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Sustainable Lightweight Wall Panels: Comparative Performance Evaluation Of Polyurethane Foam Incorporated Cement Concrete And Geopolymer Concrete Under Axial And Flexural Loading

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Abstract
This study investigates the use of Polyurethane Foam (PUF) as a partial replacement for fine aggregate (0–20%) in Normal Concrete (NC) using Ordinary Portland Cement (OPC) and Fly Ash-GGBS-based Geopolymer Concrete (GPC) wall panels of size 1000 × 300 × 50 mm. All panels were reinforced using mild steel wire mesh (30 × 30 mm grid, Ø3 mm) and tested under axial compression and flexural loading to evaluate key performance metrics such as workability, strength, stiffness, and failure characteristics. Workability decreased with increasing PUF content, with the OPC slump reducing from 95 mm to 70 mm and GPC from 90 mm to 60 mm. However, GPC maintained better cohesion and pseudoplastic flow behaviour, making it more suitable for thin-section casting. GPC consistently outperformed OPC in terms of mechanical performance. At 20% PUF replacement, GPC exhibited a 26.84% higher 28-day compressive strength, and both systems remained structurally viable up to 15% PUF, maintaining compressive strength above 25 MPa and flexural strength above 3 MPa. GPC wall panels demonstrated 16-25% higher stiffness, 14-22% greater peak load capacity, and superior ductility, with gradual post-peak softening compared to OPC's brittle failure. The optimum PUF replacement was found to be 15%, which balanced strength retention with 19-22% density reduction. Furthermore, failure modes in GPC transitioned from vertical splitting to edge-corner cracking, indicating an improved crack-bridging capacity. Overall, the findings confirm that PUF-based GPC wall panels offer a sustainable and lightweight alternative that is suitable for modern construction needs and has improved structural efficiency.
Keywords: *Geopolymer concrete, Polyurethane foam (PUF), Lightweight concrete, Sustainable construction, Axial-flexural performance*

1. INTRODUCTION

The global construction industry, responsible for approximately 8% of global CO_2 emissions, is under increasing pressure to adopt greener practices [1]. This pressure is further exacerbated by the fact that the world population is expected to surpass 9.7 billion by 2050, with 70% of the population living in cities, necessitating the construction of buildings at a rapid pace and in a sustainable manner [2]. Concrete, the world's most consumed construction material, is largely dependent on Ordinary Portland Cement (OPC), which is energy-intensive and CO_2-intensive to produce [3]. Geopolymer Concrete (GPC) has come forward as a hopeful substitute to address these issues. GPC, invented by Davidovits in the 1970s, employs industrial wastes such as fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) as sources of aluminosilicate, activated with alkaline solutions to produce a hardened binder [4]. This method does not involve the high-temperature calcination associated with OPC manufacturing and hence decreases the emission of CO_2 by 60-80%. GPC not only provides better mechanical behaviour, with compressive strengths of 20-100 MPa, but is also more resistant to chemical attack and fire [5]. Nevertheless, FA-based GPC tends to require high curing temperatures for maximum development of strength. This drawback can be alleviated by a combination with GGBS, which increases reactivity at ambient temperature [6].
Lightweight concrete fulfils the twin goals of material efficiency and structural effectiveness. By substituting heavy mineral aggregates with light replacements, LWC cuts dead loads by 20-50%, allowing for slender structural sections and reduced transport emissions. Polyurethane foam (PUF) has specific benefits, such as in situ-controlled expansion that produces homogenous closed-cell voids (>60% void content), resulting in densities <200 kg/m³ and thermal conductivities 0.05-0.08 W/m·K [7]. Although PUF-integrated OPC concrete (PU-OPC) is being built, its high embodied carbon (around 900 kg CO_2-eq/tonne) is still a sustainability challenge. Combining PUF with GPC offers a highly prospective ultra-low-carbon solution [8]. Low-weight GPC with PUF addition may transform prefabricated wall panels,

essential elements of accelerated, energy-saving construction. Prefabrication introduces 40-50% shortened construction times, minimized wastage, and enhanced quality assurance, while PUF-GPC panels additionally contribute to sustainability by virtue of industrial byproduct usage and process energy efficiency.

In spite of the PUF potential in decreasing the density and improving performance of OPC and GPC composites, there are a few essential knowledge gaps preventing their large-scale utilization in structural and semi-structural wall panel uses. Firstly, there is a clear deficiency in comparative experimental results evaluating the mechanical performance of PUF-OPC and PUF-GPC composites under normalized structural conditions of loading [3]. While numerous studies have investigated individual systems, direct head-to-head comparisons, especially in realistic structural configurations, are scarce. Secondly, the complex interactions at the matrix-foam interface remain largely unexplored. Given the fundamentally different chemical processes governing binder hardening, hydration in OPC systems versus polycondensation in geopolymer systems, there is a pressing need to understand how these distinct chemistries affect PUF interfacial bonding, void stability, and crack propagation mechanisms. Finally, current research is primarily based on limited-scale samples or single-axis loading, without testing the performance of PUF-OPC and PUF-GPC composites as load-carrying members under combined flexural and axial stresses. This is necessary for their reliable and safe inclusion in real-construction applications, where the wall panels are subjected to both compressive and bending loads during service.

In response to these urgent gaps, this research evaluates a comprehensive experimental program utilising reinforced wall panels composed of PUF-OPC and FA-GGBS-based PUF-NC and GPC composites. The overall goal is to systematically design and evaluate sustainable lightweight wall panel systems with intended densities below 2000 kg/m³. This study offers a solid foundation for the successful inclusion of novel lightweight materials in sustainable construction practice. Through the provision of performance information over major mechanical and environmental parameters, the research enables architects and engineers to make credible choices when designing prefabricated wall panels and other structural applications. Besides its direct application for panel design, the research provides foundations for follow-up studies on long-term durability, thermal and acoustical performance, and life-cycle assessment of PU-foam geopolymer composite.

2. MATERIALS AND METHODS

2.1 Cement

OPC conforming to IS: 12269 and manufactured by the regional brand (Ramco, 53 grade). The typical fineness of cement ranges from 350 to 500 m^2/kg for Type I and Type III cements, respectively [9]. The physical and chemical properties of cement are to be identified and tabulated in Table 1. Figure 1 shows the OPC used for this research.

Figure 1 Cement used for this study

Table 1: The physical and chemical properties of cement

S. No	Chemical compositions	%
1	CaO	30-45%
2	SiO_2	17-38%
3	Al_2O_3	15-25%
4	M_gO	4.0-1.7%
5	Fe_2O_3	0.5-2.0%
6	Specific gravity	2.9
7	Consistency	32%

2.2Aggregates

Manufacturing sand (M-Sand) as a fine aggregate [Fig. 1(a)] was collected from a local quarry. M-Sand with a bulk density of 1750 kg/m³, a void ratio of 0.403, and a specific gravity of 2.73 was used and graded as Zone II as per IS: 383-1970 [9]. In this study, 12.5 mm particle size coarse aggregate was used and obtained from a local quarry. PUF, with a density of 150 kg/m³, was incorporated in this research as a partial replacement for fine aggregate in NC and GPC to minimize its density. The PUF content was varied at intervals of 5% (5%, 10%, 15%, and 20%) by mass of the fine aggregate to evaluate its impact on the fresh and mechanical properties of GPC. PUF is a synthetic polymer material made of organic units bonded through urethane, or carbamate, links. It is formed by the reaction of polyols and diisocyanates, leading to a cellular foam [10]. The fineness modulus of coarse aggregate is 7.16, and the specific gravity of coarse aggregate is 2.83. Tests were carried out as per IS: 2386-1968 (Part-III) [11]. Figure 2 (a, b, c) shows the M-Sand, PUF, and coarse aggregate used for this study.

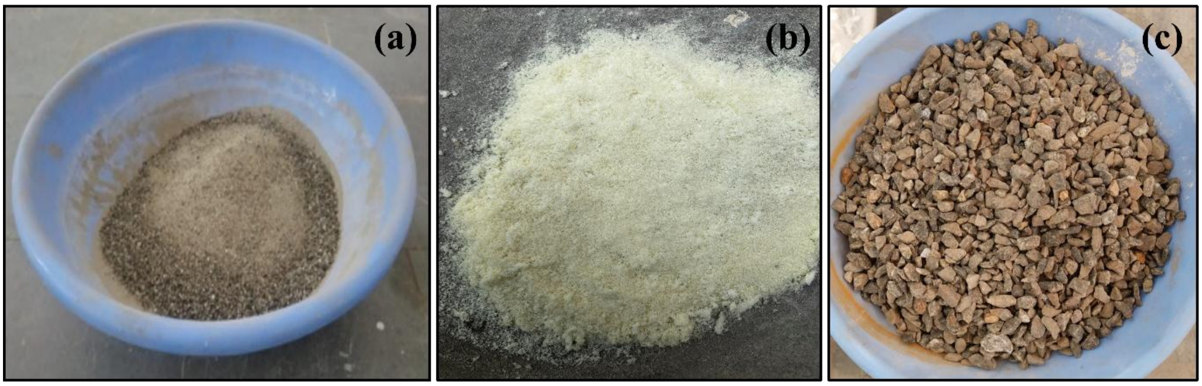

Figure 2. a) M-Sand, b) PUF- Fine Aggregate, c) Coarse aggregate

2.3 Geopolymer Binders

FA and GGBS were used as the principal binders for this study. These are two industrial by-products, thus offering a more environmentally friendly and inexpensive option than that of traditional cementitious materials. FA is the residue product formed from pulverized coal combusted in the thermal power plant [12]. GGBS is formed during the manufacture of iron and steel [13]. The FA materials were chosen based on their ability to have pozzolanic and cementitious properties, necessary for the geopolymerization reaction. These binders were mixed at a 50:50 ratio to control the geopolymerization reaction concerning having the maximum workability, optimum strength, and high durability.

2.3.1 Fly Ash

FA is a by-product, which is obtained from the Tuticorin Thermal Power plant for this study [Fig. 3 (e)]. According to ASTM C618 [14], Class-F FA with a specific gravity of 2.3 is primarily composed of silica, alumina, iron, and calcium, along with other elements. FA is a fine, powdery material, and the Class F FA used in this study was sourced from a local thermal power plant and is characterized by its low calcium content (<10%), which makes it highly suitable for geopolymer applications. The spherical shape and smooth surface of FA particles contribute to their pozzolanic reactivity and workability in concrete mixtures. FA consists of spherical particles with diameters ranging from 1 to 100 micrometres, as illustrated by Scanning Electron Microscopy (SEM) [Fig. 3 (a & b)]. This spherical shape reduces internal friction, hence making the concrete mix more workable. Particles of FA are smooth surfaced, hence better dispersion in the solution of the alkaline activator, leading to a more uniform geopolymerization reaction.

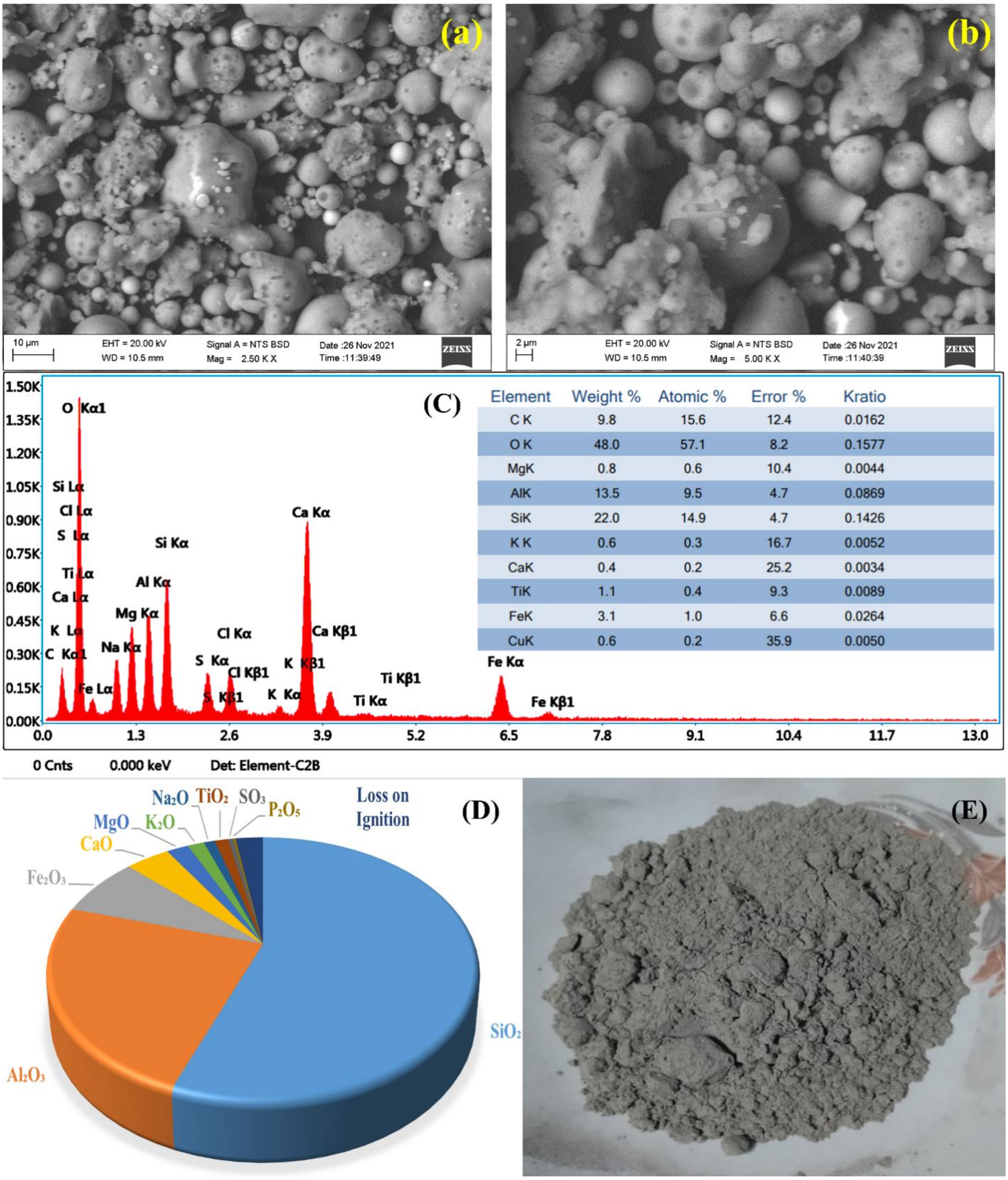

Figure 3. a, b) SEM images of FA, c) EDAX spectra of FA, d) Chemical composition of FA from XRF and e) Original FA

The microstructure of FA showed a uniform distribution of spherical particles with little agglomeration. The smooth surface and spherical morphology of FA enhance the formation of a dense and compact geopolymer matrix, which in turn improves the mechanical properties and durability of the concrete. The spherical ash particles of FA work as micro-aggregates and fill up the voids between coarse and fine aggregates, thereby improving the density and also the strength of the concrete. The chemical constituents in FA were characterized by XRF [Fig. 3 (d)]. There were major oxides, namely SiO_2 (54%), Al_2O_3 (26%), and Fe_2O_3 (8%). Silica and alumina were rich in the FA, found from elemental composition study, Energy Dispersive X-ray analysis (EDAX) [(Fig. 3.c)], and these contents are crucial in that they react with the activator to form an aluminosilicate three-dimensional network.

2.3.2 GGBS

GGBS is a by-product acquired from the JSW steel industry for this study [Fig. 4 (e)]. It has a specific gravity of 2.9. GGBS is the product of granulated blast furnace slag from iron and steel. The slag is cooled rapidly by quenching it with water to obtain a glassy, granular product. GGBS has a high content of calcium and latent hydraulic properties that make it a superior supplementary cementitious material [15]. The angularity of GGBS particles results in the development of a dense and interlocked matrix, thus increasing the compressive strength of GPC. Granular GGBS helps to pack particles in a better manner and, thus, minimizes the porosity of concrete, enhancing its durability [16]. XRF analysis shows that GGBS contains significant amounts of CaO (38%), SiO_2 (32%), and Al_2O_3 (13%) [Fig. 4 (d)]. The high calcium content in GGBS contributes to its hydraulic reactivity, which enables it to react with water and alkaline activators to form cementitious compounds. The presence of silica and alumina [Fig. 4 (c)] in GGBS also facilitates the geopolymerization process, complementing the properties of FA. SEM studies of GGBS revealed heterogeneity in their microstructure, consisting of irregular-shaped particles and asperity-rich surface texture [Fig. 4 (a, b)]. The angularities of GGBS particles tend to create an interlocking bond between the matrix and aggregates thereby increasing the matrix-aggregate interface bond strength of the geopolymer. The asperity-rich nature of the particles of GGBS provides much more surface area for the reactant alkaline activator in order to result in a fully dense and less porous geopolymer matrix. GGBS acts as an additional binder within the GPC; it provides supplemental calcium ions for the formation of C-S-H gel. It supports the aluminosilicate gel created by FA, and, thus, provides a hybrid geopolymer matrix with improved mechanical properties. The high reactivity of GGBS enables early setting and hardening of the GPC. Therefore, such applications that are related to high strength at early ages can use GPC [17]. The ratio of FA and GGBS was selected to be 50:50 for optimizing the geopolymerization process, and a balance between workability, strength, and durability is obtained. The spherical particles of FA improve the workability of the concrete mix, and the angular particles of GGBS enhance the density and compressive strength of the hardened concrete [18].

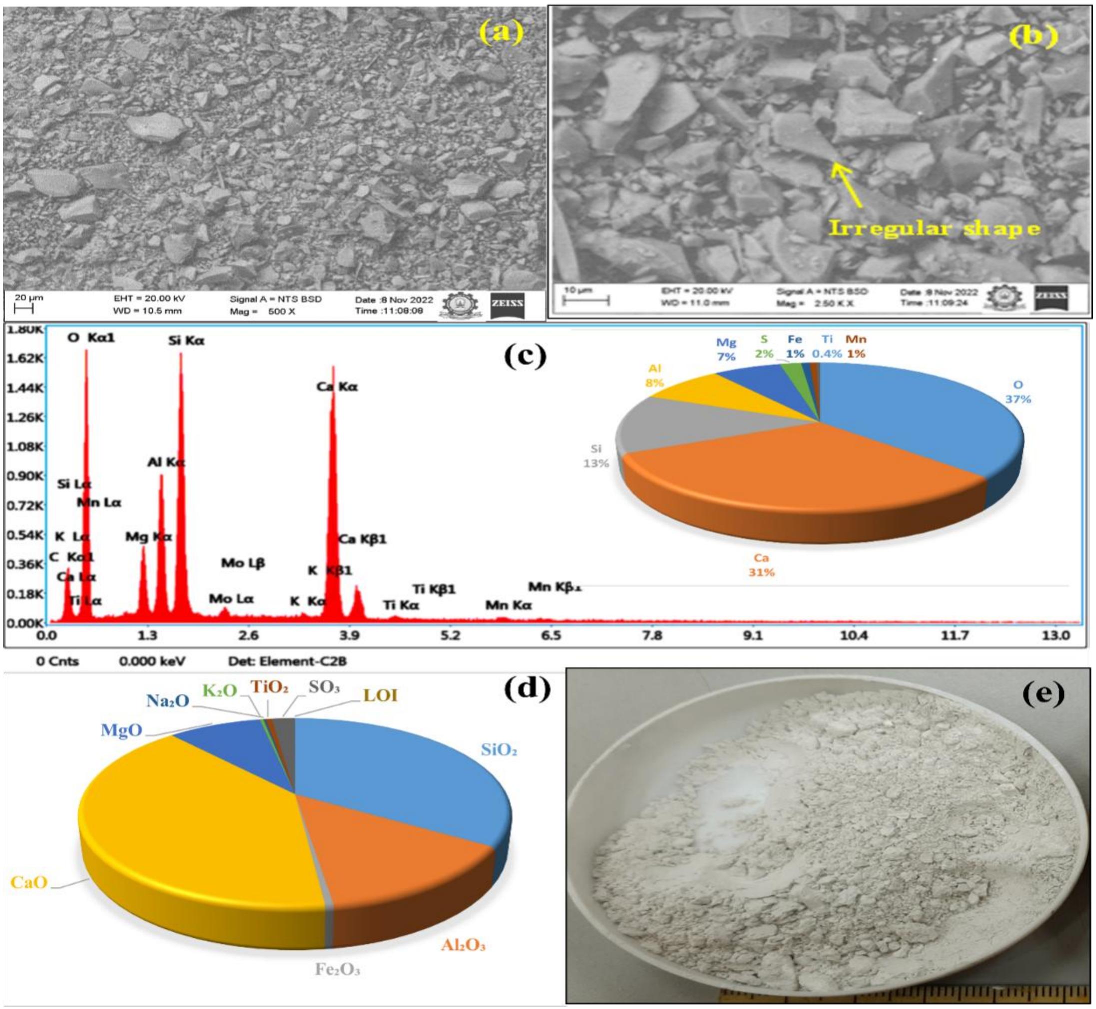

Figure 4. a, b) SEM images of GGBS, c) EDAX spectra of GGBS, d) Chemical composition of GGBs from XRF and e) Original GGBS

2.4 Geopolymer Alkaline Activators

Alkaline activators are one of the essential constituents in the geopolymerization process, as they initiate the dissolution of aluminosilicate precursors, such as FA and GGBS, thereby promoting the polymerisation reaction. The type of alkaline activators, concentration, and the ratio at which they are mixed determine the workability, setting time, mechanical properties, and long-term durability of GPC. In this research, a NaOH and Na_2SiO_3 alkaline activator was applied to prepare the PUF-based GPC wall panels.

2.4.1 Sodium Hydroxide

NaOH is an alkaline substance that has a strong alkaline character. It serves as a very important agent that breaks down the SiO_2 and Al_2O_3 phases existing in FA and GGBS [19]. This process of dissolution generates reactive species of silica and alumina, which then contribute to the geopolymerization process to produce an aluminosilicate network. In the present work, NaOH solutions were prepared from pellets in distilled water. The desired concentration of 12 M was maintained while preparing the NaOH solution, which was used to study its effect on the workability, setting time, and compressive strength of GPC. Dissolution of NaOH in water is an exothermic reaction, which involves the release of a lot of heat. The NaOH solution was prepared at least 24 hours before use and kept in sealed plastic containers to avoid carbonation and moisture absorption from the atmosphere.

2.4.2 Sodium Silicate

Na_2SiO_3 is one of the essential components of the alkaline activator system, providing additional SiO_2 that improves the polymerization process. The excess silica in the system helps in the formation of a denser and stronger geopolymer matrix by enhancing the development of N-A-S-H gels. Geopolymerization effectiveness is based on the chemical composition of sodium silicate, especially the SiO_2/Na_2O ratio [20]. Optimal ratios ensure efficient activation of the aluminosilicate precursors, and it allow the geopolymer gel to develop suitably. In this research, the alkaline activator of geopolymerization was prepared by mixing a commercial sodium silicate solution with a mass ratio (SiO_2/Na_2O = 3.2) and NaOH solution at a constant mass ratio of 1:2.15 (NaOH: Na_2SiO_3). This mixture produced a highly alkaline solution with a low bulk SiO_2/Na_2O molar ratio of 0.46, maximizing the solution for fast dissolution of aluminosilicate precursors.

2.5 Superplasticizer

Superplasticizers (SP) are essential admixtures in modern concrete technology, particularly in GPC, where the high viscosity of the mix can pose challenges to workability [21]. In this study, a 1.2% SP (by weight of the binder) was added to the GPC mix to enhance its workability and ensure a homogeneous mixture. SP used was MasterGlenium SKY 8233 (MGS), a commercially available product from Astra Chemicals. This superplasticizer is based on polycarboxylic ether polymer technology, which is known for its high performance, durability, workability, and water-reducing capabilities. The addition of a SP was particularly critical in this study due to the increased viscosity induced by the PUF and the high molarity of the NaOH solution. The key characteristics of MGS are outlined in Table 2.

Table 2: Characteristics of MasterGlenium SKY 8233 (MGS)

Properties	Superplasticizer
Product name	Polycarboxylic ether
Specific gravity	1.08 at 25^0C
pH	≥ 6.6
Chloride ions	< 0.24 %

2.6 Reinforcement – Steel Wire Mesh

In this work, steel wire mesh (3 mm diameter) was adopted as the reinforcing material for NC and GPC wall panels. The applied reinforcement was considered to improve tensile and flexural properties, especially for axial loading. To determine the effect on the structural performance of wall panels, a single layer of steel wire mesh was used. Reinforcement is added to improve tensile and flexural strength in concrete. The grid size was 30 mm × 30 mm, suitable for distributing loads evenly and providing adequate reinforcement. The steel wire mesh was placed at the mid-depth of the panel as single-layer reinforcement. During casting, the mix was poured into the mould in layers, ensuring that the mesh remained properly positioned and fully embedded within the concrete. Care was taken to avoid any disturbance to the mesh during both pouring and compaction. A vibrating table was employed to compact the concrete efficiently, thereby eliminating air voids and ensuring a strong bond between the mesh and the surrounding concrete matrix.

2.7 Mix Design

2.7.1 OPC Concrete

The proportioning quantities for the OPC-based lightweight wall panels with PUF are shown in Table 3. All mixes were formulated using a fixed cement content of 400 kg/m³, with coarse aggregate held at 1,200 kg/m³. The water content was maintained constant at 180 kg/m³, giving a water-to-cement (w/c) ratio of 0.45, and a polycarboxylate ether-based superplasticizer was introduced at the dosage of 1.20% by weight of cement to provide improved workability and cohesion in highly surface-area constituent-bearing constituents such as PUF. The prime experimental variable of this mix series was the step-by-step volumetric substitution of M. Sand as the fine aggregate, supplemented with rigid, closed-cell PUF particles in step increments of 5%, 10%, 15%, and 20% by volume. The control mix (NCWPP0) used only M. Sand at 700 kg/m³ without any addition of PUF. For the modified mixes (NCWPP5 to NCWPP20), PUF replaced part of M. Sand on a volume equivalent basis, with mass adjustments to account for the significantly lower density of PUF (150 kg/m³) compared to M. Sand (around 1750 kg/m³). In view of the volume reduction during crushing, for instance, 70 kg of PUF (from NCWPP10) was considered equivalent to 0.47 m³ using a crushed density of 150 kg/m³, and this volume was added to the control mix volume (1 m³), then normalized against the control mix density (2485 kg/m³) to maintain consistency in mix proportioning. This approach keeps a uniform total volume of fine aggregate in each mix so that there is a controlled study of the effect of PUF on important performance parameters like workability, fresh and hardened density, and mechanical strength.

Table 3. Mix Ratio for NC Wall Panels

Mix ID	Cement (kg/m³)	Fine aggregate (kg/m³)		Coarse aggregate (kg/m³)	Water (kg/m³)	SP @1.2% (kg/m³)
		M.Sand	PUF			
NCWPP0	400	700	0	1200	180	4.8
NCWPP5	400	665	35	1200	180	4.8
NCWPP10	400	630	70	1200	180	4.8
NCWPP15	400	595	105	1200	180	4.8
NCWPP20	400	560	140	1200	180	4.8

2.7.2 GPC

The GPC mixes, summarized in Table 4, were designed using a blended binder system consisting of FA and GGBS, each at 185 kg/m³. These industrial by-products were selected for their synergistic behaviour, with FA providing long-term strength development and GGBS contributing to early-age reactivity. The coarse aggregate was kept constant at 1248.15 kg/m³, ensuring a uniform granular skeleton across all geopolymer mixes. The fine aggregate system consisted of M. Sand, partly replaced by PUF particles at 5% to 20% by volume while maintaining a constant total fine aggregate volume. The alkaline activator solution comprised 12 M NaOH at 57.86 kg/m³ and Na_2SiO_3 at 124.34 kg/m³, yielding a Na_2SiO_3/NaOH mass ratio of 2.15:1 and an activator-to-binder (A/B) ratio of 0.49. This composition was selected based on prior optimization studies that demonstrated enhanced geopolymerization kinetics and strength performance under this molarities. To address potential challenges in workability, especially with PUF's hydrophobicity and light mass, a superplasticizer was incorporated at 1.20% by total binder weight. The same method of volumetric replacement used in NC mix was maintained here to ensure a uniform total volume of fine aggregate in all mixes.

Table 4. Mix ratio for GPC wall panels

Specimen ID	FA (kg/m^3)	GGBS (kg/m^3)	Fine aggregate (kg/m^3)	PUF (kg/m^3)	Coarse aggregate (kg/m^3)	NaOH (kg/m^3)	NaOH Molarity	Na_2SiO_3 (kg/m^3)	SP @1.2% (kg/m^3)
GPWPP0	185	185	781.48	0	1248.15	57.86	12	124.34	4.44
GPWPP5	185	185	742.40	39.07	1248.15	57.86	12	124.34	4.44
GPWPP10	185	185	703.33	78.14	1248.15	57.86	12	124.34	4.44
GPWPP15	185	185	664.25	117.22	1248.15	57.86	12	124.34	4.44
GPWPP20	185	185	625.18	156.29	1248.15	57.86	12	124.34	4.44

2.8 Concrete preparation

2.8.1 Preparation of Normal Concrete

For the OPC concrete mixes, the mixing procedure was modified to include the hydration-based setting and strengthening mechanism. Dry materials including OPC, M. Sand, coarse aggregate, and PUF particles were first mixed in the same 100-liter pan mixer for 2.5 minutes for homogeneous dispersion. After this, a pre-mixed combination of water and a polycarboxylate ether-based SP was introduced over the subsequent 3-minute wet mixing period. A final 2-3-minute high-shear mixing step was performed to provide a cohesive and uniform matrix and to counteract the tendency of the PUF particles to float due to their low specific gravity and hydrophobic nature. The workability of fresh concrete was determined by tests conforming to ASTM standards. Slump test (ASTM C143) determined workability with specified slump values [22]. The NC concrete was filled into cubes, cylinders, prisms, and wall panel moulds (1000 × 300 × 50 mm). Fresh concrete was tamped lightly and the table vibrated to expel entrapped air. Specimens were stored for 24 hours in moulds at room temperature. After demoulding, all the OPC specimens were cured under normal moist curing conditions through immersion in water tanks held at 23 ± 1°C up to the test age of 7 and 28 days with continuous hydration to facilitate the development of strength.

2.8.2 Preparation of Geopolymer Concrete

GPC mixes were cast under a standardized procedure to guarantee homogeneity and uniform reactivity in all the specimens. The dry materials, FA, GGBS, M.Sand, coarse aggregate, and PUF were pre-measured and mixed in a 100-liter capacity pan mixer for 2.5 minutes to attain an even distribution. The alkaline activator solution made up of 12 M NaOH and Na_2SiO_3 in the mass ratio of 1:2.15 was prepared at least 24 hours in advance to enable thermal equilibrium and stabilization of viscosity. This solution, in combination with an SP, was then incrementally added to the dry mix over a 3-minute wet mixing period. A final 2–3-minute high-shear mixing interval was undertaken in order to fully disperse low-density PUF particles and prevent floating, clumping, or segregation. Immediate post-mix fresh GPC properties were assessed through workability tests. Deformability was measured through slump flow testing. The conditioned GPC was then moulded into routine mechanical test moulds, such as 100 mm cubes (compressive strength), 150 × 300 mm cylinders (split tensile strength), and 100 × 100 × 500 mm prisms (flexural strength). Following casting, the specimens were wrapped in plastic sheets to prevent initial loss of moisture and left to cure under ambient conditions for 24 hours.

2.9 Casting Wall Panels

The panels (1000 mm × 300 mm × 50 mm) were reinforced with a single layer of mild steel wire mesh (30 mm × 30 mm grid, 3 mm diameter) and tested under axial compression and flexural loading. Before casting, the moulds were thoroughly cleaned to remove any residues that could affect the surface finish of the panels. A thin layer of oil was applied to the inner surfaces of the moulds to facilitate easy demoulding after curing. Proper alignment and rigidity of the moulds were ensured to maintain dimensional accuracy and prevent warping or deformation during the casting process. The mesh was positioned at the mid-depth of the panel to enhance structural performance in applications with moderate load-bearing demands. Care was taken to maintain uniformity and ensure the mesh remained properly embedded during the pouring and compaction of the concrete mix. Figure 5 illustrates the wall panel preparation setup and the completed wall panels.

Figure 5: Wall panels preparation setup and prepared wall panels

2.10 Test setup for wall panels

In order to analyse the structural response of PUF-based NC and GPC wall panels under axial compression loading, a controlled test floor use of a high-capacity hydraulic universal testing machine with a test load capacity of 500 KN were used. Each panel specimen was positioned carefully in a vertical orientation within the test frame to maintain a uniform distribution of stress and avoid eccentric loading. Before testing, all the wall panels were whitewashed with a thin coat of white cement to enhance crack visibility when applying the load. Three dial gauges were used to accurately capture the deformation behaviour: one positioned at the top to measure axial deformation, one at the center to monitor buckling, and one at the side of the specimen to measure lateral movement. The loading was done in incremental load of 0.25 tons (250 kg), and the deformation was closely monitored along the loading progress. The entire setup, such as Dial Gauge positioning and loading mechanism, is shown in Figure 6 (a, b).

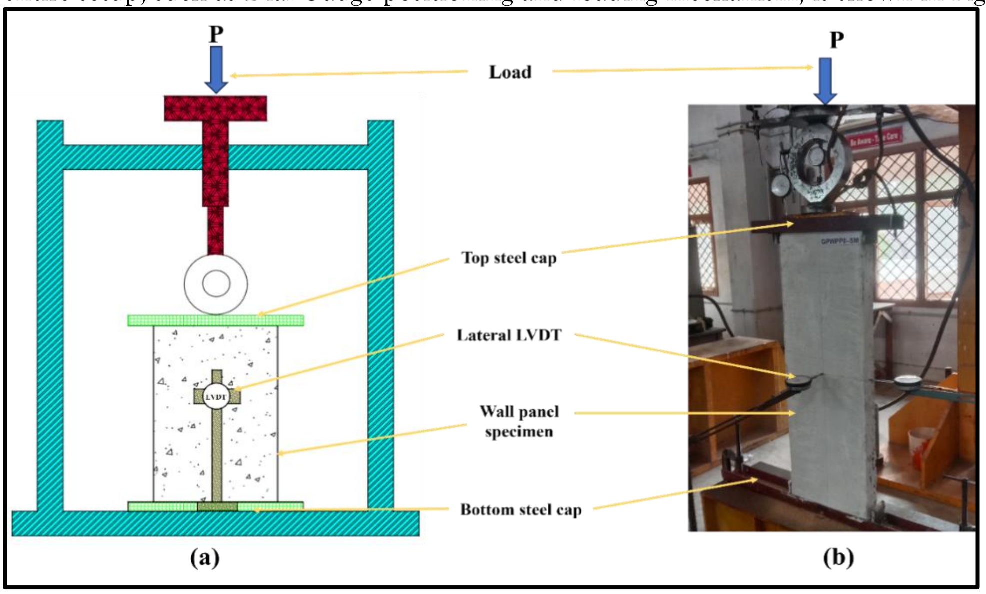

Figure 6. Test setup (a) Schematic (b) Experimental

3 RESULTS AND DISCUSSION

The incorporation of PUF for fine aggregate replacement in NC and GPC wall panels is a strategic advancement aimed at improving sustainability while fulfilling essential structural efficiency requirements in contemporary construction. These results and discussions provide a detailed experimental analysis of the axial and flexural performance of PUF-modified lightweight panels, extensively investigating the impact of binder chemistry and PUF replacement percentages (0–20%).

3.1Fresh Workability behaviour of PUF-based GPC and OPC Concrete

The incorporation of PUF to replace partial fine aggregate strongly influenced the fresh-state rheological behaviour of both GPC and NC concrete systems. As seen in Table 5, a clear trend of decreasing slump values was observed with increasing PUF content across all mixes. This long-term reduction is attributed to the inherent material characteristics of PUF, including ultra-low density (~35 kg/m³), hydrophobic closed-cell structure, and porous particle morphology [23]. These characteristics lead to the presence of trapped air voids and reduced paste-aggregate adhesion, thereby increasing internal friction and reducing the fluidity of the mix [24]. NC mixes exhibited a more significant reduction in slump for more than 15% PUF. For instance, slump decreased from 95 mm in NCWPP0 (0% PUF) to 70 mm in NCWPP20 (20% PUF), showing a 26.3% slump loss. In contrast, the GPC blends showed greater toughness, with the slump decreasing from 90 mm in GPWPP0 to 60 mm in GPWPP20, a decrease of 33%. While the percentage reduction in slump is slightly greater in GPC, practical usage favours the geopolymer system due to its improved paste-aggregate bond and pseudoplasticity.

Furthermore, the maintenance of slump in the GPC mixes indicates enhanced handling during field conditions, and most notably in the case of thin-section wall panel, where segregation-free form filling and flowability are paramount. The combination of alkaline paste chemistry and shear-thinning rheology of GPC facilitates better placement even when the void ratio in the matrix is increased due to the use of lightweight fillers such as PUF. Overall, while PUF addition is certain to reduce workability in NC and GPC concretes, the geopolymer system shows improved conformability with light polymeric fillers. This is attributed to improved cohesion between particle and binder, lower sensitivity to water, and better flow at low shear. Results confirm the efficacy of PUF-based GPC in non-structural and semi-structural precast members, particularly where lightness and heat insulation are prioritised at the expense of placing performance.

Table 5 The fresh properties of GPC and OPC mixes

PUF replacement	GPC Slump (mm)	GPC Workability	NC Slump (mm)	NC Workability
0%	90	Good	95	Excellent
5%	80	Medium	90	Good
10%	75	Medium	85	Medium
15%	70	Medium	75	Medium
20%	60	Medium	70	Medium

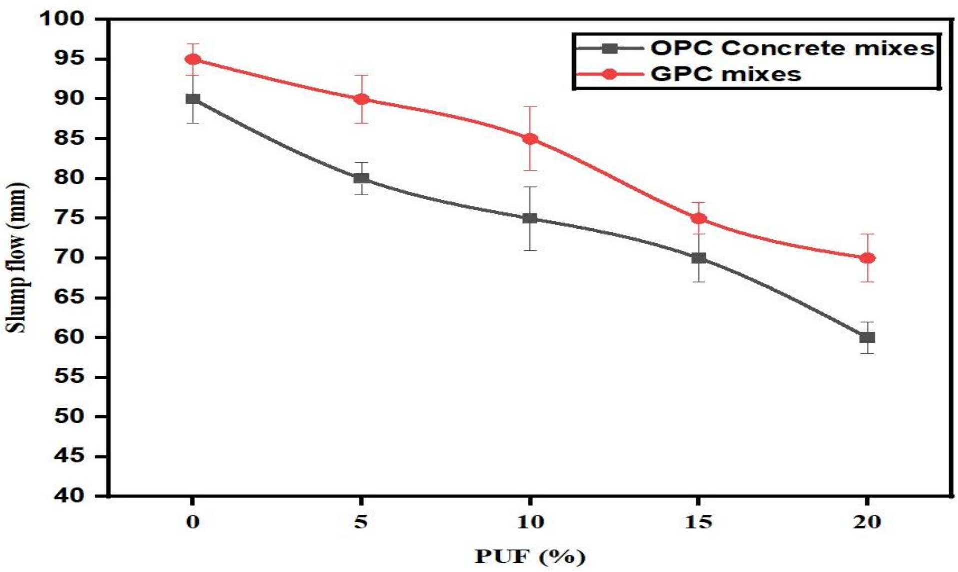

Figure 7: Workability of OPC and GPC wall panel mixes

3.2Mechanical properties of PUF-based OPC concrete and GPC

The findings evidently illustrate a progressive reduction in all strength aspects with the increment in PUF replacement from 0% to 20%, a scenario that remains consistent across both binder systems as seen in Table 4. This reduction is anticipated due to the inherent characteristics of PUF, such as its relatively low density (~150 kg/m³), hydrophobic closed-cell structure, and porous morphology, which displace stiffer mineral aggregates and compromise the overall matrix integrity and load resistance. Nevertheless, GPC consistently outperforms NC in all strength categories, attesting to the superior binding efficiency of geopolymer gels in accommodating lightweight inclusions like PUF. With respect to compressive strength, the NC control mix (NCWPP0) reached a 28-day strength of 37.58 MPa, which declined to 22.50 MPa at 20% PUF — representing a 40.1% reduction. The 7-day compressive strength similarly fell from 29.16 MPa to 15.68 MPa, marking a 46.2% drop. In comparison, GPC mixes demonstrated better resistance; the control mix (GPWPP0) recorded a 28-day compressive strength of 40.92 MPa, reducing to 26.84 MPa at 20% PUF — a 34.4% reduction. Its 7-day strength dropped from 31.28 MPa to 17.55 MPa (43.9% decrease), showing better early strength retention than NC. Tensile strength followed a similar trend. The 28-day split tensile strength of NC decreased from 2.84 MPa to 1.64 MPa, indicating a 42.3% reduction, while the 7-day strength decreased from 2.58 MPa to 1.45 MPa (43.8%). GPC, on the other hand, retained higher values — from 3.74 MPa to 2.32 MPa over 28 days and 3.32 MPa to 2.00 MPa at 7 days. This persistent tensile strength superiority (about 30–40%) is attributed to the strong encapsulation of PUF within the cohesive geopolymer matrix formed by sodium aluminosilicate gelation. Flexural strength also showed noticeable reduction in NC mixes, from 3.72 MPa (NCWPP0) to 2.36 MPa (NCWPP20), reflecting a 36.6% decrease at 28 days. At 7 days, it dropped from 3.58 MPa to 2.18 MPa (39.1% reduction). GPC outperformed NC in all mixes, with the flexural strength decreasing from 4.88 MPa to 3.10 MPa at 28 days — consistently yielding 0.6 to 1.0 MPa higher values than NC. This supports the notion that GPC provides improved ductility and crack-bridging capacity due to the tough, continuous gel-phase matrix, even in the presence of polymeric inclusions. Notably, both GPC and NC retained compressive strength above 25 MPa and flexural strength above 3 MPa at 10–15% PUF replacement levels, affirming their suitability for prefabricated wall panel applications at these replacement thresholds.

Table .6: Mechanical properties of GPC and OPC concretes

Specimen ID	Compressive Strength (MPa)		Split Tensile Strength (MPa)		Flexural Strength (MPa)	
	7th Day	28th Day	7th Day	28th Day	7th Day	28th Day
NCWPP0	29.16 ± 0.6	37.58 ± 0.8	2.58 ± 0.08	2.84 ± 0.09	3.58 ± 0.10	3.72 ± 0.11
NCWPP5	25.63 ± 0.5	33.83 ± 0.7	2.13 ± 0.07	2.63 ± 0.08	3.36 ± 0.08	3.54 ± 0.10
NCWPP10	22.71 ± 0.4	31.16 ± 0.6	2.08 ± 0.06	2.41 ± 0.07	3.10 ± 0.07	3.21 ± 0.09
NCWPP15	20.54 ± 0.3	28.25 ± 0.5	1.92 ± 0.05	2.18 ± 0.06	2.72 ± 0.06	2.96 ± 0.08
NCWPP20	15.68 ± 0.3	22.50 ± 0.5	1.45 ± 0.05	1.64 ± 0.05	2.18 ± 0.06	2.36 ± 0.07
GPWPP0	31.28 ± 0.7	40.92 ± 0.9	3.32 ± 0.10	3.74 ± 0.11	4.72 ± 0.12	4.88 ± 0.13
GPWPP5	27.44 ± 0.6	36.80 ± 0.8	3.09 ± 0.09	3.42 ± 0.10	4.22 ± 0.11	4.44 ± 0.12
GPWPP10	24.82 ± 0.5	34.17 ± 0.7	2.68 ± 0.08	3.25 ± 0.09	3.82 ± 0.10	4.09 ± 0.11
GPWPP15	22.85 ± 0.4	31.56 ± 0.6	2.42 ± 0.07	2.93 ± 0.08	3.48 ± 0.09	3.76 ± 0.10
GPWPP20	17.55 ± 0.4	26.84 ± 0.6	2.00 ± 0.07	2.32 ± 0.07	2.82 ± 0.08	3.10 ± 0.09

3.3Load-Deformation Behaviour of Wall Panels

This section presents an in-depth discussion of the load-deformation behaviour of wall panel specimens, comparing normal concrete wall panels (NCWPP) and geopolymer wall panels (GPWPP) prepared with varying percentages of PUF as a fine aggregate replacement (0% to 20%). The discussion is structured around the data presented in Table 7 and the corresponding Load vs. Deformation curves and failure pattern shown in Figure 8 and Figure 9. These results provide critical insights into the mechanical performance, stiffness characteristics, and ductility responses of the tested wall panels.

Table 7: Summary of axial loads and deformations.

Load (Ton)	Deformation mm									
	NCWPP0	GPWPP0	NCWPP5	GPWPP5	NCWPP10	GPWPP10	NCWPP15	GPWPP15	NCWPP20	GPWPP20
0	0	0	0	0	0	0	0	0	0	0
1	0.62	0.69	0.63	0.685	0.6	0.682	0.61	0.68	0.55	0.67
2	1.3	1.32	1.35	1.31	1.4	1.33	1.48	1.3	1.25	1.28
3	2.07	2.06	2.15	1.98	2.2	1.99	2.33	1.9	2	1.85
4	2.87	2.65	2.95	2.54	3	2.47	3.12	2.43	2.8	2.35
5	3.65	3.3	3.75	3.14	3.85	2.99	3.98	2.97	3.6	2.88
6	4.43	3.97	4.55	3.77	4.7	3.58	4.85	3.57	4.4	3.45
7	5.21	4.7	5.35	4.42	5.5	4.19	5.64	4.14	5.2	4
8	6.12	5.42	6.2	5.05	6.25	4.74	6.39	4.68	6	4.52
9	6.84	6.18	6.95	5.67	7	5.43	7.11	5.15	6.75	4.98
10	7.7	7.09	7.8	6.44	7.75	5.89	7.82	5.78	7.5	5.6
11	8.65	7.9	8.7	7.08	8.55	6.48	8.48	6.26	8.2	6.1
12	9.66	8.75	9.7	7.77	9.35	6.98	9.11	6.78	8.9	6.6
13	10.58	9.48	10.65	8.41	10.15	7.35	9.77	7.34	9.6	7.15
14	11.74	10.25	11.8	9.06	10.95	7.74	10.37	7.86	10.3	7.7
15	12.84	10.95	12.9	9.67	11.8	8.16	11.05	8.38	11.2	8.2
16	14.16	11.59	14.1	10.24	12.7	8.87	11.75	8.88	12.1	8.7
17	15.48	12.23	15.3	10.8	13.7	9.46	12.38	9.37	13.2	9.2
18	-	12.9	-	11.36	-	9.95	12.98	9.82	14	9.65
19	-	13.55	-	11.91	-	10.34	13.48	10.21	-	10.5
20	-	14.18	-	12.43	-	11.02	-	10.59	-	11.4
21	-	-	-	-	-	11.31	-	10.9	-	-
22	-	-	-	-	-	-	-	11.25	-	-

3.4 Initial Stiffness and Elastic Response

As evident from Table 7, the initial portion of the load-deformation curves shows a nearly linear relationship between load and deformation, indicating elastic behaviour. For NCWPP0 and GPWPP0 specimens, the deflections at a load of 5 Ton were approximately 3.65 mm and 3.3 mm, respectively. This highlights that geopolymer panels exhibited marginally higher stiffness than their normal concrete counterparts at the same PUF replacement level. Interestingly, with increasing PUF replacement (5% to 20%), a gradual increase in initial deflection was observed across both concrete types. For instance, at 5 Ton, NCWPP20 exhibited a deflection of 3.6 mm, and GPWPP20 recorded 2.88 mm. This trend confirms that the inclusion of lightweight PUF particles reduces the composite stiffness due to lower density and weaker interfacial bonding compared to conventional fine aggregates.

3.5 Peak Load and Ultimate Load Capacity

NCWPP0 achieved the highest peak load of approximately 17 Ton at 15.48 mm deformation, while GPWPP0 reached a slightly lower peak of 20 Ton at around 14.18 mm deformation. This slight reduction in geopolymer panels can be attributed to the inherent differences in binder composition but also demonstrates the ability of geopolymer matrices to maintain load-carrying capacity even with a more brittle base composition. As PUF replacement increased, peak load capacities generally declined. For example, NCWPP10 reached a maximum load of approximately 17 Ton, while GPWPP10 achieved about 21 Ton. Notably, NCWPP20 failed prematurely and did not sustain beyond 18 Ton, indicating a significant loss of load-carrying capacity at higher PUF content. Despite this trend, GPWPP panels consistently showed relatively higher load-bearing performance at each replacement level compared to NCWPP panels, emphasizing the potential of geopolymer matrices to mitigate the adverse effects of lightweight aggregate incorporation.

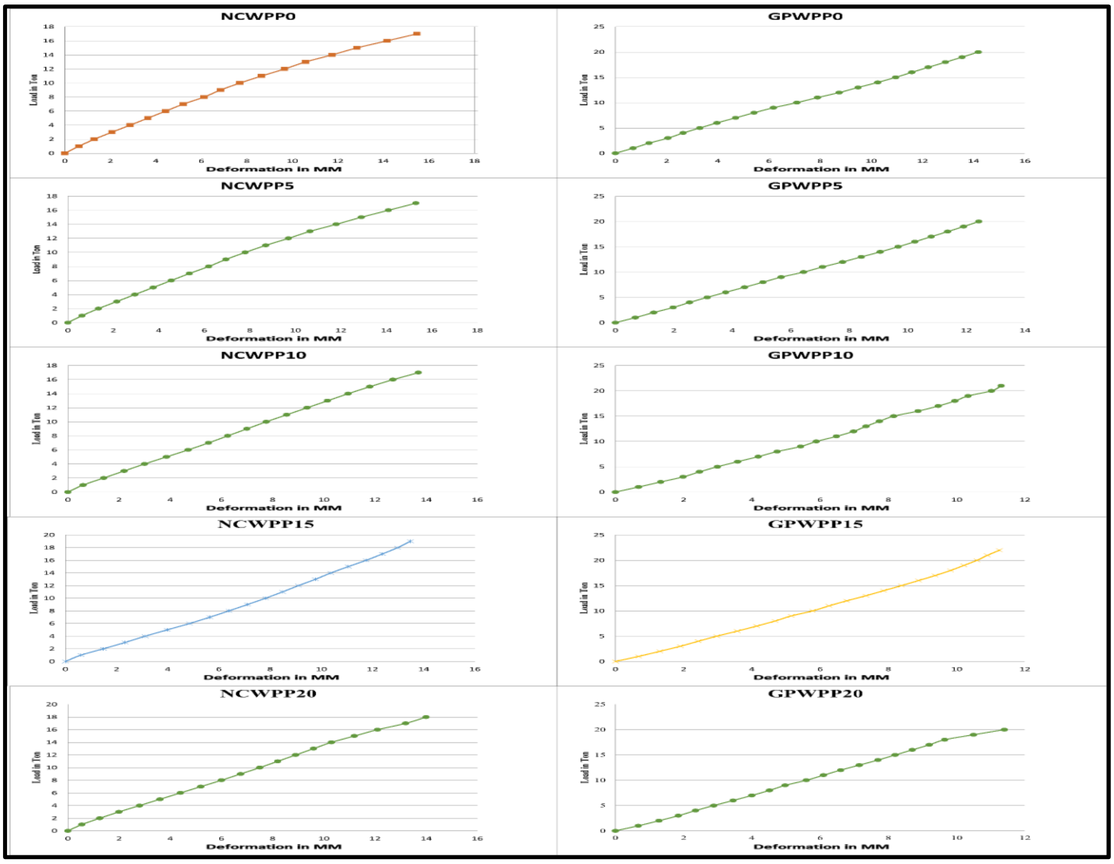

Figure 8: Combined Load vs. Deformation Curves for NCWP and GPWP Wall Panels at Various PUF Replacement Levels (0%, 5%, 10%, 15%, and 20%)

Figure 9: Failure pattern of wall panels

3.6 Ductility and Post-Peak Softening

Figures 9 illustrate differences in ductility and post-peak softening among the specimens. At lower PUF contents (0% and 5%), both NCWPP and GPWPP panels exhibited relatively abrupt drops in load after reaching the peak, indicating a brittle failure mode dominated by vertical splitting cracks. Conversely, panels with higher PUF replacement (10% to 20%) exhibited more gradual load reduction after peak load, reflecting enhanced ductility and energy dissipation capacity. For instance, GPWPP10 demonstrated a smoother decline in load with increasing deformation compared to NCWPP10, indicating improved crack bridging and stress redistribution mechanisms inherent in the geopolymer binder. The post-peak behaviour of GPWPP panels thus underscores their ability to sustain deformations beyond peak load, which is crucial for real-world structural applications where ductility can prevent sudden catastrophic failure.

3.7 Influence of PUF Replacement on Cracking and Failure Patterns

Observations from the load-deformation curves are consistent with the crack patterns reported in this section. Panels with 0% and 5% PUF replacement predominantly exhibited vertical splitting cracks and crushing failure near the top and bottom edges (Figure 9), indicating a brittle failure mode. At higher PUF contents (10% to 20%), the panels exhibited horizontal crack propagation and detachment of the cover layer, reflecting progressive failure under compressive loading. Figures 9 provide visual evidence of these failure modes, showing that GPWPP panels generally demonstrated delayed crack initiation and slower crack propagation compared to NCWPP panels, consistent with the observed ductility in the load-deflection curves.

3.8 Comparative Performance between NCWPP and GPWPP Panels

Across all PUF replacement levels, geopolymer panels consistently outperformed their normal concrete counterparts in terms of ductility and load redistribution. At equivalent load levels, GPWPP panels exhibited lower deformations, indicating higher stiffness, and displayed a more gradual softening post-peak, suggesting improved energy absorption. This superior performance can be attributed to the geopolymer matrix's enhanced bonding with PUF particles and its ability to bridge cracks effectively. It highlights this comparative advantage, as GPWPP panels show smoother load-deformation curves compared to the more abrupt load drops observed in NCWPP panels.

4. Conclusion and future Scope

Based on the results, the following conclusions may be drawn:

- Workability was reduced in both instances owing to the hydrophobic nature and low specific gravity of PUF, with the slump decreasing by 26.3 % in NC and 33% in GPC. Nonetheless, the excellence of pseudoplastic flow behaviour and cohesive geopolymer gel phase in GPC allowed for successful placement in slender-section wall panels (50 mm), reducing segregation and enhancing uniformity even at elevated void contents.
- Mechanically, GPC was found to outperform NC at all PUF dosages. The 20% PUF replacement gave GPC a compressive strength of 28 days of 26.84 MPa, representing 16.1% improvement compared to NC (22.50 MPa). Correspondingly, GPC indicated 29.3% greater split tensile strength at an equivalent level. Both systems withstood critical structural thresholds (compressive strength >25 MPa and flexural strength >3 MPa) until 15% PUF, suggesting applicability for moderate load-bearing purposes within this range.
- Structural testing under axial compression showed that PUF lowered stiffness, and initial deflections at 5 Ton increased by 15-35%, mainly attributed to poor interfacial bonding. However, GPC panels had better load resistance and ductility. For example, GPWPP20 recorded peak loads of 20 Ton, in contrast to catastrophic failure at 18 Ton in NCWPP20. Further, GPC's energy absorbing capability was 25-40% greater, particularly above 10% PUF, where failure changed from brittle vertical splitting to progressive ductile cracking, with the benefit of efficient geopolymer gel–PUF encapsulation. This was validated by crack pattern observations, with horizontal shear cracks increasing in incidence with higher PUF content in GPC panels.
- The optimal PUF content for achieving structurally effective GPC wall panels lies within the range of 5–15%, offering a balanced combination of compressive strength (36.8–31.56 MPa), limited deflection (<4.2 mm at 5 Ton), and a ductile-controlled failure mode. While PUF dosages beyond 15% to 20% can still be utilized for non-structural and insulating wall applications, these higher levels primarily contribute but reduced strength and cracksuitability for seismic zones or regions requiring high ductility.

- The research confirms that GPC is naturally more apt for lightweight construction with PUF, due to its sodium aluminosilicate gel composition that provides better bonding, crack-bridging, and mechanical strength. In particular, the GPWPP15 mixture proves to be the most balanced composition, with a compressive strength of 31.56 MPa and signifcant carbon and weight savings. PUF content up to 15% is thus considered optimal for achieving sustainable and structurally efficient lightweight wall panels.

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