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Performance Evaluation of Bio-Based Fire-Retardant Composites for Ceiling Board Applications

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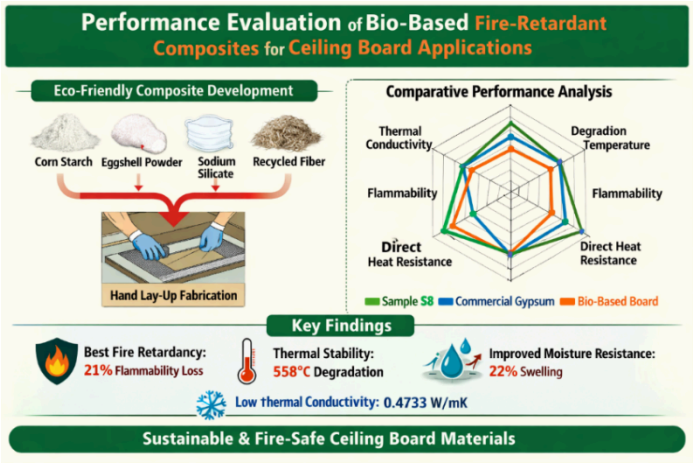
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ABSTRACT

The increasing demand for sustainable and fire-safe construction materials has encouraged the development of bio-based composites for building applications such as ceiling boards. However, their inherent flammability and moisture sensitivity remain key challenges. This study investigates the performance of eco-friendly fire-retardant composite ceiling boards fabricated from corn starch, sodium silicate, eggshell powder, and recycled fiber using a Taguchi mixture design. Eight formulations were prepared via the hand lay-up method and evaluated for thermal, fire, mechanical, and hygroscopic properties. The results show that material composition significantly influences performance. The lowest thermal conductivity (0.4733 W/mK) was obtained for Sample S5, indicating superior insulation, while Sample S3 exhibited the highest degradation temperature (558°C), reflecting excellent thermal stability. The maximum tensile strength (3.01 MPa) was achieved by Sample S1. Notably, Sample S8 demonstrated the best fire-retardant performance, with the lowest flammability weight loss (21%), along with good resistance to direct heat and the lowest swelling (22%), indicating improved dimensional stability. Although the developed composites exhibit promising fire-retardant behavior and sustainability advantages, further improvements in thermal insulation and moisture resistance are required to meet commercial standards. These findings highlight the potential of bio-based composites as viable alternatives for ceiling board applications.

KEYWORDS

bio-based composites, fire-retardant material, ceiling board application, thermal stability, sustainable construction



Graphical abstract

INTRODUCTION

The construction industry is under more and more pressure to lower embodied carbon, use fewer non-renewable resources, and switch to safer material systems without losing functional performance. In this context, bio-based composites have become appealing options for building materials because they come from renewable sources, can include agricultural or industrial waste, and usually have low density, good specific strength, and good thermal behavior [1]–[4]. It is especially interesting that they could be used in interior building elements like wall linings, insulation panels and ceiling boards. This is because these uses need materials that are light, stable in size, long-lasting and thermally efficient, as well as being cheap [2, 3, 8–10]. Even with these benefits, bio-based composites are still not widely used in building projects because of one major problem: they are more likely to catch fire. Natural fibres and many bio-derived polymeric constituents are abundant in cellulose, hemicellulose, and lignin, which can experience thermal decomposition and maintain combustion when exposed to fire [1, 2, 6, 7].. This is a big problem for applications in the built environment, where fire performance is not optional but a main requirement for life safety, code compliance, and material acceptance [2, 5, 6]. In this regard, most of the current reviews emphasize that although natural-fiber and bio-based composites represent attractive materials compared to conventional composites, their flammability, smoke production, thermal degradation, and loss of mechanical properties at high temperatures continue to limit their broad application as structural and semi-structural elements [1, 5, 6].

However, these concerns become particularly relevant in the case of ceiling board usage. The ceiling board material must be not only aesthetically pleasing but must also provide safety and comfort for people residing or working in the building. In operation, it should be lightweight, durable, moisture-proof, and thermally

efficient. Under fire conditions, it should not ignite rapidly, exhibit a slow flame propagation, and emit less heat, and, at the same time, it should be sufficiently durable not to fail fast[2, 6, 8–10].. As shown in the literature, natural-fiber composite panels intended for external and internal use in buildings can provide useful thermal insulation and, in some cases, competitive mechanical properties in comparison with existing commercial building boards. However, these benefits are typically offset by low fire resistance and poor durability due to moisture damage or unsatisfactory fiber-matrix interaction [6, 8, 10]. For example, jute-based composite panels are known for their excellent thermal barrier efficiency and desirable mechanical properties for constructions, while polymer-based composites reinforced with bamboo and coconut shell are studied for their use in ceiling boards for increased strength and durability[8–9] . However, ceiling boards fabricated from coir fibres and recycled materials also demonstrate high mechanical, thermal, and durability properties, thus supporting the idea of sustainable ceiling board utilization [10].

A wide variety of efforts have been invested in developing eco-friendly fire-retardant bio-based composite systems in order to solve the fire-limit issue. The use of halogenated flame retardants was widely practised in the past due to their effectiveness but now researchers pay special attention to the development of halogen-free solutions [4, 5, 7]. Nowadays, fire-resistant systems based on phosphorus, nitrogen, silicon, mineral compounds and living organisms, intumescent and char-forming formulations are developed along with various types of surface modifications that provide additional char formation, suppression of volatile emissions, reduced rate of heat release, and enhanced barrier properties during the burning process [1, 4–7] . Among the most innovative materials that are capable of providing condensed-phase char formation are lignin, phytic acid, tannic acid, chitosan, polydopamine, biomass ash, and other renewable and by-product materials that contribute to fire-retardance and sustainability [3, 5, 7]. Also, the enhancement of fire behaviour characteristics often negatively impacts dispersion properties, interfacial adhesion, toughness, density, hydrophobicity and general processability. Hence, some optimization of flame retardant systems is needed [4-7].

An important point worth mentioning is that the assessment of material performance should not focus only on one property. Fire safety cannot be considered as an indicator enough to make a product fire-resistant ceiling board appropriate. If a particular material successfully passes all flammability tests but fails to bend, becomes hygroscopic, expands or exhibits low thermal stability, it is not likely to be useful. As far as natural fiber composites are concerned, their swelling, increased absorption of moisture, and microcracking make

interfacial interactions weaker thus reducing their mechanical reliability in the long term [6, 8] . Therefore, selecting bio-based fire-retardant ceiling boards requires taking into account a number of factors including fire behavior, thermal stability, strength, density, hygroscopicity, and structural properties [2, 6, 8] . This multi-factor demand elucidates the reason why many promising formulations described in the literature remain at the laboratory stage and necessitate application-oriented research [2, 5 , 6].

While the general literature on flame-retardant natural-fiber composites has grown quickly, there is still a clear lack of studies that focus on ceiling board applications and look at bio-based flame-retardant composite formulations in terms of their fire, physical, thermal, and mechanical performance. Numerous review articles examine general flame-retardant mechanisms and sustainable additives [1–7] , whereas application-focused studies on ceiling materials predominantly emphasise thermal comfort, density, or fundamental strength [8–10] . Consequently, there remains a necessity for methodical research to evaluate whether a bio-based composite can meet the particular functional requirements of ceiling boards while enhancing fire performance. This study is significant not only from a materials engineering standpoint but also for promoting sustainable building products that are safer, have a reduced environmental impact, and are more in line with new priorities in green construction [2, 3, 5, 7] .

In light of this, the current study examines the efficacy of bio-based fire-retardant composites for ceiling board applications. The study is driven by the necessity to create sustainable ceiling-board materials that integrate diminished flammability with satisfactory physical and mechanical characteristics for practical application. This study seeks to assess fire-related behaviour alongside essential application-specific properties to ascertain the viability of bio-based fire-retardant composite systems as substitutes for traditional ceiling-board materials and to evaluate the degree to which flame-retardant modifications can improve fire safety without compromising overall board performance.

MATERIALS AND METHODS

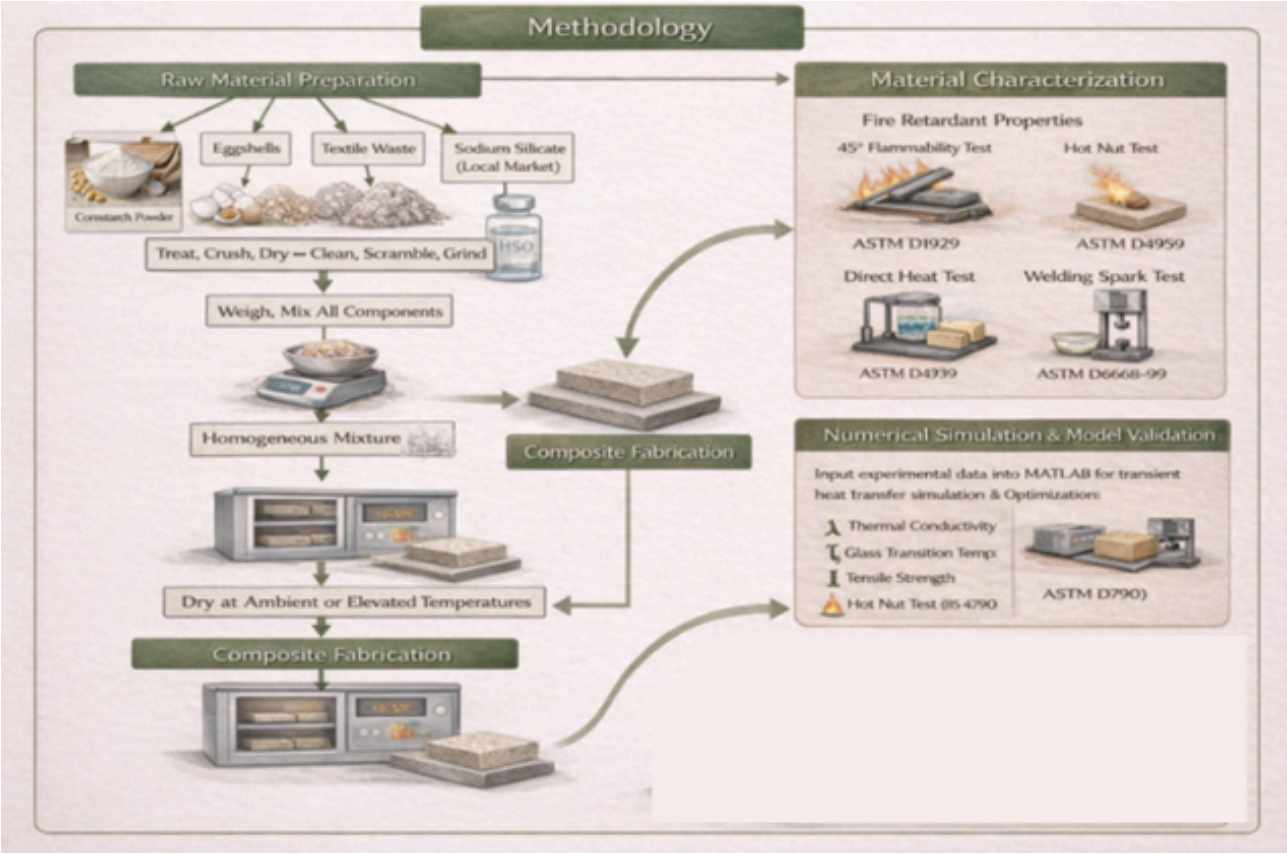


Figure 1. Methodology of bio-based fire-retardant composites for ceiling board applications

Materials Selection

The choice of materials is meant to make a composite that is both environmentally friendly and fire-resistant by mixing organic and inorganic parts that work well together. The main matrix is corn starchbecause it breaks down naturally and forms a protective layer of char when heated, which helps keep heat from moving through it. The eggshell powder containing primarily calcium carbonate is incorporated as a filler for the material's flame retardancy. During its heating, it decomposes to yield carbon dioxide and thus creates a shielding layer preventing combustion. The inclusion of textile fibers in the matrix serves the purpose of reinforcement in order to enhance the stability of the composite. Sodium silicate, in turn, is included for its flame-retardant properties and binding ability. On exposure to high temperature, sodium silicate forms a layer based on silica, thus making the material more heat-resistant. Thus, the combination of these materials yields an environmentally friendly composite that has enhanced fire resistance and mechanical stability.

Cornstarch (Char Formation)

Under heat, cornstarch (a carbohydrate) decomposes to form a carbonaceous char:

$$(C_6H_{10}O_5)_n \overset{heat}{\rightarrow} C(char) + CO_2 + H_2O + volatilegases \quad (1)$$

The char layer acts as an insulating barrier, reducing heat transfer and oxygen access.

Eggshell Powder (Calcium Carbonate Decomposition)

$$CaCO_3 \overset{heat}{\rightarrow} CaO + CO_2 \quad (2)$$

Effects are CO_2 release dilutes flammable gases and suppresses flame. CaO residue forms a protective inorganic layer.

Sodium Silicate (Silica Barrier Formation)

$$Na_2SiO_3 \overset{heat}{\rightarrow} SiO_2 + Na_2O \quad (3)$$

The formed SiO_2 (silica) creates a thermal barrier layer that blocks oxygen, slows heat penetration, protects underlying material.

So, Endothermic decomposition absorbs heat, Gas release (CO_2, H_2O) dilutes combustible gases and Char + mineral + silica layers form a multi-barrier system.

This combination significantly reduces flammability, heat transfer, and flame spread. These reactions represented the expected decomposition pathways that should be formed during suitable environment.

Composite Fabrication

In order to obtain the right mixture proportions, a Taguchi mixture design strategy was used. In accordance with the mentioned design, eight different formulations were obtained; they all comprised a 100% mixture of corn starch, sodium silicate, eggshell powder, and recycled fibre, yet had a varied proportion of these materials. As a result of this strategy, optimal proportions were identified and applied further to make fire-resistant composites. Eggshells were cleaned, dried, and grinded into powder form before making samples. Recycled fibres were treated accordingly. A thick binder solution was prepared using corn starch and water as key materials by dissolving the former in the latter with heat application. Taguchi design indicated the required amount of each component, and they were measured precisely. Afterwards, a homogeneous mixture

was formed by combining the mentioned ingredients. The composites were prepared manually through the procedure known as hand-laying-up. It involves laying of the homogeneous mixture in flat moulds with further compaction in order to ensure proper bonding of the particles. At first, the moulded samples were left in air and after that baked in an oven at a certain temperature, as long as the constant weight was reached. Finally, they were removed from the moulds.

Table 1. Formulations of the bio-based composites using Taguchi mixture design

Sample	Corn starch (%)	Sodium silicat (%)	Eggshell powder (%)	Recycled fiber (%)
S1	45	25	20	10
S2	40	20	25	15
S3	35	30	20	15
S4	35	25	15	25
S5	30	20	20	30
S6	30	25	25	20
S7	25	30	25	20
S8	25	35	25	15

A Taguchi design for mixture was employed to explore the impact of constituent ratios on thermal, fire-retardant, mechanical and hygroscopic characteristics of the developed ceiling-board composites with each formulation composition determined.

Fire Performance Testing

The fire performance tests become essential when analyzing the behavior of building materials during fires. In particular, ceiling boards should be able to resist fire and withstand increased temperature without catching fire and spreading flames to other areas. Thus, fire performance tests include an analysis of ignition potential, the burning rate, thermal decomposition, and thermal stability of the examined materials. As a result, fire-resistant materials will restrict the spread of flames, reduce the amount of heat emission, and provide additional time for evacuating occupants while limiting the damage to structures.

The Flammability Test (Weight Loss %) and the Direct Heat Test (Weight Loss %) are key indicators that measure the fire performance of materials analyzed in the current paper. The former one shows the probability of ignition upon contact with fire and how fast the material starts burning. Weight loss percentage becomes the indicator of material consumption due to the burning process. The smaller the value is, the higher the flammability resistance of the material will be. The latter one estimates the thermal stability of materials exposed to direct heating. The lower the weight loss is, the better the thermal resistance is.

Thus, the mentioned fire performance tests demonstrate how much material will burn under the influence of fire and heat. This criterion becomes crucial for estimating ceiling board performance.

Thermal Analysis

The following tests evaluate the thermal behavior and heat-related performance of the composite su such as thermal Conductivity (W/mK) which measures the material's ability to conduct heat (insulation performance). The degradation Temperature (°C) which indicates the temperature at which the material begins to thermally decompose. The flammability Test (Weight Loss %) which assesses material behavior under flame exposure and the direct Heat Test (Weight Loss %) that evaluates resistance to sustained high-temperature exposure.

Mechanical Testing

Test evaluates the structural strength of the composite was tensile Strength (MPa) that measures the maximum stress the material can withstand under tension.

Hygroscopic Properties

For Water Absorbency in 24 hrs (%) which measures moisture uptake and swelling (%) which evaluates dimensional stability in the presence of moisture.

Data Analysis

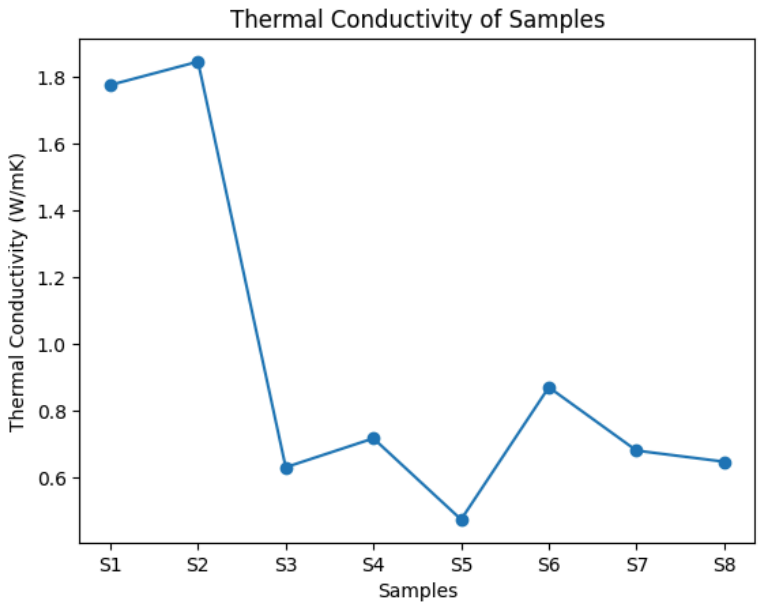


Figure 2. Thermal conductivity test analysis

A clear difference can be observed among the samples represented in Figure 2. It can be noted that sample S5 has the least value of thermal conductivity (around 0.47 W/mK), thus having excellent insulating ability. Since there is a larger amount of fibers present in the mixture, the probability of having air cavities in the material is also increased, which in turn makes heat transfer difficult. In contrast, sample S2 has the largest value of thermal conductivity (around 1.85 W/mK).

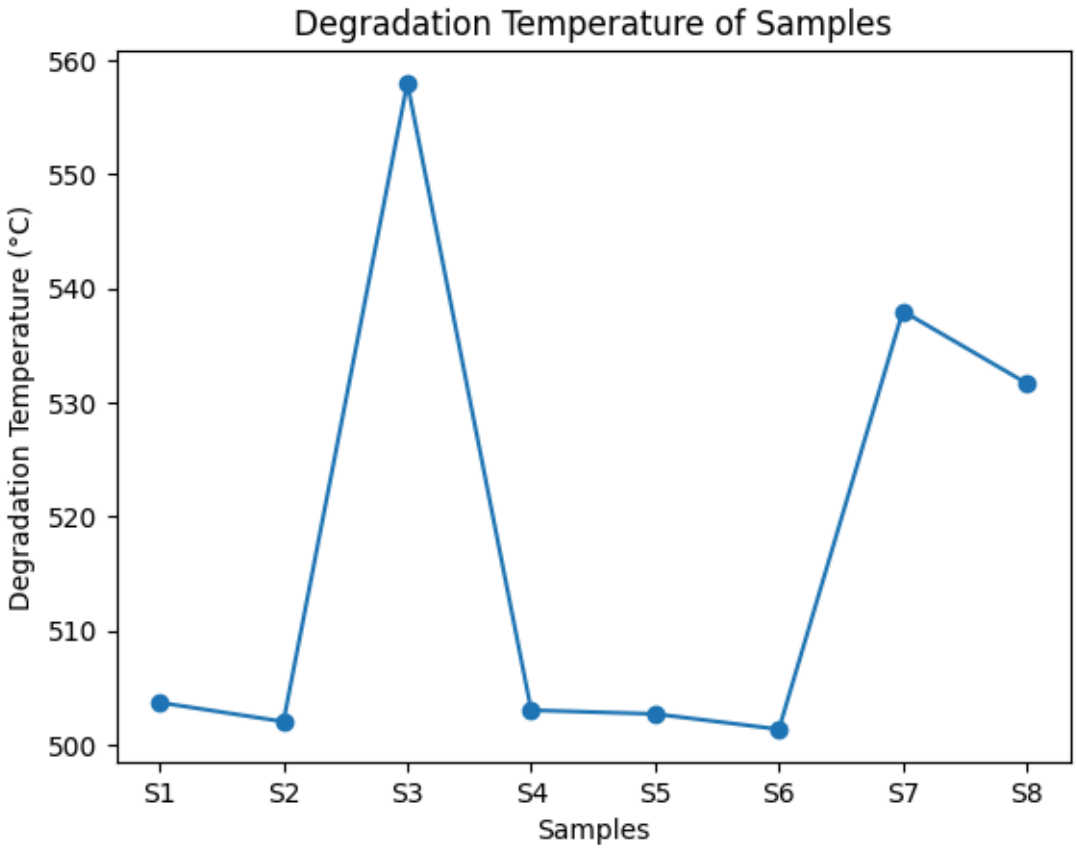


Figure 3. Sample stability analysis at high temperature

This is depicted by Figure 3 showing the thermal stability of temperature in the investigated samples. The sample S3 (about 558°C) is found to have the highest temperature of degradation. This shows that this sample has good stability against thermal degradation. Samples S7 and S8 have good thermal stability since their temperature of degradation is above 530°C.Meanwhile, the thermal stability of samples S5 and S6 is not high as their temperature of degradation is about 501-503°C.

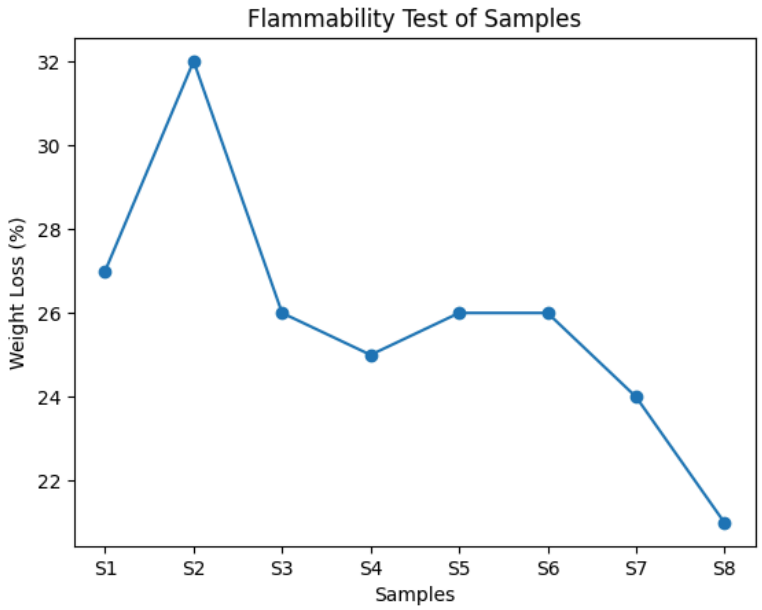


Figure 4. Flammability analysis for sample

Loss of matter during combustion is shown by Figure. 4. The lower the value, the more fire resistant is the material. Specimen S8 having an approximate percentage loss of 21% is the most fire-resistant one among all the specimens. Whereas, specimen S2 is the least fire-resistant due to the highest loss of weight amounting to around 32%.

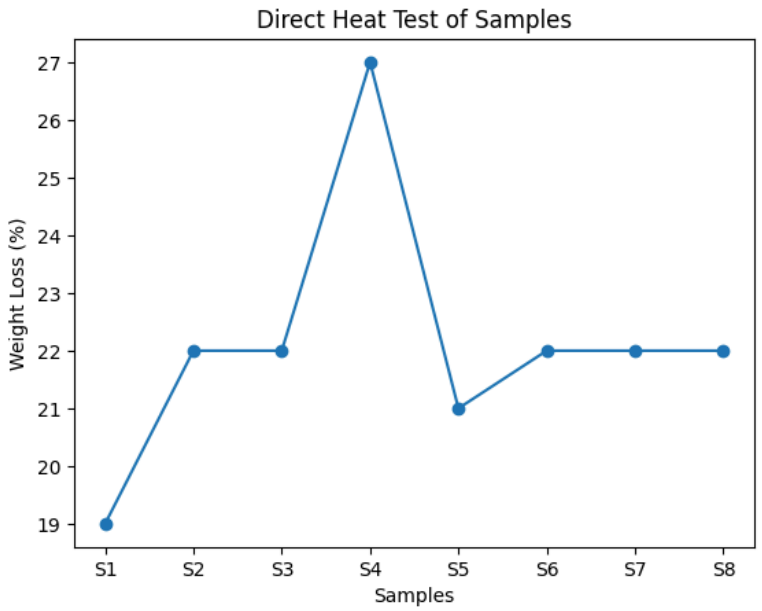


Figure 5. Sample analysis at direct heat

The direct heat test is shown in Figure 5, which examines the capability of the material to endure the continuous action of heat energy. Sample S1 with weight loss percentage of about 19% shows the lowest degradation and hence has the highest level of performance when exposed directly to heat. Majority of the samples, S2, S3, S6, S7, and S8, demonstrate similar weight loss of about 22%, showing some degree of thermal resistance. Sample S4 shows the highest degradation with weight loss of about 27%.

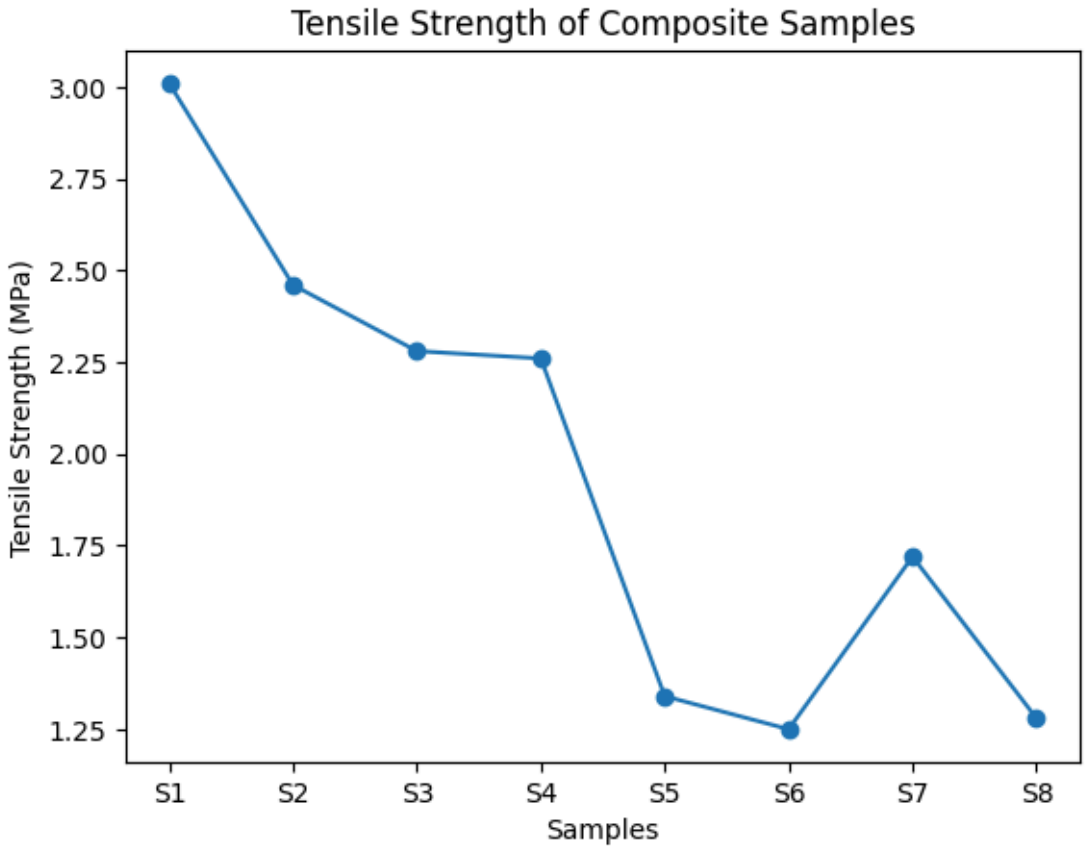


Figure 6. Tensile Strength (MPa) analysis of composite material

The graph of tensile strength describes the performance of each sample under tensile stress. The graph clearly shows that Sample S1 (3.01 MPa) is characterized by a maximum level of tensile strength. The reason lies in its high load-carrying capacity as well as strong binding between the matrix (consisting of corn starch and sodium silicate) and reinforcement (including fiber and eggshell powder). Thus, one can assume that a low fiber ratio (RF10) and optimal binder ratio contribute to effective stress transmission in the composite.

Then, the tensile strength decreases gradually until it reaches approximately 2.26 to 2.46 MPa, which means that Sample S4 has moderate tensile strength. At the same time, Sample S5 and S6 (with 1.25 to 1.34 MPa)

are associated with the largest reduction in the tensile strength. One possible explanation can be that high fiber ratio (RF20) makes the encapsulation process less efficient causing many voids and poor bonding. Sample S7 (1.72 MPa) has a slight increase compared to previous samples due to its better composition, which means the binder is used more efficiently. On the other hand, Sample S8 (1.28 MPa) shows lower strength again since too much fiber or binder causes negative mechanical properties.

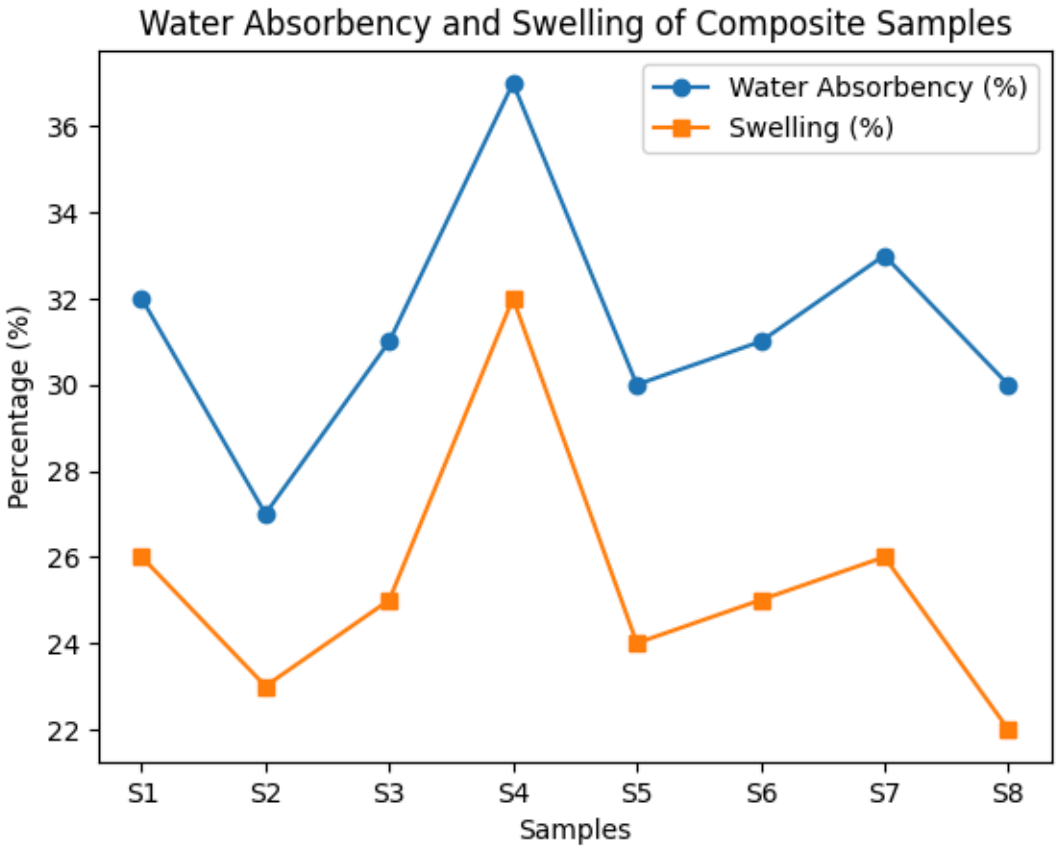


Figure 7. Hygroscopic Analysis of composite material

The Figure 7 below presents the moisture stability of composite samples, based on the evaluation of water absorbency and swelling percent after 24 hours immersion, which provides vital information about the durability and dimensional stability of samples under moisture exposure. As shown, there is a significant difference in the water absorbency of samples, in which sample S2 has the smallest water absorbency with 27%, which means less water absorption ability. In contrast, sample S4 has the largest water absorbency with 37%, indicating high porosity and poor binding capacity. The same pattern can also be seen from swelling percentage, in which sample S8 has the smallest swelling percent at 22%, suggesting good dimensional stability, while

sample S4 has the poorest performance with 32%. It is obvious that there is a clear relation between water absorbency and swelling percent, in which increased moisture content causes increased swelling. The cause of this phenomenon can be explained by moisture absorption within composite materials causing expansion of fibers and deformation of matrix. The results imply that modification in matrix properties, including adequate amount of sodium silicate and binders, will enhance moisture stability through the decrease in porosity and proper fiber encapsulation. Based on all results, sample S8 shows best moisture stability and should be used in applications that involve moisture exposure.

RESULTS

Thermal Analysis

According to the results obtained from the thermal analysis of the new composites, there were differences in their behavior in terms of a number of parameters, such as thermal conductivity, degradation temperature, fire resistance, and resistance to direct heat. Notably,S5 demonstrated the lowest thermal conductivity value (0.4733 W/mK). Thus, its heat-insulating properties can be considered optimal. The higher recycled-fiber content in S5 probably led to more void formation within the matrix and reduced thermal energy transfer, which may have contributed to lower thermal conductivity. Moreover, sample S3 had the highest degradation temperature (558°C), which proves the high thermal stability of the material. As for fire resistance, the highest resistance was shown by sample S8 with a minimal weight loss of 21%. In turn, sample S1 demonstrated high resistance to direct heat with a weight loss value of 19%.

As for the analysis of all thermal parameters together, sample S3 should be recognized as the best among the tested samples. It demonstrates high thermal stability and moderate thermal conductivity and acceptable fire resistance. Even though this sample does not give the best value in some cases, it provides the most favorable overall result. Therefore, it can be recommended for ceiling boards manufacturing.

Mechanical Analysis

The sample S3 demonstrated the best thermal stability and balanced thermal insulation performance among the other developed samples. For example, it shows the highest value for the temperature of decomposition which equals 558°C. Thus, it possesses the best characteristics of thermal stability when subjected to high temperatures. Moreover, the low thermal conductivity of the material equal to 0.63 W/mK proves that it has good heat insulating features. When the fire performance index is concerned, sample S3 demonstrates an acceptable burning loss equal to 26% as well as the direct heat loss of 22%. These values correspond to those

of other materials, which makes it highly competitive. Although sample S1 has the best tensile strength and sample S5 has the lowest thermal conductivity, sample S3 offers the best compromise between thermal and insulation properties.

Hygroscopic Analysis

The sample S8 can be regarded as the most favorable material with regards to its moisture properties because of the minimal level of swelling (22%) that shows great dimensional stability after moisture. The other important property of the same sample is that it shows moderate moisture absorptivity (around 30%). Taking into consideration that there is a strong connection between the mentioned properties (moisture absorptivity and swelling), it may be stated that S8 has denser and better structured composition with fiber embedding and can be used as a ceiling board material.

Best Sample

The fire performance of the eight different formulations was examined based on three characteristics. Namely, the first was the flammability expressed through the percentage of weight loss, the second was the resistance to direct heat expressed through the percentage of weight loss, and the third was the thermal stability expressed in terms of the temperature of degradation (°C). For the purpose of assessing flammability, formulation S8 showed the best results as the sample exhibited the lowest percentage of weight loss (21%). The second sample that showed good results for this characteristic was S7 (24%), whereas S2 scored the lowest grade (32%). When it comes to direct heat evaluation, the best results were obtained by S1 (19%), whereas S5 (21%) and S8 (22%) scored almost as good as other samples. With regard to thermal stability, the best value was recorded by S3 (558°C), followed by S7 (538°C) and S8 (531.67°C).

Therefore, it could be concluded that S1 scored the best direct heat resistance but had higher flammability loss (27%); S2 performed the poorest in terms of fire resistance because of the highest flammability loss; S3 scored well in thermal stability, but it was just average when it came to fire loss; S4 showed moderate flammability but poor resistance to direct heat (27%); S5 showed adequate results concerning direct heat resistance but only moderate flammability; S6 scored intermediate grades in both evaluations but had rather poor thermal stability; S7 proved to be a good sample in all aspects; and S8 demonstrated good results with regards to all fire-related features.

Therefore, S8 can be considered the optimal sample in terms of fire-retardent and moisture-resistance performance. The improved fire-retardant performance of S8 can be ascribed to its highest relative amounts

of sodium silicate and eggshell powder, which favored the formation of a silica layer and acted as thermal shields during combustion. The fact that it had lower flammability loss indicates that the combustibility of the sample decreased. Furthermore, its higher degradation temperature indicated improved resistance to heat. These facts suggest that higher content of eggshell powder, corn starch, sodium silicate, and recycled fibre leads to creation of a more stable protective layer during heating.

DISCUSSION

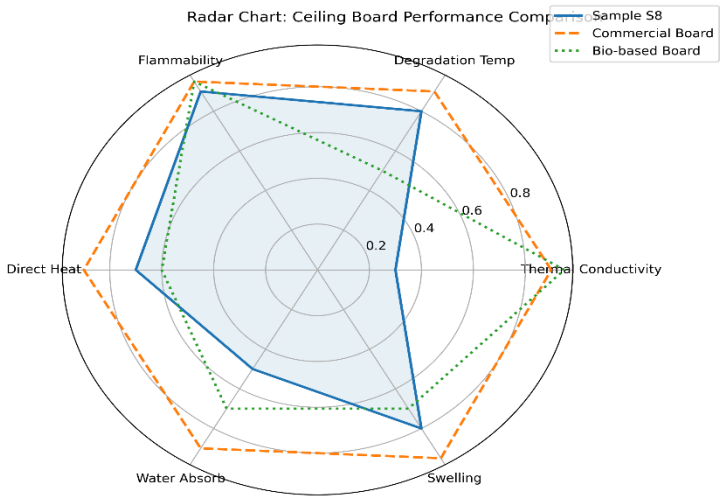


Figure 8. Radar chart analysis

Figure 8 shows the performance comparison between Sample S8, commercial gypsum ceiling boards, and bio-based ceiling materials by means of a radar chart, based on normalized performance parameters that include thermal conductivity, degradation temperature, flammability, direct heat resistance, water absorbency, and swelling.

Fire retarding capabilities are one of the best characteristics of Sample S8 as illustrated in Figure 8. Its performance is almost equivalent to commercial gypsum boards and bio-based ceiling boards. This can be attributed to the use of sodium silicate and eggshell powder to produce char and act as thermal barriers. Similar results have been reported for bio-based composites where the incorporation of minerals increases fire retarding capabilities by limiting oxygen diffusion and heat dissipation [11].

Thermal stability is another key feature associated with Sample S8 as demonstrated by the radar chart above. Its degradation temperature is relatively high, allowing for high heat exposure before rapid degradation occurs. Although commercial gypsum ceiling boards perform better because of their non-combustible nature, thermal stability of sample S8 is similar. The reason for this is the release of chemically-bound water upon heat exposure, which takes away some of the heat [12].

The worst characteristic shown in the graph above is that Sample S8 is not an excellent thermal insulator. In other words, its thermal conductivity is not very effective compared to commercial gypsum ceiling boards and bio-based ceiling boards. Commercial ceiling boards achieve low thermal conductivities by optimizing porosity and designing. Nanocellulose-based systems increase insulation effectiveness [11, 13] .

The capability of Sample S8 to resist direct heat is moderately good as shown above. Direct heat resistance of Sample S8 makes it less durable as a result of long-term exposure to heat than commercial ceiling boards. This is due to the fact that matrix degradation of natural fiber composites is enhanced by increased temperature levels [14].

When it comes to moisture resistance, Sample S8 has moderate water absorbency and swelling ability. Despite having better dimensional stability compared to other developed samples, Sample S8 has inferior dimensional stability when compared to commercial boards [13].

From the discussion above, it can be concluded that Sample S8 has good fire retardant ability, thermal stability, and dimensional stability. Thus, it can be considered as an eco-friendly ceiling board. Nevertheless, to meet the performance standards of commercial ceiling boards, it needs further improvements.

CONCLUSION

This study used a Taguchi mixture design to make eco-friendly composite ceiling boards and then tested their mechanical, thermal, fire, and moisture properties. Among the developed samples, sample S3 showed superior thermal stability, whereas sampel S8 exhibited the best fire-retardent and dimentional-stability performance. Other samples had strengths in specific properties. The composites that were made show promise, especially in terms of fire resistance. However, they need to be better at keeping heat and moisture out in order to be as good as commercial ceiling boards. In general, the materials seem like they could be good long-lasting options for building use. Furthermore, samples were fabricated through hand lay-up, which offers precision control of material proportion at the lab level. It is to be noted that hand lay-up is only appropriate for small-scale experimental validation. In commercial scale production for ceiling boards, industrial methods

of compression molding or automated lamination are suggested to ensure the thickness and consistent quality throughout. Thus, while not aimed at industrial scale fabrication this work is material feasible and performance oriented. Also, direct experimental verification of phase formation was notevaluated by XRD and FTIR which should be focused on future works.

Author Contributions

Conceptualization – Faysal, Kowser and Chowdhury; methodology – Faysal, Kowser and Chowdhury; formal analysis – Faysal, Kowser and Hossain; investigation – Faysal, Hossain and Limon; sources – Faysal, Kowser and Chowdhury; writing-original draft preparation – Faysal and Hossain; writing-review and editing – Faysal and Limon; visualization – Faysal, Hossain and Limon; supervision – Kowser and Chowdhury. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest

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Hazards

This study did not involve any chemicals, procedures, or equipment with unusual or significant hazards. All materials and methods used were standard and posed no inherent risk beyond typical laboratory practices.

Human research subjects

This research did not utilize any human participants or human-related data.

Animal research subjects

This research did not utilize any animal participants or animal-related data.

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