Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Compressive and flexural strength of mortar and concrete facings with expanded polystyrene and particle board cores sandwich panels

Check for updates

Akintayo A. Adeniji[a,b]*, Bamidele I. O. Dahunsi[b], David Kolawole[c], Williams K. Kupolati[a], Everardt Burger[a], Jones R. Moloisane[a]

[a] Civil Engineering Dept., Tshwane University of Technology, Pretoria, South Africa.
[b] Civil Engineering Dept., University of Ibadan, Ibadan, Nigeria.
[c] Civil Engineering Dept., Elizade University, Ilara-Mokin, Nigeria.
*Corresponding author Email: akintayoadeniji@gmail.com, AdenijiAA1@tut.ac.za

HIGHLIGHTS

- EPS and particle board were obtained and used as core materials for sandwich panels.
- Cement and aggregates were used as facing materials in the sandwich panel production.
- Sandwich panels with various concrete and mortar facings and EPS or PB cores were fabricated.
- Flexural strength followed similar patterns: concrete-faced PB-core panels increased by 96% from 9.18 N/mm² at 7 days to 9.48 N/mm² at 28 days.
- ANOVA analysis showed that mechanical performance was strongly affected by facing materials.

Keywords:
Lightweight sandwich panels
Particle board core
Expanded polystyrene core
Compressive strength

ABSTRACT

Lightweight sandwich panels are mainly utilized in the aerospace and automobile industries, and are increasingly explored for sustainable construction. This study investigates the mechanical performance of sandwich panels composed of mortar and concrete facings with expanded polystyrene (EPS) and particle board (PB) cores. Mortar facings were a 1:3 mix of cement and sand, a 0.65 water-cement ratio, and a 1:2:4 mix of cement, sand, and granite for the concrete, with a 0.5 water-cement ratio. Cube (75 × 75 × 75 mm³) and prism (100 × 100 × 400 mm³) samples were fabricated with 15 mm facings and 45 mm cores, then cured and tested for compressive and flexural strength at 7, 14, 21, and 28 days in line with BS EN 12390-3:2019 and ASTM C293. At 28 days, concrete-faced PB-core panels achieved a compressive strength of 8.18 N/mm², approximately 17% higher than 6.96 N/mm² of EPS-core. Mortar-faced PB-core panels reached 6.44 N/mm², 64.13% compared to 4.13 N/mm² for mortar-faced EPS panels. Flexural strength followed similar patterns: concrete-faced PB-core panels increased by 96% from 9.18 N/mm² at 7 days to 9.48 N/mm² at 28 days, while EPS-core panels improved by 87.9% from 6.56 N/mm² to 7.46 N/mm². ANOVA (α = 0.05) confirmed statistically significant differences between core types, with PB consistently outperforming EPS due to higher stiffness and improved core–facing bonding. EPS and PB core panels remain suited for non-load-bearing applications.

1. Introduction

The demand for innovative building materials that integrate structural performance and sustainability has become increasingly prominent in modern construction [1,2]. In response to rapid urbanization, researchers and practitioners are shifting toward solutions that facilitate both efficient and sustainable construction [3,4]. Conventional partition and non-load-bearing elements, such as sandcrete blocks, fired bricks, and gypsum boards, are widely used for their mechanical reliability and availability [5,6].

However, these materials are often heavy, labour-intensive to install, and require a longer installation time [7], rendering them less suitable for modern prefabricated and energy-efficient building systems [8,9]. Lightweight cementitious sandwich panels have emerged as a promising alternative due to their multifunctional performance, offering advantages such as reduced weight, ease, and reduction of installation time, and improved thermal behavior [10-12].

Sandwich panels are typically composed of two rigid facings bonded to a lightweight insulating core [13,14]. They are widely applied in the automobile and aerospace industries and are being rapidly adopted in the civil and building construction industries. These panels exhibit a high stiffness-to-weight ratio and diminished thermal bridging, making them suitable for both

http://doi.org/10.30684/etj.2025.163997.2006
Received 13 August 2025; Received in revised form 30 September 2025; Accepted 01 October 2025; Available online 27 November 2025
2412-0758/University of Technology-Iraq, Baghdad, Iraq

structural and enclosure applications [15,16]. Their use aligns with the principles of sustainable design and the growing emphasis on dry and prefabricated construction techniques.

Expanded Polystyrene (EPS) and Particle Board (PB) are among the most commonly explored core materials in sandwich panel systems [17]. EPS is a closed-cell thermoplastic foam that offers excellent low-density, resistance to moisture, and thermal insulation [18]. Nevertheless, its mechanical strength and fire resistance are limited, and its environmental footprint is particularly due to its non-biodegradable nature, which raises sustainability concerns [19]. On the other hand, PB are manufactured from recycled wood particles and agricultural residues bonded with resin, providing higher structural rigidity, moderate acoustic insulation, and better sustainability characteristics [20,21]. However, the moisture susceptibility and lower fire performance limit its use in certain environments [22,23].

Previous studies have highlighted the individual advantages of EPS and PB in building applications, such as Gautam's work on thermal insulation with EPS [24], [25] findings on the acoustic and dimensional stability of PB, and [26] enhancement of EPS fire resistance using intumescent coatings. Few studies offer a comparative assessment of these core materials within cementitious sandwich systems. Moreover, the influence of different facing materials, such as mortar and concrete, on the composite behavior of such panels remains inadequately explored.

Building on these prior findings, the present study introduces a comparative investigation that simultaneously evaluates EPS and PB cores within cementitious sandwich panels incorporating two different facing materials: mortar and concrete. Unlike previous studies that examined EPS and PB in isolation, this work provides a direct performance comparison under uniform experimental conditions, focusing on both physical and mechanical properties. The combined effect of core type and facing configuration has not been systematically studied in existing literature. By integrating EPS and PB with mortar and concrete facings, this research offers new insights into how different material pairings influence properties and overall panel efficiency. This dual-core and facing assessment represents a novel contribution, addressing the knowledge gap on optimal combinations for sustainable and prefabricated construction applications.

Given the increasing adoption of performance-based codes and sustainability frameworks such as ASHRAE 90.1, the International Building Code (IBC), and ISO 21930, there is a pressing need to validate the structural efficiency of these lightweight sandwich panels empirically [27]. This study, therefore, aims to investigate the mechanical properties, both the compressive and flexural strength, of structural lightweight sandwich panels composed of mortar and concrete facings integrated with EPS and PB cores. The research evaluates the physical properties of the constituent materials and examines the composite panels' compressive strength, density, and flexural failure modes. The outcomes are expected to inform material selection for prefabricated and sustainable construction systems that optimize mechanical integrity.

2. Experimental work

2.1 Materials

This study utilized locally sourced materials as shown in Figure 1 (a-d), including Portland Lime Cement (CEM II 42.5N) as binder for concrete and mortar, clean river sand, 12 mm crushed granite (in accordance with ASTM C33) [28], expanded polystyrene, particle board, and potable water. All materials were evaluated to ensure compliance with relevant standards before use. For mortar facings, a mix ratio of 1:3 cement to sand by weight was adopted. The dry components were thoroughly blended before gradually adding water to achieve a water and cement (w/c) ratio of 0.65. Mixing continued until a consistent paste was formed, in line with ASTM C270 [29]. For concrete facings, a nominal 1:2:4 mix ratio (cement: fine and coarse aggregate) by volume was used, with a w/c ratio of approximately 0.5. Mixing was done manually in small batches to ensure uniformity and prevent early setting, using clean tools and trays at ambient temperature. The EPS and PB were used as core materials. EPS samples were cut to mould dimensions to ensure uniform thickness and a tight fit, while PB panels were sourced pre-cut and checked for dimensional stability and surface integrity. Both core materials were conditioned at 23 ± 2 °C and 65 ± 5% relative humidity for 48 hours before use. Sandwich panels were fabricated by casting either mortar or concrete facings around the core within pre-cleaned steel molds. The facings were applied in two stages and simultaneously: first, the base of each face was applied, ensuring the core was centrally positioned at the mid-point, followed by the top facing. Manual compaction using a tamping rod ensured the bonding and air removal. Panels were demolded after 24 hours and cured in water for 28 days to ensure strength development and consistency before testing.

2.2 Properties of materials for Sandwich panels

2.2.1 Particle size distribution of Aggregates

The particle size distribution of both fine and coarse aggregates was determined in accordance with BS 1377-2. A representative oven-dried sample weighing approximately 1000 g was used for each test. Conglomerated particles and lumps within the sample were gently disaggregated to ensure accurate results. The mass of the prepared sample was measured using a calibrated digital weighing balance. A standard stack of test sieves was arranged in descending order of aperture size, with the coarsest sieve at the top and the finest at the bottom, and a receiver pan placed underneath. The 1000 g soil sample was poured into the top sieve, covered with a lid, and the entire assembly was secured in a mechanical sieve shaker. The shaker was operated for 10 minutes, in line with standard procedure, to facilitate effective separation by size. After shaking, the mass of material retained on each sieve and in the pan was carefully collected and weighed separately. These values were then used to calculate the percentage retained and cumulative percentage passing for each sieve size, allowing for the generation of a gradation curve. This test provided essential data on aggregate size distribution, necessary for evaluating the suitability of the materials for use in mortar and concrete facings. The uniformity of a soil is expressed as the uniformity coefficient, Cu, and the coefficient of curvature, Cc, or the coefficient of gradation, Cg, in Equation 1 (a and b).

$$\text{Coefficient of uniformity (Cu)} = \frac{D_{60}}{D_{10}} \tag{1a}$$

where D_{60} = particle size such that 60 % of the soil is finer than this size, and D_{10} = particle size such that 10 % of the soil is finer than this size.

$$\text{Coefficient of curvature (Cc)} = \text{Coefficient of curvature (Cc)} = \frac{(D_{30})^2}{D_{10}\ x\ D_{60}} \tag{1b}$$

where D_{30} is the particle size corresponding to 30% finer. For a well-graded soil, the value of the coefficient of curvature lies between 1 and 3

Figure 1: a) Samples of expanded polystyrene, b) Samples of particle board, c) Sand aggregate, and d) Cement mortar mixtu

2.2.2 Specific Gravity Test

The specific gravity of aggregates is a fundamental property used to determine various phase relationships, such as void ratio, degree of saturation, and soil unit weight. In this study, the specific gravity of soil solids was determined using the water displacement method as outlined in ASTM D854-23. This method applies to soils passing through the 9.5 mm sieve and involves using a pycnometer to determine the volume of soil solids through water displacement. The standard defines two procedures; the test procedure involves oven drying a representative soil sample, cooling it in a desiccator, and accurately weighing it before placing it in a calibrated pycnometer. Distilled, equilibrated water was then added to the pycnometer containing the soil, and the system was gently agitated and subjected to deairing, typically via vacuum or boiling, to remove entrapped air bubbles that could otherwise affect accuracy. The pycnometer was filled with water and allowed to reach thermal equilibrium. The mass of the pycnometer filled with water and soil was recorded, and the temperature of the mixture was measured to determine the density of water at test conditions. Using the known mass of the dry soil, the volume of the pycnometer, and the measured temperature, the specific gravity was calculated using the following formula in Equation 2:

$$\text{S.G} = \frac{W2 - W1}{(W4 - W1) - (W3 - W2)} \tag{2}$$

where: S.G = Specific Gravity, W1 = Weight of empty bottle, W2 = Weight of bottle and fine aggregate, W3 = Weight of bottle, water, and fine aggregate, W4 = Weight of water and bottle.

2.3 Properties of cement (fineness, initial and final setting time, consistency, penetration test)

A series of standardized laboratory tests was conducted to assess the physical and mechanical properties of cement in sandwich production. The fineness test of cement was carried out in accordance with BS EN 196-6:2018 using a sieve analysis method to determine the particle size distribution, as described in Equation 3. Finer cement offers a larger surface area for hydration, which results in faster strength development and increased heat evolution. The test revealed the distribution of particles critical for early (1-day) and later (28-day) strength gain, with fractions below 3 microns and between 3 and 25 microns influencing the performance. The consistency test followed the standard procedure involving the mixing of 300 g of cement with 97 g of water. The cement was added to water in a controlled manner and mixed for 3 minutes. The resulting paste was placed into a mould to determine the water content required to produce a cement paste of standard consistency, which is crucial for ensuring uniformity in further tests. The penetration test was performed using a calibrated Vicat apparatus fitted with a plunger to determine the depth of penetration into freshly prepared paste, indicating its plasticity and stiffness. The plunger was released 4 minutes after mixing began, and the depth was recorded to measure workability. In the initial and final setting time determination, the Vicat apparatus was employed using a needle and ring attachment. The initial setting time was recorded when the needle could no longer penetrate beyond a certain depth, indicating the beginning of solidification. The final setting time was noted when the ring attachment no longer left a mark on the paste surface, indicating complete hardening. These values help in defining the time limits for placing and finishing concrete.

$$\text{Fineness test} = \frac{weight\ of\ sample\ after\ \ experiment}{weight\ of\ sample\ before\ experiment} \times 100 \tag{3}$$

2.4 Composition of sandwich panel samples

The core materials used in the sandwich panels were Expanded Polystyrene and Particle Board, each prepared to a uniform thickness of 45 mm to fit precisely within the mould dimensions. EPS panels were measured, cut, and trimmed with care; however, due to their low adhesive affinity with mortar and concrete, binding wires were introduced to enhance the shear connection between the EPS core and the facing mortar. For PB, medium-density fiberboard (MDF) was used and laminated with adhesive to achieve the required thickness. To improve mechanical interlock and anchorage, galvanized nails were inserted at regular intervals through the PB core, ensuring better bond strength and structural integrity.

Table 1 presents composite sandwich panels that were cast into cubes and prisms, as shown in Figure 2 (a-d), for tests of compressive and flexural strengths, respectively. The cubes were 75 × 75 × 75 mm^3, and the prisms were 100 × 100 × 540 mm^3. The sample dimensions were selected in accordance with relevant testing standards. Cube specimens were chosen for compressive strength tests because they are widely accepted in BS EN 12390-3 and ASTM C109 for assessing cementitious composites, providing uniform stress distribution and minimizing size-related variability. Similarly, prisms were adopted for flexural strength tests to satisfy the dimensional requirements of ASTM C293, ensuring an appropriate span-to-depth ratio for accurate bending behavior assessment. The overall thickness of 75 mm, with a 45 mm core and two 15 mm facings, was selected to maintain consistency across samples, represent practical lightweight wall elements, and guarantee sufficient interaction between core and facing materials. These dimensions provided a balance between laboratory feasibility, representativeness of real construction applications, and compliance with international testing protocols, enabling robust comparison of EPS- and PB-core panels with mortar and concrete facings. The casting process ensured a consistent total panel thickness of 75 mm, with a 45 mm core embedded between two 15 mm facings, resulting in compact, stable sandwich panels suitable for curing and performance evaluation. Demolding was after 24 ± 2 hours. Loose laitance was removed to avoid mechanical damage to facings. Clean water wet curing was adopted for cementitious specimens per BS EN 12390-2; maintain water temperature at 20 ± 2 °C and replace water when contaminated. The panels with PB cores were not submerge. The use of sealed high-humidity curing (95 ± 5% RH) was adopted to provide curing moisture while protecting PB from direct soak. Panel edges were sealed where possible to prevent core swelling. EPS tolerates submersion, but hot water above 40 °C and strong solvents were avoided.

(a) (b) (c) (d)

Figure 2: a) Samples of EPS core, b) Samples of PB core sandwich Sandwich Panel, c) Sample of EPS core Sandwich Panel d) Sample of PB core sandwich panel

Table 1: Composite sandwich panel specifications

Composite ID	Facing materials	Core materials	Facing thickness (mm)	Core thickness (mm)	Overall thickness (mm)	Test specimen Type	Specimen dimensions (mm)
Concrete – EPS	Concrete	Expanded Polystyrene	15	45	75	Cube	75 × 75 × 75
Concrete – PB	Concrete	Particle Board	15	45	75	Cube	75 × 75 × 75
Mortar - EPS	Mortar	Expanded Polystyrene	15	45	75	Cube	75 × 75 × 75
Mortar – PB	Mortar	Particle Board	15	45	75	Cube	75 × 75 × 75
Concrete - Control	Concrete	None (solid panel)	Full thickness	N/A	75	Cube	75 × 75 × 75
Mortar - Control	Mortar	None (solid panel)	Full thickness	N/A	75	Cube	75 × 75 × 75
Mortar - EPS	Mortar	Expanded Polystyrene	15	45	75	Prim	100 × 100 × 400
Mortar - PB	Mortar	Particle Board	15	45	75	Prism	100 × 100 × 400

2.5 Compressive strength test of sandwich panel samples

The compressive strength test shown in Figure 3 (a and b) was conducted in accordance with BS EN 12390-3:2019 to evaluate the load-bearing capacity and failure behavior of the sandwich panel specimens under axial compression. Before loading, the bearing platens of the 2000 kN capacity universal testing machine were cleaned to remove debris, ensuring uniform contact. Each specimen was positioned so that the load was applied laterally to the faces rather than to the top and bottom, simulating service conditions. The load was applied without shock at a uniform rate of 0.94 kN/s until the specimen failed, defined by a significant drop in resistance or visible fracture. The maximum load at failure (F) was recorded, and the compressive strength (P) was calculated using Equation 4. Visual observations of crack initiation, propagation, and failure mode were noted to complement the numerical results, providing further insight into the structural integrity and failure mechanisms of the sandwich panels compared with control specimens.

$$P = \frac{F}{A} \tag{4}$$

where A is the cross-sectional area subjected to compression.

(a) **(b)**

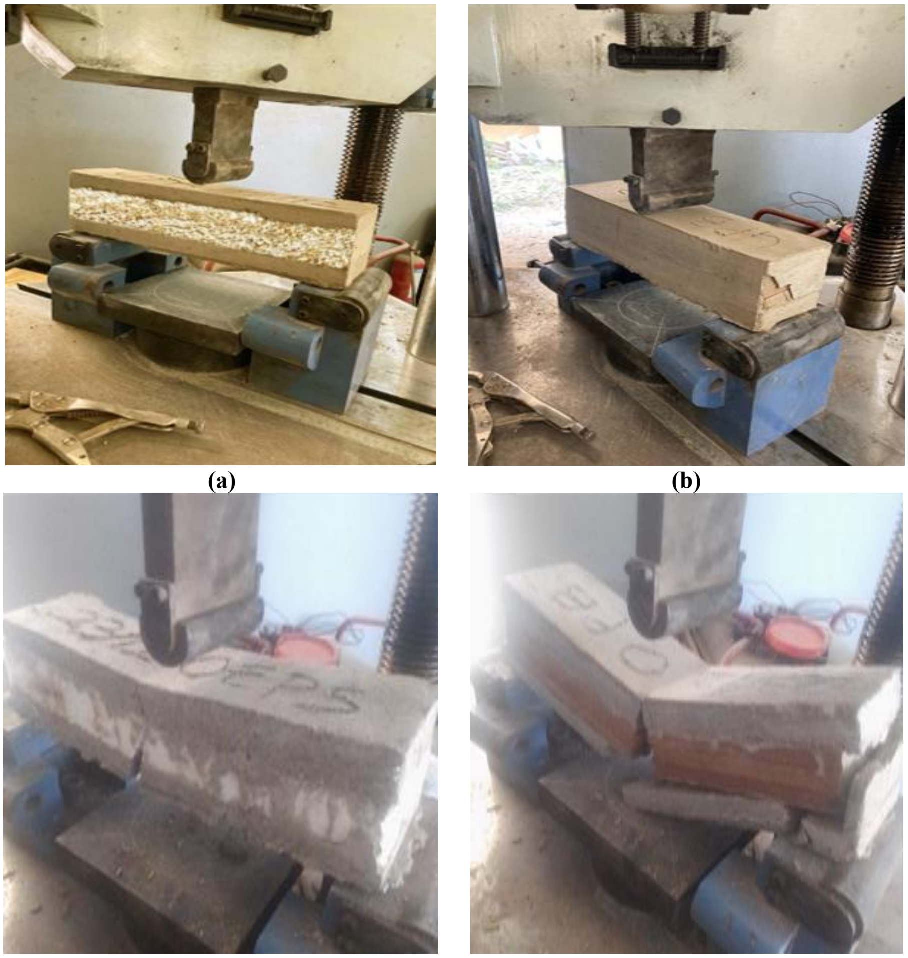
Figure 3: a) Compressive strength test, b) Failed sample at compressive strength test

2.6 Flexural strength test of sandwich panel samples

The flexural strength test, as shown in Figure 4 (a-c), was conducted on prism specimens measuring 100 × 100 × 400 mm^3 under center-point loading in accordance with ASTM C293. The objective was to determine the resistance of the sandwich panels to bending failure and to evaluate their modulus of rupture. Three composite beams consisting of expanded polystyrene (EPS) cores with concrete facings were tested alongside one full concrete control beam, and three composite beams consisting of particle board (PB) cores with concrete facings were tested alongside one full concrete control beam. In total, 18 composite beams and 6 control beams were tested, and the corresponding flexural strengths were calculated using Equation 5.

Before testing, each beam was weighed and positioned centrally on the flexural testing machine's support span, ensuring a supported arrangement with the load applied at the midspan. The center point of each beam was marked to guide accurate load application. The machine's calibrated scale was zeroed before loading. The load was applied gradually, and deflection and crack development were observed throughout the process. The test continued until the first visible crack was detected, at which point the corresponding load and deflection were recorded. The modulus of rupture was calculated using the standard formula for center-point loading, based on the failure load, span length, and specimen dimensions. This test provided critical insight into the bending performance, stiffness, and failure modes of the sandwich panels in comparison to full concrete beams.

$$\text{Flexural Strength} = \frac{\text{Applied load on deflection curve x specimen span length}}{\text{width of the specimen x depth of specimen}} \quad (5)$$



(a) **(b)** **(c)** **(d)**

Figure 4: a) Sample of EPS core ready for flexural strength test, b) Sample of PB core ready for flexural strength test, c) Failed sample of EPS core at flexural strength test, d) Failed sample of PB core at flexural strength test

3. Results and discussion

3.1 Properties of expanded polystyrene and particle board as core materials

Properties of EPS shown in Table 2 give compressive strength ranging from >70.3 kPa for EPS 15 to >204.8 kPa for EPS 29 at 10% deformation. EPS exhibits tensile strengths of 110–186 kPa, flexural strengths of 172–517 kPa, and shear strengths of 124–255 kPa, with no capillarity and water absorption below 4% by volume. It has a low thermal expansion coefficient of 6.3 × 10^{-5} m/m·°C, a maximum long-term service temperature of 75 °C, and meets UL fire ratings with a flame spread index of 20. It is a lightweight, closed-cell thermoplastic foam with densities ranging from 14.4 to 28.8 kg/m³, offering excellent thermal insulation with a thermal conductivity (k-value) of 0.029–0.038 W/m·K and corresponding R-values of 0.68–0.88 m²·K/W for a 25 mm thickness. Particle Board (PB) is an engineered wood product composed of wood chips, sawdust, and agricultural residues bonded with synthetic resins under heat and pressure. It has a density typically ranging from 600–750 kg/m³, providing moderate structural strength and dimensional stability. PB exhibits flexural strengths of 11–25 MPa, tensile strengths of 0.4–0.6 MPa perpendicular to the surface, and screw-holding capacities of 800–1200 N. Thermal conductivity is approximately 0.12–0.15 W/m·K, offering moderate insulation. While PB performs well in dry interior environments, it is susceptible to moisture-induced swelling and degradation. Fire resistance varies with resin type, and formaldehyde-free adhesives improve the environmental performance of the material.

3.2 Properties of aggregates and cement for facing materials

Table 3 Laboratory characterization of the sand and cement, with results confirming their suitability for mortar and concrete production. The particle size distribution analysis of the sand revealed that 0.07% passed through the 0.075 mm sieve and 27.05% passed through the 0.425 mm sieve, indicating a well-graded fine aggregate with less than 35% fines content. According to the AASHTO classification system [30]. The sand falls into category A-1-b, denoting a granular material with specific characteristics. The Unified Soil Classification System classified the granite as well-graded gravel (GW), meeting the requirement of 5–70% passing the 300 µm sieve.

Cement properties also met standard specifications. The fineness of the Ordinary Portland Cement was 3.9%, indicating good particle dispersion for hydration. The initial setting time was 50 minutes, and the final setting time was 420 minutes, both within the limits specified by BS 12, ensuring neither excessively rapid nor delayed setting. The standard consistency was recorded as 26.4%, consistent with typical hydration water demand. These results comply with the recommendations of the Portland Cement Association (1988), confirming that the selected materials are suitable for producing mortar and concrete composites with predictable setting and hardening characteristics.

Table 2: Properties of expanded polystyrene (ASTM Standards)[34]

Property	ASTM Method	Unit	EPS 15 (Type I)	EPS 19 (Type VIII)	EPS 22 (Type II) / EPS 29 (Type IX)
Density (min.)	D303 / D1622	kg/m³	14.4	18.4	21.6/28.8
Density Range	–	kg/m³	14–18	18–29	22–29/29–35
Compressive Strength (1% def.)	D1622	kPa	>25	>40	>78/>90
Compressive Strength (5% def.)	D1622	kPa	>55	>90	>148/>183
Compressive Strength (10% def.)	D1622	kPa	>70	>110	>167/>205
Shear Strength	C273	kPa	124–152	159–172	179–221/228–255
Shear Modulus	–	MPa	1.9–2.2	2.6–2.8	3.2–3.4/4.1–4.4
Modulus of Elasticity	C1623	MPa	1.2–1.5	1.7–2.1	2.2–2.5/3.2–3.4
Tensile Strength	C203	kPa	110–138	117–145	124–152/159–186
Flexural Strength	C518	kPa	172–207	207–262	276–345/345–517
Thermal Conductivity	C518	W/m·K	0.023–0.026	0.022–0.025	0.021–0.024 / 0.020–0.023
Water Absorption (Vol. %)	C272	%	3.9–4.4	4.0–4.8	4.2–4.6/4.4–5.0
Surface Burning (Flame Spread)	E84	UL Rating	≤20	≤20	≤20/≤20
Smoke Developed Index	E84	–	300	300	300/300

3.3 Properties of fresh concrete and mortar

Previous studies have reported that the fresh properties of concrete are key indicators of its workability, homogeneity, and potential performance in its hardened state. The slump test, as described in BS EN 12350-2, has been widely used to evaluate concrete consistency. Normal-weight concrete typically exhibits slump values between 25–100 mm for medium workability mixes and up to 175 mm for high-workability mixes incorporating superplasticisers. Excessively high slump values often indicate the risk of segregation and bleeding, while very low slumps may suggest inadequate compaction potential. The density (unit weight) of fresh normal-weight concrete generally falls within 2300–2450 kg/m³, depending on aggregate type, moisture condition, and mix proportions. Lightweight concrete mixes may show densities between 1600–2000 kg/m³, with reductions primarily due to the incorporation of lightweight aggregates or cores such as EPS. The yield, defined as the total volume of concrete produced per batch from a known mass of ingredients, has been reported to align closely with design volumes when batching accuracy is maintained, with typical deviations not exceeding ±1.5%. Air content whether entrained or entrapped has been shown to affect durability, particularly in freeze–thaw environments. For normal structural concrete, air contents typically range from 1–3%, while air-entrained concrete intended for cold climates contains 4–7% air to improve resistance to cyclic freezing and thawing. Excessive air content, however, can reduce compressive strength by approximately 5% for each additional 1% air volume beyond the optimum range. Table 4 presents the properties of fresh concrete, the experimental and literature results with the corresponding references are stated.

Table 3: Properties of cement, sand, and granite

Properties	Cement	Fine aggregate (sand)	Coarse aggregate (granite)	Standard constraints range
Fineness (%)	3.9	-	-	< 10 (BS EN 197-1)
Initial setting time (min)	50	-	-	> 45 (BS EN 197-1)
Final setting time (min)	420	-	-	<600 (BS EN 197-1)
Consistency (%)	26.4	-	-	25-30 (BS EN 197-1)
CaO (%)		-	-	60-70 (ASTM C150 / BS EN 197-1)
SiO_2 (%)		-	-	17-25 (ASTM C150 / BS EN 197-1) [31]
Al_2O_3 (%)		-	-	3-8 (ASTM C150 / BS EN 197-1) [31]
Fe_2O_3 (%)		-	-	0.5-6 (ASTM C150 / BS EN 197-1) [31]
MgO (%)		-	-	0.1-4 (ASTM C150 / BS EN 197-1) [31]
SO_3 (%)		-	-	1-3 (ASTM C150 / BS EN 197-1) [31]
$Na_2O + K_2O$ (%)		-	-	0.2-1.3 (ASTM C150 / BS EN 197-1) [31]
% Passing 0.075 sieve	-	0.07	-	< 3 (ASTM C33/BS 882) [32]
% Passing 0.425 sieve		27.05	51	10 – 30; 45 – 60 (ASTM C33/BS 882) [32]
Specific gravity (g)		2.60	2.66	2.55 – 2.75 (ASTM C33/BS 882) [32]
AASHTO classification		A-1-b	Well Graded	Well-graded distribution required (ASTM C33/BS 882) [33]

Table 4: Properties of fresh concrete

Property	Experimental result	Literature range	Ref.
Slump (mm)	32	25–100 (medium workability), up to 175 (high workability)	[36]
Density (kg/m³)	1413	2300–2450 (normal weight), 1600–2000 (lightweight)	[37]
Yield (m³)	1.45% deviation	Design yield ±1.5% deviation	[37]
Air Content (%)	2.5%	1–3% (normal concrete), 4–7% (air-entrained for freeze–thaw)	[36]

3.4 Compressive Strength of Sandwich Panels

The compressive strength test results presented in Table 5, Figures 5 and 6 reveal significant variations among the different composite panels and control specimens over the 7, 14, and 28 day curing periods. For each material type, three specimens were tested at each curing age, and the values presented in the table represent the average compressive strength obtained from these replicate tests. The control samples, concrete and mortar without core materials, recorded the highest strength values across all curing periods. The plain concrete control achieved a compressive strength of 15.66 N/mm² at 28 days, while the plain mortar recorded 10.54 N/mm². This confirms their structural superiority, likely due to the absence of low-density core materials, which can reduce mechanical performance. Among the composite panels, those faced with concrete generally demonstrated higher compressive strength than those with mortar facing. Specifically, the concrete-faced panel with particle board core recorded the highest compressive strength of 8.18 N/mm² at 28 days among the sandwich panels, followed closely by the concrete-faced panel with expanded polystyrene (EPS) core at 6.96 N/mm². This suggests that concrete facings contribute significantly to the load-bearing capacity of the panels, even when lightweight core materials are introduced. In contrast, the mortar-faced panels exhibited lower compressive strength, with the particle board core achieving 6.44 N/mm² at 28 days and the EPS core yielding the lowest value of 4.13 N/mm². Figures 7 and 8 highlights the influence of both the facing material and the core type on the structural performance of composite panels. Particle board, being denser and more rigid than EPS, offers better support under load. At the same time, EPS, though beneficial for weight reduction and insulation, compromises structural strength due to its low density and compressibility. The experimental results revealed that particle board (PB) core sandwich panels consistently demonstrated superior compressive strength compared to expanded polystyrene (EPS) core panels, regardless of facing material. At 28 days, concrete-faced PB-core panels achieved 8.18 N/mm², approximately 17% higher than the 6.96 N/mm² recorded for their EPS-core counterparts. Mortar-faced PB-core panels also outperformed EPS-core panels, reflecting the beneficial effect of higher stiffness and improved load transfer through denser cores. These findings are consistent with Kumar et al. [34], who reported that EPS-based lightweight panels exhibited lower compressive capacity compared to panels incorporating denser aggregates such as marble waste and LECA, achieving up to 29.85 N/mm² when optimized for stiffness and bonding. Similarly, Serri et al. [37] observed that low-stiffness insulating cores, including EPS, suffered from reduced shear transfer efficiency and higher deformation under loading, limiting composite action unless additional connectors or surface modifications were introduced. In this study, mortar-faced EPS-core panels showed limited late-age strength gains, supporting the literature’s observation of interface bond challenges with EPS. Overall, while EPS cores provide notable weight reduction and thermal benefits, PB cores deliver superior load-bearing capacity due to their higher rigidity and enhanced interface bonding, making them more suitable for structural applications where mechanical performance is a priority.

Table 5: Compressive strength result

S/N	Facing Materials	Core Materials	7 days	14 days	28 days
1	Concrete	Expanded polystyrene	5.70	6.39	6.96
2	Concrete	Particle board	7.47	7.77	8.18
3	Mortar	Expanded polystyrene	4.49	4.70	4.13
4	Mortar	Particle board	5.64	6.12	6.44
5	Concrete	-	13.12	13.16	15.66
6	Mortar	-	8.61	9.30	10.54

3.5 Flexural strength of sandwich panels

The experimental flexural strength results indicate that concrete with standard facings consistently achieved the highest values, increasing from 9.90 N/mm² at 7 days to 10.88 N/mm² at 28 days as presented in Table 6 and Figures 9 and 10, demonstrating superior resistance to bending forces. Concrete panels with particle board (PB) cores, while slightly weaker, showed moderate flexural strength ranging from 9.18 to 9.48 N/mm² over the same period, reflecting the stiffer core’s ability to transfer loads effectively. Expanded polystyrene (EPS) core panels recorded the lowest strengths, increasing from 6.56 to 7.46 N/mm², confirming that while EPS enhances thermal insulation, it compromises bending resistance due to its lower stiffness and weaker interface bonding. These findings agree with Serri et al. (2019), who reported reduced flexural capacity in EPS-core panels compared to higher-density core materials, largely due to diminished composite action and shear transfer. Kumar et al. (2024) similarly observed that lightweight panels with denser aggregates exhibited significantly higher flexural performance, attributing this to improved rigidity and load distribution. For mortar-based systems, standard mortar achieved the highest flexural strength (0.37–0.43 N/mm²), followed by mortar–PB composites (0.32–0.38 N/mm²) and mortar–EPS composites (0.27–0.30 N/mm²), mirroring the concrete panel trend. Overall, results reinforce literature consensus that lower-density core materials, particularly EPS, reduce flexural strength, whereas PB and denser aggregates offer a better balance of lightness and bending resistance (Kumar et al., 2024; Serri et al., 2019).

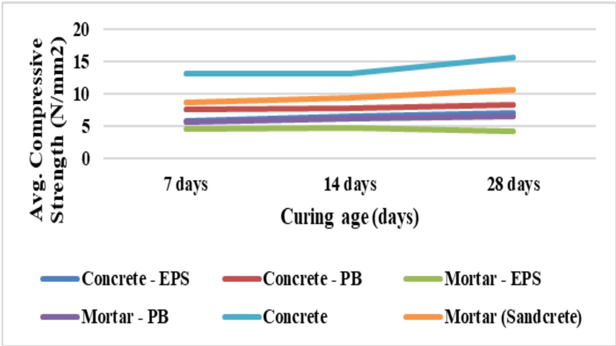


Figure 5: Progression of strength over time per sandwich panel

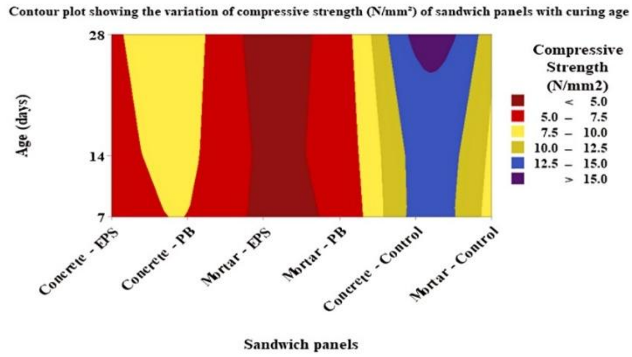


Figure 6: Compressive strength and curing age variation

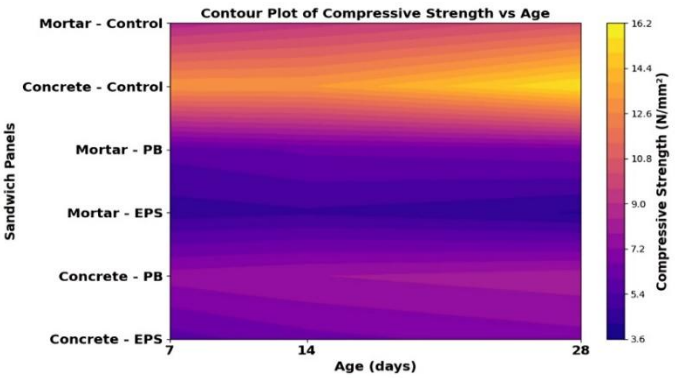


Figure 7: Plot of compressive strength and maturity age

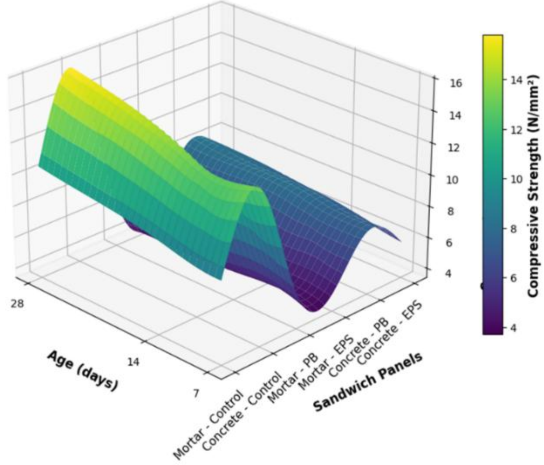


Figure 8: 3D surface plot of compressive strength

Table 6: Flexural strength result

S/N	Composite	Avg. Flexural Strength (N/mm^2)		
		7 days	14 days	28 days
1	Mortar-PB	5.64	6.39	8.44
2	Mortar-EPS	4.19	4.40	4.73
3	Mortar	8.16	9.30	10.54
4	Concrete-PB	9.18	9.23	9.48
5	Concrete-EPS	6.56	7.40	7.46
6	Concrete	9.90	10.43	10.88

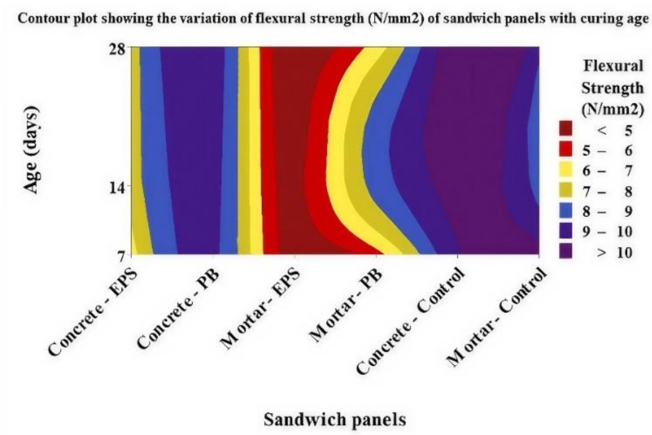


Figure 9: Flexural strength of sandwich panels with curing age

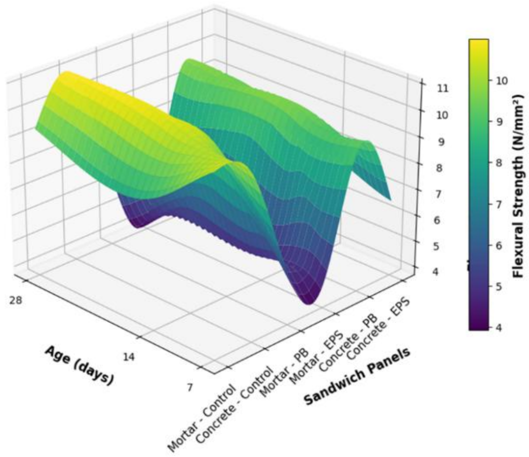


Figure 10: 3D surface plot of flexural strength

3.6 Statistical analysis (ANOVA results)

The results of the ANOVA test are presented in Table 7 The calculated F-value of 15,642.941 with an associated p-value of < 0.0001 is well below the standard significance threshold of α = 0.05. This extremely low p-value demonstrates that the differences in compressive strength observed among the various sandwich panel types are statistically significant and not attributable to random variation. Consequently, the null hypothesis is rejected, confirming that the composite configuration, specifically the combination of facing and core materials, exerts a decisive influence on panel strength.

These findings carry important implications for material selection in sandwich panel design. The statistical evidence validates the experimental observations that panels with concrete facings consistently achieve higher compressive strengths than those with mortar facings. At the same time, particle board (PB) cores outperform expanded polystyrene (EPS) cores in terms of structural capacity. The ANOVA model substantiates that these patterns represent genuine performance differences rather than experimental anomalies, reinforcing the conclusion that both facing type and core material selection are critical determinants of mechanical performance. Table 7 presents the individual compressive strength values obtained from three replicates for each composite panel type at 28 days. These replicates are essential to ensure the accuracy and consistency of the average values reported earlier in Table 1. In contrast, Table 8 summarizes the key statistical parameters (count, average, and variance) for each group of replicates. This descriptive information provides the foundation for conducting a meaningful ANOVA test.

Table 7: Replicate compressive strength results for sandwich panels (28 days)

S/N	Sandwich panel					
	Concrete – EPS	**Concrete - PB**	**Concrete Control**	**Mortar – EPS**	**Mortar - PB**	**Mortar - Control**
1	6.96	8.18	15.66	4.13	6.44	10.54
2	7.01	8.10	15.71	4.18	6.40	10.50
3	6.89	8.26	15.61	4.08	6.49	10.58

Table 8: Summary statistics of compressive strength data

Groups	Count	Sum	Average	Variance
Concrete – EPS	3	20.86	6.953333	0.003633
Concrete – PB	3	24.54	8.18	0.0064
Concrete Control	3	46.98	15.66	0.0025
Mortar – EPS	3	12.39	4.13	0.0025
Mortar – PB	3	19.33	6.443333	0.002033
Mortar – Control	3	31.62	10.54	0.0016

Table 9: ANOVA test results for compressive strength data

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Groups	243.3346	5	48.66693	15642.94	1.91E-22	3.105875
Within Groups	0.037333	12	0.003111			
Total	243.372	17				

3.7 Independent Welch's t-test analysis

Welch's t-tests (unequal variances) on pairs that are most relevant to hypotheses (PB versus EPS for same facing and sandwich versus control). Concrete-PB versus Concrete-EPS: $t = 21.211$, $p = 5.1 \times 10^{-5}$. Here, a statistically significant difference; Concrete-PB panels are stronger than Concrete-EPS ($p < 0.05$). Mortar-PB versus Mortar-EPS: $t = 59.510$, $p = 1.0 \times 10^{-6}$. Here, the Mortar-PB panels are highly significant and outperform Mortar-EPS. Concrete-Control vs Concrete-PB: $t = 137.331$, $p \approx 0.0$ (numerical underflow; $p < 0.001$). Here, control concrete is significantly stronger than PB-cored sandwich panels. Mortar-Control vs Mortar-PB: $t = 117.717$, $p \approx 0.0$. Here, control mortar specimens are significantly stronger than mortar-faced PB sandwich panels. All tested differences above are highly statistically significant (p-values far below $\alpha = 0.05$). These tests confirm, with high confidence, the experimental observation that PB cores provide higher compressive strength than EPS cores for the same facing, and full concrete/mortar controls have substantially higher compressive capacity than their sandwich counterparts. The previous report included an ANOVA with $F = 15{,}642.941$, $p < 0.0001$. This extremely small p-value supports the t-test results: the different panel configurations produce statistically different compressive strengths (reject H_0). Mentioning both the ANOVA (global test) and the pairwise t-tests (post-hoc style comparisons) strengthens the statistical narrative.

These results follow literature trends where EPS-core panels offer better lower weight but reduced mechanical capacity, while denser cores (PB or aggregate-filled cores) increase stiffness and strength.

3.8 Visual analysis of performance patterns

To complement the tabulated results and ANOVA findings, Figure 11 provide heatmap and contour visualizations of both thermal conductivity and compressive strength. Figures 10 and 11 clearly show that the lowest thermal conductivity is observed in the concrete–EPS panel configuration, reinforcing its superior insulating performance. In contrast, Figures 12 and 13 highlight the compressive strength distribution, with the concrete-PB panel exhibiting the highest values among the sandwich panel group. These charts reveal a consistent performance gradient from EPS to particle board to control (no core), and from mortar to concrete facings. Notably, the contour plots highlight how strength and thermal performance are influenced by the synergy between facing material and core type. These visualizations further validate the statistical conclusion that panel configuration significantly affects mechanical and thermal behavior.

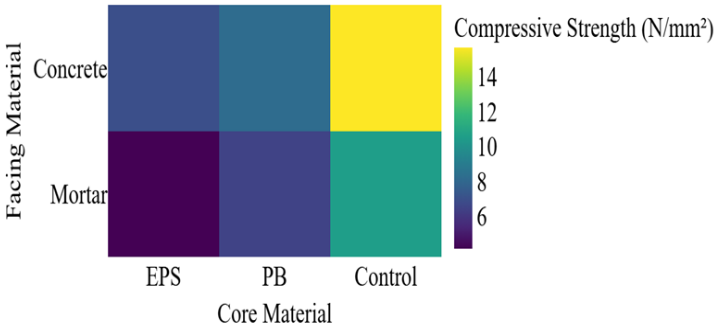


Figure 11: Compressive strength heatmap of sandwich panels

4. Conclusion

The mechanical assessment of lightweight sandwich panels demonstrated that the choice of core material plays a decisive role in determining both compressive and flexural strength performance.

1) Particle board (PB) cores deliver superior compressive and flexural strengths compared to expanded polystyrene (EPS), due to higher stiffness and better core–facing bonding.
2) Concrete-faced PB-core panels provide the highest structural reliability, while mortar-faced and EPS-core panels exhibit lower mechanical performance.
3) EPS-core panels, though weaker structurally, remain advantageous for lightweight and thermal insulation-focused applications.
4) Careful selection of core–facing combinations is essential; hybrid designs and surface treatments could enhance EPS bonding and overall panel efficiency.

Author contributions

Conceptualization, **A. Adeniji**, **B. Dahunsi**, **D. Kolawole**, **W. Kupolati**, **E. Burger**, and **J. Moloisane**; data curation, **A. Adeniji**, and **D. Kolawole**; formal analysis, **D. Kolawole**; investigation, **W. Kupolati**, **B. Dahunsi**; methodology, **A. Adeniji**, **E. Burger**; project administration, **A. Adeniji**; resources, **J. Moloisane**; software, **A. Adeniji**; supervision, **W. Kupolati**, **B. Dahunsi**; validation, **B. Dahunsi**, **W. Kupolati,** and **A. Adeniji**; visualization, **A. Adeniji**; writing—original draft preparation, **A. Adeniji**; writing—review and editing, **A. Adeniji,** and **J. Moloisane**. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] A. De Jong, J. Mark Van Dijk, J. Meyer, Analysis of Innovative Practices in Advanced Materials and Structural Engineering, Fusion of Multidisciplinary Research An International Journal, 2 (2021) 178–188. https://doi.org/10.63995/JWFN9981.

[2] Y. Nasr, H. El Zakhem, A.E.A. Hamami, M. El Bachawati and R. Belarbi, Comprehensive review of innovative materials for sustainable buildings energy performance, Energies, 16 (2023) 7440. https://doi.org/10.3390/en16217440.

[3] O. S. Dobrzyńska, A legal framework for energy-conscious urban planning in Poland and Germany, Energies, 16 (2023) 6428. https://doi.org/10.3390/en16186428.

[4] W. Shafik, Energy policies and infrastructure requirements for efficient green buildings, in: Sustainable Technologies for Energy Efficient Buildings, 1st ed., CRC Press, 2024, pp. 212–240.

[5] S. N. Jonnala, D. Gogoi, S. Devi, M. Kumar and C. Kumar, A comprehensive study of building materials and bricks for residential construction, Constr. Build. Mater., 425 (2024) 135931. https://doi.org/10.1016/j.conbuildmat.2024.135931.

[6] S. Momenifar, A Hybrid Decision Support System for Partition Wall Selection with an Application in Masonry Wall Systems, Ph.D. Thesis, University of Alberta, Edmonton, Canada, 2024. https://doi.org/10.7939/r3-egsf-fn27.

[7] M.A. Kamal, Advances in Bricks and Blocks for Building Construction, Materials Research Foundation, Millersville, PA, USA, 2021.

[8] Y. Al-Radhi, K. Roy, H. Liang, K. Ghosh, G.C. Clifton and J.B. Lim, Thermal performance of different construction materials used in New Zealand dwellings comparatively to international practice – A systematic literature review, J. Build. Eng., 72 (2023) 106346. https://doi.org/10.1016/j.jobe.2023.106346.

[9] D. Vijayan, A. Mohan, J. Revathy, D. Parthiban and R. Varatharajan, Evaluation of the impact of thermal performance on various building bricks and blocks: A review, Environ. Technol. Innov., 23 (2021) 101577. https://doi.org/10.1016/j.eti.2021.101577.

[10] M. F. Ghazy, M. A. A. Abd Elaty, M. A. E. Sakr and E. M. Arafa, Thermo-Mechanical Performance of Sustainable Lightweight Sandwich Panels Utilizing Ultra-High-Performance Fiber-Reinforced Concrete, Buildings, 15 (2025) 593. https://doi.org/10.3390/buildings15040593.

[11] T. P. Sah, A. W. Lacey, H. Hao and W. Chen, Prefabricated concrete sandwich and other lightweight wall panels for sustainable building construction: State-of-the-art review, J. Build. Eng., (2024) 109391. https://doi.org/10.1016/j.jobe.2024.109391.

[12] E. Vladimirova, M. Gong, Advancements and applications of wood-based sandwich panels in modern construction, Buildings, 14 (2024) 2359. https://doi.org/10.3390/buildings14082359.

[13] Q. Ma, et al., A review of the recent trends on core structures and impact response of sandwich panels, Journal of Composite Materials, 55 (2021) 2513–2555. https://doi.org/10.1177/0021998321990734.

[14] S. K. Sahu, P. R. Sreekanth, S. K. Reddy, A brief review on advanced sandwich structures with customized design core and composite face sheet, Polymers, 14 (2022) 4267.

[15] D. O. J. Dos Santos, P. R. L. Lima, R. D. Toledo Filho, Flexural Behavior of Lightweight Sandwich Panels with Rice Husk Bio-Aggregate Concrete Core and Sisal Fiber-Reinforced Foamed Cementitious Faces, Materials, 18 (2025) 1850. https://doi.org/10.3390/ma18081850.

[16] R. Kassab, P. Sadeghian, Design Guidelines for FRP-Faced Foam Core Sandwich Panels: Review and Building Code Compliance, J. Archit. Eng., 31 (2025) 03125002. https://doi.org/10.1061/JAEIED.AEENG-1920.

[17] M. I. Rofdi, N. S. M. Tamat, A. Nuryawan, H. Sakagami and A. Hermawan, Studies on particleboard production using Expanded Polystyrene (EPS) waste as a binder for construction applications, Constr. Build. Mater., 449 (2024) 138279. https://doi.org/10.1016/j.conbuildmat.2024.138279.

[18] P. Boruszewski, P. Borysiuk, A. Jankowska and J. Pazik, Low-density particleboards modified with expanded and unexpanded fillers characteristics and properties, Materials, 15 (2022) 4430. https://doi.org/10.3390/ma15134430.

[19] H. J. Muhammada, Assessment of Expanded-Polystyrene (EPS) as an Alternative and Sustainable Building Material to Conventional Construction with Emphasis on Environmental Degradation, Int. J. Eng. Technol. Innov., (IEC 2024) (2024) 01–09.

[20] R. Garcia, I, Calvez, A. Koubaa, V. Landry and A. Cloutier, Sustainability, circularity, and innovation in wood-based panel manufacturing in the 2020s: Opportunities and challenges, Curr. For. Rep., 10 (2024) 420–441. https://doi.org/10.1007/s40725-024-00229-1.

[21] S. H. Lee, W. C. Lum, J. G. Boon, L. Kristak, P. Antov, M. Pedzik, Particleboard from agricultural biomass and recycled wood waste: A review, J. Mater. Res. Technol., 20 (2022) 4630–4658. https://doi.org/10.1016/j.jmrt.2022.08.166.

[22] M. Assel, Evaluation of selected properties of boards with increased fire resistance, M.Sc. Thesis, České vysoké učení technické v Praze, 2023.

[23] A. Kremensas, S. Vaitkus, S. Vejelis, S. Cslonka and A. Kairyte, Hemp shivs and corn-starch-based biocomposite boards for furniture industry: Improvement of water resistance and reaction to fire, Industrial Crops and Products, 166 (2021) 113477. https://doi.org/10.1016/j.indcrop.2021.113477.

[24] A. Singh, A. K. Srivastava, A. Kumar and P. Gautam, Design for low thermal conductivity and low vibrational impact without efflorescence of the composite bricks developed by waste plastic resin/fly ash/glass powder/gypsum, International Journal on Interactive Design and Manufacturing (IJIDeM), 19 (2) (2025) 949–960. https://doi.org/10.1007/s12008-023-01582-4

[25] T. Singh, S. Sehgal, Structural health monitoring of composite materials, Archives of Computational Methods in Engineering, 29 (2022) 1997–2017. https://doi.org/10.1007/s11831-021-09666-8

[26] K. Li, Y. Li, Y. Zou, B. Yuan, A. Walsh and D. Carradine, Improving the fire performance of structural insulated panel core materials with intumescent flame-retardant epoxy resin adhesive, Fire Technol., 59 (2023) 29–51. https://doi.org/10.1007/s10694-021-01203-0.

[27] S. K. Kirme, V. S. Kapse, A comprehensive review of residential building energy efficiency measures in India, Energy Build., (2024) 114537. https://doi.org/10.1016/j.enbuild.2024.114537.

[28] J. Yzenas, Bulk density, relative density (specific gravity), pore structure, absorption, and surface moisture, in: Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM International, 2006, pp. 346–354.

[29] ASTM, C270 Standard Specification for Mortar for Unit Masonry, American Society for Testing and Materials, West Conshohocken, PA, USA, 2014.

[30] AASHTO T121, Standard Method of Test for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete, American Association of State Highway and Transportation Officials, Officials: Washington, DC.

[31] ASTM C150/C150M-20, Standard specification for Portland cement, Technical Report, ASTM International, West Conshohocken, PA, USA, 2020.

[32] ASTM C33, Standard specifications for concrete aggregates, ASTM Standard Book, 2003.

[33] BSI, British Standard: Specification for aggregates from natural sources for concrete, BS 882:1992, British Standards Institution, London, UK, 1992.

[34] G. Barrera Castro, L. Ocampo Carmona and J. Olaya Florez, Production and characterization of the mechanical and thermal properties of expanded polystyrene with recycled material. Ingeniería y Universidad 21(2): 177-194 (2017). https://doi.org/10.11144/javeriana.iyu21-2.mtpe

[35] P. Kumar, R. Kumar, S. Surabhi, M.R. Rahman and S. Khan, Development of sustainable precast concrete sandwich wall panels using artificial aggregates and mineral admixture, in: E3S Web Conf., 596 (2024) 01006, EDP Sciences. https://doi.org/10.1051/e3sconf/202459601006

[36] Neville, A. M. and Brooks, J. J., Concrete Technology. 2nd Edition, Pearson Education Ltd., London 2010.

[37] Sukontasukkul, P. and S. Mindess, The shear fracture of concrete under impact loading using end confined beams, Mater. Struct., 36 (2003)372-378. https://doi.org/10.1007/BF02481062

[38] E. Serri, B. Raghavan, D. Yeoh, W. Al-Azzawi, Mechanical properties of precast concrete sandwich panels: Effect of insulation type and shear connector configuration, Case Stud. Constr. Mater., 11 (2019) e00266. https://doi.org/10.1016/j.cscm.2019.e00266