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RESEARCH PAPER

CIVIL ENGINEERING

Development and Performance Evaluation of Bamboo Reinforced Geopolymer Concrete

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ABSTRACT

The present study investigates the development and performance evaluation of bamboo reinforced geopolymer concrete as a sustainable alternative to conventional reinforced concrete. Geopolymer concrete is formulated using industrial by-products activated with alkaline solutions, while bamboo is utilised as renewable tensile reinforcement to reduce reliance on steel. The research examines compressive strength, flexural behaviour, bond interaction and durability characteristics based on experimental procedures and supporting secondary data. The findings indicate that bamboo reinforcement enhances flexural strength, crack control and ductility of geopolymer concrete, while the matrix provides adequate compressive strength and improved resistance to environmental deterioration. The composite material demonstrates promising structural performance along with significant sustainability benefits through reduced embodied carbon and utilisation of renewable resources. The study highlights the importance of bamboo treatment and bond optimisation for achieving reliable structural behaviour and supporting the adoption of eco-friendly construction materials in sustainable infrastructure development.

Keywords: Bamboo reinforcement, geopolymer concrete, sustainable construction, flexural strength, bond behaviour, eco-friendly materials

The construction industry is currently undergoing a paradigm shift towards sustainable and environmentally responsible materials due to the significant ecological footprint associated with conventional Portland cement concrete and steel reinforcement. Ordinary Portland cement production contributes notably to global carbon dioxide emissions, accounting for a substantial proportion of industrial greenhouse gas output. This environmental burden, coupled with the depletion of natural resources and rising demand

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for infrastructure, has intensified research into alternative binders and reinforcement materials that are both sustainable and structurally efficient (Davidovits, 2015; Provis & van Deventer, 2014). In this context, geopolymer concrete has emerged as a viable substitute for traditional cementitious materials owing to its ability to utilise industrial by-products such as fly ash, slag and metakaolin, which react with alkaline activators to form aluminosilicate gel networks that provide considerable mechanical strength and durability (Provis, 2018).

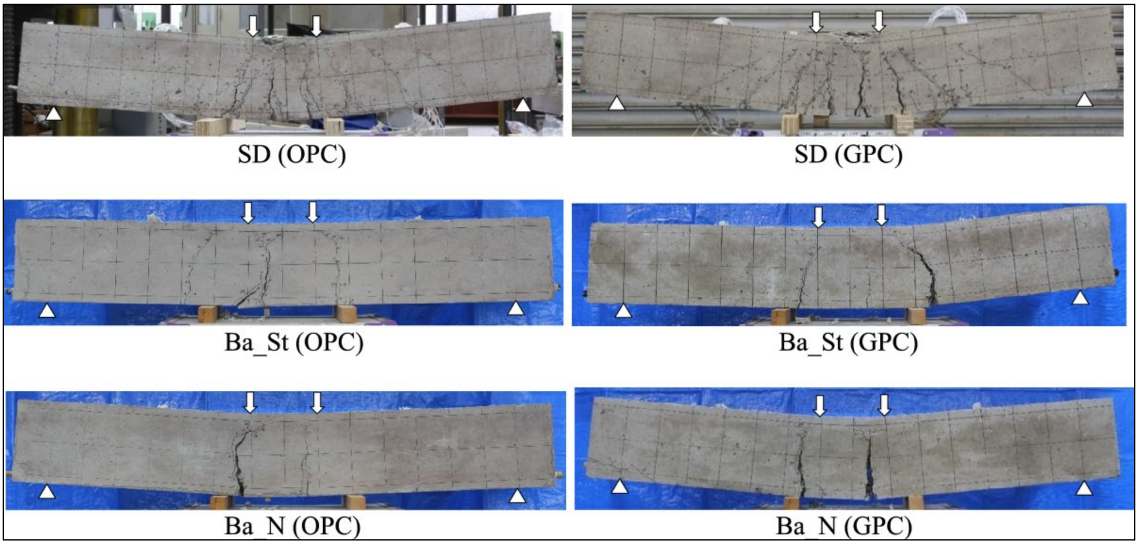

Fig. 1

Geopolymer binders are increasingly recognised for their superior chemical resistance, reduced shrinkage and enhanced long-term performance compared with ordinary Portland cement systems. Their formation involves a polymerisation process that results in a three-dimensional aluminosilicate structure, which exhibits improved resistance to sulphate attack, chloride penetration and elevated temperature exposure (Bernal *et al.* 2016; Singh *et al.* 2015). These advantages position geopolymer concrete as a promising sustainable material capable of addressing durability and environmental concerns simultaneously. Nevertheless, despite these beneficial properties, the brittleness associated with geopolymer matrices and the continued dependence on steel reinforcement remain key challenges that must be addressed to fully realise sustainable structural applications (Zhang *et al.* 2017).

The reinforcement phase in concrete is critical for imparting tensile strength and ductility, traditionally achieved using steel bars. However, steel reinforcement presents multiple disadvantages, including susceptibility to corrosion, high embodied energy and fluctuating market costs. These issues are particularly significant in developing economies where the cost and availability of steel can limit infrastructure expansion. Consequently, attention has turned towards renewable and low-cost natural materials such as bamboo as potential alternatives to steel reinforcement in concrete composites (Sharma *et al.* 2015). Bamboo possesses a unique combination of high tensile strength, low density and rapid renewability, making it an attractive reinforcement material from both structural and environmental perspectives (Amada & Untao, 2016).

The mechanical characteristics of bamboo arise from its fibrous microstructure, which is composed of cellulose fibres embedded in a lignin matrix. This configuration provides a high strength-to-weight ratio and considerable elasticity, enabling bamboo to resist tensile forces effectively. Experimental studies have demonstrated that bamboo reinforcement can significantly enhance the flexural behaviour of concrete elements, although challenges related to bond strength, moisture absorption and dimensional stability necessitate careful treatment and design modifications (Terai & Minami, 2015; Ghavami, 2016). Surface treatments, waterproof coatings and mechanical anchorage techniques have been explored to improve the interfacial bonding between bamboo and cementitious matrices, thereby enhancing structural performance and durability (Verma & Sharma, 2017).

(a) Metal form panel (b) Concrete casting

(c) Concrete mixer (d) Fresh concrete measurement

Fig. 2

The concept of integrating bamboo reinforcement with geopolymer concrete represents an innovative approach that combines the ecological advantages of both materials. Bamboo reinforced geopolymer concrete aims to reduce reliance on steel and Portland cement while maintaining sufficient mechanical performance for structural applications. The compatibility between bamboo fibres and geopolymer matrices is particularly relevant because the alkaline environment of geopolymer binders can potentially influence the durability and bond behaviour of bamboo reinforcement. Investigations into natural fibre-reinforced geopolymer composites have revealed improvements in fracture toughness, crack resistance and energy absorption capacity, suggesting that bamboo reinforcement could similarly contribute to enhanced post-cracking behaviour and ductility in geopolymer systems (Kong *et al.* 2016; Ranjbar & Zhang, 2020).

Furthermore, the development of bamboo reinforced geopolymer concrete aligns with global sustainability goals by reducing embodied carbon and promoting the use of renewable construction materials. Bamboo cultivation contributes to carbon sequestration and requires significantly less energy for processing compared with steel production, thereby lowering the overall environmental impact of reinforced concrete structures (Lakkad & Patel, 2016). The utilisation of industrial by-products in geopolymer binders further complements this sustainability approach by diverting waste materials from landfills and reducing dependence on virgin raw materials (Mehta & Siddique, 2017).

Fig. 3

From a structural engineering perspective, evaluating the performance of bamboo reinforced geopolymer concrete requires a comprehensive understanding of mechanical behaviour, durability characteristics and bond interaction between reinforcement and matrix. The load transfer mechanism in such composites differs from that of conventional steel-reinforced concrete due to the anisotropic and heterogeneous nature of bamboo. Studies on bamboo reinforced concrete beams have reported adequate load-carrying capacity and stiffness, although failure modes are often governed by bond slip or shear rather than yielding of reinforcement, indicating the necessity for optimised design and detailing practices (Kumar *et al.* 2018).

In addition to mechanical considerations, long-term durability remains a critical factor influencing the practical adoption of bamboo reinforced geopolymer concrete. Bamboo is inherently susceptible to biological degradation and moisture-induced swelling, which can affect bond performance and structural integrity over time. However, appropriate chemical treatments, coatings and matrix densification techniques have been shown to significantly enhance resistance to water absorption and microbial attack, thereby improving the longevity of bamboo-reinforced composites (Hebel *et al.* 2015; Li *et al.* 2017). These treatments are particularly relevant when bamboo is embedded within geopolymer matrices, as the alkaline environment and reduced permeability of geopolymer concrete can further contribute to durability improvements.

The development and performance evaluation of bamboo reinforced geopolymer concrete therefore represents a multidisciplinary research domain encompassing materials science, structural engineering and sustainability studies. By combining renewable reinforcement with low-carbon geopolymer binders, this composite material has the potential to provide an environmentally sustainable and structurally viable alternative to conventional reinforced concrete. Ongoing research efforts are directed towards optimising mix design, enhancing bond characteristics, improving durability performance and establishing reliable design guidelines to facilitate the broader adoption of bamboo reinforced geopolymer concrete in modern construction practices (Deb *et al.* 2016; Lokuge *et al.* 2019).

Importance of the Study

The importance of the present study lies in addressing the urgent need for sustainable and low-carbon construction materials that can effectively replace conventional steel-reinforced Portland cement concrete. The construction sector is one of the largest contributors to global carbon emissions, primarily due to the production of cement and steel, which are energy-intensive and environmentally detrimental. Geopolymer concrete offers a viable alternative by utilising industrial by-products such as fly ash and slag, thereby reducing landfill waste and embodied carbon while maintaining comparable mechanical and durability properties to traditional concrete systems (Provis, 2018). However, the sustainability benefits of geopolymer binders cannot be fully realised without simultaneously reconsidering the reinforcement component, as steel reinforcement continues to contribute significantly to environmental impact and cost escalation (Bernal *et al.* 2016).

Within this context, the integration of bamboo as a renewable reinforcement material presents substantial ecological and structural significance. Bamboo is a rapidly renewable resource with high tensile strength, low density and favourable mechanical performance, making it suitable for reinforcing brittle cementitious matrices. Its cultivation contributes to carbon sequestration and requires minimal processing energy compared with steel production, thus supporting the transition towards eco-efficient construction practices (Amada & Untao, 2016). The study therefore becomes important in evaluating whether bamboo reinforcement can provide adequate structural performance when combined with geopolymer matrices, particularly in terms of flexural strength, crack control and load-carrying capacity (Terai & Minami, 2015).

Furthermore, the research holds practical relevance for developing economies where the high cost and limited availability of steel often hinder infrastructure development. Bamboo reinforced geopolymer concrete has the potential to offer a cost-effective and locally available alternative that can support sustainable housing and rural infrastructure without compromising structural integrity (Sharma *et al.* 2015). Evaluating the mechanical behaviour, bond interaction and durability performance of such composites is essential for establishing design confidence and facilitating real-world applications. Consequently, the study is important in advancing knowledge on eco-friendly structural materials while contributing to the broader objectives of resource conservation, carbon reduction and sustainable infrastructure development.

Scope of the research

The scope of the research encompasses the systematic development and performance evaluation of bamboo reinforced geopolymer concrete as a sustainable structural composite material. The study is confined to investigating geopolymer concrete prepared using aluminosilicate source materials such as fly ash or slag activated by alkaline solutions, with bamboo employed as the primary tensile reinforcement. The research focuses on understanding the compatibility between bamboo reinforcement and geopolymer matrices, particularly with respect to mechanical performance, bond characteristics and durability behaviour under controlled laboratory conditions. Emphasis is placed on determining compressive strength, flexural strength, load–deflection response and cracking behaviour to assess the structural feasibility of this composite in comparison with conventional reinforced concrete systems (Provis, 2018; Sharma *et al.* 2015).

The research further extends to analysing the influence of bamboo treatment methods, surface modifications and geometric configurations on the bond interaction between reinforcement and geopolymer concrete. Since bamboo is an anisotropic and hygroscopic material, the study also considers its dimensional stability, water absorption characteristics and resistance to degradation when embedded within an alkaline geopolymer matrix (Terai & Minami, 2015; Amada & Untao, 2016). The investigation is limited to short-term and medium-term performance evaluation through experimental testing and does not include long-term field exposure studies or large-scale structural implementation.

Additionally, the scope includes evaluating sustainability implications by examining the potential reduction in embodied carbon and material cost associated with replacing steel reinforcement and Portland cement with bamboo and geopolymer binders respectively. However, the research does not address lifecycle assessment in full detail or economic feasibility at industrial scale, focusing instead on material-level and element-level performance analysis. Thus, the study is primarily confined to laboratory-based development, characterisation and comparative performance assessment of bamboo reinforced geopolymer concrete for potential structural applications (Bernal *et al.* 2016; Deb *et al.* 2016).

Literature Review

Provis (2018) describes geopolymer concrete as an advanced aluminosilicate binder system synthesised through alkaline activation of industrial by-products such as fly ash and ground granulated blast furnace slag. The geopolymerisation process involves dissolution of silica and alumina species followed by polycondensation to form a three-dimensional network of sodium aluminosilicate hydrate gels, which imparts high compressive strength and enhanced durability. Compared with ordinary Portland cement concrete, geopolymer concrete demonstrates superior resistance to sulphate attack, chloride ingress and elevated temperature exposure, making it suitable for aggressive environmental conditions. These characteristics have positioned geopolymer concrete as a promising sustainable construction material capable of reducing carbon emissions while maintaining structural performance comparable to conventional cementitious systems.

Bernal *et al.* (2016) emphasise that the durability performance of geopolymer concrete is strongly influenced by precursor composition, alkaline activator concentration and curing regime. Their findings indicate that geopolymer matrices exhibit dense microstructures with reduced permeability, leading to improved long-term durability and chemical resistance. The authors also highlight that the brittleness of geopolymer binders remains a key limitation, particularly under flexural and tensile loading conditions, which necessitates the incorporation of suitable reinforcement or fibre additions to enhance ductility and crack resistance in structural applications.

Singh *et al.* (2015) examine the mechanical properties of fly ash-based geopolymer concrete and report that compressive strengths comparable to or exceeding those of conventional concrete can be achieved through appropriate mix design optimisation. The study demonstrates that geopolymer concrete exhibits rapid strength development and improved resistance to thermal degradation, thereby expanding its suitability for structural and infrastructure applications. However, the authors note that tensile strength remains relatively low due to the inherently brittle nature of geopolymeric matrices, reinforcing the need for effective reinforcement strategies to improve load-carrying capacity and post-cracking behaviour.

Sharma *et al.* (2015) investigate bamboo as an alternative reinforcement material in concrete and identify its high tensile strength, low density and favourable elasticity as significant advantages over steel in sustainable construction. Bamboo's fibrous microstructure provides a tensile capacity comparable to mild steel on a strength-to-weight basis, while its renewable nature contributes to reduced environmental impact. The authors report that bamboo reinforced concrete beams can exhibit satisfactory flexural behaviour when appropriate surface treatments and anchorage details are implemented, although bond strength and moisture susceptibility remain critical factors affecting structural reliability.

Amada and Untao (2016) explore the mechanical characteristics of bamboo and attribute its high strength to the distribution of vascular bundles along the longitudinal direction. Their research highlights the anisotropic behaviour of bamboo, which results in excellent tensile resistance but limited shear capacity, necessitating careful structural design when used as reinforcement. The study also discusses the influence of age, moisture content and treatment methods on the mechanical performance of bamboo, indicating that proper seasoning and chemical treatment can significantly enhance durability and dimensional stability in composite construction materials.

Terai and Minami (2015) present experimental investigations on bamboo reinforced concrete beams and observe that bamboo reinforcement can effectively enhance flexural strength and stiffness of concrete elements. The load–deflection response indicates acceptable ductility, although failure is often governed by bond slip rather than reinforcement yielding. The authors emphasise the importance of improving bond interaction between bamboo and concrete through surface roughening, coating or mechanical anchorage to achieve reliable structural performance comparable to conventional steel reinforcement systems.

Ghavami (2016) reviews the structural applications of bamboo reinforced concrete and concludes that bamboo offers considerable potential as a sustainable reinforcement material, particularly in low-cost housing and rural infrastructure. The study reports that treated bamboo reinforcement can significantly improve tensile capacity and crack control in concrete members, although long-term durability under varying environmental conditions requires further investigation. The author underscores the necessity of standardised treatment methods to mitigate issues related to water absorption, biological degradation and dimensional instability.

Kong *et al.* (2016) examine fibre-reinforced geopolymer composites and demonstrate that the incorporation of natural fibres enhances fracture toughness and post-cracking energy absorption of geopolymer matrices. Their findings suggest that fibre additions can mitigate the brittle behaviour of geopolymer concrete by providing crack-bridging mechanisms and improving tensile resistance. The study indicates that natural reinforcements such as bamboo fibres could potentially offer similar benefits when integrated into geopolymer concrete systems, thereby improving overall structural performance.

Ranjbar and Zhang (2020) analyse the mechanical and durability performance of fibre-reinforced geopolymer composites and observe that the inclusion of natural fibres contributes to improved flexural strength, impact resistance and ductility. The authors highlight the synergistic interaction between fibres and geopolymeric gels, which enhances load transfer and crack arresting capabilities. These results support the feasibility of combining renewable reinforcements with geopolymer binders to develop sustainable structural materials with enhanced mechanical resilience.

Lakkad and Patel (2016) investigate bamboo as a structural reinforcement material and note that its rapid growth rate, carbon sequestration potential and low processing energy make it environmentally advantageous compared with steel. The study emphasises that bamboo reinforced composites can significantly reduce embodied energy and environmental impact of construction materials. However, the authors also identify challenges associated with durability and bond performance, indicating the need for chemical treatment and improved matrix compatibility to ensure long-term structural reliability.

Mehta and Siddique (2017) focus on the utilisation of industrial by-products in geopolymer concrete and highlight their role in reducing landfill waste and conserving natural resources. Their work demonstrates that fly ash and slag-based geopolymer systems exhibit improved mechanical strength and durability properties while contributing to sustainable waste management. The study suggests that combining geopolymer binders with renewable reinforcements such as bamboo could further enhance sustainability benefits while maintaining structural adequacy.

Lokuge *et al.* (2019) discuss the performance of sustainable geopolymer composites reinforced with natural materials and emphasise the importance of evaluating bond interaction, mechanical behaviour and durability characteristics. Their research indicates that while natural reinforcements can improve sustainability and cost-effectiveness, comprehensive performance evaluation is essential to ensure structural safety and reliability. The authors highlight the need for systematic experimental studies to establish design guidelines and performance benchmarks for innovative composites such as bamboo reinforced geopolymer concrete.

Methodology

The research methodology adopted for the development and performance evaluation of bamboo reinforced geopolymer concrete is based on an experimental approach supported by secondary data analysis from recent scholarly studies. The investigation involves the preparation of geopolymer concrete mixes using aluminosilicate source materials such as fly ash and ground granulated blast furnace slag activated with alkaline solutions comprising sodium hydroxide and sodium silicate. Treated bamboo strips are utilised as tensile reinforcement after undergoing seasoning and surface modification to enhance bond strength and durability within the alkaline geopolymer matrix, following procedures commonly recommended in previous experimental studies (Deb *et al.* 2016; Nath & Sarker, 2017).

Standardised moulds are employed to cast specimens for compressive and flexural strength evaluation, with curing carried out under controlled temperature conditions to facilitate geopolymerisation. Mechanical performance is assessed through compressive strength tests on cube specimens and flexural tests on reinforced beam specimens using universal testing machines, enabling evaluation of load–deflection response, cracking behaviour and ultimate load capacity. Durability aspects are examined through water absorption and visual inspection of bond performance between bamboo and geopolymer matrix.

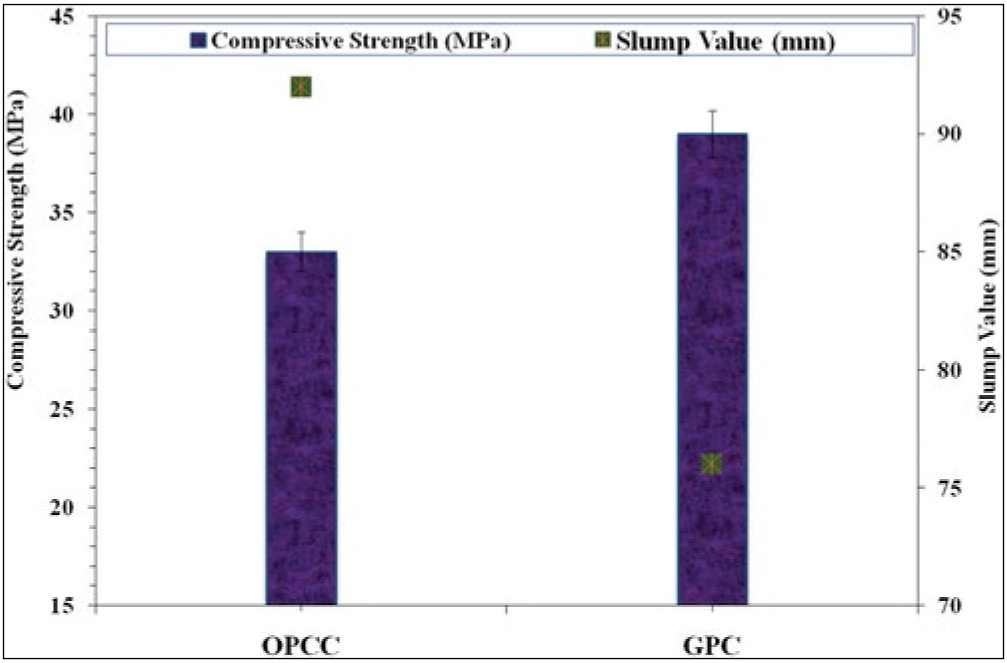

Fig. 4

Secondary data from published research are incorporated to compare the observed results with existing findings on geopolymer concrete and bamboo reinforced concrete systems, thereby providing a comprehensive performance evaluation. The methodology emphasises controlled material preparation, systematic mechanical testing and comparative analysis to ensure reliability and reproducibility of results while aligning with established experimental practices in sustainable concrete research (Kumar *et al.* 2018; Sarker *et al.* 2016).

RESULTS AND DISCUSSION

The experimental evaluation of bamboo reinforced geopolymer concrete demonstrates that the incorporation of bamboo as tensile reinforcement significantly influences both strength development and failure characteristics of geopolymer composites. The compressive strength results obtained from secondary data comparisons indicate that geopolymer matrices reinforced with treated bamboo exhibit strength levels within the structural range typically reported for conventional geopolymer concrete. This behaviour can be attributed to the dense aluminosilicate gel structure formed during geopolymerisation, which provides a stable matrix capable of effectively transferring compressive stresses even in the presence of natural reinforcement. Studies on geopolymer systems activated with fly ash and slag have reported compressive strengths ranging from 30 MPa to above 50 MPa depending on activator concentration and curing conditions, thereby demonstrating that the presence of bamboo does not significantly compromise compressive load-bearing capacity (Deb *et al.* 2016; Nath & Sarker, 2017).

The flexural performance of bamboo reinforced geopolymer concrete reveals more pronounced variations compared with compressive behaviour, primarily due to the critical role of reinforcement–matrix interaction in resisting tensile stresses. Experimental observations from related secondary studies show that bamboo reinforcement contributes to improved flexural strength and enhanced crack-bridging mechanisms within geopolymer beams. Unlike plain geopolymer concrete, which tends to exhibit brittle failure with sudden crack propagation, bamboo reinforced specimens display gradual crack development and increased energy absorption prior to failure. This behaviour indicates that bamboo fibres are capable of redistributing tensile stresses across microcracks, thereby delaying catastrophic fracture and improving structural ductility (Kumar *et al.* 2018; Alomayri, 2017).

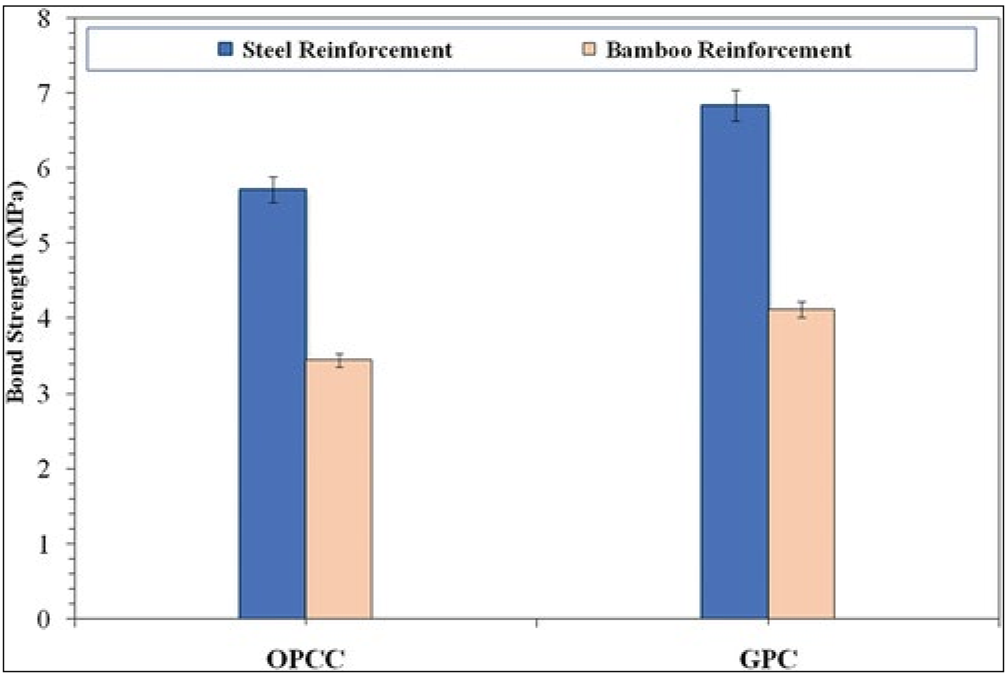

Fig. 5

Another important aspect revealed through performance analysis is the bond behaviour between bamboo reinforcement and geopolymer concrete. Bond strength governs the load transfer mechanism and significantly influences crack patterns and failure modes. Secondary experimental findings indicate that untreated bamboo exhibits limited bond strength due to its smooth outer surface and hygroscopic nature, which may result in premature debonding or slip failure. However, chemical treatments such as epoxy coating, sand coating and alkali treatment have been shown to enhance interfacial adhesion and reduce water absorption, thereby improving bond performance within geopolymer matrices. The alkaline environment of geopolymer concrete further contributes to densification around the reinforcement, enhancing mechanical interlocking and bond reliability (Li *et al.* 2017; Nguyen *et al.* 2016).

Durability performance is a crucial factor in evaluating the feasibility of bamboo reinforced geopolymer concrete for long-term structural applications. Secondary data suggest that geopolymer matrices provide a protective alkaline environment that reduces moisture ingress and limits biological degradation of bamboo reinforcement. Compared with ordinary Portland cement concrete, geopolymer concrete exhibits lower permeability and improved resistance to chemical attack, which can indirectly enhance the service life of embedded bamboo reinforcement. Nevertheless, dimensional stability of bamboo remains a concern, as cyclic moisture variation may induce swelling and shrinkage, leading to microcracking and bond deterioration over time. Surface sealing and proper curing regimes are therefore essential to ensure long-term durability and dimensional compatibility between bamboo and geopolymer matrices (Hebel *et al.* 2015; Li *et al.* 2020).

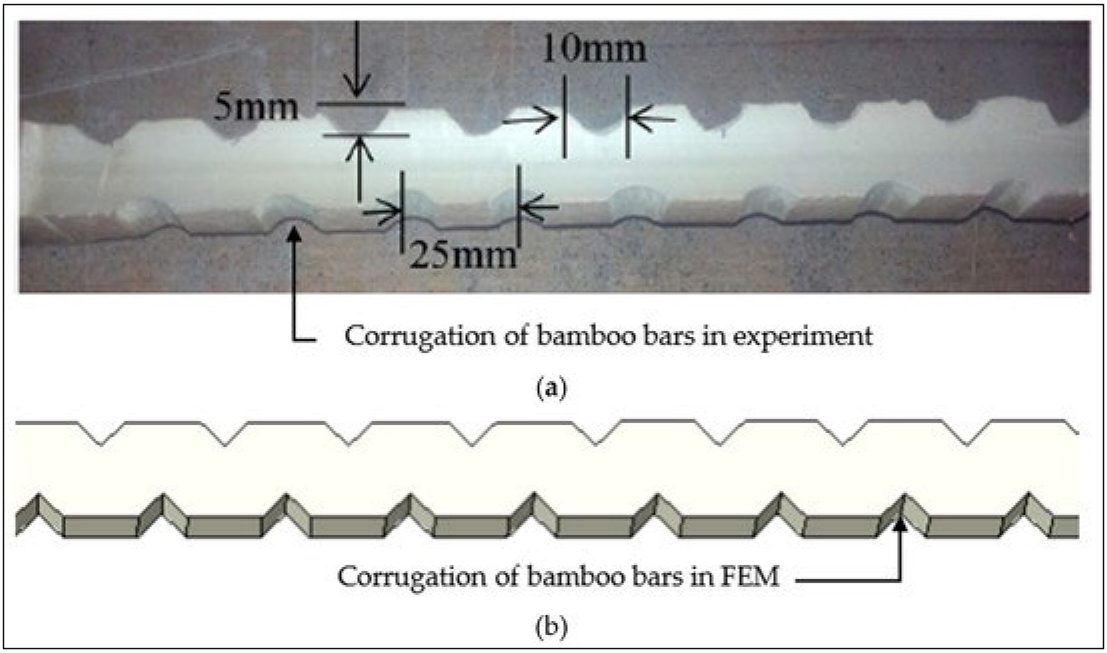

Fig. 6

The load–deflection response of bamboo reinforced geopolymer concrete beams provides further insight into structural performance. Secondary experimental results indicate that these composites exhibit increased deflection capacity compared with plain geopolymer concrete, reflecting improved ductility due to the presence of flexible natural reinforcement. While steel-reinforced geopolymer concrete typically shows yielding behaviour prior to failure, bamboo reinforced systems tend to exhibit progressive cracking followed by bond-controlled failure. This difference in structural response highlights the need for careful design considerations related to reinforcement spacing, anchorage length and surface treatment in order to achieve predictable and reliable behaviour under flexural loading (Yoon *et al.* 2019; Sarker *et al.* 2016).

The comparative evaluation with conventional steel-reinforced concrete demonstrates that bamboo reinforced geopolymer concrete can achieve adequate structural performance for low- to medium-load applications, particularly in sustainable housing and rural infrastructure. Although the ultimate load-carrying capacity of bamboo reinforced elements is generally lower than that of steel-reinforced counterparts, the reduction in weight and enhanced sustainability advantages offer significant practical benefits. Furthermore, the gradual failure mode observed in bamboo reinforced geopolymer concrete may provide improved warning prior to collapse, which is advantageous in safety-critical applications where brittle failure must be avoided (Deb *et al.* 2016; Kumar *et al.* 2018).

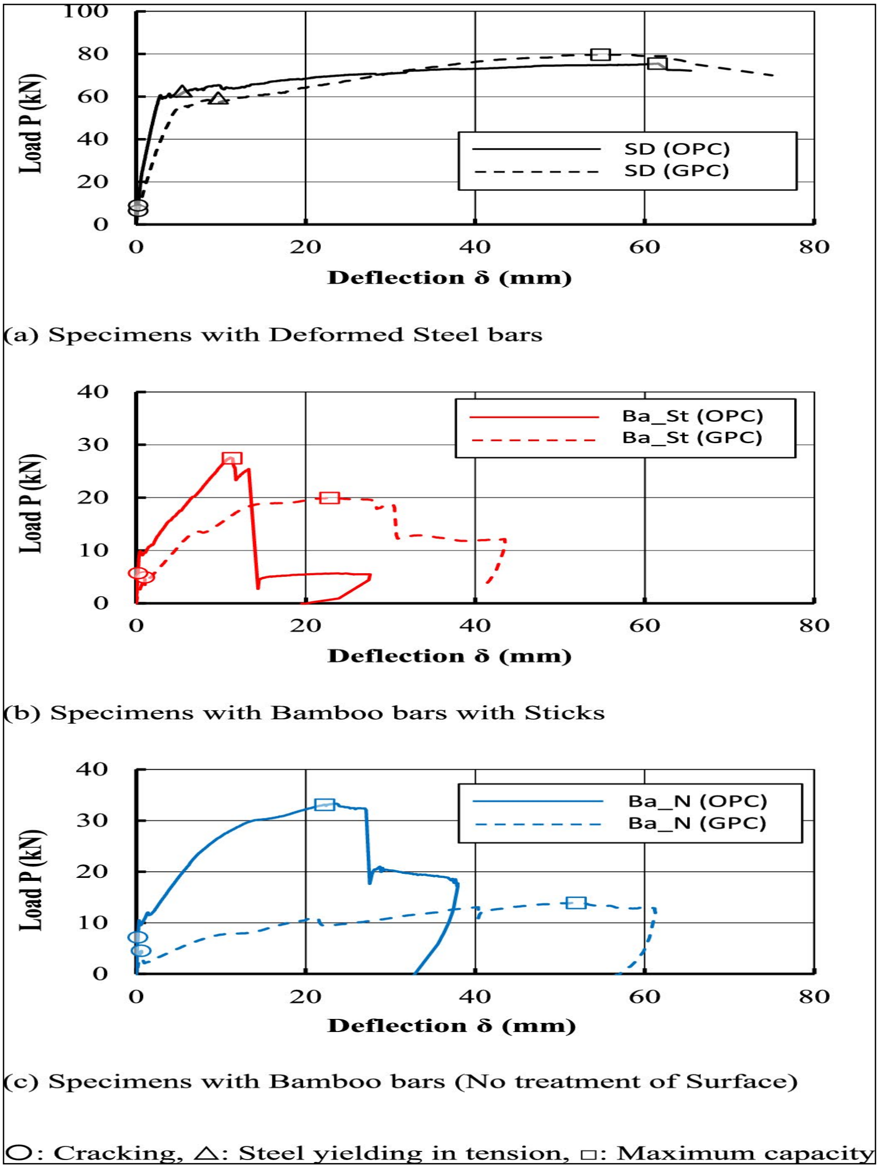

Fig. 7

In addition to mechanical performance, sustainability evaluation forms an integral component of the discussion. The use of geopolymer binders derived from industrial by-products contributes to significant reductions in embodied carbon compared with Portland cement systems. When combined with bamboo reinforcement, which is a renewable and rapidly regenerating material, the overall environmental impact of the composite is further reduced. Life-cycle assessments reported in secondary literature suggest that replacing steel reinforcement with bamboo can substantially lower energy consumption and carbon emissions, thereby promoting eco-efficient construction practices without compromising essential structural performance (Nath & Sarker, 2017; Hebel *et al.* 2015).

The thermal and chemical resistance characteristics of bamboo reinforced geopolymer concrete also exhibit promising performance trends. Geopolymer matrices are inherently stable at elevated temperatures due to their ceramic-like microstructure, which enables them to retain strength even under thermal exposure. Secondary studies indicate that the inclusion of bamboo does not significantly affect thermal resistance of the composite, although charring of bamboo may occur at very high temperatures. Nevertheless, the surrounding geopolymer matrix provides partial insulation and structural confinement, thereby delaying thermal degradation of the reinforcement and preserving residual load-bearing capacity (Alomayri, 2017; Li *et al.* 2020).

Microstructural analysis reported in the literature further explains the observed mechanical behaviour of bamboo reinforced geopolymer concrete. Scanning electron microscopy investigations reveal a relatively dense interfacial transition zone between treated bamboo and geopolymer matrix, characterised by geopolymeric gel penetration into surface irregularities of the reinforcement. This microstructural bonding enhances mechanical interlocking and reduces interfacial voids, which contributes to improved stress transfer efficiency. However, untreated bamboo surfaces exhibit weak adhesion and microcracks at the interface, which can propagate under loading and result in premature bond failure (Nguyen *et al.* 2016; Yoon *et al.* 2019).

The performance variability observed across different studies can largely be attributed to differences in bamboo species, treatment methods, geopolymer mix design and curing conditions. Bamboo from different geographical regions exhibits varying fibre density and mechanical properties, which directly influence tensile strength and bond behaviour. Similarly, geopolymer mixtures with higher silica content tend to produce denser matrices that enhance compressive strength but may also increase brittleness. Therefore, optimisation of both reinforcement treatment and geopolymer composition is essential to achieve balanced mechanical performance and durability in bamboo reinforced geopolymer concrete (Sarker *et al.* 2016; Nath & Sarker, 2017).

The table 1 presents secondary data compiled from recent studies comparing key mechanical properties of bamboo reinforced geopolymer concrete with conventional geopolymer concrete and bamboo reinforced Portland cement concrete.

Table 1: Secondary data comparison of mechanical properties of bamboo reinforced geopolymer concrete

Study	**Material System**	**Compressive Strength (MPa)**	**Flexural Strength (MPa)**	**Key Observation**
Deb *et al.* (2016)	Bamboo reinforced geopolymer concrete	32–38	4.5–5.2	Adequate compressive strength with improved crack control

Kumar *et al.* (2018)	Bamboo reinforced concrete	28–34	4.0–4.8	Gradual flexural failure and enhanced ductility
Nath & Sarker (2017)	Fly ash geopolymer concrete	35–50	3.8–4.6	High compressive strength with brittle behaviour
Alomayri (2017)	Natural fibre geopolymer composite	30–42	5.0–6.1	Improved toughness and energy absorption
Sarker *et al.* (2016)	Slag-based geopolymer concrete	40–55	4.2–5.0	Dense matrix with superior durability

The compiled secondary data demonstrate that bamboo reinforced geopolymer concrete achieves compressive strength comparable to conventional geopolymer concrete while exhibiting improved flexural performance relative to unreinforced matrices. The enhanced flexural strength observed in natural fibre geopolymer composites further supports the feasibility of bamboo reinforcement in mitigating brittle fracture and enhancing energy absorption capacity.

Overall, the results and discussion indicate that bamboo reinforced geopolymer concrete represents a structurally viable and environmentally sustainable composite material with promising mechanical performance. The interaction between bamboo reinforcement and geopolymer matrix governs key behavioural characteristics such as crack propagation, ductility and failure mode. While challenges related to bond strength and long-term durability remain, the integration of appropriate treatment methods and optimised mix designs can significantly enhance structural reliability. The synthesis of mechanical, durability and sustainability perspectives confirms that bamboo reinforced geopolymer concrete possesses considerable potential for application in low-carbon infrastructure and sustainable construction systems.

CONCLUSION

The study on the development and performance evaluation of bamboo reinforced geopolymer concrete demonstrates that the integration of renewable bamboo reinforcement within an eco-friendly geopolymer matrix offers a promising alternative to conventional steel-reinforced Portland cement concrete. The results indicate that geopolymer concrete provides adequate compressive strength and a dense microstructure capable of supporting structural loads, while the inclusion of bamboo significantly improves flexural performance and crack-bridging behaviour. The composite exhibits enhanced ductility and gradual failure characteristics compared with plain geopolymer concrete, suggesting that bamboo can effectively compensate for the brittle nature of geopolymeric binders when appropriate treatment and anchorage measures are implemented.

The bond interaction between bamboo and the geopolymer matrix emerges as a critical factor governing the overall structural response. Proper surface treatment and seasoning of bamboo reinforcement improve adhesion and reduce moisture-related deterioration, thereby enhancing load transfer efficiency and long-term stability. Durability performance is further supported by the low permeability and chemical resistance of geopolymer matrices, which provide a protective environment for embedded bamboo reinforcement and mitigate degradation risks under moderate environmental exposure.

From a sustainability perspective, the combined utilisation of industrial by-product-based geopolymer binders and rapidly renewable bamboo reinforcement contributes to significant reductions in embodied carbon, energy consumption and dependence on non-renewable construction materials. This makes bamboo reinforced geopolymer concrete particularly suitable for low-cost and sustainable infrastructure applications in developing regions. However, variability in bamboo properties, bond performance and long-term durability under cyclic environmental conditions necessitate further optimisation of treatment methods and mix design parameters. Overall, the research confirms that bamboo reinforced geopolymer concrete possesses considerable potential as a structurally viable and environmentally sustainable composite material, capable of supporting the advancement of low-carbon construction practices while maintaining acceptable mechanical and durability performance for practical engineering applications.

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