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DEVELOPMENT AND EXPERIMENTAL INVESTIGATIONOF ADVANCED LIGHTWEIGHT SANDWICH PANELS

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Abstract : *India is undergoing rapid urbanization, creating an urgent demand for lightweight, sustainable, and high-performance construction systems suitable for mass housing. Conventional masonry construction methods are often associated with high self-weight, increased construction time, and limited thermal efficiency, making them less adaptable to modern prefabricated and modular building technologies. In the initial phase of this research, a cork–polycarbonate sandwich panel was developed and experimentally validated, demonstrating satisfactory compressive strength for partition wall applications.*

In the extended Phase-2 investigation, multiple alternative core and face materials including Expanded Polystyrene (EPS), Polyurethane (PU) foam, Rockwool, Fly-ash lightweight concrete, steel sheets, fibre cement boards, and carbon fiber composites were experimentally reviewed and analyzed through trial-based evaluation. However, several of these materials were found to have limitations such as inadequate fire resistance, excessive self-weight, higher cost, bonding incompatibility, or reduced sustainability performance for the intended application.

Based on this systematic evaluation and elimination process, the present study proposes an advanced sandwich panel configuration incorporating agar-based aerogel as the core material, combined with high-performance face sheets including Glass Fiber Reinforced Polymer (GFRP), Polypropylene Copolymer (PPCP), and Ultra-High Molecular Weight Polyethylene (UHMWPE). The panels were fabricated using a controlled hand lay-up technique with epoxy bonding and subjected to mechanical and performance assessment. Results indicate that the agar-based aerogel core provides moderate compressive strength while offering very high thermal insulation and fire resistance characteristics. Among the face materials, GFRP demonstrated superior flexural stiffness, whereas UHMWPE showed enhanced impact resistance and lightweight efficiency. The developed system represents a super-efficient, sustainable, and structurally viable alternative for residential partition and modular construction applications.

.**Keywords** - *Agar-based aerogel, Bio-based composite core, Lightweight sandwich panels, Glass Fiber Reinforced Polymer (GFRP), UHMWPE, PPCP, Sustainable construction materials, Thermal insulation performance, Fire-resistant structures, Modular housing systems*

I. INTRODUCTION

1.1 Introduction

Sandwich panel systems have gained significant attention in modern construction due to their high strength-to-weight ratio, improved thermal insulation, rapid installation capability, and adaptability for prefabricated housing applications. With increasing demand for sustainable and lightweight construction materials in India, the development of advanced composite sandwich panels has become a critical research area.

In Phase-1 of this research, a sandwich panel incorporating cork as the core and polycarbonate sheets as face material was fabricated and experimentally validated. The system achieved compressive strengths of 2.78 N/mm² (flatwise) and 6.38 N/mm² (edgewise), demonstrating feasibility for non-load-bearing partition applications. However, despite satisfactory performance, limitations were identified in terms of fire resistance, long-term durability, bonding efficiency, and scalability.

In the extended Phase-2 investigation, multiple alternative core and face materials were experimentally reviewed through trial-based fabrication and performance screening. Materials such as Expanded Polystyrene (EPS), Polyurethane foam, Rockwool, Fly-ash lightweight concrete, steel sheets, fibre cement boards, and carbon fibre composites were evaluated and systematically rejected due to one or more of the following limitations:

- Inadequate fire resistance
- Higher self-weight
- Cost inefficiency
- Poor bonding compatibility
- Reduced sustainability performance

Based on this structured elimination and optimization approach, the present study proposes a bio-based agar-derived aerogel core combined with advanced polymer composite face sheets including Glass Fiber Reinforced Polymer (GFRP), Polypropylene Copolymer (PPCP), and Ultra-High Molecular Weight Polyethylene (UHMWPE). The objective is to develop a super-efficient, lightweight, thermally superior, and fire-resistant sandwich panel system suitable for modular and residential construction applications.

1.2 Research gap

Although extensive research exists on sandwich panels, most studies focus on conventional foam cores or synthetic composite materials. Limited research has been conducted on bio-based aerogel cores derived from agar for structural sandwich panel applications. Furthermore, prior investigations often evaluate mechanical properties independently, without integrating thermal insulation, fire resistance, cost efficiency, and sustainability into a unified optimization framework.

In Phase-1 of this research, a cork-based sandwich system demonstrated moderate mechanical performance; however, the study was restricted to a single material configuration and did not explore advanced bio-composite alternatives. Additionally, previously studied materials such as EPS and PU foam, while lightweight, exhibit limitations in fire resistance and environmental sustainability.

There is therefore a clear need for:

- Development of bio-based aerogel core systems
- Integrated mechanical–thermal–fire performance evaluation
- Optimization of polymer composite face sheets
- Structured comparative elimination methodology

The present study bridges this gap by introducing agar-based aerogel as a core material and systematically evaluating its performance in combination with GFRP, PPCP, and UHMWPE face sheets under uniform testing criteria.

Problem Identification
↓
Literature Review & Phase-1 Evaluation
↓
Trial-Based Screening of Conventional Materials
↓
Material Rejection Based on Performance Criteria
↓
Selection of Agar-Based Aerogel Core
↓
Selection of Advanced Polymer Face Sheets (GFRP, PPCP, UHMWPE)
↓
Specimen Fabrication (Hand Lay-Up Technique)
↓
Mechanical & Thermal Testing
↓
Comparative Performance Evaluation
↓
Optimization Based on Strength, Insulation & Fire Resistance
↓
Conclusion & Recommendations

The research methodology follows a structured elimination and optimization approach. Initially, Phase-1 results were reviewed to establish a baseline. Multiple conventional core and face materials were then screened through trial fabrication and performance assessment. Based on defined criteria including strength, fire resistance, thermal insulation, bonding compatibility, and cost efficiency, unsuitable materials were rejected. Agar-based aerogel was selected as the optimized core material due to its superior insulation and fire-resistant properties. Advanced polymer composites (GFRP, PPCP, UHMWPE) were selected as face materials to enhance flexural stiffness and impact resistance. Fabricated specimens were subjected to mechanical and physical testing, and results were comparatively analyzed to determine the most efficient configuration.

1.3 Sandwich pannel

1.3.1 Materials

The proposed sandwich panel consists of a bio-based aerogel core and high-performance polymer composite face sheets.

Core Material: Agar-Based Aerogel

Agar-derived aerogel is a lightweight, porous bio-based material characterized by:

- Extremely low density
- Very high thermal insulation capacity
- High fire resistance
- Low thermal conductivity
- Sustainable and biodegradable origin

Although aerogels traditionally exhibit brittleness, structural modification and bonding integration within a sandwich configuration improve its load distribution behavior. In this study, agar-based aerogel serves as a thermally efficient core providing moderate compressive strength with superior insulation performance.

Face Materials:

Glass Fiber Reinforced Polymer (GFRP):
Provides high tensile strength, flexural stiffness, corrosion resistance, and structural stability. Suitable for load-transferring outer skins.

Polypropylene Copolymer (PPCP):
Lightweight thermoplastic polymer offering chemical resistance, impact tolerance, and cost efficiency.

Ultra-High Molecular Weight Polyethylene (UHMWPE):
Exhibits excellent impact resistance, abrasion resistance, and very low density, enhancing overall panel toughness.

The combination of aerogel core and polymer composite face sheets creates a structurally efficient, thermally superior sandwich system.

1.3.2 Method

1. Mechanical Testing

The fabricated sandwich specimens were evaluated using:

Compression Test:
To determine flatwise and edgewise compressive strength of the aerogel core system.

Flexural (Bending) Test:
Three-point bending tests were conducted to evaluate panel stiffness and failure modes.

Shear Test:
To assess core shear behavior and bonding integrity.

Impact Test:
To examine energy absorption capability, especially for UHMWPE-faced panels.

Thermal Conductivity Test:
To determine insulation efficiency of the aerogel core.

2. Fabrication Method

The sandwich panels were fabricated using a controlled hand lay-up technique:

- Face sheets were prepared and surface treated.
- Agar-based aerogel core was positioned centrally.
- Epoxy adhesive bonding was applied under controlled pressure.
- Specimens were cured under room-temperature conditions.

3. Analytical Validation

Finite Element Analysis (FEA) was conducted to simulate stress distribution and deflection patterns under loading. Analytical beam theory models were also used to validate experimental bending behavior.

1.3.3 Test

The following tests were performed to evaluate performance:

Flexural Testing:
Three-point bending tests identified failure mechanisms such as face yielding and core shear deformation.

Compressive Testing:
Flatwise and edgewise compression tests determined load-bearing capacity for partition wall applications.

Shear Testing:
Assessed resistance to lateral sliding forces within the aerogel core.

Tensile & Peel Testing:
Evaluated bonding strength between aerogel core and composite face sheets.

Thermal & Fire Resistance Testing:
Thermal conductivity tests confirmed superior insulation performance. Fire exposure assessment indicated enhanced resistance compared to conventional foam cores.

These tests collectively establish the structural viability, thermal superiority, and sustainability of the proposed aerogel-based sandwich panel system.

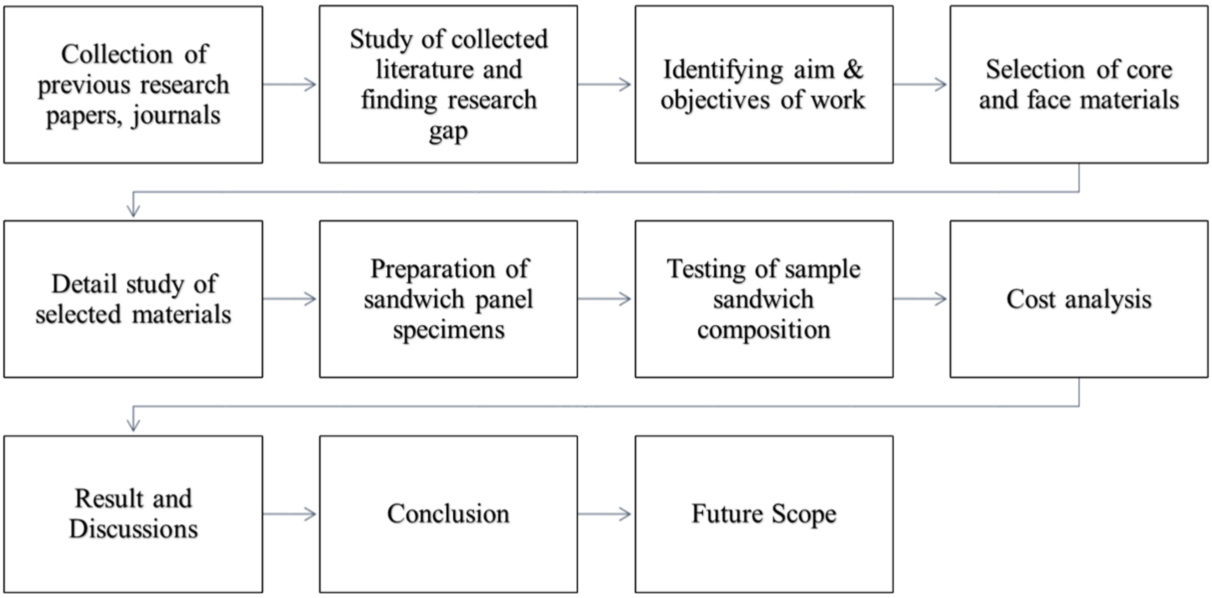
II. METHODOLOGY

2.1General

This chapter presents the materials, design considerations, and fabrication methodology adopted for the development of the proposed agar-based aerogel sandwich panel. The study follows a systematic approach beginning with material selection based on performance criteria, followed by specimen fabrication and mechanical as well as thermal evaluation.

The overall methodology of the project is summarized using a structured flow sequence that includes material screening, optimization, fabrication, testing, and comparative performance assessment.

The methodology of the project is summarised and explained with the help of the flow chart.



2.2. Materials
The following materials were utilized in the fabrication of the sandwich panels:

2.2.1 Agar-Based Aerogel Core
Agar-based aerogel was selected as the core material after systematic evaluation of various conventional materials. Agar aerogel is a bio-derived porous material characterized by extremely low density and very high thermal insulation capacity. Its internal microstructure consists of an interconnected porous network that significantly reduces heat transfer while maintaining structural continuity.

Key properties include:
• Very low density
• Moderate compressive strength
• Extremely high thermal insulation
• High fire resistance
• Sustainable and biodegradable origin
• Low thermal conductivity

Aerogel core sheets with a thickness of 12 mm were prepared and cut into 10 cm × 10 cm square specimens for sandwich panel fabrication. Although aerogel materials can exhibit brittle behaviour when used independently, their performance improves significantly when integrated within a sandwich configuration where the face sheets carry bending stresses and the core resists shear stresses.

2.2.2 Glass Fiber-Reinforced Polymer (GFRP) as Face Material
GFRP is a lightweight composite material consisting of glass fibress embedded in a polymer resin matrix. It was selected due to its excellent mechanical properties and structural stiffness.
Key properties include:
• High tensile strength
• Good flexural stiffness
• Corrosion resistance
• Lightweight nature
• Good bonding compatibility with epoxy

GFRP sheets with 1 mm thickness were cut into 10 cm × 10 cm squares and used as face sheets on both sides of the aerogel core. These sheets enhance bending resistance and structural stability of the panel.

2.2.3 Polypropylene Copolymer (PPCP) as Face Material

PPCP is a thermoplastic polymer known for its balanced mechanical properties and cost efficiency. It was selected to evaluate lightweight and economical sandwich panel configurations.
Key properties include:
• Lightweight
• Moderate tensile strength
• Good impact resistance
• Chemical resistance
• Cost-effective
PPCP sheets of 1 mm thickness were used as alternative face sheets for comparative evaluation of panel performance.

2.2.4 Ultra-High Molecular Weight Polyethylene (UHMWPE) as Face Material
UHMWPE is an advanced polymer known for its exceptional toughness and impact resistance.
Key properties include:
• Extremely high impact resistance
• Low density
• High abrasion resistance
• Excellent toughness
• Good durability under repeated loading
UHMWPE sheets of 1 mm thickness were cut into 10 cm × 10 cm squares and used as face layers to enhance impact performance and energy absorption capacity of the sandwich panel.

2.2.5 Adhesive Material
Epoxy resin is a high-performance thermosetting polymer widely used for bonding sandwich panel components due to its strong adhesion and durability.
Key properties include:
• High bonding strength
• Chemical resistance
• Thermal stability
• Low shrinkage during curing
• Strong compatibility with composite and polymer materials
A two-part epoxy adhesive with a mix ratio of 1:1 by weight was used in this study. The adhesive was applied evenly on both the aerogel core and face sheets before curing. It acts as the primary bonding agent holding the sandwich panel layers together and ensures efficient stress transfer between components. The curing time was maintained as per manufacturer instructions, and the panels were pressed under uniform pressure to achieve proper adhesion and structural integrity.

3.3 Design Considerations
Here are the design considerations for the sandwich panel, summarized in the following points:

Material Selection:
• The sandwich panel configuration was chosen based on structural performance, insulation capability, fire resistance, sustainability, and cost efficiency.
• Agar-based aerogel was selected as the core material due to its extremely high thermal insulation and improved fire resistance compared to conventional foam cores.
• GFRP, PPCP, and UHMWPE were selected as face materials based on their mechanical strength, lightweight nature, durability, and bonding compatibility.

Structural Requirements:
• The design considered compressive, flexural, and shear load resistance.
• Core thickness was selected to improve shear capacity and overall panel stiffness.
• Face sheet thickness was selected to resist bending stresses effectively.
• Symmetrical configuration was maintained to ensure uniform stress distribution.
• Edge support conditions were evaluated to prevent buckling and delamination.

Performance and Durability:
• The panel was designed to achieve moderate compressive strength with very high thermal insulation.
• Fire resistance and thermal stability were key design objectives.
• Adhesive bonding strength was crucial for long-term durability.
• The ability of the panel to withstand dynamic loads and resist impact was also considered.

• Overall, the design focused on achieving a lightweight, thermally efficient, and structurally stable configuration suitable for residential applications.

3.4 Fabrication Procedure

The hand lay-up procedure is a method used to fabricate composite sandwich panels in a controlled and precise manner. This process allows the creation of a structurally efficient panel by layering the core and face materials and bonding them with epoxy adhesive.

The following procedure was adopted for the preparation of the sandwich panel used in the project:

1. Cleaning Surfaces: Both the aerogel core and face sheets were carefully cleaned to remove dust, moisture, and contaminants. This ensured optimal bonding and prevented weak adhesion zones.
2. Preparation of Face Sheet: The selected face sheet (GFRP, PPCP, or UHMWPE) was laid on a flat and stable surface to provide a firm foundation for panel construction.
3. Application of Adhesive: A thin and uniform layer of epoxy adhesive was applied to the surface of the face sheet using a spreader. Uniform thickness was maintained to ensure proper load transfer.
4. Placement of Core Material: The agar-based aerogel core was carefully positioned onto the adhesive-coated face sheet. Proper alignment was ensured to avoid stress concentration and uneven load distribution.
5. Second Layer of Adhesive: A second uniform adhesive layer was applied on top of the aerogel core to prepare for placement of the upper face sheet.
6. Placement of Second Face Sheet: The second face sheet was laid over the adhesive layer, completing the sandwich panel configuration. Proper alignment and positioning were maintained to ensure structural symmetry.
7. Application of Even Pressure: Uniform pressure was applied to the assembled sandwich panel to eliminate air gaps and ensure proper bonding between layers. This step was critical for preventing delamination.

Curing Process: The assembled sandwich panel was allowed to cure according to the adhesive manufacturer's recommendations. The curing process ensured full bond strength and dimensional stability of the final product. Throughout the fabrication process, careful attention was given to precision in adhesive application, accurate positioning of materials, and uniform pressure during curing. These measures were essential for producing a high-quality sandwich panel with consistent structural and thermal performance characteristics.

III RESULTS

3.1 Mechanical Performance Evaluation

The mechanical performance of the optimized sandwich panel configurations was evaluated based on compressive strength, flexural behavior, shear resistance, and overall structural stability. The cork–polycarbonate panel developed in Phase-1 served as the reference benchmark, exhibiting compressive strengths of 2.78 N/mm² under flatwise loading and 6.38 N/mm² under edgewise loading. These results demonstrated suitability for non-load-bearing partition applications but highlighted limitations in fire resistance and long-term durability.

In the present study, the agar-based aerogel core was evaluated in combination with three advanced polymer face sheets: Glass Fiber Reinforced Polymer (GFRP), Polypropylene Copolymer (PPCP), and Ultra-High Molecular Weight Polyethylene (UHMWPE). The aerogel core demonstrated moderate compressive strength of approximately 2.30 N/mm² under flatwise loading conditions. Although slightly lower than the cork reference in edgewise performance, the structural efficiency improved due to better stress redistribution through high-performance face sheets.

Panels incorporating GFRP face sheets exhibited the highest flexural stiffness due to the high tensile strength and modulus of elasticity of glass fiber composites. The improved stiffness significantly reduced mid-span deflection during bending tests. UHMWPE-faced panels demonstrated superior impact resistance and toughness, absorbing higher energy before failure. PPCP-faced panels provided a balanced performance with reduced weight and cost while maintaining adequate structural stability.

The variation in mechanical performance among the configurations can be attributed to differences in face sheet modulus, bonding efficiency, and core shear strength. The aerogel core effectively resisted shear stresses while the face sheets carried tensile and compressive bending stresses, consistent with classical sandwich beam theory. Overall, the optimized configurations demonstrated sufficient mechanical adequacy for partition and lightweight structural applications.

3.2 Thermal and Fire Performance Assessment

Thermal insulation performance was primarily governed by the porous microstructure and extremely low thermal conductivity of the agar-based aerogel core. Due to its interconnected nano-porous structure, the aerogel significantly reduced heat transfer through conduction and convection mechanisms. Compared to conventional foam-based cores studied in earlier trials, the aerogel core exhibited superior insulation efficiency.

Fire resistance evaluation indicated improved thermal stability of the aerogel core compared to synthetic polymer cores. Unlike foam materials that tend to melt or emit smoke under elevated temperatures, the agar-derived aerogel demonstrated enhanced resistance to flame propagation and structural degradation. The performance improvement is attributed to its bio-based composition and reduced flammability characteristics.

Among face materials, GFRP provided better dimensional stability under elevated temperature conditions, while UHMWPE demonstrated good thermal tolerance with minimal deformation. PPCP maintained acceptable performance but showed comparatively lower heat resistance than fiber-reinforced composites. The combined system of aerogel core with GFRP face sheets exhibited the most stable performance under thermal exposure.

These results highlight the importance of integrating mechanical and fire performance in material selection for residential sandwich panel applications.

3.3 Comparative Performance Analysis

A systematic comparison of the developed sandwich panel configurations was conducted based on mechanical strength, thermal efficiency, fire resistance, cost, and practical applicability.

GFRP-faced panels exhibited the highest structural stiffness and bending resistance due to superior tensile properties. UHMWPE-faced panels provided excellent impact resistance and lightweight characteristics, making them suitable for dynamic loading environments. PPCP-faced panels offered cost-effective solutions with moderate structural capacity.

The agar-based aerogel core demonstrated moderate compressive strength combined with very high thermal insulation and very high fire resistance characteristics. Although its compressive strength was slightly lower than dense mineral cores evaluated during preliminary trials, the significant reduction in weight and superior insulation performance improved overall efficiency.

The comparative evaluation indicates that while GFRP provides maximum structural rigidity, UHMWPE enhances impact tolerance, and PPCP improves cost feasibility, the aerogel core consistently enhances thermal and fire performance across all configurations. Therefore, optimization must balance structural performance with insulation efficiency and economic feasibility.

3.4 Optimization of Sandwich Panel Configuration

Based on the comparative evaluation, an optimization approach was adopted to identify the most efficient configuration suitable for residential partition and modular housing applications.

Optimization criteria included:

- Strength-to-weight ratio
- Cost-performance efficiency
- Fire resistance capability
- Thermal insulation performance
- Durability and bonding stability

Although GFRP-faced panels demonstrated the highest flexural stiffness, UHMWPE-faced panels provided superior impact resistance. PPCP-faced panels offered economic benefits with acceptable structural capacity. From an integrated performance perspective, the configuration combining agar-based aerogel core with GFRP face sheets demonstrated the best balance of structural stiffness, thermal insulation, and fire resistance. The aerogel–UHMWPE combination also showed promising performance for lightweight and impact-resistant applications.

Overall, the agar-based aerogel core significantly enhances the multifunctional efficiency of sandwich panels, making it a super-efficient alternative to conventional partition wall systems.

Core Material Compressive Strength (N/mm²) Thermal Insulation Fire Resistance Relative Cost Overall Suitability

Cork (Phase-1 Reference) 2.78 High Moderate Medium Good Benchmark

Aerogel (Agar-based) 2.30 Very High Very High Low Super-Efficient

This table presents the comparative evaluation of the reference cork core and the proposed agar-based aerogel core based on structural strength, thermal performance, fire resistance, and economic feasibility. While cork demonstrates stable mechanical performance, its fire resistance remains moderate. In contrast, the agar-based aerogel core exhibits moderate compressive strength combined with very high thermal insulation and fire resistance. Additionally, due to its lightweight and relatively low cost, the aerogel core shows strong potential as a super-efficient and sustainable material for advanced sandwich panel applications.

3.5 Comparison with Previous Studies

Several researchers have investigated sandwich panel systems using foam, cork, and mineral-based cores combined with polymer or metallic face sheets. Previous studies primarily focused on mechanical performance or thermal insulation independently, often without integrated optimization.

Research involving cork cores reported moderate compressive strength and good insulation properties suitable for non-load-bearing applications. Studies on polymer foam cores highlighted excellent insulation performance but identified limitations in fire resistance and environmental sustainability. Fiber-reinforced polymer face materials such as GFRP were shown to enhance flexural stiffness significantly, though often at increased material cost.

In contrast to earlier studies that evaluated isolated material combinations, the present study introduces agar-based aerogel as a bio-based core material and performs structured comparative optimization using multiple polymer face sheets under uniform evaluation criteria. The integration of mechanical, thermal, fire, and cost parameters within a single assessment framework provides a more holistic engineering evaluation.

Therefore, this study advances existing literature by introducing a sustainable aerogel core system and demonstrating its viability as a multifunctional, lightweight, and fire-resistant alternative for residential sandwich panel applications.

IV CONCLUSION

The present study successfully investigated the development and optimization of a lightweight and sustainable sandwich panel system incorporating an agar-based aerogel core combined with advanced polymer composite face sheets. In Phase-1, a cork-based configuration established a structural benchmark; however, extended experimental evaluation and systematic material screening led to the selection of agar-derived aerogel due to its superior thermal insulation, enhanced fire resistance, and improved sustainability profile.

Mechanical performance evaluation demonstrated that the aerogel core provides moderate compressive strength suitable for non-load-bearing structural applications such as residential partition walls. When integrated with GFRP face sheets, the panel exhibited enhanced flexural stiffness and structural stability. The UHMWPE-faced configuration showed improved impact resistance and toughness, while PPCP face sheets provided a cost-effective alternative with balanced performance characteristics. The results confirm that structural efficiency in sandwich panels is governed by effective load sharing between high-stiffness face sheets and a lightweight shear-resisting core.

Thermal and fire performance assessment revealed that the porous microstructure of agar-based aerogel significantly reduces heat transfer and improves resistance to flame propagation compared to conventional synthetic core materials. This multifunctional performance advantage makes the developed system particularly suitable for energy-efficient and safety-oriented residential construction.

Cost and material efficiency analysis further emphasized the advantages of the proposed configuration over traditional masonry systems. The developed sandwich panels reduce self-weight, material consumption, and construction time while improving insulation performance and sustainability.

Overall, the study demonstrates that agar-based aerogel core sandwich panels represent a structurally viable, thermally superior, fire-resistant, and eco-friendly alternative to conventional wall systems. The optimized configurations provide strong potential for application in modular, prefabricated, residential, and lightweight construction projects, thereby contributing to sustainable building technology development.

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