Development of Lightweight Thermal Insulation Board: A Study on Physical and Mechanical Properties of Sandwich Board Made of Perlite, Polystyrene, and Formica Sheet

Mehedhi Hasan[1*], G M Ismail Hossain[1], Md Aasef Azhar Khan[2], Md Ahatashamul Haque Khan Shuvo[1], Torikul Islam[3], Md Tahmid Hasan[2]

[1]Department of Mechanical Engineering, Sonargaon University (SU),
Dhaka-1205, Bangladesh
[2]Department of Mechanical Engineering, Khulna University of Engineering & Technology,
Khulna-9203, Bangladesh
[3]Department of Biomedical Engineering (BME),
New Jersey Institute of Technology,
Newark, NJ, USA
[*] Corresponding author: mehedhi.22hasan@gmail.com

Abstract

This study focused on the development of thermal insulation boards by utilizing expanded perlite (EP) and expanded polystyrene (EPS) within a lightweight core, in conjunction with a Formica sheet serving as the exterior layer. The sandwich specimens were fabricated by employing epoxy resin as a binding material, with the volume fractions of EP and EPS being adjusted. A detailed assessment was undertaken to evaluate the physical, mechanical, and thermal conductivity via Lee's disc method. The core's flexural strength, modulus, and energy absorption were found to be superior when the EP volume fraction within it was at its ideal level of 100%. As predicted, there was a positive correlation between the thermal conductivity and the proportion of EP particles. Significantly greater swelling and water absorption were seen in sandwiches composed of 100% EP compared to those composed of 100% EPS. The introduction of EP particles into EPS resulted in a reduction in facial wrinkling during flexural failure, as well as an enhancement in deboning and skin delamination. This research study presents significant findings on the behavior of composite materials, which has the potential to contribute to the advancement of thermal insulation technology.

Keywords:
Sandwich insulation board, Mechanical properties, Swelling percentage, Thermal properties.

1. Introduction

A sandwich composite structure is a three-layered panel comprising three unique layers: an outside layer, a core, and an interior layer, each serving a specialized purpose in providing thermal insulation, high load capacity, and relatively high compressive and flexural strength and stiffness. These sandwich boards promote energy efficiency, maintain temperature control, and improve a structure's comfort and energy performance. The middle layer is the principal component for providing different thermal and mechanical properties. The materials commonly utilized in this layer are expanded polystyrene (EPS), expanded perlite (EP), extruded polystyrene (XPS), polyurethane foam, fiberglass, mineral wool, foam board, etc.

Polystyrene (PS) is one of the general-purpose plastics with a wide variety of applications due to its good mechanical properties, anti-corrosion capacity, and processing performance (Zhao Z et al. 2020). However, it generates a lot of waste, as it is used in low-cost articles with very short use time. One way to reuse them is using them as composite materials. Expanded Polystyrene (EPS) is a lightweight, thermoplastic foam with insulation and durability characteristics. Investigated the mechanical behavior of EPS sandwich composites with varying fabric reinforcements

(Crameri, S et al. 2023). The mechanical properties of these composite structures change with the variation of core density (G. M. Hossain et al. 2023). It was observed in the work of A S M Aziz et al. (2022) that while using an expanded perlite/sodium silicate composite reinforced with nylon fiber, the energy absorption during flexural and compression tests had improved despite the deterioration of the compressive and flexural properties. M Arifuzzaman, et al. (2017) showed the flexural behavior of sandwich structures made of perlite composite foam with sodium silicate binder and brown paper as skin. The study demonstrated that perlite foam reinforced with brown paper had a load-carrying capacity of 3-7 times higher than the unreinforced structure. The thermal insulation characteristics of the EPS have been tested previously in various works. Fine grain size of expanded perlite was used as an additive in a ceramic mass, which led to decreases in products' density by 2.9 % up to 7.1% and in the thermal conductivity coefficient by 5.4% up to 9.5%(Makrygiannis et al. 2022). The use of expanded polystyrene and expanded perlite as lightweight aggregates for the preparation of lightweight geo-polymers is tested through physical, mechanical, and thermal testing (Kioupis et al.2022).

A novel arrangement of hollow concrete blocks was manufactured on-site to assess the commercial viability of these hollow concrete blocks, four distinct variants (perlite, vermiculite, scoria, and polystyrene) were investigated (Al-Tarbi et al. 2023). Durmuş, G. & Topuz, H. C. (2022) used expanded perlite and granular polystyrene foam as aggregates in foam concrete, as well as creating an aerogel layer on the concrete surface. MAHS Khan et al. (2018) studied the low-velocity impact of EPS-based composite, finding non-linear displacement and linear maximum principal strain increase with impact energy, causing damage after 8J.Four different sandwich samples were explored for use in cold storage chambers, and the results showed that polyurethane had a homogeneous distribution of size and shape with closed cells, which can improve the retention of the insulation gas (Sartori, Ana P. et al. 2023). The perlite-based insulating material is developed to meet ASTM C610 standards in a form of the board in order to meet the requirements of thermal conductivity and moisture resistance (Keawprak, N. et al 2022). Yucel et al. (2021) investigated expanded polystyrene materials' thermal conductivity through experimental testing using the plate method. Lakatos, Á. and Kalmár, F. (2012) demonstrated the thermal conductivities of expanded polystyrene (EPS) insulation materials, with different thicknesses and air pore content. Tahir, M.N. and Hamed, E. (2021) performed an experimental investigation on metal-faced sandwich panels with EPS core and exposing them to different numbers of thermal cycles and high temperatures. The work also evaluated the degradation of the mechanical properties of the sandwich structure after the application of thermal cycles.

Therefore, in this work, EP and EPS were blended in a variety of ratios to create a sandwich structure that is thermally insulated, with a Formica sheet serving as the skin. The density, swelling thickness percentage, static flexural strength, modulus, energy absorption, failure behavior, and thermal conductivity of the sandwich board panels are among the physical and mechanical characteristics examined.

2. Experimental details

2.1 Materials

Particles of expanded perlite (EP) with a bulk density of 0.072 g/cm3 and a size range of 4-5.6 mm were purchased from King Caster Perlite in China. In the meantime, RFL in Bangladesh provided expanded polystyrene (EPS) particles with bead diameters of 5 to 6 mm and a determined bulk density of 0.009 g/cm3. Formica sheets, well-known for their numerous uses in furniture design, architectural ornamentation, and interior design, were used at a thickness of 0.5 mm and a density of 1246 g/cm3. Epoxy resin (Araldite), with a recommended resin-to-hardener ratio of 3:1 following the manufacturer's instructions, was used to fabricate the sandwich board. To reduce viscosity and improve workability, acetone, a transparent and colorless solvent, was added to the resin-hardener mixture at a rate of 20% of the mass of the mixture.

2.2 Method of Production

Compression molding was used to create the composite foams. Based on the manufacturer's suggested 3:1 weight ratio, an epoxy resin and hardener mixture was made. The resin mixture was thinned out with the addition of acetone. The EPS was then added to this mixture in a container, and the mixture was thoroughly agitated for five minutes to achieve evenness. The surface of the mold was greased before pouring the mixture to make it easier to remove the finished composite foam. The final composite foam size that the mold was intended to produce was 150 mm 150 mm 12 mm. A 150kg load was applied to the mold setup over 24 hours while it was being used to prepare samples utilizing universal testing equipment.

The system was taken apart, and to totally eliminate acetone, it was heated in an electric oven at 60°C for 24 hours. As shown in Table 1, this procedure was repeated to create additional specimens with different EPS and EP content ratios. The Formica sheets received an adhesive coating made of epoxy resin and hardener before being adhered to both sides of the synthetic composite foams. The sandwiches were divided into test-appropriate-sized pieces after curing for 24 hours under a 150 kg load.

a) b) c) d) e)

Figure 1. Sequential steps in sample preparation for sandwich structure creation - (a) wetted EPS and EP mixture pouring; (b) upper formica skin placement; (c) upper mold ladle placement; (d) compression process; and (e) final prepared sandwich structures.

Table 1. Mix proportion for sandwich core manufacturing.

Sl. No.	Sample code	EP (ml)	EPS (ml)	Volume percentage of EPS and EP	Epoxy (g)	Hardener (g)
1	EPS100-EP0	0	400	EPS=100%; EP=0%		
2	EPS75-EP25	100	300	EPS=75%; EP=25%		
3	EPS50-EP50	200	200	EPS=50%; EP=50%	30	10
4	EPS25-EP75	300	100	EPS=25%; EP=75%		
5	EPS0-EP100	400	0	EPS=0%; EP=100%		

2.3 Mechanical and Thermal Testing

The static flexural test was conducted in accordance with ASTM C393 standards using a Universal Testing Machine (Shimadzu AGXV-300kN, Japan). The testing was conducted at a crosshead speed of 5 mm/min. Four specimens from each type of sandwich-type were tested. The flexural test specimen size was 150 mm×25 mm×12 mm: span length 100mm. A photograph taken during the flexural test is given in Fig. 1 (a). The peak point after the linear portion of the flexural stress vs. strain curve was used as flexural strength for the specimens containing perlite particles. Additionally, the modulus was determined from the slope of the most linear portion of the stress- strain curve prior to the failure initiation. Furthermore, the energy absorbed per unit volume up to 1st core failure of cross-head displacement was found from the area under the flexural stress-strain curves. In the swelling and water absorption tests, specimens with dimensions of 150 mm, 25 mm and 12 mm were used. After the samples were submerged in water for 24 hours, the extent of swelling and water absorption were evaluated simultaneously. Looking into more details on screws retaining capacity, both perpendicular and parallel, like cantilever beams, were hold, and then the screws was clamped in them. Where span length was 100mm.The retaining capacity of the samples was determined by inserting the screw into the sample and applying a force perpendicularly and in parallel. The well-known Lee's disk method F. Hossain et al. (2023) was used to test the thermal conductivity of the insulation board in order to determine the thermal conductivity of the sandwiches. The samples had a 100mm diameter and were cut into circles.

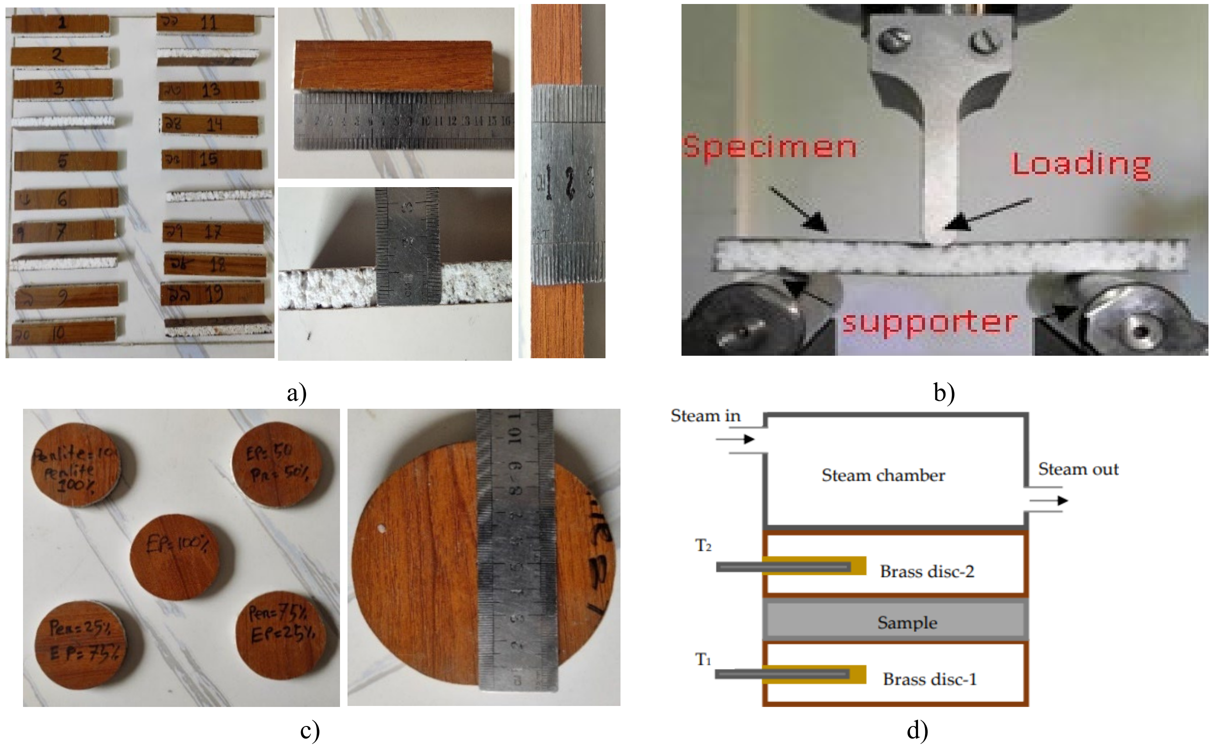

Figure 2. (a) & (b) - Test samples and Flexural test setup, and (c) & (d) - Test samples and Thermal Conductivity test block diagram (F. Hossain et al. 2023).

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3. Results and Discussion

As part of the mixture preparation process for creating the core, the density of the sandwich composite is shown in Table 2. The density range measured was 0.18 ± 0.01 g/cm^3 to 0.45 ± 0.02 g/cm^3. The sandwich made entirelyof EP was determined to have the maximum density, and the composite made entirely of EPS to have the lowest density. Because EP particles have a higher density than EPS particles (0.072 g/cm3 for EP and 0.009 g/cm3 for EPS), the density of the sandwich made entirely of EPS was 61.25 percent less dense than the sandwich made of EP. Sandwiches became denser as the volume proportion of EP was raised. The swelling grew as the perlite content did as well. Similar to what is seen with perlite, it is noted that the water absorption rises by around 11 times after 24 hours. While 100% EPS often has a relatively poor screw retention capacity, 100% perlite has beenproven to have the maximum retention capacity. The ability of 100% EPS was 11N/mm when the screw holdingcapacity was measured perpendicularly, but that of 100% perlite was around 32 N/mm. In a similar fashion, in a parallel circumstance, the screws holding capacities of 100% EPS were 3 N/mm and 100% perlite were 23 N/mm,which is a respectable amount.

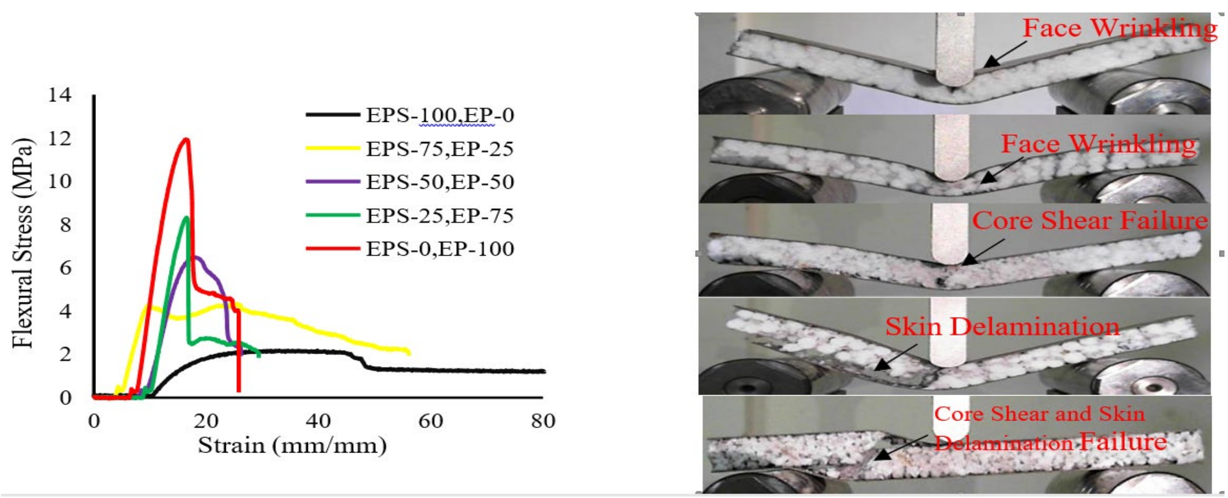
Table 2. Physical and mechanical properties of insulation board

Parameter	**EPS-100,EP-0**	**EPS-75,EP-25**	**EPS-50,EP-50**	**EPS-25,EP-75**	**EPS-0,EP-100**	**Unit**
Density	0.18 ± 0.01	0.29 ± 0.02	0.37 ± 0.03	0.44 ± 0.02	0.45 ± 0.02	gm/cm^3
Swelling in thickness after 24 h	< 1.00	1.25	1.75	2.00	2.58	%
Water absorption after 24 h	< 1.00	2.85	4.56	7.26	11.39	%
The capacity to retain screws perpendicularly	11 ± 1.00	13 ± 1.86	21 ± 2.89	26 ± 1.53	32 ± 0.53	N/mm

Ability to hold screws parallel	3 ± 0.5	7 ± 0.8	13 ± 1	18 ± 0.3	23 ± 0.8	N/mm
Static flexural strength	2.18 ± 0.36	4.33 ± 0.28	6.50 ± 0.21	8.32 ± 0.32	11.94 ± 0.21	MPa
Static flexural modulus	0.20 ± 0.05	0.43 ± 0.02	0.70 ± 0.24	0.89 ± 0.05	1.20 ± 0.03	MPa
Flexural Energy absorption	30.45 ± 3.00	40.12 ± 4.00	50.13 ± 2.00	65.32 ± 3.00	78.98 ± 2.00	J
Heat conduction	0.037	0.040	0.044	0.047	0.050	W/(m-k)

The sandwich structure's flexural stress-strain curves, shown in Figure 3, provide a thorough analysis of the material's behavior at different EP concentrations. In sandwiches largely made of EP particles, a recognizable pattern appears: an initial peak, a warning of impending failure evidenced by a drop in stress, followed by a persistent plateau before eventual core failure. However, the sharp peak seen in EP-based equivalents is conspicuously lacking in the stress-strain curve of the sandwich made entirely of EPS, as shown by the strong black solid line in Figure 3. This extended plateau clearly illustrates the extraordinary energy-absorbing capacity of these sandwich composites. A 100% EP-based core is seen to have multiple fissures, skin delamination, and particle deboning at a 12 mm deformation upon closer inspection. In contrast, the incidence of cracking and deboning gradually increases as the volume proportion of EP particles rises in a sandwich made entirely of EP. Notably, the stress-strain curve of the sandwich made entirely of EP lacks a clear peak, indicating that plastic deformation rather than material breakdown dominates the mode.While sandwiches made of EP particles may have distinct peaks caused by the breaking of EP particles, the pointat which structural failure of EP particles occurs is shown by a steep decrease immediately after the apex in Figure 3.

There is a clear pattern that shows that increasing the amount of EP particles within the sandwich core causes the stress post-peak to decrease more significantly. Furthermore, an increase in perlite levels correlates with a rise in destructive failure. This underscores a pivotal observation: higher perlite content amplifies the susceptibility tostructural failure, suggesting an important consideration in material formulation and engineering applications.



a) b)

Figure 3. (a) Typical flexural stress vs strain curves recorded during flexural tests and (b) Images captured during the failure of the flexural test for various sample configurations EPS ranges from 100%at the top to 0% at the bottom.

Table. 2 displays the flexural strength, modulus, and energy absorption of different sandwiches. Overall, as the EP concentration increased, so did the flexural strength, modulus, and energy absorption. For an EP volume percentage of 100 percent, the highest values of flexural strength, modulus, and energy absorption were discovered. The 100% EP-based sandwich outperformed the 100% EPS-based sandwich in terms of flexural strength, modulus, and energy absorption by 5.47, 6, and 2.59 times, respectively. The table demonstrates that more perlite may be added to EPS to improve its mechanical characteristics, such as strength, modulus, and energy absorption. As a consequence, the mechanical characteristics of EPS may be optimized. However, the mechanical characteristics of EPS increased when the volume of perlite in the samples was increased to 25%.

The flexural failure characteristics of five different sandwich boards, each made up of different ratios of expanded polystyrene (EPS) and expanded polyurethane (EP) materials, are shown in Figure 3(b). Skin wrinkling was the most common failure mode seen in cases where the insulating core was entirely made of EPS. Core shear failure became the major failure mode at the 50% EPS composition as the fraction of EP in the core increased, accompanied by a decrease in EPS content. Notably, the failure mode changed to skin delamination at an EP level of 75%, which worsened as the EP value reached 100%.

In general, perlite has a much higher thermal conductivity than EPS, hence the thermal conductivity of the sample increases as the perlite content does as well. As may be stated, the thermal conductivity of 100 percent EPS was discovered to be 0.037 W/ (m - k). Similarly, the thermal conductivity rose with the addition of perlite, as the sample with 100 percent perlite had a thermal conductivity of 0.050 W / (m - k). Therefore, more perlite may be added to EPS to improve its mechanical and thermal characteristics. The mechanical and thermal performance ofEPS will be significantly improved as a consequence, and an ideal lightweight composite material may be created.

4. Conclusion

In this work, lightweight sandwich structures were fabricated using expanded perlite and expanded polystyrene beads with varying proportions. The density, swelling thickness percentage, static flexural strength and modulus, energy absorption, failure behavior, and thermal conductivity of the composite structures were investigated. The findings of the study are summarized as follows:

- The density of the sandwich structure has a proportional relation with the EP particles in the sandwich core due to the higher density of EP particles.
- Due to higher EP content, it was found that the swelling and water absorption grew higher than that of EPS. The capacity to retain screws perpendicularly and to hold screws in parallel was observed to be lower for the 100% EPS specimen than that of 100% EP.
- It was found from the flexural tests that as the EP percentage in the sandwich structures increased, the flexural strength, modulus, and energy absorption increased. With the blending of EP and EPS, cracking and deboning were increased in the specimens.
- The long plateau after the peak in the stress-strain curves indicated the high energy absorption capability of the developed sandwich structures.
- The flexural properties of sandwich panels including strength, modulus, and energy absorption along with thermal conductivity were significantly affected by the replacement of EPS particles with EP particles. However, the combination of 25%EP particles with 75% EPS particles proved to be an optimum mixer for the improvement in the mechanical characteristics.
- The mixer of EP and EPS to manufacture lightweight sandwich structures showed a positive effect in terms of flexural and thermal insulation properties.

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Biographies

Mehedhi Hasan is an enthusiastic researcher on composite materials and their applications. He graduated from Sonargaon University with a degree in mechanical engineering. In addition to doing research on sandwich structures, reinforcing effects, and thermal insulation boards. He has several conference papers published. Additionally, biomedical engineering and biocompatibility interest his attention. His dedication to groundbreaking research is shown by his published conference papers and current studies on sandwich structures, the effects of reinforcement on composites, and thermal insulation boards.

G M Ismail Hossain, a Mechanical Engineering graduate from Khulna University of Engineering and Technology, is a passionate researcher and educator on composite materials and their applications. He has published conference papers and conducted research on sandwich structures, reinforcement effects, and thermal insulation boards. Ismail also serves as a Lecturer at Sonargaon University, teaching and mentoring students in various mechanical engineering domains.

Md Aasef Azhar Khan completed his Bachelor of Science in Mechanical Engineering from Khulna University of Engineering and Technology (KUET). Currently he is working on the research of manufacturing composite material in KUET as part of his research work.

Md. Ahatashamul Haque Khan Shuvo got his B.Sc. in Mechanical Engineering from Khulna University of Engineering & Technology, Khulna, Bangladesh. He is currently working as an assistant professor in Sonargaon University (SU). He has published 2 peer-reviewed journal articles and 4 peer-reviewed international conference papers. He is also a reviewer of Journal of Engineering Advancements (JEA).

Torikul Islam received B.Sc. degree in biomedical engineering from Khulna university of engineering & Technology, Khulna, Bangladesh. He is currently pursuing the Ph.D. degree in biomedical engineering with New Jersey Institute of Technology, Newark, NJ, USA. He has published 3 peer-reviewed journal articles and 5 peer-reviewed international conference papers.

Md Tahmid Hasan, a fresh graduate with a Bachelor of Science in Mechanical Engineering from Khulna University of Engineering & Technology, Bangladesh, is a passionate researcher with interests in various fields such as Fiber Reinforced Composites, Polymer Composites, Additive Manufacturing, 3D Printed Polymer Composites, and High-Temperature Materials. He is currently an Adjunct Lecturer at Sonargaon University in Bangladesh. Hasan has completed five successful projects and published several conference papers.