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Enhancing Fire Resistance of Coconut Fiber-Reinforced Polymer Composites with Fire-Retardant Fillers

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Abstract: This study aims to enhance the fire resistance of fiber-reinforced polymer composites (FRPC) which are in high demand in modern industry, mainly due to their favourable weight-to-strength ratio. Despite their widespread use, FRPCs are generally highly flammable. To address this issue, this research focuses on improving the fire resistance of FRPC made from coconut fiber (coir) and low-density polyethylene (LDPE) by incorporating various fire-retardant fillers. A series of experiments were conducted following the UL-94 standard, using Aluminium trihydrate, Magnesium hydroxide, Boric acid, and Magnesium carbonate as fire retardants. The composites were subjected to the UL-94 horizontal burn (HB) test to evaluate their flammability. Results indicate that the burning rate of the composite increases with the increase in fiber content and decreases with an increasing percentage of fire retardant chemicals. Notably, the composite incorporated with 10% boric acid exhibited the lowest burning rate of 21.1 mm/min. Findings demonstrate that the fire resistance of FRPCs improves with higher concentrations of fire retardants. Although the increase of additive filler percentage enhanced the fire resistance, it is still observed to be insufficient for the composite to get self-extinguished.

Keywords: Coconut fiber, Fiber-reinforced polymer composite, Fire resistance, Fire-retardant filler, Low-Density Polyethylene,

1. Introduction

The use of natural and synthetic fibers to produce different construction materials has been extensively researched during the past few decades. Synthetic fibers such as carbon and glass are significantly used in engineering applications. However, natural fibers are preferred due to their growing environmental friendliness and renewable properties [1]. It is observed that most research had focused on establishing solutions using natural fibers. Apart from environmental friendliness, natural fibers show several other advantages, such as biodegradability, low cost, renewability, and manufacturing flexibility [2]. Different natural fibers such as Bamboo, Jute, Sisal, Flax, Hemp, and coir fiber can be used as reinforcement for polymer composites [3]. Sri Lanka and India supply a significant portion of the world's coir fiber requirement, where Sri Lanka produces three-quarters of the world's brown coir fiber production [4]. Therefore, coir fibers are more readily available than other natural fibers. Furthermore, coir fiber has a slow degradation level due to its higher lignin content [5]. Moreover, fibers exhibit noteworthy qualities and are feasible for composite construction [6], [7].

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As far as sustainability and environmental friendliness are considered, one of the major concerns is the large amount of plastic waste being generated globally. Approximately 8,300 million tons of plastic is produced annually, and 6,300 million tons of plastic waste is either disposed of in landfills or released into the environment [8]. Sri Lanka generates around 6 kg of plastic per individual per annum [9]. Therefore, utilizing waste polyethylene for fiber-reinforced polymer composites (FRPC) has been highly recommended to minimize the adverse effects of waste polythene [10], [11].

According to Kona et al. [13], different manufacturing techniques can be adopted to develop the FRPC, such as hand lay-up, spray, compression, and injection molding [12], [13]. A study performed by Dharmaratne et al. [14] emphasized that better mechanical properties are shown when the coir fiber content is between 20-30% of the total weight of the composite in FRPC.

FRPCs are in high demand in modern industry due to their lightweight and high strength-to-weight ratio. Additionally, these materials exhibit various advantageous properties, including high durability, stiffness, flexural strength, damping properties, and resistance to corrosion and fire [15], [16]. Consequently, FRPCs have been extensively used across various industries, such as construction, mechanical, biomedical, automotive, and marine [17], [18]. In the construction industry, FRPCs are mainly utilized for the fabrication of concrete beams, deck panels, and other structural components [19], [20].

Even though FRPCs are widely used in different industries, they are highly flammable. Because of this, it causes serious safety issues that negatively affect the industry [21], [22]. The flammability of natural FRPC mainly depends on their oxygen concentration, heat stimulus, and air circulation in the composite material's surface area [23]. The type of fiber and the percentage of cellulose in the fiber influence the flammability of the composite [24]. A study by Khuntia and Biswas [25] on the flammability of coir, FRPCs showed a "V-0" rating from the UL 94 HB testing for the composite manufactured using 30% of coir out of the total weight.

According to past research, researchers have adopted several methods to increase the fire resistance of polymer composites. These include applying a surface coating to the material, developing the material using resin modification, adopting different additive and reactive fire-retardant fillers, using nano clay as a filler, or using nanotubes or nanofillers [26]. The simplest and easiest method to increase fire resistance is the application of a fire-retardant coating on the surface [27], [28]. However, the cost of the process is relatively high. Apart from using a surface coating, the other most suitable and effective method is to use different additive fillers to increase the fire resistance of the FRPCs [29], [30].

Different standards such as the UL-94 [31], [32], Cone calorimeter testing [33], [34], and Limiting Oxygen Index (LOI) testing [35] are used to evaluate the fire resistance of the polymer composite. However, according to Dharmaratne et al. (2021), the UL-94 standard is the best standard for assessing the fire performance of wall panels comprised of FRPCs. Two main tests are conducted to evaluate the fire performance of the polymer composite under the UL-94 standard, namely, the horizontal burn (HB) test (UL-94 HB) and the vertical burn test (UL-94 V) [36], [37]. The horizontal burn test is required to obtain the HB rating, and the standard test arrangement is shown in Figure 1.

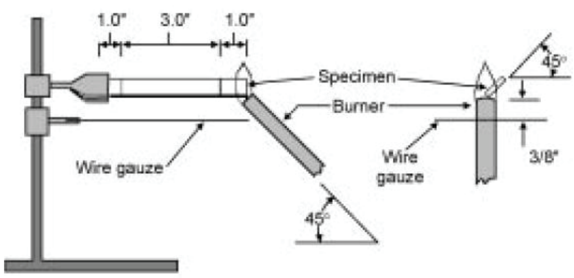


Figure 1 - Horizontal burning test setup [38]

Several studies have been conducted to evaluate and improve the thermal resistance properties of FRPCs with different additive fillers, as summarized in Table 1.

Table 1 - Past studies on the thermal properties of Fiber reinforced polymer composites

Composite Matrix	Filler Material	Thermal Properties	Reference
Wood Flour/ Polypropylene Composite	Aluminium Hydrogen Phosphonate (AHP) and Triphenyl Phosphate (TPP)	The addition of AHP was not good enough to act as an effective protective barrier to the composite.	[36]
Jute/ Polypropylene Composite	Ammonium Polyphosphate and Polypropylene Powder	The surface flame-retardant layer improved flame-retardant efficiency and lowered the horizontal burning rate.	[39]
Kenaf/ Polypropylene Composite	Magnesium Hydroxide (MH)	MH filler increased the flame-retardant properties of the composite. Peak temperature was increased. MH absorbed heat and prevented the decomposition of kenaf fiber.	[40]
Sisal/ General Polymer Composites	Nano Clay Filler	The effect of nano clay increased the thermal stability of sisal fibre-reinforced composite	[41]
Bamboo/ Polypropylene Composite	Melamine Pyrophosphate (MPP) and Aluminium Hypophosphite (AP)	Exhibits considerable improvement in flame retardant modulus with flame retardant addition. MPP and AP are involved in the combustion process in gas and condensed phases.	[42]
Oil Palm/ Clay Reinforced High Density Polyethylene	Clay Filler (Bayada)	Thermal analysis shows that the addition of clay has increased the degradation temperature of the composite, which increases the thermal stability of the composite.	[43]
Wood Flour/High-Density Polyethylene	Boric Acid and Borax	Thermal and fire characteristics increase with the increment of fiber loading. The burning rate of the composite decreased around 50% after the addition of flame retardant.	[44]

Many researchers have examined the physical and mechanical properties of coir and sisal fiber composites. The nature of the fiber, morphology, and matrix determine these properties. However, their composites have shown higher flammability than glass, carbon, and fiber-reinforced composites [45], [46]. Kabir et al. [47] found five parameters that govern the qualities of composites: fiber structure, thermal stability, length of fiber, orientation of fiber, presence of voids, and water absorption of fiber.

The use of advanced polymer matrix composites is expanding, especially in the structural and automotive industries regularly. Flammability is vital in many industrial applications, particularly in the renovation sector, where compact spaces make fires a significant risk [48].

The fire resistance behaviour of flax fiber and glass fiber-reinforced epoxy resin composites were compared by Chai et al. [49]. According to their investigation, flax fiber-reinforced composites burn faster, producing more heat, and their structure deforms significantly during combustion.

The fire-retardant performance of polyester resin and sansevieria fiber-reinforced polyester resin composite was investigated by K. Ramanaiah et al. [50]. According to their findings, it catches fire faster and produces more carbon dioxide and total smoke during combustion compared to that of unreinforced polyester resin. Although the commercial applications of natural fiber-based polymers are rapidly expanding, many elements of their behaviour, such as fire-retardant properties, are still poorly understood. In this context, there is a high requirement to assess the burning rates of coir FRPC.

After thoroughly investigating previous research, the objective of this study is to identify the appropriate filler material to enhance the fire resistance performance of FRPC manufactured using coconut fiber and waste LDPE.

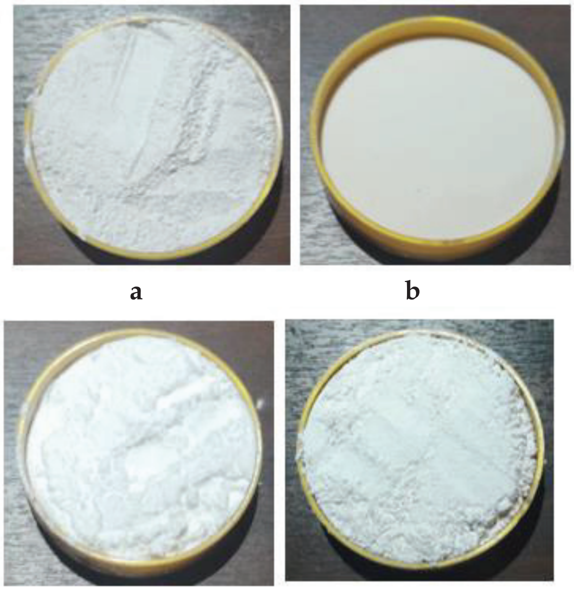
2. Materials and Method

The primary raw materials used for the composite manufacturing process during the present work are coir and waste LDPE, as shown in Figure 2. Waste LDPE was used as a matrix material in FRPCs. After collecting waste LDPE, it was washed using clean water to remove impurities and unwanted materials and was allowed to dry in the air. Then, LDPE was cut into small pieces using the shredder machine. According to the study by Dharmaratne et al. the maximum flexural properties of FRPC could be achieved using 3 cm coir fibers [14] . Hence, the same size of fiber was used to prepare FRPC in this study.

The experiments were conducted in two stages. Firstly, the flammability performance of the composites was studied for the composites by varying the coir: LDPE ratio to determine the effect of fiber content on the flammability performance. Then, at the second stage, the ability to use the fire retarders to enhance the flammability was determined. In this case, the composite samples were prepared with coir to polythene in a 3:7 ratio, which is the most effective weight ratio of coir to polythene for FRPC with the highest flexural performance [14]. Four additives were selected and added in varying percentages from 1% to 10% of the total weight to identify the best dosage for better flammability performance. The selected four additives included Magnesium Hydroxide [40], Aluminium Tri-hydrate, Boric Acid [44] and Magnesium Carbonate. Figure 3 shows the additives used for this experiment. The test UL-94 was conducted using the horizontal flame propagation test method for polymers [51]. The test was performed at a room-temperature in the flammability chamber using a controlled Bunsen burner flame. Five specimens from each composite sample were tested.

(a) (b)

Figure 2 - (a) Coir fiber (b) Waste polythene



a b

c d

Figure 3 - Additive Filler (a) Magnesium Hydroxide, (b) Aluminium Tri-Hydrate, (c) Boric Acid, (d) Magnesium Carbonate

Composite manufacturing process

The hot press equipment was used to prepare the FRPC. The required quantities of coir fiber, LDPE, and additive filler were weighted according to the mix design. The weighted materials were hand-mixed by skilled labourers for 20-25 minutes until a uniform mixture was obtained.

Thereafter, the Silica emulsion was sprayed on the steel mould to minimize the adhesion of material on the same. Then, the mixture was placed inside the steel mould. Throughout the manufacturing process, 25 tons of pressure and 140 ^{0}C temperature were maintained in the hot-press equipment [14]. After the process took place for 6 minutes in the hot press equipment, the heated mould with the composite was placed inside a cooler for 15-20 minutes to solidify the material. Figure 4 shows the prepared composite board.

Figure 4 - Prepared composite board

Fire resistance test

The fire resistance test was carried out according to the test method specified in the UL-94 standard. The material's fire resistance was graded under the horizontal burn tests. The sample was 125 mm long, 13 ± 0.5 mm wide, and 3.2 mm thick. 1st 25 mm was allowed for the burning to start (flame application), whereas 2nd 75 mm for burning time measurements, 3rd 25 mm for the spacing between the holder and the burning terminated point, and the last 25 mm was allocated for holding the sample. The horizontal burning rate of the sample was determined by calculating the time taken for the flame to propagate over a sample length of 75 mm. Figure 5 shows the composite strip prepared for the horizontal burning test.

Figure 5 - Test sample

Subsequently, a flame at a 45° angle was applied for 30 seconds to the horizontally clamped sample. The burning time of each sample was measured, and the burning rate was calculated.

3. Results and Discussion

Step I

The 25 specimens, five from each fiber weight fraction, were tested for flammability properties through the horizontal UL-94 test. The results revealed that the burning rate of the composites increased with increased fiber content. The coir FRPCs burned with horizontal burning rates in the range of 25.33 - 31.91 mm/min. According to the standard given in UL-94, if the range is below 40 mm/min, the given composite material is highly flammable. Then the tested samples are categorized under the HB category.

Figure 6 shows the average horizontal burning rate variation with coir weight percentage. A major disadvantage of FRPCs is that they are highly flammable materials that can burn at a higher burning rate. This highlights the importance of improving flammability by incorporating suitable methods. Therefore, in the second step of this experiment series, the possibility of using flame-retardant additives was tested to delay and control the burning.

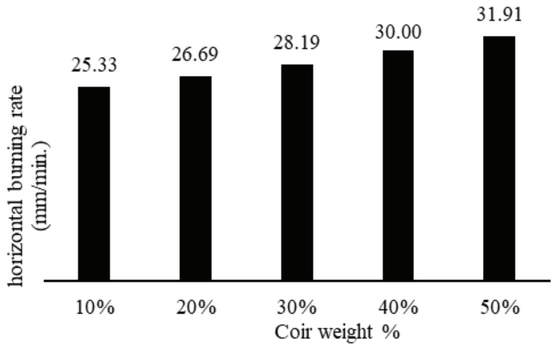


Figure 6 - Variation of the average horizontal burning rate with coir weight percentage

Step II

According to the results obtained from the horizontal burn (HB) test, as shown in Table 2, the composite's flammability capacity was reduced when each chemical's percentage was increased. The variation of the burning rate with 4 different additive contents is shown in Figure 8. It also shows that all the samples from each chemical percentage have achieved a burning rate below 40 mm/min. Hence, all samples are under HB rating under the horizontal burn test.

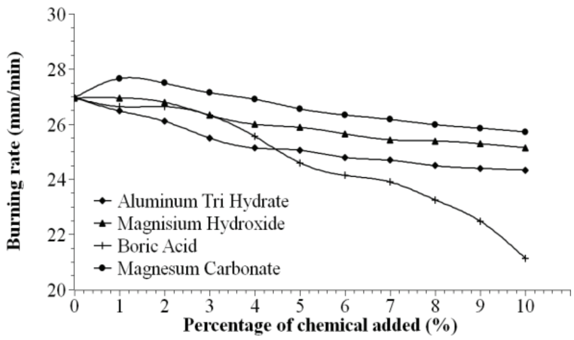


Figure 7 - Variation of burning rate with additive percentage

Table 2 - The average burning rate for all the test samples

Percentage of Chemical	Burning rate (mm/min)			
	Aluminium Tri Hydrate	Magnesium Hydroxide	Boric Acid	Magnesium Carbonate
Control sample	26.946			
1 %	26.471	26.946	26.627	27.648
2 %	26.094	26.789	26.627	27.478
3 %	25.485	26.316	26.316	27.134
4 %	25.124	25.987	25.547	26.893
5 %	25.048	25.874	24.590	26.548
6 %	24.783	25.643	24.134	26.324
7 %	24.684	25.424	23.895	26.163
8 %	24.484	25.384	23.247	25.973
9 %	24.387	25.283	22.475	25.846
10 %	24.324	25.140	21.127	25.714

Figure 7 illustrates the variation in the burning rate against the additive percentage. When the results were compared, it was observed that the burning rate varies depending on the additive type and the percentage addition. The observations revealed that the burning rate decreased for all the selected chemicals with increased additive filler. However, while the Boric acid showed better results, the other three chemicals (Aluminium Tri-Hydrate, Magnesium Hydroxide, and Magnesium Carbonate) showed similar variation patterns. In summary, although there are varying patterns in the burning rate, adding a higher percentage of chemicals reduces the burning rate for all four chemicals used.

4. Conclusion

The main objective of this study was to assess the flammability performance of FRPCs and the ability to enhance the fire resistance of the same by employing various additive fillers. This study used coir fiber and waste LDPE to produce the composite. Several additive fillers were identified from the literature review that can increase the fire resistance of fibre-reinforced polymer composites. For this study, 4 additive fillers were selected to determine their impact on fire resistance: Aluminium Tri-Hydrate, Magnesium Hydroxide, Magnesium Carbonate, and Boric Acid.

The hand lay-up technique and the hot press machine were used to develop the coir FRPC. The filler percentage varied from 1 to 10% of the total weight of the composite. The UL-94 standard was adopted, and a horizontal test was conducted to evaluate the fire resistance rate of the composite with different additives.

The results showed that when the fiber content increases, the burning rate increases, and as the chemical percentage increases, the burning rate reduces for all test samples. Even though the addition of an additive filler percentage increased fire resistance, it is still insufficient for the composite to provide the ability to self-extinguish when it is ignited, which is still observed to be highly flammable.

Hence, it is recommended that further research be conducted to develop the fire resistance up to the required standard, which is 40 mm/min over a 75mm span, as it is a vital property for its usage as a sustainable material in the building industry.

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