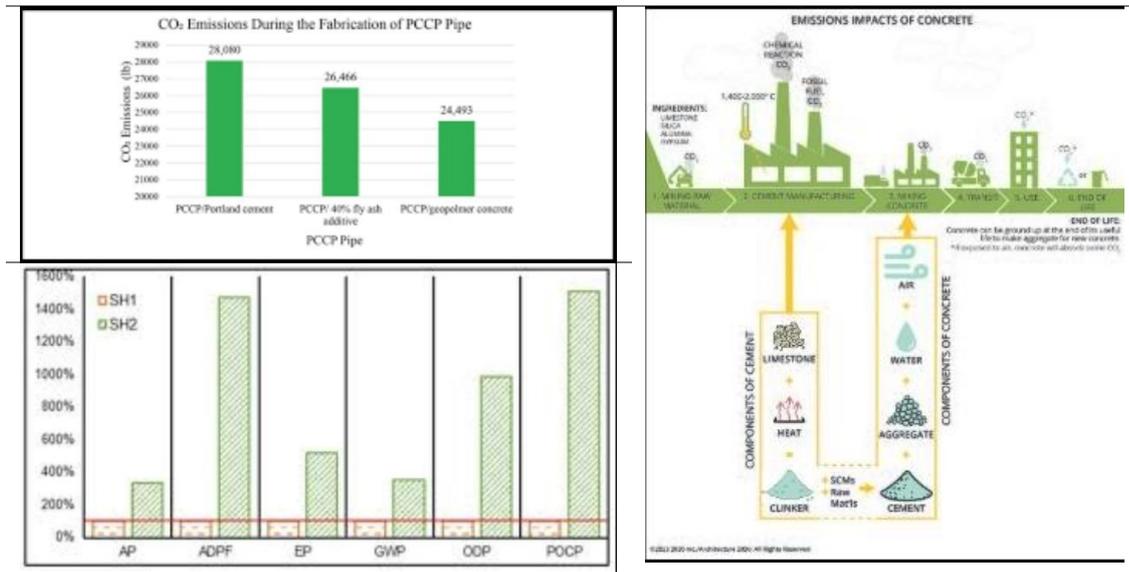


Figure 4: Environmental impact comparison between OPC concrete and Green Geopolymer Concrete, highlighting CO₂ emission reduction and water conservation benefits.

3.1 Carbon Emission Reduction

By eliminating cement entirely, GGC reduces CO₂ emissions by up to **80%**, addressing one of the most critical contributors to climate change in the construction sector.

3.2 Water Conservation

GGC requires approximately **50% less mixing water** than conventional concrete, directly supporting national water-conservation objectives in an arid climate.

3.3 Circular Economy Integration

The use of industrial by-products and recycled aggregates diverts large volumes of waste from landfills, promotes resource efficiency, and supports the UAE’s Circular Economy Policy.

4. Experimental Program and Laboratory Validation

An extensive experimental program was conducted at the **Construction Materials Research Laboratory (CMRL), Fujairah Municipality**, involving multiple trial mix designs with varying proportions of industrial waste materials.

4.1 Testing Methodology

- Workability assessment using slump tests
- Cube compressive strength testing at 1, 3, 7, and 28 days
- Durability evaluation including sulfate resistance, chloride penetration, and water absorption



Figure 2: Laboratory testing program conducted at CMRL, including slump test for workability assessment and compressive strength testing of geopolymer concrete cubes.

4.2 Key Findings

- Compressive strengths exceeding **63 MPa at 28 days**
- Improved early-age strength development
- Superior durability compared to OPC-based concrete
- Stable performance under UAE climatic conditions

These results confirm that GGC not only meets but often surpasses the performance benchmarks of conventional concrete.

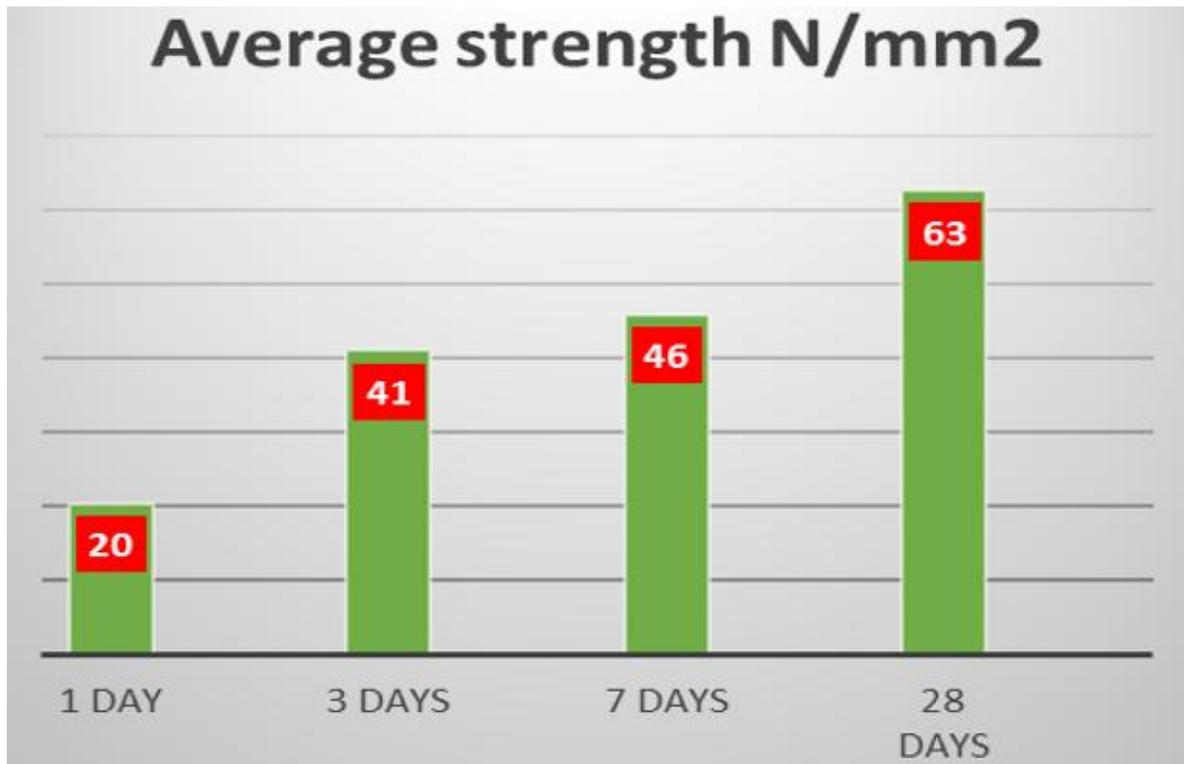


Figure 3: Comparative compressive strength development of Green Geopolymer Concrete (GGC) and Ordinary Portland Cement (OPC) concrete at 1,3,7, 14, and 28 days.

◆ **TABLE 1 — EXPERIMENTAL RESULTS**

PARAMETER	OPC Concrete	Green Geopolymer Concrete
CEMENT CONTENT	High	0%
7-DAY STRENGTH (MPA)	25–30	35–40
28-DAY STRENGTH (MPA)	40–45	> 60
DURABILITY (SULFATE/CHLORIDE)	Moderate	High
WATER PERMEABILITY	Higher	Lower
SUITABILITY FOR UAE CLIMATE	Limited	Excellent

5. Industry Collaboration and Pilot-Scale Implementation

To bridge the gap between laboratory research and real-world application, the initiative partnered with:

- **Grey Matters Consultancy**
- **Gulf Ready Mix Company**

Pilot-scale batching, on-site casting, and field performance monitoring demonstrated:

- Consistent quality during production
- Reduced curing temperature requirements
- Faster setting times
- Reliable structural performance

These outcomes validated GGC's readiness for municipal and infrastructure deployment.



Figure 5: Pilot-scale production and field implementation of Green Geopolymer Concrete in collaboration with ready-mix industry partners.

6. Applications and Use Cases

Green Geopolymer Concrete is suitable for a wide range of applications, including:

- Residential and commercial buildings
- Road pavements and bridges
- Precast concrete elements (blocks, panels, boundary walls)
- Marine and coastal infrastructure
- Municipal non-structural components

Its versatility enables phased adoption across multiple construction sectors.

7. Strategic Implementation Roadmap (2025–2040)

A four-phase roadmap has been established to ensure responsible and scalable adoption:

- **Phase 1 (2025–2026):** Research validation and pilot projects
- **Phase 2 (2027–2029):** Commercial production and municipal integration
- **Phase 3 (2030–2035):** Standardization, certification, and regulatory inclusion
- **Phase 4 (2036–2040):** UAE-wide and GCC-level adoption

This approach balances innovation with risk management, industry readiness, and policy alignment.

8. Policy Alignment and Regulatory Integration

The GGC initiative directly supports:

- UAE Net Zero 2050 Strategy
- Sustainable public procurement frameworks
- Green building regulations and certification systems

It provides a technically sound foundation for updating construction standards to include low-carbon alternatives.

9. Economic and Long-Term Impact

- **Lifecycle cost savings:** 30–40% through reduced maintenance
- **Market potential:** Estimated value exceeding **AED 150 billion by 2040**
- **Infrastructure resilience:** Longer service life and improved durability

These benefits position GGC as both an environmental and economic enabler.

10. Conclusion

Green Geopolymer Concrete represents a transformative advancement in sustainable construction materials. By combining rigorous scientific research, industrial collaboration, and policy alignment, this initiative demonstrates how industrial waste can be converted into a high-performance, low-carbon solution suitable for modern infrastructure demands.

Through this work, **Fujairah Municipality** exemplifies how public-sector leadership can drive innovation, accelerate sustainability, and contribute meaningfully to global climate objectives. Green Geopolymer Concrete is not merely an alternative to cement—it is a cornerstone for the future of responsible construction.

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