



Investigation on Strength and Durability of Geopolymer Concrete

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ABSTRACT

Geopolymer Concrete (GPC) is an environmentally sustainable alternative to conventional cement-based concrete, offering a promising solution to reduce carbon emissions associated with cement production. It is synthesized using industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBFS), which are activated by alkaline solutions to form aluminosilicate-based binding systems. This study focuses on the development of a high-strength, ambient cured, modified GPC suitable for *in situ* structural applications. The experiments involved optimizing mix proportions by incorporating industrial by-products and enhancing their performance characteristics. The mechanical properties, including compressive strength, and tensile strength, were systematically evaluated, demonstrating significant improvements with the inclusion of GGBFS and fly ash. Additionally, durability studies confirmed superior resistance of the modified GPC to acid attack, fire exposure, and thermal shock, with minimal strength degradation. The findings establish modified GPC as a viable, eco-friendly alternative to conventional concrete, ensuring high strength and durability without the need for elevated-temperature curing, making it highly suitable for sustainable construction practices.

Keywords: Fly ash; Ground granulated blast furnace slag; Geopolymer concrete; Mechanical properties; Durability studies; Ambient curing

1. INTRODUCTION

Concrete is one of the most widely used construction materials due to its versatility, durability, fire resistance, and strength. However, conventional concrete relies on Ordinary Portland Cement (OPC) as a binder, the production of which significantly contributes to environmental pollution. The cement industry accounts for nearly 7% of global carbon dioxide (CO₂) emissions, with approximately 900 kg of CO₂ released per ton of cement produced. These emissions result from both the chemical breakdown of limestone and the combustion of fossil fuels in cement kilns. Furthermore, the unsustainable extraction of limestone for cement production has led to severe environmental degradation, including deforestation and landscape depletion (Davidovits, 1994).

To address these concerns, alternative binding materials such as Geopolymer Concrete (GPC) have been explored. It is a sustainable, eco-friendly construction material with superior mechanical properties and durability. By utilizing industrial by-products such as fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) as binding agents, GPC eliminates the need for cement, reducing carbon emissions and promoting sustainable construction practices (Duxson *et al.* 2007). Geopolymers are inorganic aluminosilicate polymers

synthesized through the reaction of silicon and aluminum in a highly alkaline environment. The concept of geopolymers was introduced by Joseph Davidovits in 1978, who proposed that the polymerization of aluminosilicate source materials in the presence of an alkaline activator could produce a cementitious binder. This reaction leads to the formation of a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds, which exhibit excellent mechanical and chemical stability (Mohammad *et al.* 2024).

The primary ingredients of geopolymers include aluminosilicate source materials such as fly ash, GGBFS, and metakaolin. These materials react with alkaline activators such as NaOH and sodium silicate (Na₂SiO₃) to form a geopolymeric gel that binds aggregates, similar to cement in conventional concrete (Hardjito and Rangan, 2005).

The fresh properties of GPC include workability, setting time, and flowability. The workability of GPC depends on the concentration and type of alkaline activator, the fineness of the raw materials, and the curing conditions. Unlike OPC concrete, which undergoes hydration, GPC undergoes polymerization, leading to a different setting behavior. The setting time of GPC is influenced by factors such as

the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio and the molarity of the activator solution (Palomo *et al.* 1999). Higher concentrations of NaOH improve early-age strength but reduce workability. Superplasticizers are often used to enhance the flowability of GPC mixes (Van *et al.* 2007).

The mechanical performance of GPC is comparable to or even superior to that of OPC concrete. Compressive strength is significantly influenced by the type and proportion of aluminosilicate materials used. The inclusion of GGBFS improves strength development, allowing ambient curing instead of heat curing (Malkawi, 2023). Splitting tensile strength and flexural strength of GPC are also enhanced by fiber reinforcement, which improves crack resistance and ductility (Nath and Sarker, 2014). Studies have shown that GPC can achieve early-age compressive strength exceeding 40 MPa within 24 hours of casting, making it a viable alternative for rapid construction applications (Kong and Sanjayan, 2008).

Geopolymer concrete exhibits excellent resistance to chemical attacks, high temperatures, and sulfate exposure. Since it does not contain calcium hydroxide ($\text{Ca}(\text{OH})_2$), which is susceptible to acid attack, GPC has superior durability in aggressive environments. Studies have demonstrated that GPC can resist pH levels as low as 3.0 without significant strength loss (Fernández and Palomo, 2005). Additionally, its resistance to sulfate attack makes it an ideal material for marine and wastewater structures (Lie *et al.* 2017). Thermal stability tests show that GPC retains over 90% of its strength even after exposure to 800°C, making it highly fire-resistant (Elzokra *et al.* 2020).

Structural elements made from GPC, such as beams and columns, exhibit comparable load-carrying capacities to conventional concrete structures. Experimental studies on geopolymer concrete beams have shown that they demonstrate enhanced flexural and shear strength due to improved interfacial bonding and fiber reinforcement (Osama *et al.* 2023). Load-deflection behavior, moment-curvature relationships, and ductility factors indicate that GPC beams perform well under static and dynamic loads. Additionally, finite element analysis (FEA) has validated the structural performance of GPC through computational simulations, showing close agreement with experimental results (Zhao *et al.* 2024).

Microstructural analysis of GPC provides insights into the polymerization mechanism and material integrity. Scanning electron microscopy (SEM) studies reveal that GPC has a dense matrix with fewer microcracks compared to OPC concrete. The presence of unreacted fly ash or GGBFS particles, along with the formation of geopolymeric gel, contributes to its superior mechanical performance (Luo *et al.* 2021). X-ray

diffraction (XRD) analysis is used to confirm the formation of aluminosilicate gel (Fazli *et al.* 2014).

The primary aim of this study is to develop and evaluate the performance of geopolymer concrete made with fly ash and GGBFS under various conditions. The study focuses on assessing fresh properties such as workability, setting time, and flowability under different mix proportions and alkaline activator concentrations. The study also aims to optimize the mix design for achieving superior mechanical and durability properties.

2. MATERIALS AND TEST METHODS

The GPC specimens were prepared using fly ash, GGBFS, NaOH, Na_2SiO_3 , fine and coarse aggregates, and water.

2.1 Mix Proportions

The mix proportions for geopolymer concrete presents six different mixtures with varying percentages of fly ash and GGBFS as binders. The replacement levels of fly ash with GGBFS range from 0% to 50% in increments of 10%, while maintaining a constant binder content of 400 kg/m³. The alkaline activator solution was prepared with a NaOH to Na_2SiO_3 ratio of 1:2, and the solution-to-binder ratio was fixed at 0.40 for all mixes to ensure consistency in workability and strength development. Table 1 shows the mix proportions of concrete mixes.

For each mix, the quantity of NaOH and Na_2SiO_3 remains constant at 53.3 kg/m³ and 106.7 kg/m³, respectively, ensuring uniform activation of the binder system. Fine and coarse aggregates were kept at 650 kg/m³ and 1250 kg/m³, respectively, to maintain adequate packing density and strength. A small amount of water (20 kg/m³) was included to aid in proper mixing. This experimental mix design aims to analyze the effect of increasing GGBFS content on the mechanical properties and durability of geopolymer concrete. Higher GGBFS content typically enhances early strength and durability due to its superior reactivity compared to fly ash.

2.2 Preparation of Concrete

The preparation of geopolymer concrete begins with procuring and measuring all required materials accurately. The primary components include fly ash and GGBFS as binders, fine and coarse aggregates, and an alkaline activator solution consisting of NaOH and Na_2SiO_3 . The alkaline solution was prepared at least 24 hours in advance to ensure complete dissolution of NaOH pellets.

The mixing process was carried out using a pan mixer to ensure uniform blending. First, the fine and coarse aggregates were added to the pan mixer and dry-

mixed for about 30 s. Next, the binders (fly ash and GGBFS) were introduced and mixed for 1–2 minutes to achieve a homogeneous dry blend. The alkaline activator solution was then gradually poured into the running mixer, allowing proper dispersion. The mixing continues

for another 2–3 minutes until the paste coats all aggregates uniformly. If required, a small amount of water is added to enhance workability, followed by another 2 minutes of mixing.

Table 1. Mix proportions of geopolymer concrete with fly ash and GGBFS (kg/m³)

Mix ID	Fly Ash (%)	GGBFS (%)	Binder	NaOH	Na ₂ SiO ₃	Fine Aggregate	Coarse Aggregate	Water
M1	100	0	400	53.3	106.7	650	1250	20
M2	90	10	400	53.3	106.7	650	1250	20
M3	80	20	400	53.3	106.7	650	1250	20
M4	70	30	400	53.3	106.7	650	1250	20
M5	60	40	400	53.3	106.7	650	1250	20
M6	50	50	400	53.3	106.7	650	1250	20

Once the mixing is complete, the fresh geopolymer concrete was placed into pre-oiled molds of standard cube, cylinder, or prism shapes. The concrete was placed in layers, with each layer being compacted using a vibrating table or manually tamped with a rod to remove trapped air and ensure proper filling of the mold. The top surface was then leveled using a trowel to achieve a smooth and uniform finish. Curing plays a vital role in geopolymer concrete as it influences the polymerization process and strength development. The specimens were ambient-cured (covered with plastic sheets to prevent moisture loss) /heat-cured at 60–80°C for 24 hours in an oven to accelerate the reaction. After curing, the specimens were demolded and stored under controlled conditions for further testing at different ages, such as 7, 14, or 28 days, to evaluate mechanical and durability properties.

3. RESULTS AND DISCUSSION

3.1 Fresh Properties

The setting time of geopolymer concrete is significantly influenced by the ratio of FA to GGBFS. The results show that as GGBFS content increases, both initial and final setting times decrease. Mix M1, which contains 100% fly ash, has the longest setting times (260 min initial, 435 min final) due to the slower reaction rate of fly ash, which primarily depends on silica-alumina polymerization. In contrast, mix M6, with 50% fly ash and 50% GGBFS sets much faster (74 min initial, 250 min final) due to higher calcium content in GGBFS, which reacts more quickly with alkaline activators. This trend indicates that higher GGBFS content accelerates geopolymerization, leading to faster setting and early strength gain, making it suitable for ambient curing applications.

From a practical perspective, mixes with higher fly ash content (M1, M2, M3) offer extended workability,

making them ideal for large structural pours and precast elements requiring heat curing. Conversely, higher GGBFS mixes (M4, M5, M6) are more suitable for applications needing rapid setting and strength gain, such as pavements, repairs, and precast elements under ambient curing. The study highlights the importance of selecting the right binder proportions based on workability, setting time, and strength development to optimize construction efficiency and durability. Table 2 illustrates the fresh properties of geopolymer concrete.

Table 2. Setting time of geopolymer concrete

Mix ID	Fly Ash (%)	GGBFS (%)	Initial Setting Time (minutes)	Final Setting Time (minutes)
M1	100	0	260	435
M2	90	10	220	397
M3	80	20	185	356
M4	70	30	132	329
M5	60	40	105	292
M6	50	50	74	250

Fig. 1 illustrates the workability (slump value in mm) for different geopolymer concrete mixes (M1 to M6) with varying proportions of FA and GGBFS. The trend clearly indicates that as GGBFS content increases, workability decreases. Mix M1, which contains 100% fly ash, exhibits the highest workability (120 mm), whereas Mix M6, with 50% fly ash and 50% GGBFS, shows the lowest workability (80 mm). The error bars in the graph suggest minor variations in the measurements, ensuring the reliability of results.

The higher workability of M1 and M2 can be attributed to the spherical shape and lower reactivity of fly ash particles, which act as lubricants in the mix, reducing internal friction and enhancing flowability. These mixes are suitable for applications requiring high flowability, such as self-compacting concrete or pumped

concrete. However, as the GGBFS content increases in M3 to M6, workability progressively decreases due to higher calcium content and faster reaction rate of GGBFS with the alkaline activator. This rapid geopolymerization leads to early stiffening, reducing slump values and making placement more challenging.

Mixes M4, M5, and M6, which contain higher GGBFS proportions, exhibit lower slump values (80–95 mm), indicating a stiffer mix. This behavior is expected, as GGBFS particles are more angular and reactive, promoting early setting and reducing the time for placement and compaction. Such mixes are ideal for precast applications, rapid-setting repairs, and structural elements requiring high early strength. The inverse relationship between GGBFS content and workability suggests that appropriate adjustments, such as the use of superplasticizers or a higher solution-to-binder ratio, may be required to optimize flowability based on project requirements.

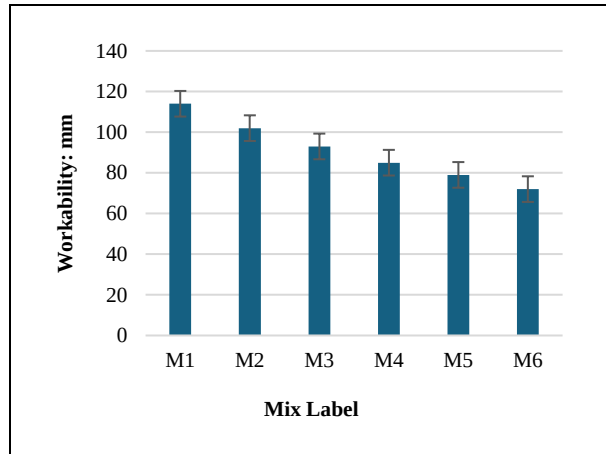


Fig. 1: Workability of geopolymer concrete

3.2 Mechanical Properties

The mechanical properties of geopolymer concrete, including compressive strength, split tensile strength, and flexural strength, are significantly influenced by the ratio of FA to GGBFS. The results show that increasing the GGBFS content enhances the overall strength performance due to its faster reaction rate and higher calcium content, which accelerates the geopolymerization process.

3.2.1 Compressive Strength

Compressive strength is one of the most important mechanical properties of concrete, as it determines its ability to withstand axial loads. The results indicate an increase in compressive strength as the percentage of GGBFS increases in the mix. Mix M1, containing 100% fly ash, has the lowest compressive strength (28.5 MPa) at 28 days, while Mix M6, with 50% fly ash and 50% GGBFS, exhibits the highest strength

(51.8 MPa). This increase in strength can be attributed to the higher reactivity of GGBFS, which leads to faster geopolymerization and formation of additional calcium-silicate-hydrate (C-S-H) gel, contributing to higher strength development (Luo *et al.* 2021; Fazli *et al.* 2014; Manvendra *et al.* 2023; Hajimohammadi *et al.* 2018).

Mixes with higher fly ash content (M1, M2, M3) demonstrate slower strength gain, as fly ash relies on the dissolution of silica and alumina under alkaline activation, which is a gradual process. These mixes require heat curing to accelerate strength gain, making them less effective for ambient curing applications. On the other hand, higher GGBFS mixes (M4, M5, M6) show improved early-age strength, making them suitable for structural applications requiring faster strength development (Fazli *et al.* 2014; Manvendra *et al.* 2023). The optimum mix for high-strength applications is M6 (50% FA, 50% GGBFS), which reaches 51.8 MPa at 28 days, making it comparable to high-strength conventional concrete. Table 3 presents the mechanical properties of geopolymer concrete samples.

Table 3. Mechanical properties of geopolymer concrete under 28 days of ambient curing

Mix ID	Fly Ash (%)	GGBFS (%)	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
M1	100	0	28.5	2.3	3.8
M2	90	10	33.2	2.7	4.2
M3	80	20	37.8	3.1	4.6
M4	70	30	42.5	3.5	5.1
M5	60	40	47.1	3.9	5.6
M6	50	50	51.8	4.2	6

3.2.2 Split Tensile Strength

Split tensile strength is a critical property that determines the concrete's resistance to tensile stresses and cracking under indirect loads. The test results (Fig. 3) indicate that the tensile strength follows a similar trend to compressive strength, increasing with the addition of GGBFS. Mix M1 (100% fly ash) has the lowest tensile strength (2.3 MPa), whereas Mix M6 (50% fly ash, 50% GGBFS) exhibits the highest tensile strength (4.2 MPa).

The improvement in tensile strength with increasing GGBFS content can be attributed to better particle packing, enhanced matrix densification, and improved interfacial bonding between the geopolymer binder and aggregates. Higher fly ash content results in a more porous structure, leading to lower tensile strength and a higher risk of micro-cracks under load. In contrast, higher GGBFS content enhances cohesion and bond strength, reducing crack propagation and improving tensile performance. From a structural perspective, mixes with higher tensile strength (M4, M5, M6) are suitable for load-bearing applications, such as beams, columns,

and structural walls. Lower tensile strength mixes (M1, M2, M3) may require the incorporation of fibers or reinforcement to enhance their crack resistance and durability (Hajimohammadi *et al.* 2018; Keke *et al.* 2019).

3.2.3 Flexural Strength

Flexural strength is a key indicator of a concrete's ability to resist bending forces and is important for pavements, slabs, and bridge decks. The results show that as GGBFS content increases, flexural strength also improves (Fig. 4). Mix M1 (100% FA) has a flexural strength of 3.8 MPa, whereas, the flexural strength of Mix M6 (50% FA, 50% GGBFS) reaches 6.0 MPa, indicating a 58% improvement.

The increase in flexural strength is primarily due to the denser and stronger geopolymer matrix formed by GGBFS, which enhances the concrete's resistance to bending and shear stresses. Fly ash-based mixes tend to exhibit higher ductility but lower flexural strength due to their lower early-age reactivity. In contrast, GGBFS enhances the rigidity and toughness of the mix, making it more resistant to flexural failure. Higher flexural strength makes mixes like M5 and M6 ideal for high-performance pavements, precast concrete elements, and structural members subjected to bending stresses. Lower flexural strength mixes (M1, M2, M3) can be optimized using fibers or reinforcement to improve their load-bearing capacity and crack resistance (Kargari *et al.* 2019).

The mechanical properties of geopolymer concrete are strongly influenced by the proportion of FA and GGBFS. Higher fly ash content results in lower strength and longer setting times, while increasing GGBFS enhances compressive, tensile, and flexural strengths due to its higher calcium content and faster reactivity. The optimum mix for high-strength applications is M6 (50% FA, 50% GGBFS), which achieves 51.8 MPa compressive strength, 4.2 MPa tensile strength, and 6.0 MPa flexural strength. These findings suggest that GGBFS plays a crucial role in enhancing the overall mechanical performance of geopolymer concrete, making it a viable alternative to conventional Portland cement concrete in structural and infrastructure projects.

3.3 Durability

The durability of geopolymer concrete is a key factor in determining its long-term performance under various environmental and chemical conditions. Properties such as water absorption, sorptivity, acid resistance, and sulfate resistance influence the structural integrity and service life of geopolymer concrete. The test results show that increasing GGBFS content enhances durability, while higher FA content results in higher porosity and lower resistance to aggressive environments.

3.3.1 Water Absorption

Water absorption is a vital indicator of the porosity and permeability of geopolymer concrete. A low water absorption value suggests a denser matrix with fewer voids, reducing the risk of moisture ingress, which can lead to freeze-thaw damage, efflorescence, and chemical deterioration. The results show that mix M1 (100% FA) exhibits highest water absorption (3.2%), indicating a more porous structure due to the slow reactivity of fly ash. In contrast, mix M6 (50% FA, 50% GGBFS) has the lowest absorption (1.5%), demonstrating improved compactness and lower permeability.

The improved water resistance in higher GGBFS mixes is attributed to the rapid geopolymerization of GGBFS, which contributes to the formation of a denser, well-packed binder matrix. This makes geopolymer concrete with higher GGBFS content more suitable for water-exposed structures such as marine applications, dams, and bridge decks, where moisture penetration can lead to strength deterioration over time.

Table 4. Durability of GPC

Mix ID	Water Absorption (%)	Sorptivity (mm/min ^{0.5})	Acid Resistance (% Strength Loss in 5% H ₂ SO ₄ , 28 Days)	Sulfate Resistance (% Strength Loss in 5% Na ₂ SO ₄ , 28 Days)
M1	3.2	0.2	9.5	7.8
M2	2.9	0.18	8.2	6.9
M3	2.5	0.15	7	6
M4	2.1	0.13	5.6	4.8
M5	1.8	0.1	4.2	3.9
M6	1.5	0.08	3	3.2

3.3.2 Sorptivity (Capillary Absorption Rate)

Sorptivity measures the rate at which water is absorbed through capillary action, which is a major durability concern in structures exposed to wet-dry cycles. The test results indicate that increasing GGBFS content significantly reduces sorptivity, with mix M1 having the highest sorptivity (0.20 mm/min^{0.5}), while mix M6 shows the lowest value (0.08 mm/min^{0.5}).

A lower sorptivity value indicates lower capillary pores, making the concrete more resistant to moisture ingress, chloride penetration, and sulfate attack. This is particularly important for geopolymer concrete used in underground structures, retaining walls, and sewage treatment plants, where resistance to moisture-induced deterioration is critical. The enhanced impermeability of higher GGBFS mixes makes them ideal for high-durability applications in aggressive environments (Lăzărescu *et al.* 2024).

3.3.3 Acid Resistance

Geopolymer concrete's ability to withstand acidic environments is critical in industrial, marine, and sewage applications, where exposure to sulfuric acid (H_2SO_4) or other aggressive chemicals can degrade concrete over time. The test results reveal that mixes with higher GGBFS content exhibit better acid resistance, as seen in the strength loss trend:

- M1 (100% FA) loses 9.5% strength after 28 days of acid exposure
- M6 (50% FA, 50% GGBFS) experiences only 3.0% strength loss

Higher fly ash content leads to greater alkali leaching, making the mix more susceptible to acid attack. In contrast, higher GGBFS content enhances the chemical stability of the geopolymer matrix, reducing deterioration and maintaining strength. The higher calcium content in GGBFS contributes to a more robust geopolymer structure, improving acid resistance. This makes M5 and M6 mixes more suitable for chemical industries, wastewater treatment plants, and marine infrastructure, where long-term durability in acidic conditions is required.

3.3.4 Sulfate Resistance

Sulfate resistance is a key factor in environments where concrete is exposed to sulfate-rich soils, seawater, or industrial effluents. Results indicate that higher GGBFS content significantly reduces strength loss due to sulfate attack. Mix M1 experiences 7.8% strength loss, while M6 loses only 3.2% after 28 days of exposure to Na_2SO_4 solution. Table 4 presents the durability properties of concrete.

Sulfate attack leads to expansion, cracking, and loss of strength in conventional cement concrete due to ettringite and gypsum formation. However, geopolymer concrete with higher GGBFS content forms a dense and durable calcium-alumino-silicate-hydrate (C-A-S-H) gel, which provides higher resistance to sulfate-induced deterioration. This makes M5 and M6 ideal for foundations, marine structures, and underground constructions that are exposed to aggressive sulfate conditions (Pouhet and Cyr, 2016).

Higher GGBFS content significantly enhances the durability of geopolymer concrete. Mixes with higher fly ash content (M1, M2, M3) exhibit greater porosity, higher water absorption, and lower resistance to acid and sulfate attacks, making them more suitable for non-aggressive environments. On the other hand, mixes with higher GGBFS content (M4, M5, M6) demonstrate superior durability, with lower permeability, reduced sorptivity, and higher resistance to acid and sulfate attack.

Among all mixes, M6 (50% FA, 50% GGBFS) performs the best in terms of durability, making it highly suitable for marine structures, wastewater treatment plants, industrial floors, and sulfate-rich environments. In contrast, M1 (100% FA) may require additional surface protection or curing techniques to improve its durability performance. Choosing the right FA-GGBFS ratio is crucial for designing geopolymer concrete optimized for long-term performance in various environmental conditions (Verma *et al.* 2013).

4. CONCLUSION

This study examined the influence of fly ash and GGBFS proportions on the workability, mechanical properties, and durability of geopolymer concrete. The results indicate that increasing GGBFS content enhances strength and durability while reducing workability. The findings provide valuable insights into optimizing mix designs based on specific structural and environmental requirements.

Future research could explore the impact of different curing methods, activator concentrations, and supplementary materials to further optimize geopolymer concrete for various structural applications. Alternatively, it can focus precursors such as metakaolin, rice husk ash, and volcanic ash to reduce dependency on fly ash and GGBFS, which have limited availability in some regions. Additionally, the reuse of industrial by-products, carbon capture technologies, and life-cycle assessments can further enhance the environmental benefits of geopolymer concrete, making it a more sustainable alternative to Portland cement-based concrete.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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