



Article

Structural and Sustainability Enhancement of Composite Sandwich Slab Panels Using Novel Fibre-Reinforced Geopolymer Concrete

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Abstract: One of the important findings of the recent decades in the construction industry is composite sandwich panels (CSPs), which have benefits of being lightweight, providing thermal insulation, and aiding the economy; they are transforming continuously through many add-ons as needed by the industry. With the demand for sustainability in the field, CSPs need structural and sustainable enhancement. In the present study, an approach for the same has been attempted with geopolymer concrete (GPC) and novel nylon fibre to improve the sustainability and structural benefits, respectively. With various material combinations including GPC reinforced with fibres, six CSPs were cast and studied. The inherent limitations of GPC have been addressed by the nylon fibre reinforcement instead of using steel fibres, which have a similar strength, considering the aim of maintaining the density of the wythe material. A comparison of the flexural behaviour of the CSPs through the parameters of load–deflection, ductility, and toughness was made using the four-point loading test. The results of the test specify that the fibres enhance the performance of the CSPs under flexural loading.

Keywords: composite sandwich slab panels; fibre-reinforced concrete; geopolymer concrete; sustainability; four-point loading



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1. Introduction

1.1. Composite Sandwich Panels: An Overview

Composite sandwich panels (CSPs) are innovative construction materials that offer several advantages by arranging materials layer by layer based on specific characteristics and functional needs within each layer. Although CSPs have been in use since the mid-19th century, their application in the construction field has gained significant traction only in recent decades [1]. Typically, CSPs consist of three layers, two outer layers and a core layer, all connected by shear connectors to form a composite element. The degree of composite action depends primarily on the bonding between the layers, achieved either through adhesive bonding or through shear connectors [2]. The outer layers of CSPs function like the flanges of an I-section, carrying normal stresses that develop during bending. The core layer, minimally affected by bending stresses, can be made of lightweight material with adequate stiffness. Together, the core layer and shear connectors primarily resist shear stresses [3,4]. CSPs are versatile and can serve various structural purposes, including load-bearing walls, slabs, floor panels, facades, and roofing, often requiring minimal adjustments to their structural configuration [5–7]. With the right material choices, CSPs can offer several benefits such as reduced self-weight, lower induced forces for instant, reduced seismic loading, decreased energy requirements for handling and transport, and cost-effectiveness [6,8].

1.2. Expanded Polystyrene (EPS) as Core Layer

The core layer in the CSPs requires materials with minimum stiffness and low density as this layer can occupy around 50% of the total slab volume. Experts prefer to use expanded polystyrene (EPS) as one of them, and EPS is suitable for the core layer, as revealed by previous studies, due to its high stiffness-to-weight ratio. EPS consists of polystyrene beads, and when its maximum volume (up to 98%) is filled with air, it has a density range from 15 to 35 kg/m³. Due to this, EPS offers good thermal insulation and impact resistance with load-bearing capacity. This petroleum byproduct, EPS, has other beneficial properties such as low water absorption and enhanced flame retardancy through fillers, making it a good material for the core layer in CSPs compared to extruded polystyrene (XPS) and balsa wood in CSP applications [9–13].

1.3. The Role of Shear Connectors in CSPs

Shear connectors play a crucial role in CSPs by facilitating stress transfer between wythes and ensuring composite action [6]. While steel connectors such as wires, bent bars, and truss designs are common, non-metallic options are sometimes preferred for improved thermal efficiency. Research has shown that truss-type connectors, particularly those oriented at 45°, achieve optimal strength, ductility, and energy absorption [2,7,10–12,14]. However, further investigation is needed to evaluate their performance under cyclic loading conditions.

1.4. Geopolymer Concrete: A Sustainable Alternative

Geopolymer concrete (GPC) has attracted scholarly interest as a sustainable substitute for conventional concrete, aligning with global sustainability goals [15]. Through the incorporation of industrial byproducts like fly ash and ground granulated blast furnace slag (GGBFS), GPC effectively lessens CO₂ emissions—by up to 80% when contrasted with traditional cement manufacturing [16]. This correlates with SDG 12 (Responsible Consumption and Production) and exhibits enhanced durability in extreme conditions.

However, GPC faces challenges such as workability issues and shrinkage-induced cracking [17]. Ambient-cured GPC offers a solution to reduce energy consumption during curing [18], with studies showing minimal durability reduction compared to heat-cured alternatives [15]. The lower tensile strength of GPC, approximately 5% of its compressive strength, contributes to GPC's quasi-brittle nature, necessitating fibre reinforcement to enhance ductility and crack resistance [19,20].

1.5. Fibre-Reinforced Concrete: Enhancing Performance

A contemporary examination conducted by Ganeshan et al. (2023) scrutinized the characteristics of nylon fibre-reinforced concrete (NFRFC) in contrast to traditional concrete. The investigation underscored the “bridge effect” of nylon fibres, which assists in averting crack genesis and propagation, consequently augmenting the mechanical integrity of the concrete, and discerned that the integration of 2% nylon filaments markedly augmented the mechanical characteristics, yielding superior crack resistance and diminishing plastic shrinkage [21].

The study by Yin et al. (2015) reveals the feasibility of utilising synthetic macro-sized fibres for fibre-reinforced concrete (FRC), mentioning their capacity to improve the mechanical properties of FRC with additional benefits such as crack resistance and durability [22]. The study on overcoming the lack of bonding of cementitious composites with fibre, especially synthetic macro-fibres, proposed various pretreatment techniques, including using cast-off concrete powder with plasma treatment to increase the bond [23]. At this point, it is to be noted that the significance of utilising synthetic fibres over steel fibres, despite the latter performing better in the case of mechanical, plastic, and post-peak behaviour, is to maintain the lightness of the structural elements after fibre addition. As in the case of steel fibre reinforcement, the structural element's weight is increasing and thereby so is the cost of transportation and installation when the project is on a large scale and when the weight restrictions are critical [24].

With this understanding of FRC and GPC, to overcome the limitations of utilising GPC in CSPs, it becomes essential to introduce new approaches. One such approach is attempted here. As per this approach, the macro nylon fibres are shape-modified to form a new shape called flattened-end nylon fibre (FENF), which will have enlarged ends in a straight nylon fibre to enhance the bonding between the fibre and matrix. This FENF is applied to elevate the structural performance of GPC, which is the key requirement in the feasibility of utilising GPC in the CSPs. It is hypothesised that the effect of the FENF will be greater from the end anchorage provided by the enlarged ends of the fibre. As depicted in Figure 1a, when a member is subjected to flexural loading, cracks develop at points of maximum stress, such as the mid-span under symmetrical loading. This crack will further develop and concentrate at the same location as the section becomes weaker, without having an even stress distribution, as there is no mean for tensile stress transfer medium in the concrete matrix except the inherent bonding strength of the cementitious material (Figure 1b).

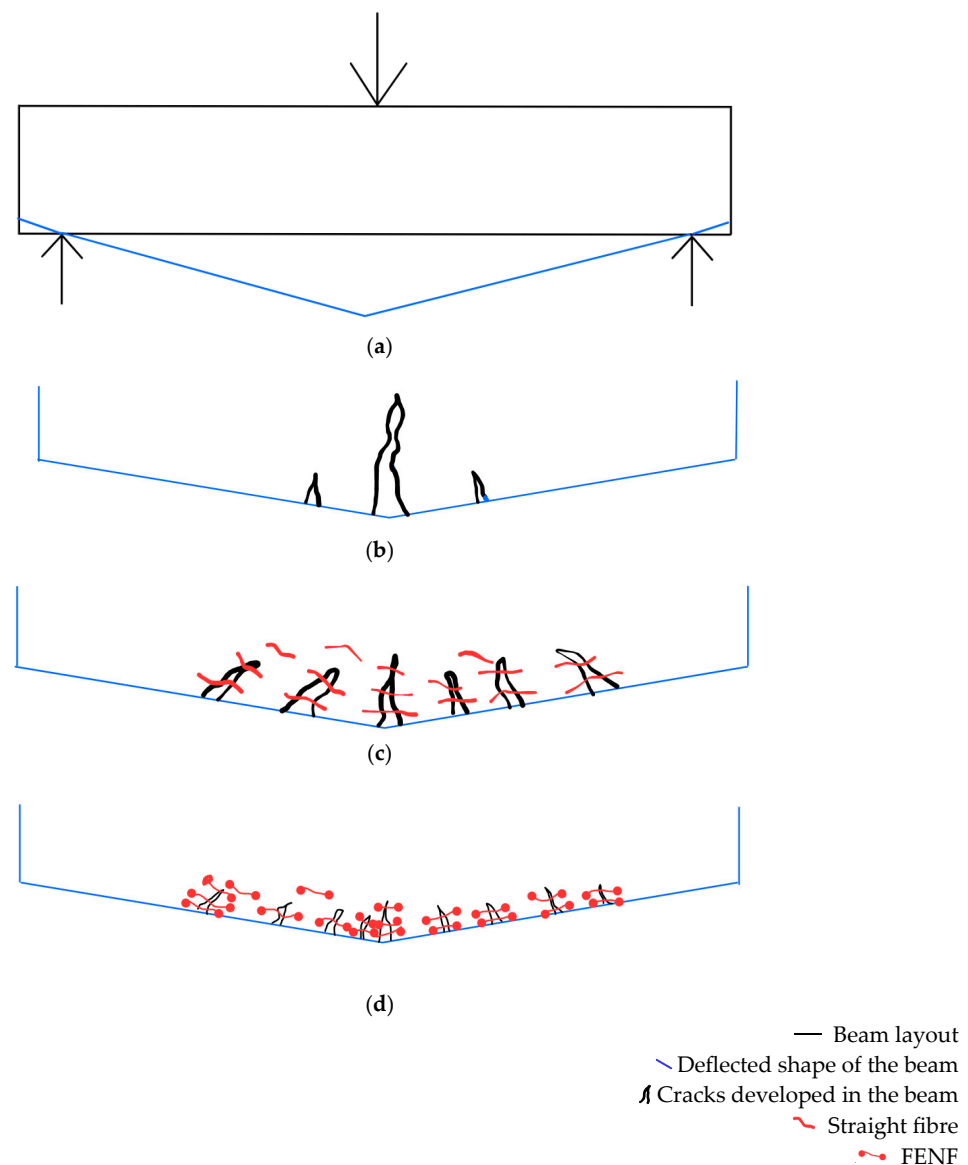


Figure 1. An illustration of the effect of the FENF over straight fibres under flexure: (a) a member subjected to flexural loading, (b) a member without fibre reinforcement with concentrated cracks and wide cracks, (c) a member with nylon fibre reinforcement with distributed cracks and reduced crack width, and (d) a member with FENF reinforcement (many distributed cracks and fine crack width).

When the fibres are introduced into the concrete, as they resist the cracks, the width of the cracks is reduced and the number of smaller cracks is increased along the span; this indicates that the tensile stress is distributed across the span of the member under loading through stress transfer by the fibres (Figure 1c). However, the capacity to arrest this crack is limited by the tensile strength of the fibre and the bonding strength between the fibre and the concrete matrix. If the bonding strength is insufficient, the full capacity of the fibre will not be utilised and the fibres may slip and fail to prevent crack growth and stress transfer. This can be overcome by the FENF, as shown in Figure 1d. The introduction of the FENF further reduces the crack width and produces a greater number of finer cracks, which is evident in the improved stress transfer compared to the straight fibres.

1.6. Potential Durability Enhancements in Fibre-Reinforced Geopolymer Concrete

GPC, a sustainable concrete made with industrial waste as the main precursor material, exhibits properties that vary based on key parameters such as the mix ratio, precursor and activating materials, binder-to-water ratio, alkaline activator-to-binder ratio, and activator concentration [25,26]. Similar works indicate that GPC made with fly ash and GGBFS, both rich in silica and alumina, is effective in binding properties, with GPC containing GGBFS as the major ingredient, showing potential for higher compressive strength [26]. To produce ambient-cured GPC without requiring elevated temperature, the composition includes approximately 70% GGBFS and 30% fly ash to achieve the desired strength. A similar mixture provides resilience without the need for high-temperature curing [26,27].

Incorporating nylon fibres increases the mechanical strength of GPC, with optimal fibre content notably enhancing flexural and tensile strength [28]. In terms of durability, the addition of fibres, including nylon, further improves longevity by enhancing properties such as water absorption [27,28], permeability [25], crack resistance, and resistance to chemical attacks, outperforming conventional cement concrete with minimal strength reduction [29–31]. However, optimizing fibre characteristics such as fibre dosage and ensuring the even distribution of fibres are crucial in achieving the expected mechanical and durability performance.

1.7. The Scope and Objectives of the Present Study

This study seeks to enhance CSP structural behaviour while improving sustainability through a combination of GPC and novel nylon fibre-reinforced concrete. The study focuses on overcoming GPC's inherent weaknesses, such as plastic shrinkage cracks, without substantially increasing self-weight. The development of the FENF aims to improve bonding and address traditional GPC limitations.

The specific objectives of this study are as follows:

1. To assess the viability of using geopolymer concrete as a wythe material in CSPs, we compare its performance to conventional concrete.
2. To evaluate the combined effects of GPC and novel nylon fibres on CSP flexural behaviour, we benchmark it against CSPs using conventional concrete and hooked-end steel fibre reinforcement.

1.8. Research Significance

The primary contribution of this study is to advance the application of GPC in CSPs, thereby introducing sustainability features such as a light weight, thermal insulation, and reduced material consumption. In addition to assessing the feasibility of CSPs from a sustainable perspective, the present study aims to enhance structural aspects like flexural strength, crack resistance, and ductility through the introduction of a novel fibre, FENF, specifically designed for thin concreting applications, as in CSP wythes.

This approach supports the adaptation of CSPs into environmentally sustainable yet structurally robust elements, increasing their potential for industry adoption in responsible construction practices.

2. Materials and Methods

To achieve the above-stated objectives, the methodology as shown in Figure 2 has been adopted.

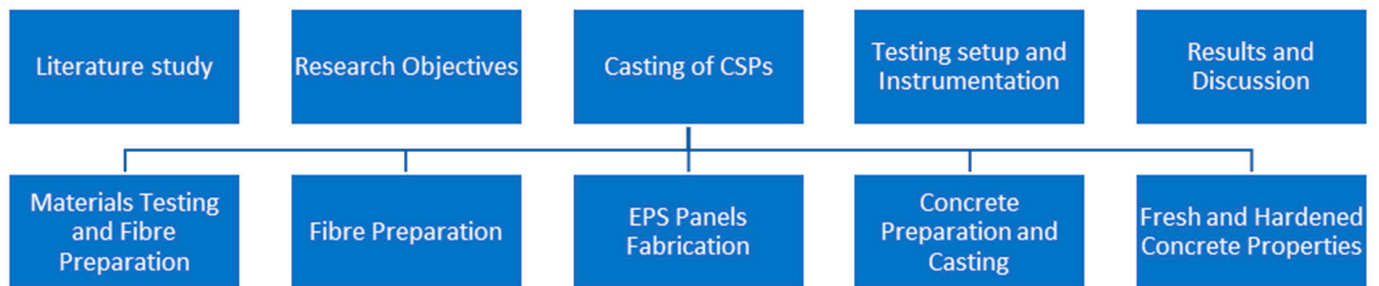


Figure 2. Work breakdown and methodology.

2.1. Material Testing and Fibre Preparation

To study the effect of GPC and FENF, the materials used in the study are conventional concrete (CC), geopolymer concrete (GPC), GPC with straight nylon fibre (SNF), GPC with FENF, and GPC with hooked-end steel fibre (HESF). The ingredients of CC include cement, fine aggregate (M-sand), and coarse aggregate. GPC incorporates fly ash (FA) and ground granulated blast furnace slag (GGBFS) as precursors, with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) serving as alkaline activators. Nylon fibres were integrated into both concrete types to create fibre-reinforced concrete (FRC).

For CC, cement (53-grade cement from Rain Cements Limited, Hyderabad, Telangana, India) properties were evaluated according to Indian Standards. The cement exhibited a specific gravity of 3.12 as per IS 4031 (Part 11): 1988 [32], a consistency of 31.2% as per IS 4031 (Part 4): 1988 [33], and a fineness of $318 \text{ m}^2/\text{g}$ as per IS 4031 (Part 2):1999 [34]. Soundness measured at 0.75 mm as per IS 4031 (Part 3):1988 [35], and setting times were 130 min for the initial setting and 230 min for the final setting as per IS 4031 (Part 5): 1988 [36]. Identical fine and coarse aggregates, locally sourced from Thiruvallur, Tamil Nadu, India, were used in both CC and GPC mixes. The M-sand (fine aggregate) had a specific gravity of 2.57 [37] and water absorption of 0.96% as per IS 2386 (Part 3): 1963 [37]. Its fineness modulus of 2.385 mm fell within acceptable ranges for concrete use as per IS 2386 (Part 1): 1963 [38]. The coarse aggregate (8–12 mm) displayed a specific gravity of 2.68 and water absorption of 0.8% as per IS 2386 (Part 3): 1963 [37]. The aggregate impact value was 27%, within the 20–35% range specified by IS 2386 (Part 4): 1963 [39].

For GPC, Class F fly ash (Astrra Chemicals, Chennai, Tamil Nadu, India) was employed, with a specific gravity of 2.2 as per IS 3812: 2013 [40] and a chemical composition suitable for ambient geopolymerization. GGBFS (Astrra Chemicals, Chennai, Tamil Nadu, India) was used as a supplementary binder ($420 \text{ kg}/\text{m}^3$) and had a specific gravity of 2.9 [41] and a fineness between 350 and $450 \text{ m}^2/\text{kg}$ as per IS 4031 (Part 2): 1999 [34]. The alkaline activator combined sodium silicate (14.45% Na_2O , 33.33% SiO_2) and 12 M sodium hydroxide solution (both from Sygmos Fine Chem, Surat, Gujarat, India).

The M25 concrete mix was designed following IS 10262:2019 guidelines, using PPC 43 cement, M-sand, 8–12 mm coarse aggregate, and water, with a water–cement ratio of 0.45. The final proportions were $554.4 \text{ kg}/\text{m}^3$ cement, $1359.82 \text{ kg}/\text{m}^3$ coarse aggregate, $619.85 \text{ kg}/\text{m}^3$ fine aggregate, and $249.48 \text{ kg}/\text{m}^3$ water. The summary of the mix design (mix proportions of materials per cubic metre of concrete and volume percentage) of the conventional concrete and the GPC are given in Tables 1 and 2.

Table 1. Mix proportions of conventional concretes.

	Cement	Fine Aggregate	Coarse Aggregate	Water
Weight in kg (per m ³)	554.4	619.85	1359.82	249.48
Volume percentage	15.13	20.52	43.15	21.19

Table 2. Mix proportions of GPC.

	Fly Ash	GGBFS	Fine Aggregate	Coarse Aggregate	Na ₂ SiO ₃	NaOH	Water
Weight in kg (per m ³)	180	420	519	1156	105	105	270
Volume percentage	7.16	16.65	17.74	39.50	3.68	3.68	11.59

2.2. Fibre Preparation

Three types of fibres were employed in this study to compare the behaviour of GPC: straight nylon fibres (SNFs), flattened-end nylon fibres (FENFs), and hooked-end steel fibres (HESFs). Macro nylon fibres were incorporated into GPC to produce fibre-reinforced concrete. To produce the nylon fibre, monofilament fishing line wires which had a tensile strength of 300 MPa and a mass density of 1100 kg/m³ were imported and utilised. Fibres were modified to have flattened ends and cut into a length of 27.5 mm, yielding aspect ratios of 55, with a uniform 0.5 mm thickness. HESF was sourced directly from market suppliers (fibre region). For nylon fibres, the optimal aspect ratio and dosage for CSP applications were determined through experimentation. Both SNF and FENF were prepared with a thickness of 0.5 mm, an aspect ratio of 55, and a dosage of 1.5%. The HESF dosage was set at 1.5% based on the literature review, as the studies mention that a 1.0% volume fraction is often recommended to achieve ductile flexural behaviour, ensuring multiple cracking and deflection hardening responses, and that a 1.5% volume can enhance tensile strength with other potential challenges such as increased density and may reduce workability and increase mixing difficulty [42,43].

FENF preparation involved a meticulous process. The ends of cut fibres were melted using a controlled heat source (a candle flame in this study). The melted ends were then gently pressed perpendicular to their axis and allowed to cool, resulting in slightly enlarged, flattened terminations. These flattened ends had an approximate radius of 1 mm (± 0.25 mm) and a length of 1–2 mm (± 0.25 mm). This modification aimed to increase the surface area of the fibre ends, thereby enhancing the bonding between the fibre and the concrete matrix. The process of preparation of the FENF is illustrated in Figure 3.

2.3. EPS Panel Fabrication

After testing the ingredients and preparing the concrete mix design, EPS panels were fabricated. The EPS panel, serving as the core layer between high tensile steel wire reinforcement meshes with truss-type shear connectors, was prefabricated at Beardsell Limited in Thiruvallur District, Tamil Nadu. For this study, the slabs were designed with dimensions of 0.5 m $\times$ 1.5 m $\times$ 0.125 m, featuring a 75 mm thick EPS core layer and a 50 mm grid-size reinforcement wire mesh in the wythes [7,10,12]. These specifications were communicated to the manufacturer for accurate production of the EPS panels.

The schematic diagram of the EPS panel with reinforcement wire meshes is shown in Figure 4.

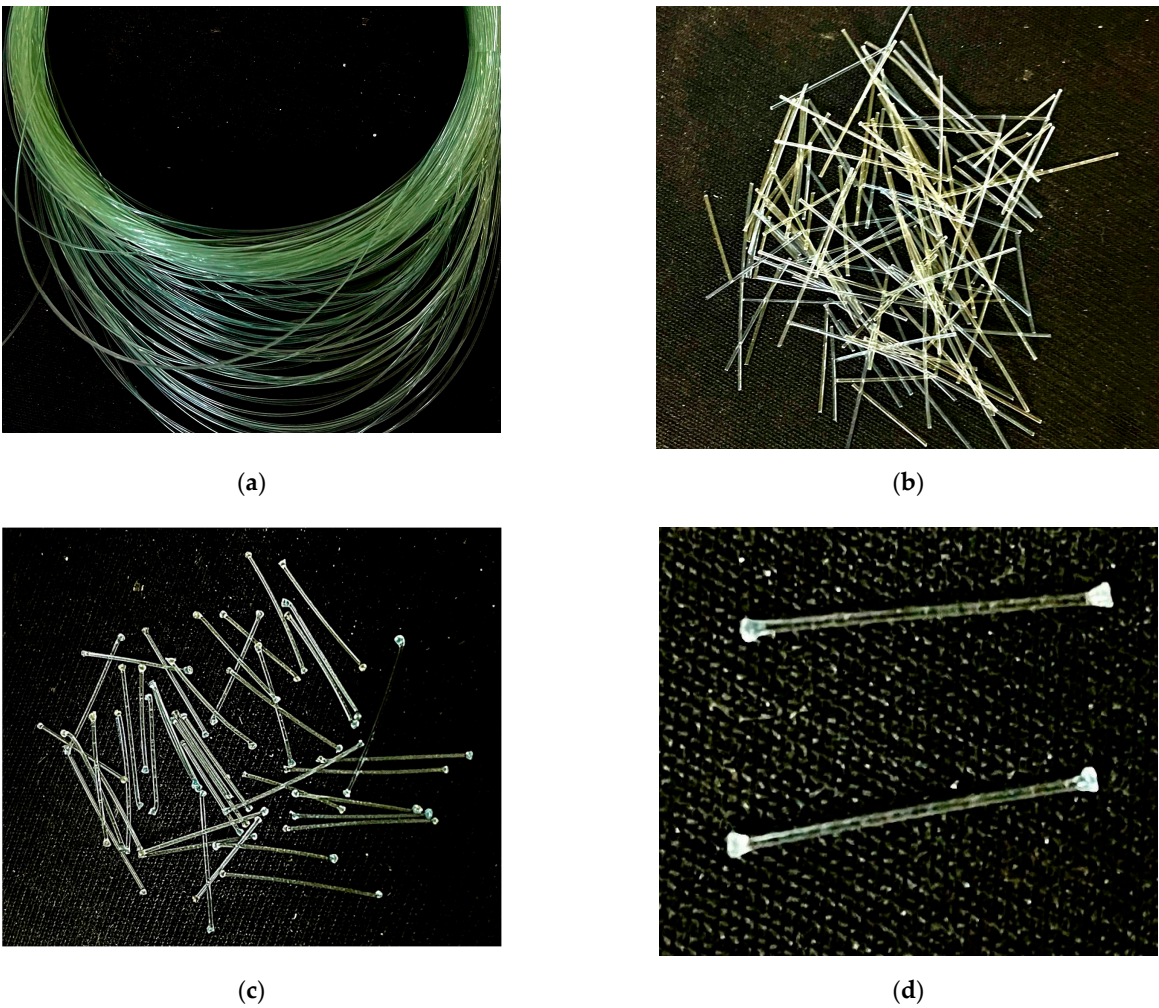


Figure 3. Illustration of FENF preparation: (a) raw nylon fibres before modification, (b) straight nylon fibres cut to specified lengths, (c) collection of FENFs after end-flattening, and (d) enlarged view of FENFs, showing straight portion and flattened ends.

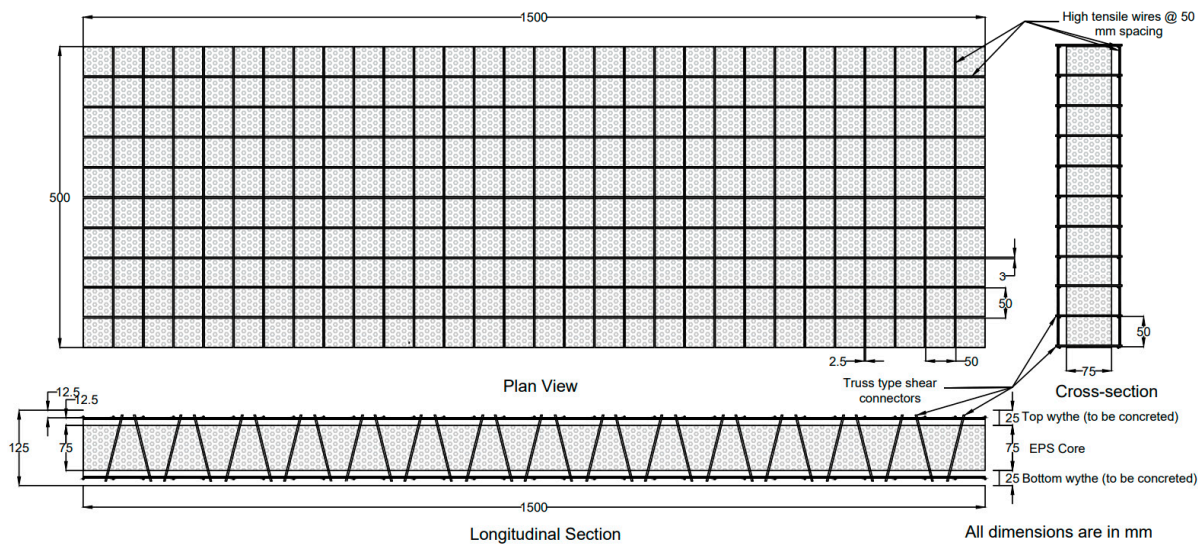


Figure 4. Dimensions of EPS panel and reinforcement wire meshes.

2.4. Concrete Preparation and Casting

Both CC and GPC, with and without fibres, were prepared according to the mix design and tested for fresh and hardened concrete properties. Slump cone tests were conducted following IS 1199 (Part 2): 2018 [44]. Mechanical properties (compressive, split tensile, and flexural strengths) were tested as per IS 516 (Part 1/Sec 1): 2021 [45]. Three samples were prepared for each test on each day for each mix. For the curing of the CSPs, normal drinking water was utilised.

2.5. Fresh and Hardened Concrete Properties

Table 3 presents the fresh and hardened concrete properties for all mixes, excluding GPC with HENF, along with the percentage increase in strength compared to conventional concrete.

Table 3. Fresh and hardened concrete properties.

Sl. No.	Concrete Type	Workability			On 28th Day			
		Slump Cone Value (mm)	Compressive Strength (N/mm ²)	% Increment	Split Tensile Strength (N/mm ²)	% Increment	Flexural Strength (N/mm ²)	% Increment
1	Conventional Concrete	115	27.04	-	2.87	-	3.52	-
2	Geopolymer Concrete	110	27.03	99.96	2.16	75.26	3.04	86.36
3	GPC with SNF	105	28.17	104.18	3.06	106.62	4.08	115.91
4	GPC with FENF	104	28.75	106.32	3.20	111.50	4.44	126.14

- not applicable.

2.5.1. Workability

The slump test results revealed varying workability among the different mixes. With a preferred slump range from 100 mm to 120 mm, the control concrete mix (CC) exhibited a slump value of 115 mm, indicating high workability due to the absence of fibres in the matrix. As anticipated, GPC and fibre-reinforced GPC showed reduced workability. This decline can be linked to the addition of fine particulates, particularly fly ash and ground granulated blast furnace slag (GGBFS), in the geopolymer concrete (GPC) and the incorporation of fibres in the fibre-reinforced concretes (FRCs). Notwithstanding the observed decrease, the FRC formulations sustained workability within the permissible limits for the designated application. Potable water was utilised for the curing process.

2.5.2. Compressive Strength

Conventional concrete and plain GPC demonstrated nearly identical compressive strengths of 27.04 MPa and 27.03 MPa, respectively. The incorporation of SNF increased GPC's compressive strength to 28.17 MPa, representing a 4.2% improvement over plain GPC. FENF further enhanced the compressive strength to 28.75 MPa, a 6.3% increase compared to plain GPC. The superior performance of FENF-reinforced GPC suggests that the novel flattened-end fibres contribute to improved load distribution and resistance.

2.5.3. Split Tensile Strength

Fibre-reinforced GPCs significantly outperformed both conventional concrete and plain GPCs in split tensile strength. Conventional concrete exhibited a split tensile strength of 2.87 MPa, while plain GPC showed a lower value of 2.16 MPa, indicating reduced resistance to tensile stresses without fibre reinforcement.

GPC with SNF achieved 3.06 MPa, marking a 41.7% improvement over plain GPC and a 6.6% increase compared to conventional concrete. GPC with FENF demonstrated the highest split tensile strength of 3.20 MPa, representing a 48.1% improvement over plain GPC and an 11.5% increase compared to conventional concrete. The enhanced performance

of FENF can be attributed to better interlocking with the concrete matrix, which results in enhanced tensile strength and resistance to cracking.

2.5.4. Flexural Strength

Flexural strength results mirrored the trend observed in split tensile strength, with fibre-reinforced concretes exhibiting superior performance. Conventional concrete showed a flexural strength of 3.52 MPa, while plain GPC had a lower value of 3.04 MPa.

GPC with SNF improved the flexural strength to 4.08 MPa, a 34.2% increase over plain GPC and a 15.9% improvement compared to conventional concrete. GPC with FENF again demonstrated the best performance, with a flexural strength of 4.44 MPa, representing a 46.1% increase over plain GPC and a 26.1% improvement compared to conventional concrete. The enhanced performance of FENF can be attributed to the flattened ends of the fibres, which likely contribute to better load transfer and crack-bridging capabilities.

As seen in Table 3, the mechanical performance of CC, GPC with SNF, and GPC with FENF surpasses that of GPC without any fibre. The lower performance of fibreless GPC can be attributed to the absence of conventional cement, which results in reduced mechanical strength, particularly in split tensile and flexural capacities [46,47]. Fibre inclusion significantly enhanced the mechanical properties of GPC-based concrete by reinforcing the concrete matrix and increasing its inherent strength, especially in split tensile and flexural strengths. Notably, FENF-based GPC exhibited the highest strength across all three tested metrics.

2.6. Casting of CSPs

The final stage in CSP manufacturing involved concreting the top and bottom wythes. Different materials were utilised for each slab type, as shown in Table 4.

Table 4. CSP details.

Sl. No.	Slab Name	Top Wythe	Bottom Wythe
1	CC	Conventional Concrete	Conventional Concrete
2	CG	Conventional Concrete	Geopolymer Concrete
3	GG	Geopolymer Concrete	Geopolymer Concrete
4	CGSN	Conventional Concrete	Geopolymer Concrete with SNF
5	CGFN	Conventional Concrete	Geopolymer Concrete with FENF
6	CGHS	Conventional Concrete	Geopolymer Concrete with HESF

Figure 3 illustrates the specific process used in this study to cast the CSPs. Initially, EPS panels were placed on a mould set prepared on the flat floor in the casting yard. Cover blocks were properly positioned at the bottom of the EPS panels to prevent them from being pierced by the weight of the concrete cast on the wythe, as shown in Figure 5a. The layering arrangement, from the floor upwards, consisted of the casting yard floor, cover blocks to support the EPS core layer reinforcement in the bottom wythe, and then the EPS core. Following this setup, the concrete mixing process began, and the mixture was manually placed on top of the EPS panel to form the top wythe concrete layer, as shown in Figure 5b. After allowing one day for the top wythe concrete to cure, the EPS panel was flipped, as shown in Figure 5c, positioning the cured top wythe at the bottom to support the concreting of the bottom wythe. The bottom wythe was then cast, and the final cast slab panels are shown in Figure 5d.

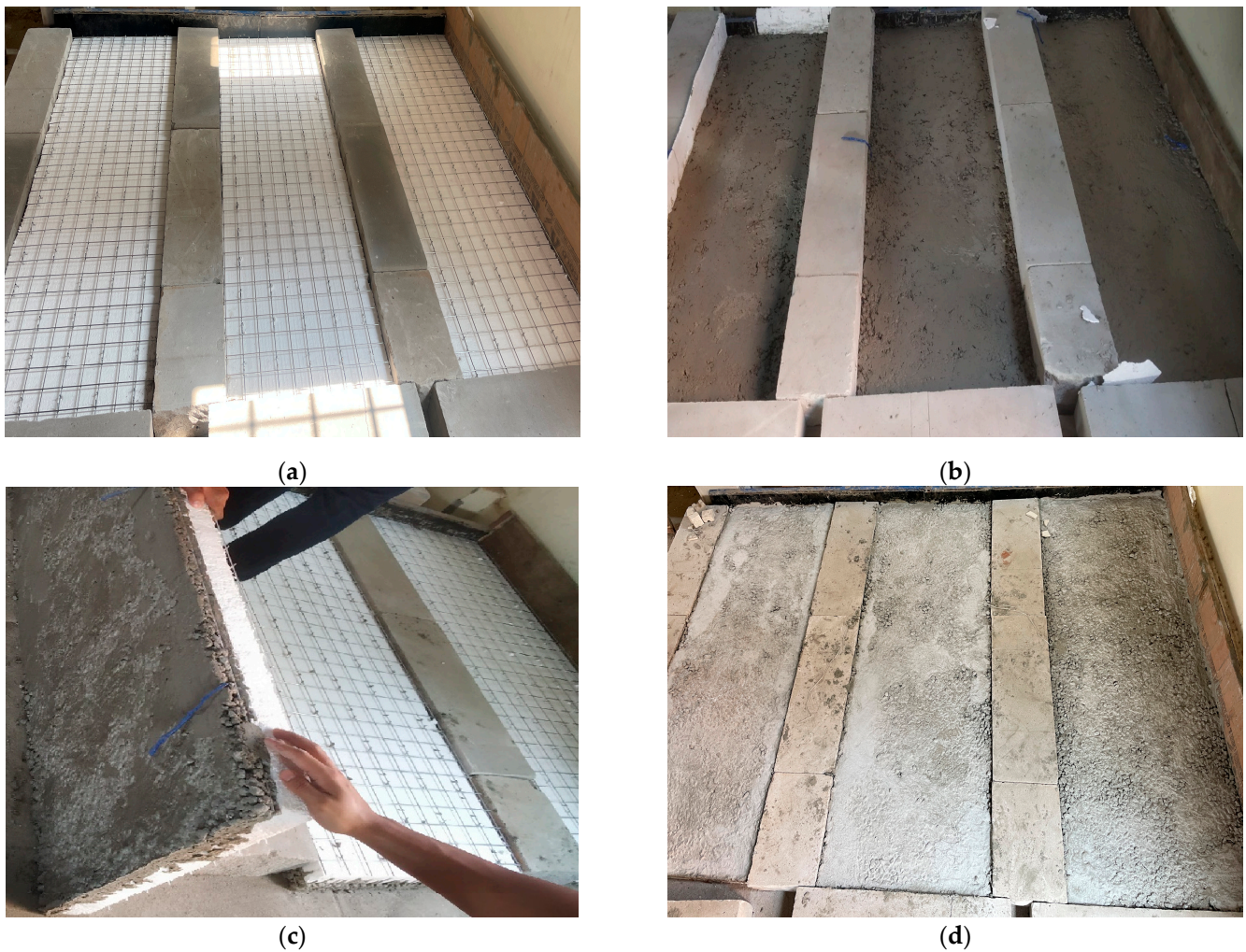


Figure 5. Casting process of CSPs: (a) EPS panels placed in casting yard; (b) top wythe concreting; (c) flipping panels for bottom wythe concreting; (d) final cast panels.

The curing methods varied depending on the CSP type. For the CC (conventional concrete) slabs, the entire panel was immersed in the curing tank, ensuring both wythes were completely cured by water. In contrast, the GG (geopolymer concrete) slabs, designed for ambient curing, received no water curing and were left in the casting yard to maintain room temperature. For the CG, CGSN, CGFN, and CGHS slabs, only the top wythes (made of conventional concrete) were cured by full immersion in the curing tank, while the bottom wythes (made of geopolymer concrete) were allowed to cure under ambient conditions.

2.7. Testing Setup and Instrumentation and Testing

After curing, the slabs underwent four-point loading tests. Figure 6 illustrates the schematic load setup, indicating the supports, effective span, load span, and LVDT location, and Figure 7 shows one of the photographs taken while testing the CSPs to illustrate the loading setup and instrumentation.

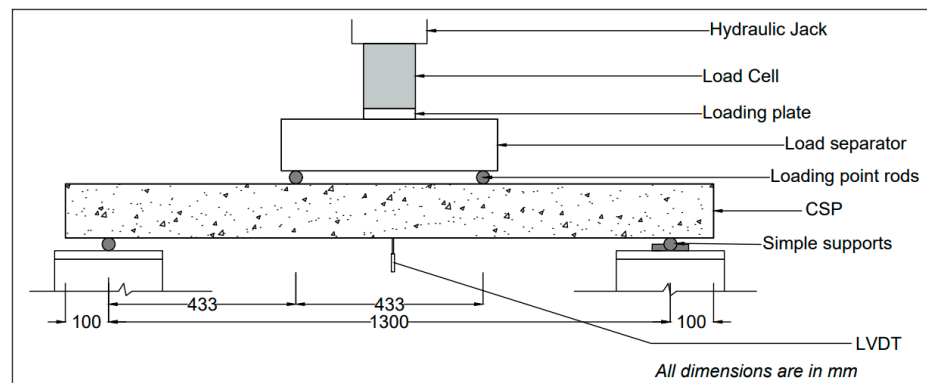


Figure 6. Schematic loading and instrumentation setup.



Figure 7. Loading arrangement with data acquisition system.

3. Results and Summary

The experimental results of six composite sandwich slab panels were analysed to evaluate their structural performance. The panels tested were CC, CG, GG, CGSN, CGFN, and CGHS. Their behaviour under loading was assessed through various parameters including load–deflection characteristics, yield and ultimate points, crack widths, ductility, stiffness, toughness, and energy dissipation. Table 5 summarizes the key performance indicators for each panel type, where P , Δ , W , and k , respectively, denote load, deflection, crack width, and stiffness.

Table 5. Summary of panel performance indicators.

Slab Type	P_{yield} (kN)	Δ_{yield} (mm)	W_{yield} (mm)	P_{ultimate} (kN)	Δ_{ultimate} (mm)	W_{ultimate} (mm)	Ductility (μ)	k_{initial} (kN/mm)	Toughness (kN·mm)	Residual Strength (kN)	Energy Dissipation (kN·mm)
CC	14.7	3.25	8	32.7	24.5	23	7.5	4.52	318.8	6.5	350
CG	14.5	3.16	11	31.2	25.3	21.5	8	4.6	315.1	6.2	360
GG	14.2	3.34	12	29.4	26.5	21	7.9	4.25	329.6	4.7	380
CGSN	14.8	3.26	8	34.5	27.8	21	8.5	4.53	400.7	10.3	450
CGFN	15.3	3.14	7.5	36.7	27.4	18	8.7	4.87	433.1	18.3	480
CGHS	16.6	2.89	7	39.2	23.1	15.5	8	5.76	452.5	27.4	500

3.1. Load–Deflection Behaviour

Figure 8 illustrates the load–deflection graphs corresponding to each of the six distinct panel configurations.

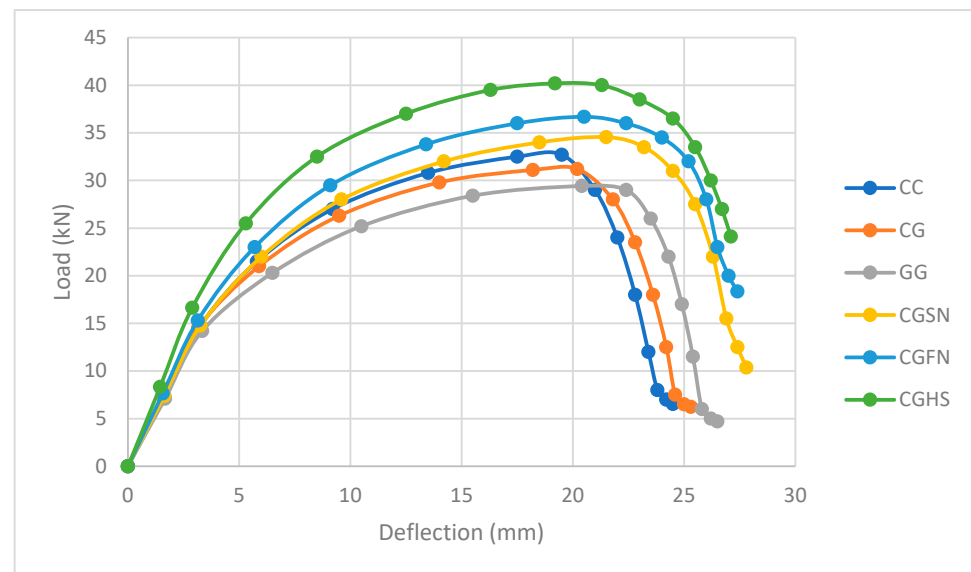


Figure 8. Load vs. deflection curves for all panel types.

Analysing the load–deflection curves (Figure 8) reveals distinct patterns for each panel type as follows. The CGHS panel, with hooked-end steel fibres in the GPC bottom wythe, demonstrated the highest load-carrying capacity (peak load of 40.2 kN at 19.2 mm deflection). The improved performance can be credited to the excellent bonding and mechanical anchorage provided by hooked-end steel fibres in the geopolymer matrix. Both CGSN (straight nylon fibre) and CGFN (flattened-end nylon fibre) panels showed improved performance compared to the basic CC and CG panels. This improvement indicates the positive impact of fibre addition on the load-carrying capacity and ductility of geopolymer concrete.

The GG panel (geopolymer concrete on both faces) showed the lowest load-carrying capacity (maximum load of 29.43 kN at 20.4 mm deflection). This suggests that while geopolymer concrete offers environmental benefits, it still underperforms compared to the CC in a few instances such as peak load at failure. The CG panel, combining conventional concrete and geopolymer concrete, showed intermediate performance, highlighting the potential for optimizing panel composition to balance strength, ductility, and sustainability.

3.2. Load–Deflection at Yield and Ultimate Points

Analysis of yield and ultimate points provides insights into the panels' performance.

Figure 9 presents the yield and ultimate load capacities of the tested panels. Under four-point loading, the CSPs demonstrated load-carrying capacities that directly corresponded to the mechanical strength values shown in Table 3. This correlation mirrors the trend observed when these concrete mixtures are used in structural elements to enhance flexural strength. Among all fibre types tested, the hooked-end steel fibres exhibited superior bending stiffness compared to macro nylon fibres. This characteristic enabled CGHS panels to significantly outperform other CSPs. Specifically, CGHS achieved the highest yield load of 16.6 kN at the smallest deflection of 2.89 mm, indicating enhanced initial stiffness. This superior performance can be attributed to the efficient stress transfer mechanism of hooked-end steel fibres. In contrast, plain geopolymer concrete (GG) exhibited the poorest initial stiffness, with the lowest yield load of 14.2 kN and the highest deflection of 3.34 mm. The panels with nylon fibre reinforcement, CGSN and CGFN, showed moderate improvement with intermediate yield loads of 14.8 kN and 15.3 kN, demonstrating that nylon fibre addition positively influences the initial strength of geopolymer concrete.

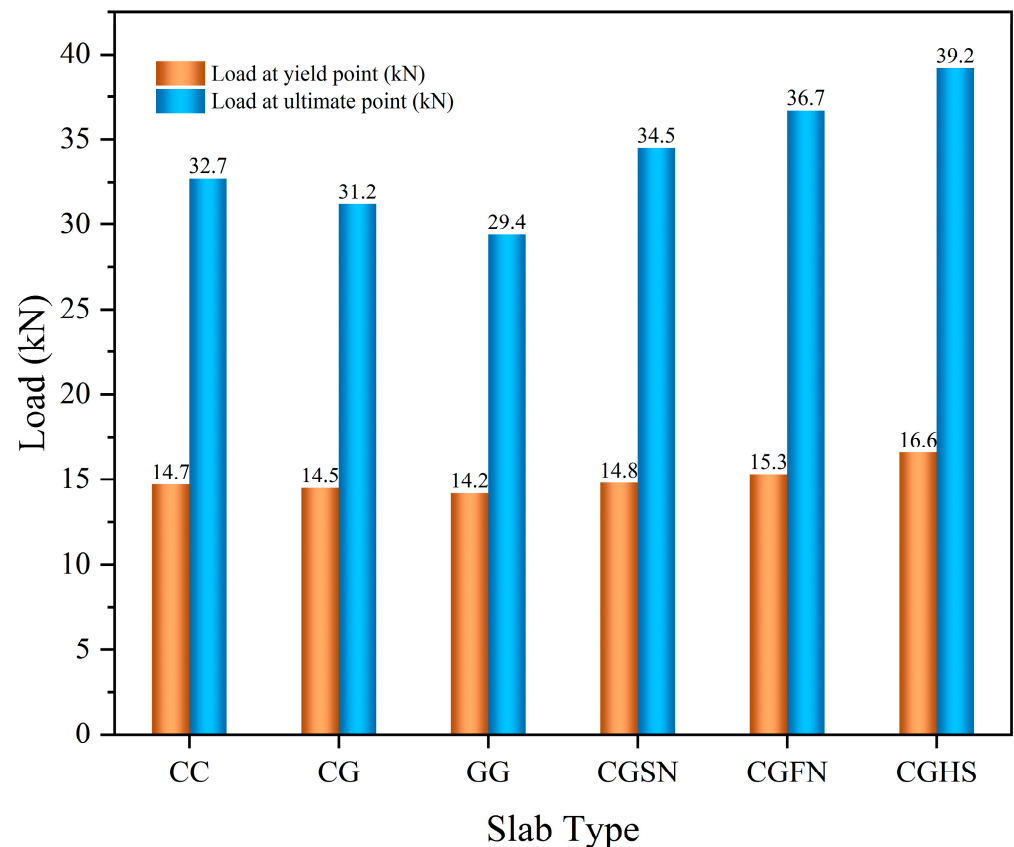


Figure 9. Yield and ultimate load capacity.

Figure 10 shows the deflection measurements at yield and ultimate loads. CGHS exhibited superior performance with the lowest deflection (2.08 mm) despite having the highest yield load (16.6 kN), attributable to the higher relative bending stiffness of steel fibres. Among the remaining CSPs, CGFN performed better with a deflection of 3.14 mm at a yield load of 15.3 kN. This superior performance compared to CGSN is due to the flattened-end portions of FENFs, which better resist fibre slippage from the matrix compared to straight nylon fibres. While the yield point deflections of CSPs appear to be similar, they must be evaluated alongside their corresponding yield loads. GG showed the highest deflection (3.34 mm) with the lowest yield load (14.2 kN), indicating a higher deflection-to-load ratio. The addition of fibres effectively addressed the inherently higher deflection nature of GPCs.

3.3. Ductility and Stiffness

Figure 11 shows the ductility factor (ratio of ultimate to yield deflections) ranging from 7.5 to 8.7. CGFN exhibited the highest ductility (8.7), demonstrating an increased deflection range between yield and ultimate loads. This enhanced ductility results from the interlocking of FENFs with the concrete matrix (as shown in Figure 1d), which enables stress transfer until either fibre or bond failure occurs. In contrast, straight nylon and steel fibres provide less effective bonding, limiting stress transfer once matrix slippage begins. The unique shape of FENFs enables CGFN panels to maintain superior ductility through extended stress transfer capacity at peak load. Fibre-reinforced geopolymer panels (CGFN and CGSN) demonstrated greater ductility (8.7 and 8.5, respectively) compared to CC and CG, highlighting the nylon fibres' role in enhancing geopolymer concrete's deformation capacity.

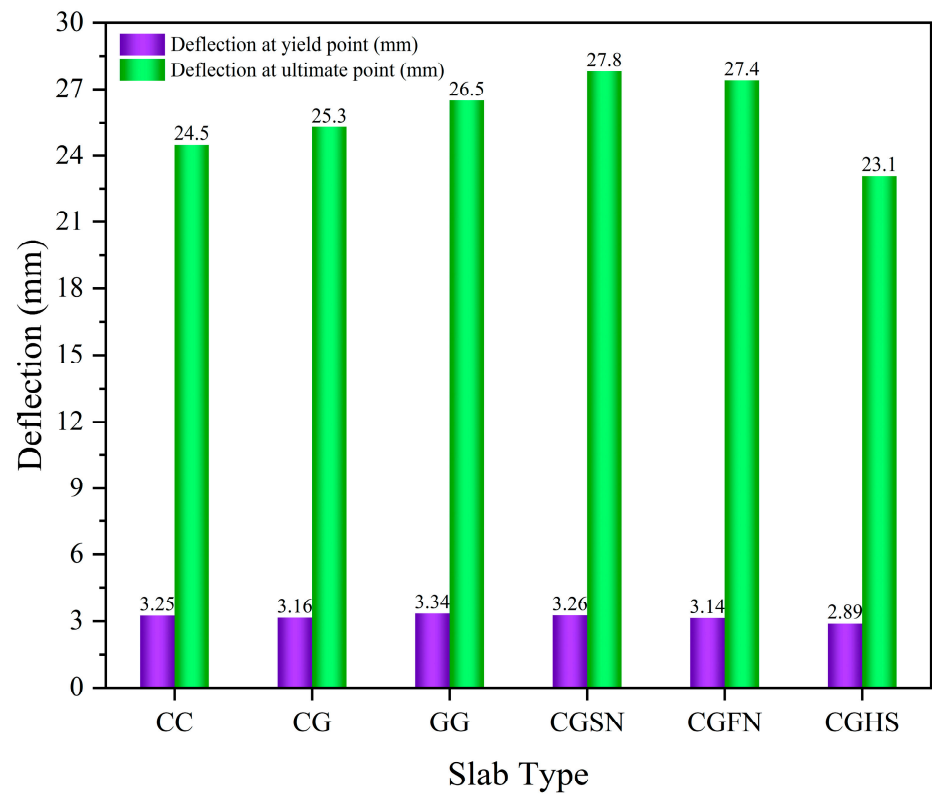


Figure 10. Deflection at yield and ultimate loads.

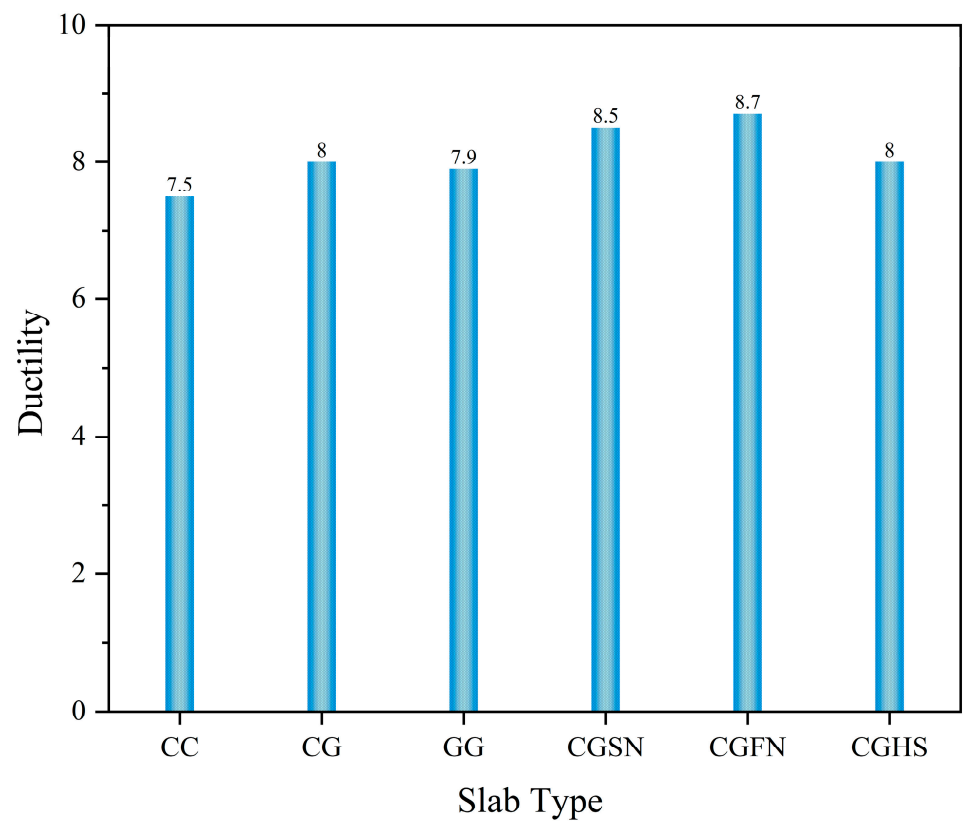


Figure 11. Ductility.

Initial stiffness measurements (Figure 12) showed that CGHS achieved the highest value of 5.76 kN/mm, significantly outperforming other CSPs due to the superior bending

stiffness of steel fibres. CGFN recorded the second highest stiffness at 4.87 kN/mm. CC and CG showed similar stiffness values of 4.6 kN/mm and 4.52 kN/mm, respectively, while CGSN achieved 4.53 kN/mm. GG exhibited the lowest initial stiffness of 4.25 kN/mm.

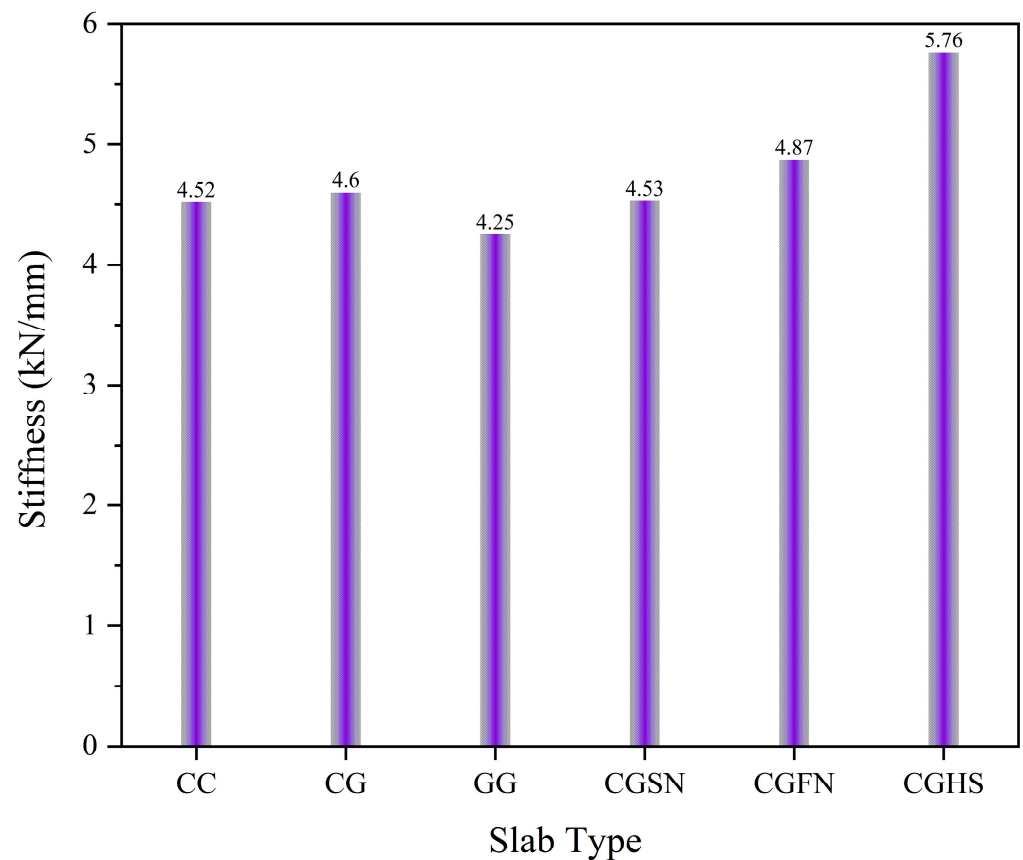


Figure 12. Initial stiffness.

CGFN and CGSN showed improved initial stiffness compared to CC, CG, and GG, indicating that nylon fibre addition enhances the geopolymer concrete's resistance to deformation. Overall, panels with fibre-reinforced geopolymer concrete bottom wythes (CGHS and CGFN) demonstrated superior initial stiffness compared to other configurations.

3.4. Crack Width Development

Figure 13 illustrates the crack widths measured while testing the slabs at the yield and ultimate loadings for each panel type.

Crack width analysis reveals important aspects of the panels' durability and serviceability. The CGHS panel exhibited the narrowest crack widths at both yield (7 mm) and ultimate (15.5 mm) points, suggesting excellent crack control properties of hooked-end steel fibres in geopolymer concrete. The GG panel showed the widest cracks at yield (12 mm) and ultimate (21 mm) points, indicating inferior crack resistance of plain geopolymer concrete. The CGSN and CGFN panels demonstrated improved crack control compared to CC and CG panels. This suggests that the addition of nylon fibres helps in distributing stresses and controlling crack propagation in geopolymer concrete. Figure 14a–f show the crack width measured at yield loadings.

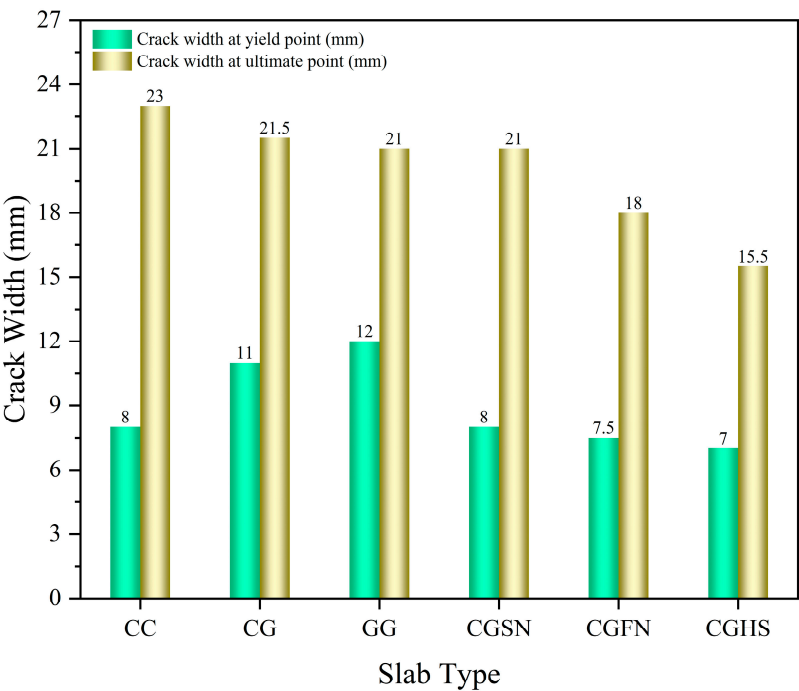


Figure 13. Crack width development vs. applied load.

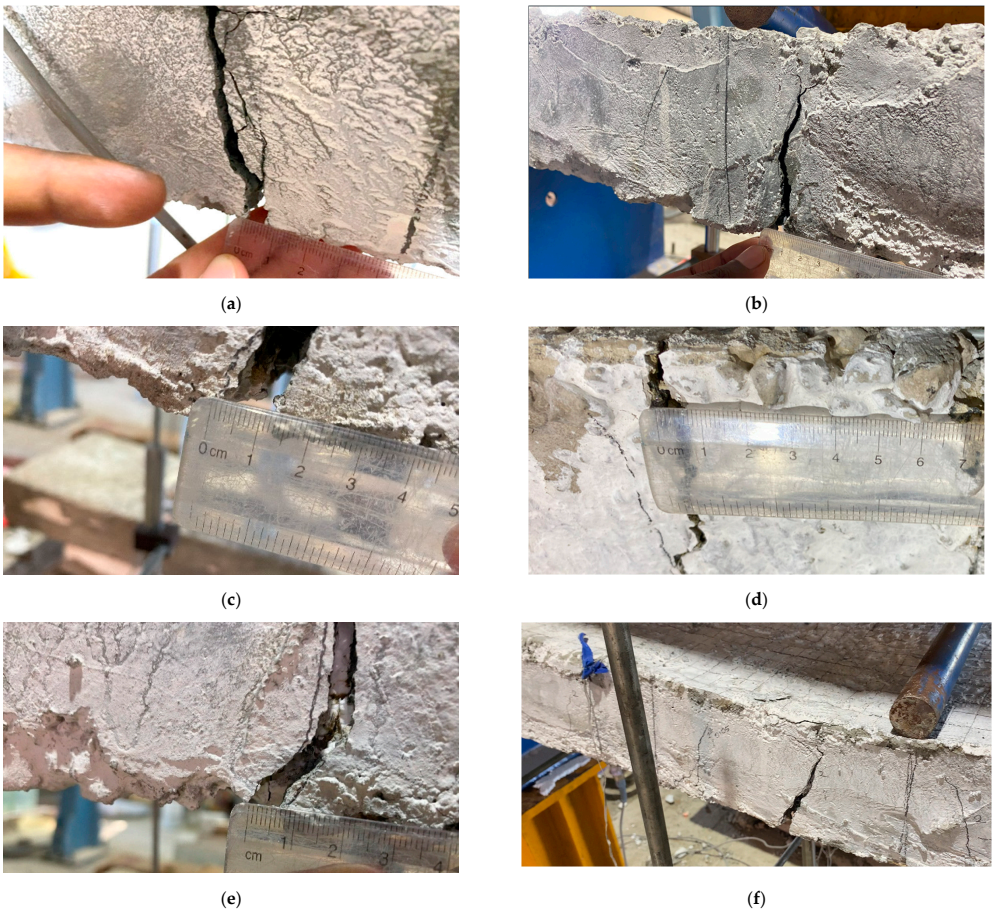


Figure 14. Crack width measured at yield loading during testing: (a) CC, (b) CG, (c) GG, (d) CGSN, (e) CGFN, and (f) CGIHS.

3.5. Toughness and Energy Dissipation

Figure 15 compares the toughness and energy dissipation of all panel types.

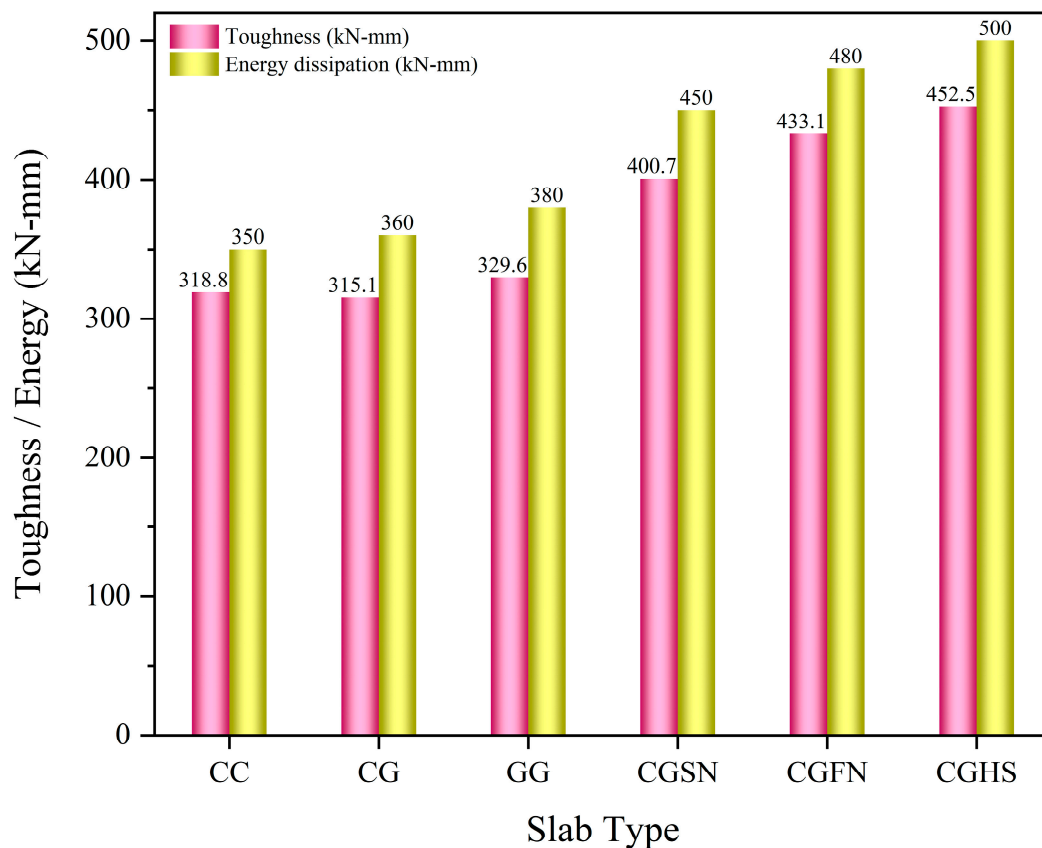


Figure 15. Bar chart comparing toughness and energy dissipation.

Toughness and energy dissipation characteristics provide insights into the panels' ability to absorb energy before failure. CGHS demonstrated the highest toughness (452.5 kN·mm) and energy dissipation (500 kN·mm), indicating the hooked-end steel fibres' capability in terms of toughness and energy dissipation. Next to the steel fibres, the nylon fibres showed significant improvement in toughness when compared with the CC and CG panels, as the CGSN and CGFN panels showed toughness values of more than 400.7 kN·mm and energy dissipation values of more than 450 kN·mm. The results indicate that the fibres play a major role in enhancing the performance of GPC in terms of toughness and energy dissipation and making GPC a suitable material for the application of CSP wythes.

It is to be noted that the toughness of the CG and GG panels is better than that of the CC panels, unlike their performances in the case of stiffness. This implies that GPC has the potential for energy dissipation which can be further enhanced by FRC.

3.6. Residual Strength

The last column of Table 5 shows the residual strengths of the CSPs and indicates that again the steel fibre-reinforced concrete is the one which carries the highest load of 27.4 kN after reaching its peak load capacity before complete failure. But the CGHS and CGSN also show significant resistance before failure, demonstrating a residual strength of 18.3 kN, which is comparatively much higher than that of the CC and CG panels. This further highlights the improvement in GPC's load-carrying capacity in extreme conditions of failure such as earthquake loads. Unlike toughness, where the CG and GG panels performed better than the CC panel, in the case of residual strength, the GG panel showed

the lowest resistance, indicating the weakness of utilising GPC directly without any fibre additions.

4. Conclusions

From the results of the experimental study conducted, the following observations can be concluded:

- The CGHS panel's (conventional concrete top wythe and geopolymer concrete with hooked-end steel fibre bottom wythe) performance remained top in all aspects, namely, yield and ultimate loads vs. corresponding deflections and crack width, stiffness, toughness, and energy dissipation capacity, except for ductility.
- Out of the remaining four panels, the effect of fibre-reinforced concrete helped the panels to show enhanced performance. Also, specifically, the CGFN panel's performance is better than that of the CGSN panel, and this indicates that the shape of the FENFs has a positive effect on concrete performance. This shall be credited to the enhanced FENFs' end anchorage-induced bonding with the concrete matrix.
- Though the GPC panels without reinforced concrete (CG and GG) performed well in terms of toughness and ductility when compared with the CC, they underperformed in terms of the yield loading and corresponding cracking. This indicates the susceptibility of durability-related problems when GPC is applied to CSPs without any fibres in it.
- The CGSN and CGFN panels indicate the positive effect of the fibres and their shape in GPC. Also, both the CGSN and CGFN panels overperformed their respective panels without fibres, as well as the conventional concrete, in all of the parameters studied. This again confirms the structural performance enhancement of the GPC due to the addition of macro nylon fibres.
- Finally, it can be concluded that to achieve the sustainability of the CSPs, it is crucial to add GPC as the wythe material; at the same time, it is essential to fulfil the structural demand for durability and flexural performance of the CSP when GPC is used. This requirement can be fulfilled through the application of macro synthetic fibres to a reasonable extent, though they do not meet the performance of steel fibres. But when the other crucial demand is the light weight of the structural elements, then it is a good choice to utilise the macro synthetic fibre.
- Future Research Directions: This study offers significant perspectives regarding the performance characteristics of composite sandwich slab panels utilising specific material applications. Further research could focus on the following:
 1. Conducting full-scale testing to validate the performance benefits observed in this study.
 2. Optimizing the properties of FENF such as its dosage and aspect ratio to best utilise it.
 3. Examining the enduring resilience and fatigue characteristics of fibre-reinforced geopolymer concrete panels under cyclic loadings.
 4. Exploring the economic feasibility and ease of manufacturing for different panel configurations.
 5. Analysing the ecological consequences and life cycle evaluation of fibre-reinforced geopolymer concrete panels with traditional concrete panels.
 6. Adopting the mix ratios to meet specific requirements such as mechanical strength and durability aspects, as the mix ratio adopted and the aspect ratio and dosage of the FENF in this study are aimed at the specific requirements of CSPs, such as ambient curing and thin wythe concreting with adequate flexural strength.

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