SciEn

Proceedings of 8th International Conference on Mechanical, Industrial and Energy Engineering 2024
02-04 January, 2025, Khulna, BANGLADESH

SciEn Conference Series: Engineering Vol. 3, 2025, pp 622-626 https://doi.org/10.38032/scse.2025.3.157

Flexural Properties of Fly Ash Reinforced Perlite/Sodium Silicate Composite and Their Sandwich Structures

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ABSTRACT

The current investigation is focused on improving the flexural properties of perlite/sodium silicate composites using fly ash as reinforcement. Perlite/sodium silicate composites are reinforced with varying amount of fly ash (15 %, 30 %, and 45 %). Formica sheet was used as skins of the sandwich structures with fly ash reinforced perlite/sodium silicate composite as core. To attach the formica sheet skins with core pure epoxy and fly ash reinforced epoxy was used. The flexural strength and modulus of perlite/sodium silicate composite, fly ash reinforced perlite/sodium silicate composite, and two types of sandwiches are determined by three point bending test according to the standard. Results showed that the flexural strength of fly ash reinforced perlite/sodium silicate composite for 30 % fly ash content was maximum and 147.62 % greater than perlite/sodium silicate composite without reinforcement. The flexural modulus increased with increasing fly ash content up to 40 % fly ash content. The maximum enhancement in flexural strength and modulus of fly ash reinforced core-based sandwiches were also found at a fly ash content of 30 %. Utilization of fly ash reinforced epoxy as adhesive layer in the interface between the core and the skin improved the flexural modulus of the sandwiches significantly but the flexural strength slightly decreased. The study suggests that fly ash is an excellent reinforcing agent for the improvement of the flexural properties of perlite/sodium silicate composites and their sandwich structures.

Keywords: Sandwich Structure, Perlite, Formica Sheet, Fly ash, Sodium Silicate Solution, Flexural Properties

1. Introduction

Sandwich structures with layers of skin and core are widely utilized in construction, marine, and aerospace industries where a high stiffness-to-weight ratio is crucial. While the core is composed of lightweight materials, the skin is usually thin but highly stiff. While the skin's primary purpose is to protect the core, the core's ability to keep the top and bottom skins apart improves the cross-sectional area's moment of inertia. The design and material selection of these structures affect their performance; the selection of skin and core materials is based on availability, cost, and material qualities.

In building materials applications, cost often becomes a primary consideration, along with other properties, due to the large volume of materials required. Expanded perlite particles could be a potential option for the core material in sandwich structures. Perlite which is a form of volcanic rock containing silica and a small amount (2 to 6%) of water expands when heated to a temperature ranging from 1400 to 2000F [1,2]. Expanded perlite particles are inexpensive porous, environment-friendly, chemically inert, lightweight, and fire-resistant. In recent years, demands for expanded perlite particles have soared mainly because of its numerous characteristics namely, providing better thermal insulation [3–5]. In one such study done by Ai et al. [6] investigated the performance of the thermal insulation of the polyurethane/expanded perlite composites and discovered that the compressive strength and heat insulation have improved significantly with the increase of expanded perlite content in the composites. In another research where expanded perlite-fumed silica composite was studied by Alam et al. [7] for an efficient vacuum insulation panel core. They found that adding perlite would lower the cost of the panel while maintaining good insulation qualities. Other studies have shown that incorporating expanded perlite exhibited better sound absorption ability [8], and enhanced mechanical properties like higher stress and modulus of elasticity [9].

Fly ash is a by-product of coal combustion in thermal power plants, which can pose a serious threat to the environment if left untreated as fly ash can pollute both water and soil and even disrupt ecological balance [10]. To tackle this predicament, scientists, over the past decade, have been trying to develop feasible application methods to use fly ash. Dindi et al. [11] reviewed relevant literature to assess the properties and performance of fly ash, with a particular focus on recent advances in the application, durability, and sustainability of fly ash as a construction material. Other studies have shown improvement in many mechanical characteristics such as compressive strength, stress, and modulus of elasticity [12,13]. Meanwhile, some studies have ventured into the possibility. Selecting the right binder material is also crucial when creating perlite composites for sandwich cores. A suitable material that has been used to manufacture composite material is sodium silicate solution. Arifuzzaman and Kim [14], in their investigation of the behavior of diluted sodium silicate for the production of perlite foams, found that sodium silicate would be a good binder alternative. Commercially known as water-glass, it is a liquid that contains dissolved glass, possessing properties similar to water [15]. Soluble silicates, especially sodium, lithium, and potassium do not have a specific chemical formula and molecular weight, what they rather are glasses or aqueous

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solutions of glasses, a result of combinations of alkali metal oxide and silica in different proportions [16]. Sodium silicate has long been utilized as deflocculants, adhesives, fire retardants, and foundry sand binding [17]. Many researchers have manufactured expanded perlite-based composite panels using sodium silicate solution as a binder in order to investigate their physical and mechanical characteristics [14, 18]. One research studied the effect of nylon fiber reinforcement on the mechanical behavior of expanded perlite/sodium silicate composites [19]. Another study analyzed the compressive behavior of perlite/sodium silicate composite foam modified by boric acid [20]. In one study, researchers added expanded particles in the paste of an alkaline solution and fly ash [21].

In the case of the outer layer, there are a range of materials chosen. For example, aluminum sheets, copper sheets, formica sheets, etc. For similar reasons to those of perlite and sodium silicate, formica sheet as sandwich skin could be another potential material for sandwich structures in construction because of its availability, affordability, and environmental compatibility. Hossain et al. [22] used formica sheets as skin in their work to manufacture perlite/sodium silicate core-based sandwich structures. The main problem with perlite/sodium silicate composites and their sandwich structures is their low bending strength due to shear failure of the fragile perlite particles in the core and skin delamination.

Therefore, this study focuses on the improvement of perlite/sodium silicate composite panels and their sandwich structures using fly ash as a filler. The perlite/sodium silicate composite core of the sandwich structure was manufactured using various proportion of fly ash. The sandwiches were fabricated using formica sheet as skins. Also, to mitigate the delamination failure, the core sandwich interface was reinforced with fly ash/epoxy mixture. The flexural properties were investigated and found that the incorporation of fly ash improved the flexural behavior of the perlite/sodium silicate composite as well as their sandwich structures.

2.0. Experimental details:

2.1 Materials:

Expanded perlite particles (Fig. 1(a)) with a size range of 4-5.6 mm were purchased from King Caster Company Ltd., China. The bulk density of the expander perlite particles was measured to be 0.072 g/cm^3. The particles that are used in this work are 3-4 mm in size and were separated using sieves. Silicon dioxide and aluminum oxide are the main ingredients of perlite. Sodium silicate solution (SSS) was obtained from Silica solution, in Chittagong, Bangladesh. It was used as a binder in the composite.

(a) (b)

Fig.1 (a) Formica Sheet, (b) Expanded Perlite Particle

The density of the sodium silicate solution was 1.381 g/cm^3, the solid content percentage was 37-38 % and the silica to sodium oxide ratio was 3.20. Formica sheets (Fig. 1(b)) were collected from a local store in Khulna. In this work, Formica sheets of 0.5 mm thickness were used which have a density of 1.246 g/cm^3. Fly ash was collected from the Maitree super-thermal power plant situated in Khulna, Bangladesh. Fly ash is a heterogeneous by-product material produced in the combustion process of coal used in power plants. Epoxy resin with hardener was used as the matrix for the preparation of the adhesive interface layer between the core and skins. A chemical reaction occurs between the mixture of resin and hardener. Epoxy resin with a recommended resin-to-hardener ratio of 10:1 following the manufacturer's instructions, was used to make the sandwich structure. The epoxy-resin mixture transforms the binding agents into a solid state within 24 hours.

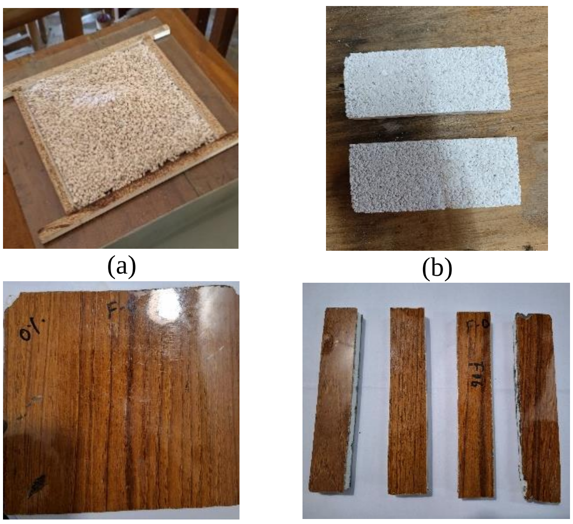
2.2 Specimen preparation:

At first, the cores were manufactured. For the base core which has 0 % fly ash content, perlite and sodium silicate solution were combined in a mass ratio of 3:1 in a mixing container. The mix ratio for various cores is shown in Table 1.

Table 1: Mix ratio for the production of sandwich cores

Batch No.	Perlite (g)	Sodium Silicate (g)	Fly Ash (g)
CF0	250	83.33	0
CF15			12.50
CF30			25.00
CF45			37.50

The wet mix was placed in a mold with inside dimensions of 150 mm ×150 mm ×15 mm (Fig. 2(a)). Before the mixture was put into the mold, the mold surface was lubricated to make it easier to remove. Then the sample was placed for curing at room temperature for 24 hours. For the cores with fly ash content, 3 cores were produced using fly ash content of 15 %, 30 %, and 45 % with sodium silicate solution.



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

Fig.2 Sequential steps in sample preparation for sandwich structure creation- (a) molded sample, (b) dried perlite/sodium silicate core, (c) sandwich, (d) test samples

After that, the skin was attached to the core to make the sandwich structures (Fig. 2(c)) where two categories were produced: "skin with fly ash" and "skin without fly ash". In the case of "skin without fly ash", a layer of epoxy resin and hardener was used as adhesive to the interface between the core and the skins. The formica sheets were cut a bit larger in dimension than the core. Then, the skins were attached to both sides of the core to prepare the sandwich structures. A metal plate along with 15 kg mass above it was placed on top of the arrangement and placed for curing at room temperature for 24 hours. For the "skin with fly ash" sample, the variation only occurred in the interface which contains fly ash along with epoxy and hardener but this time fly ash was added with the mixture of epoxy and hardener with a ratio of 1:1 (5.5 g epoxy with hardener and 5.5 g fly ash) and the skin were attached on both sides of the core to prepare the sandwich structures. Finally, all the sandwiches were cut to make test samples (Fig. 2(d)).

2.3. Experimental setup and testing:
The universal testing machine (Shimadzu AGXV-300kN, Japan) was used to perform the static flexural test in compliance with ASTM C393 requirements. A crosshead speed of 5 mm/min was used for the tests. Each sandwich type was examined with four specimens per batch. The dimensions of the flexural test specimen were approximately 150 mm x 25 mm x 12 mm, with a span length of 100 mm. The diameter of the loading and support rollers were respectively 10 mm and 35 mm. Fig. 3 shows a photograph taken during the flexural test.

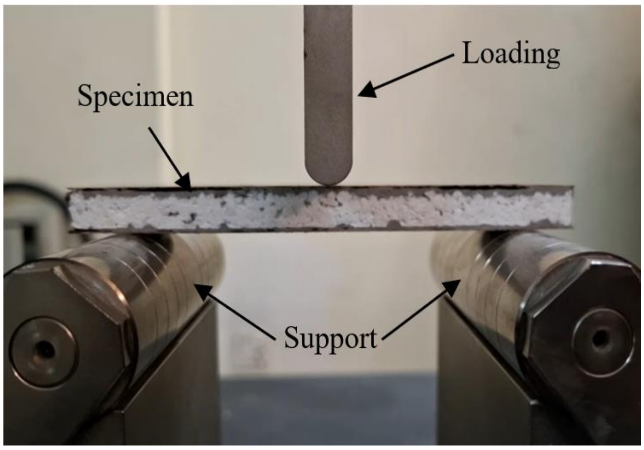


Fig.3 Flexural test setup

For the specimens with perlite particles, the flexural strength was determined by taking the peak point that follows the linear part of the flexural stress vs. strain curve. Furthermore, the slope of the most linear section of the stress-strain curve before the failure onset was used to calculate the modulus. Additionally, the area under the flexural stress-strain curves up to the first core failure was used to determine the energy absorbed.

3. Results and Discussions

The flexural strength of the perlite/sodium silicate composites and their sandwich structures are given in Fig. 4. It is observed that the flexural strength of perlite/sodium silicate composites increased with increasing fly ash content up to 30 % followed by a decrease at 40 %. For a constant perlite to sodium silicate solution ratio, 30 % fly ash may be treated as optimum to enhance the flexural strength of perlite/sodium silicate composites. At 30 %, fly ash content, the flexural strength of perlite/sodium silicate composite is increased by 147.62 %.

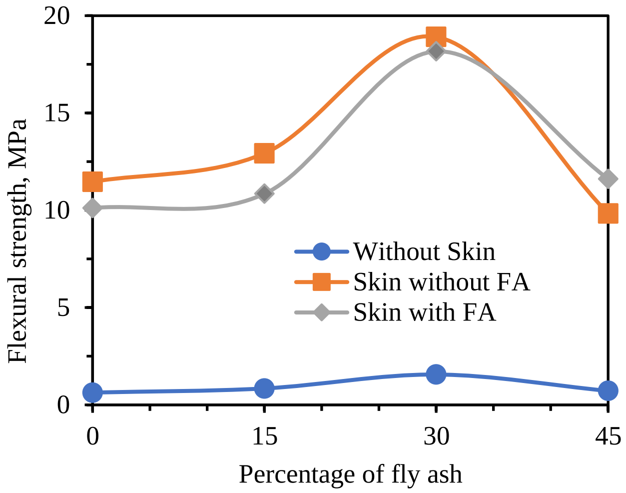


Fig.4 Flexural strength for various percentage of fly ash in the cores

The sandwich structure outperforms the core in terms of strength regardless of the percentage of fly ash in the core as expected (Fig. 4). Similar to the flexural strength of perlite/sodium silicate composite core, the flexural strength of the sandwich structures increased up to an optimum percentage of fly ash in the core i.e., 30 %. However, it is interesting to see that the sandwiches with fly ash reinforced epoxy interface showed slightly lower flexural strength compared to the sandwiches with epoxy only interface up to 30 % fly ash content in the core. The reason lies in the failure mechanism of the sandwich structures. A typical failure mechanism is shown in Fig. 5.

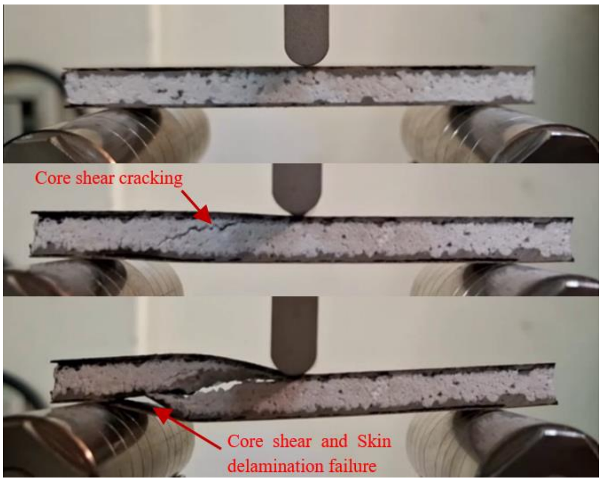


Fig.5: Various stages of crack development during the flexural test.

It is seen that the failure of the sandwich initiates within the core of the sandwich and the interface did not have any influence. Hence, with the increase in fly ash content the flexural strength increased in both types of sandwiches. However, the sandwiches with a stiff fly ash reinforced epoxy interface caused slightly premature failure of the core resulting in a lower flexural strength. Nonetheless, at 30 % fly ash content, the flexural strengths of sandwiches without fly ash reinforced interface and with fly ash reinforced interface showed respectively 79.55 % and 65.01 % enhancement. The increase in flexural strength of perlite/sodium silicate composites with the incorporation of fly ash can be attributed to the interaction between the fly ash and sodium silicate providing stronger bonding. However, at 40 % fly ash content, since the sodium silicate content was not increased (see Table1), the bonding between the fly ash and sodium silicate become weak and resulted in a decrease in the flexural strength.

The flexural modulus of the perlite/sodium silicate composites with and without fly ash, and their sandwich structures are given in Fig. 6. For perlite/sodium silicate composites, the flexural modulus increased with increasing fly ash content up to 45 % fly ash content. However, the flexural modulus of the sandwiches increased with increasing fly ash content up to 30 % fly ash content followed by a decrease. The flexural modulus of the sandwiches with fly ash reinforced epoxy as adhesive in the interface showed higher flexural modulus compared to the sandwiches with the epoxy resin only as interface between the core and the sandwiches.

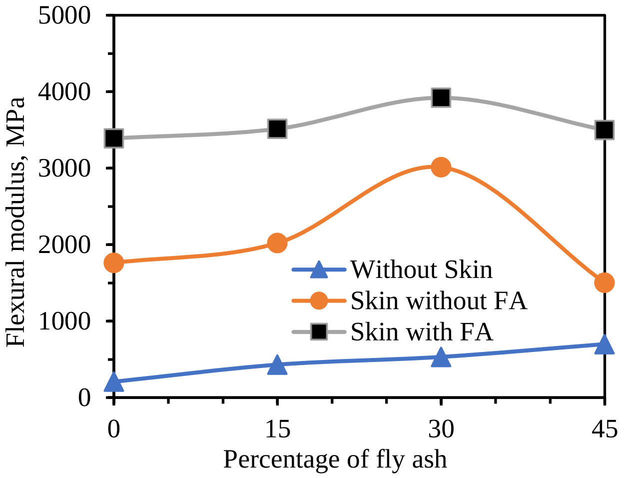


Fig.6: Flexural modulus for various percentage of fly ash in the cores

The reason for higher modulus of the sandwiches with fly ash reinforced epoxy interface is the higher load bearing capacity of the interface. Because during flexural test top and bottom side of the specimen are subjected to the severe stress and determines the modulus of the sandwich structures. For the sandwiches with epoxy only interface and fly ash reinforced epoxy interface, at 30 % fly ash content in the core, the flexural strength increased by 70.86 % and 15.67 % respectively compared to the respective sandwiches without fly ash.

At 30 % fly ash in the core, due to using fly ash reinforced epoxy in the interface, the flexural modulus of the sandwich increased by 30.18 %. The drop in flexural modulus at 40 % fly ash in the core may be attributed to the weaker core due to insufficient sodium silicate content. The flexural modulus of the perlite/sodium silicate composites increased remarkably with the incorporation of formica sheet skins.

4. Conclusion

In this work, the effect of fly ash content on the flexural behavior of perlite/sodium silicate composites and their sandwich structures were investigated. It is found that the flexural properties of perlite/sodium silicate composites and their sandwich structure improved significantly due to incorporation of fly ash. It indicates the effectiveness of the fly ash in enhancing the flexural properties of perlite/sodium silicate composites. Using the fly ash reinforced epoxy instead of pure epoxy in the interface between the core and the skins of the sandwich significantly enhanced the flexural modulus but the flexural strength was slightly affected.

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