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The Effect of Clay Tile Particle Addition on the Flame Retardancy and Impact Toughness of Ramie Fiber-Reinforced Polypropylene Composites

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Abstract

Environmental concerns regarding polypropylene (PP) plastic waste have driven the demand for more sustainable alternative materials through composite development. This study aims to analyze the effect of adding Sokka roof tile particles as a filler on the flame retardancy and impact toughness of ramie fiber-reinforced composites. The composite materials utilize a polypropylene matrix, ramie fiber reinforcement, and Sokka roof tile particles as filler with concentration variations of 2%, 4%, and 6%. The results demonstrate that increasing the filler volume significantly improves the material's flame-retardant properties, with the 6% variation achieving the best thermal performance and the lowest burn rate of 214.27 mm/min. However, in terms of mechanical properties, a decline in impact toughness was observed as the filler content increased; the average energy absorption dropped from 1.075 Joules at 2% concentration to 0.735 Joules at 6%, which is consistent with the decrease in impact strength from 0.0364 J/mm² to 0.0204 J/mm². This phenomenon indicates that while inorganic particles effectively serve as a thermal barrier, excessively high concentrations increase material brittleness, thereby reducing the impact energy absorption capacity. In conclusion, a 6% concentration of Sokka roof tile particles is recommended for applications prioritizing fire safety, while considering the compromise in mechanical strength.

Keywords: *Polypropylene; Sokka Roof Tile Particles; Ramie Fiber; Hot Press; Burning Test; impact Test.*

Abstrak

Permasalahan lingkungan akibat sampah plastik jenis polipropilena (PP) memicu kebutuhan akan material alternatif yang lebih berkelanjutan melalui pengembangan komposit. Penelitian ini bertujuan untuk menganalisis pengaruh penambahan partikel genteng Sokka sebagai bahan pengisi terhadap karakteristik ketahanan bakar serta ketangguhan impak pada komposit berpenguat serat rami. Material komposit menggunakan serat rami. bematriks polipropilena partikel genteng sokka sebagai filler dengan dan variasi konsentrasi partikel sebesar 2%, 4%, serta 6%. Hasil pengujian menunjukkan bahwa peningkatan volume partikel secara signifikan memperbaiki sifat hambat api material, di mana variasi 6% mencatatkan performa termal terbaik dengan laju perambatan api terendah sebesar 214,27 mm/menit. Namun, pada aspek mekanik, terjadi penurunan ketangguhan impak seiring bertambahnya kadar pengisi; energi serap rata-rata merosot dari 1,075 Joule pada variasi 2% menjadi 0,735 Joule pada variasi 6%, yang selaras dengan penurunan harga impak dari 0,0364 J/mm^2 ke 0,0204 J/mm^2. Fenomena ini mengindikasikan bahwa meskipun partikel anorganik efektif berfungsi sebagai penghalang panas, konsentrasi yang terlalu tinggi meningkatkan kegetasan material sehingga mereduksi kapasitas penyerapan energi benturan. Sebagai simpulan, penggunaan 6% partikel genteng Sokka direkomendasikan untuk aplikasi yang memprioritaskan faktor keamanan api, dengan mempertimbangkan kompromi pada aspek kekuatan mekanisnya.

Kata kunci: Polipropilena; Genteng Sokka; Serat Rami; Hot Press; Uji Bakar; Uji Impak.

1. Introduction

The increasing amount of polypropylene (PP) plastic waste has become an environmental problem due to its extensive use in packaging, household products, and automotive components. The non-biodegradable nature of PP leads to long-term accumulation in the environment [1]. Recycling is considered a relevant solution; however, material innovation is required to enhance the added value of this waste. One promising approach is the utilization of recycled polypropylene as a composite matrix with the addition of reinforcements and fillers to improve mechanical performance and thermal resistance [2].

Ramie fiber has been widely studied as a natural reinforcement due to its relatively good mechanical properties and renewable characteristics. An increase in the ramie fiber fraction in polypropylene composites has been shown to improve tensile strength and stiffness [3]. This fiber has a low lignin content, making it easier to process. In addition, its renewable, lightweight, non-toxic, and non-abrasive properties enhance its attractiveness as a reinforcement material. The mechanical properties of ramie fiber indicate a tensile strength ranging from 400 to 1050 MPa and a Young's modulus of approximately 61.5 GPa. [4] Homogeneous fiber distribution plays an important role in improving the mechanical strength of composites. This finding confirms that the performance of ramie fiber-based composites is strongly influenced by matrix–fiber interaction and material composition [5].

In addition to natural fibers, the incorporation of inorganic fillers has also been carried out to improve thermal resistance and flame-retardant properties. Sokka roof tile particles, which contain silica and alumina, have potential as fillers that can enhance thermal stability. Experimental observations have shown that increasing the Sokka roof tile content in composite formulations positively correlates with improved flame resistance in test specimens. The highest flame resistance was recorded in composites containing 40 wt.% Sokka roof tile particles [6]. However, increasing the mineral particle content may cause the material to become more brittle, thereby reducing impact toughness. Therefore, an appropriate composition is required to achieve a balance between flame resistance and mechanical properties [7].

Although various studies have examined ramie fiber-reinforced polypropylene composites and the use of Sokka roof tile particles separately, studies investigating the combination of both materials in a recycled polypropylene matrix remain limited. In particular, few studies have evaluated the effect of varying Sokka roof tile particle content on both flame resistance and impact toughness within a single composite system. This limitation indicates the existence of a research gap that requires further investigation. [9]

Based on this background, the present study aims to analyze the effect of varying Sokka roof tile particle content (2%, 4%, and 6%) on the flame resistance and impact toughness of recycled polypropylene composites reinforced with ramie fibers. The results are expected to contribute to the development of sustainable composite materials with a balanced mechanical performance and thermal resistance.

2. Material and Method

The materials used in this study, including ramie fibers, Sokka roof tile particles sieved through a 200-mesh screen, and the polypropylene matrix, are presented in Figure 1. The ramie fibers were cleaned under running water to minimize impurities and subsequently arranged in a random orientation with a fiber length of 5 mm. Polypropylene pellets were ground into a finer form to reduce defects during the manufacturing process. Furthermore, the three materials were molded in a cavity with dimensions of 260 mm x 90 mm x 3 mm. The molding process involved applying a compressive load of 80 kgf until the mold reached a temperature of 190°C. Once the target temperature was attained, a holding time of 20 minutes was maintained. Finally, the composite was allowed to cool to room temperature before being removed from the mold.

The burn test and Charpy impact test specimens were fabricated according to ASTM D635 and ASTM 5942 standards, with composition ratios of 2% Clay : 28% SR : 70% PP, 4% Clay : 26% SR : 70% PP, and 6% Clay : 24% SR : 70% PP, as illustrated in Figure 2-3.

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Figure 1. Specimen Preparation Process, (A) Polipropylene, (B) Cleaning of Ramie Fibers, (C) The ramie fibers were cut into a length of 5 mm, (D) Sokka Roof Tile Powder and (E) Hot Pressing Process

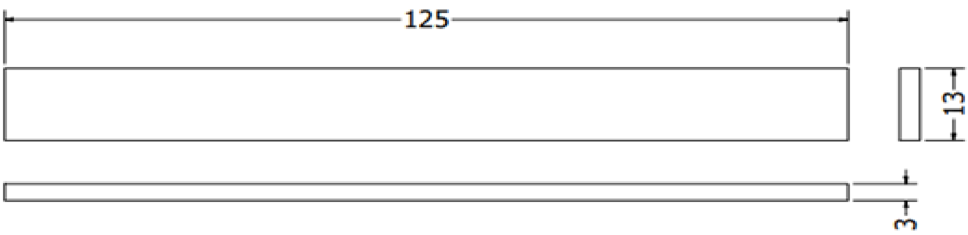


Figure 2. Burn Test Specimen (ASTM 635)

The testing method was carried out to assess the material's resistance to fire, specifically to determine the duration the material burns (Time of Burning) and its combustion propagation speed (Rate of Burning) [8], see Eq. 1.

$$\mathbf{V} = \frac{\mathbf{60L_{burned}}}{\mathbf{t_{creep}}} \tag{1}$$

The burning rate (V), also known as Rate of Burning (ROB), is expressed in millimeters per minute (mm/minute) and indicates the speed at which the specimen burns during the flammability test. This value is determined based on the burned specimen length (Lburned), measured in millimeters (mm), and the propagation time (Tcreep), measured in minutes. The burned specimen length represents the distance traveled by the flame along the specimen surface, while the propagation time is the duration required for the flame to spread across that distance. A higher burning rate indicates that the material burns faster, whereas a lower value shows better flame resistance.

Impact testing is conducted to determine the amount of potential energy absorption produced by a pendulum swung from a certain height, which suddenly strikes the specimen, causing it to undergo deformation. The impact test specimens were prepared in accordance with the ASTM D5942 standard. [10]

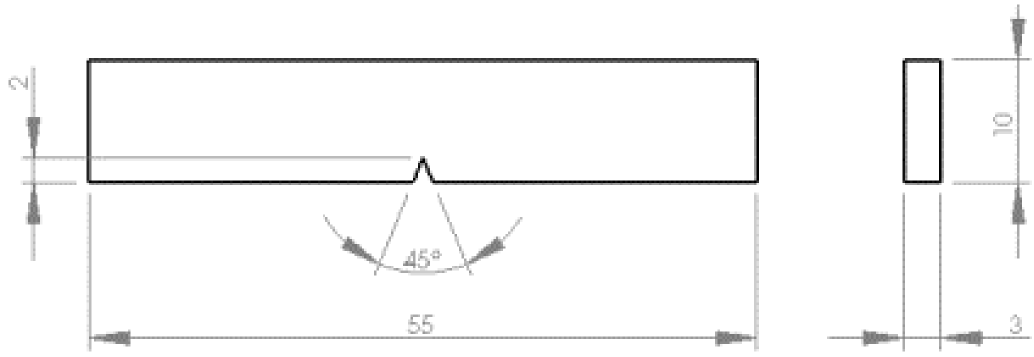


Figure 3. Impact Test Specimen

Absorbed Energy = Initial Energy - Residual Energy

$= m.g\ h_0 - m.g.h$

$= m.g\ (R.\cos\beta) - (R.\cos\alpha)$

$= m.g.\ R\ (\cos\beta - \cos\alpha)$

In the impact test, the absorbed energy (Eabs) is expressed in Joules and represents the energy absorbed by the specimen during fracture. This value is influenced by several parameters, including the pendulum mass (m) in kilograms, gravitational acceleration (g) in m/s^2, arm length (l) in meters, pendulum radius (R) in meters, initial distance between the pendulum and specimen (h_0) in meters, final distance after impact (h_1) in meters, initial swing angle (α) in degrees, and final swing angle (β) in degrees.

The impact strength (IS) is calculated using the equation IS = Ea/A, where Ea is the absorbed energy (Joule) and A is the cross-sectional area of the specimen (mm^2). The cross-sectional area is determined by the equation A = (w − notch depth) × t, where w is the specimen width (mm), notch depth is the depth of the notch, and t is the specimen thickness (mm). This calculation indicates the material's ability to withstand sudden impact loads per unit area.

3. Results and Discussion

3.1. Burn Test Results

The test was conducted using a burn test apparatus. The composite specimens for the burn test were prepared in accordance with the ASTM D635 standard. Examples of burn test specimens with composition ratios of 2% Clay : 28% SR : 70% PP, 4% Clay : 26% SR : 70% PP, and 6% Clay : 24% SR : 70% PP can be seen in Figure 4.

For each variation, the test was performed three times. From these three specimen tests, three data points were collected for each variation, from which the average values for absorbed energy and impact toughness were calculated. The tensile test results can be seen in Table 1.

(A) (B) (C)

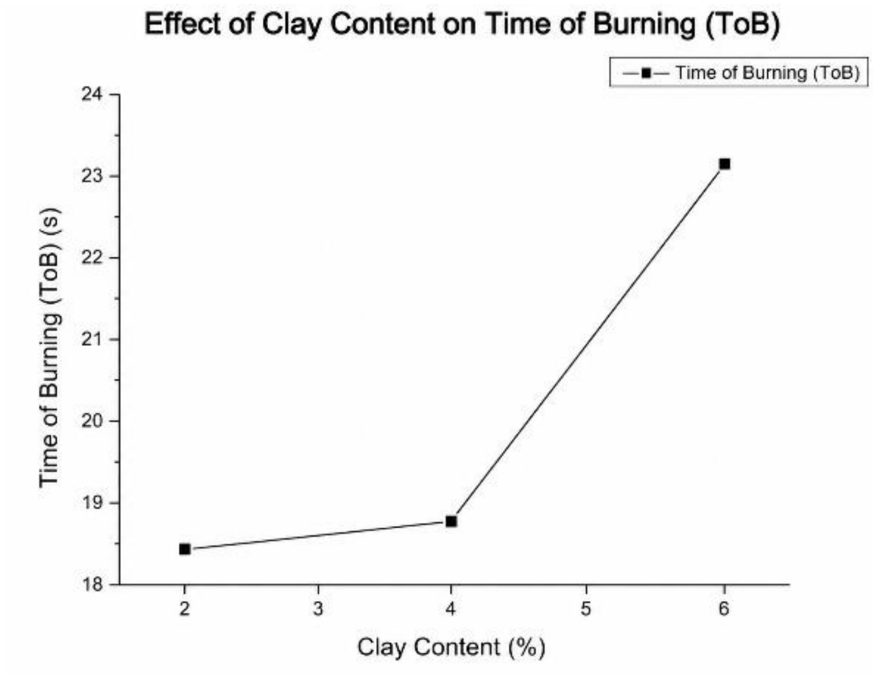
Figure 4. Burn Test specimen, (A) 2% Clay : 28% SR : 70% PP, (B) 4% Clay 26% SR : 70% PP, and (C) 6% Clay : 24% SR : 70% PP

Table 1. Burn Test Results

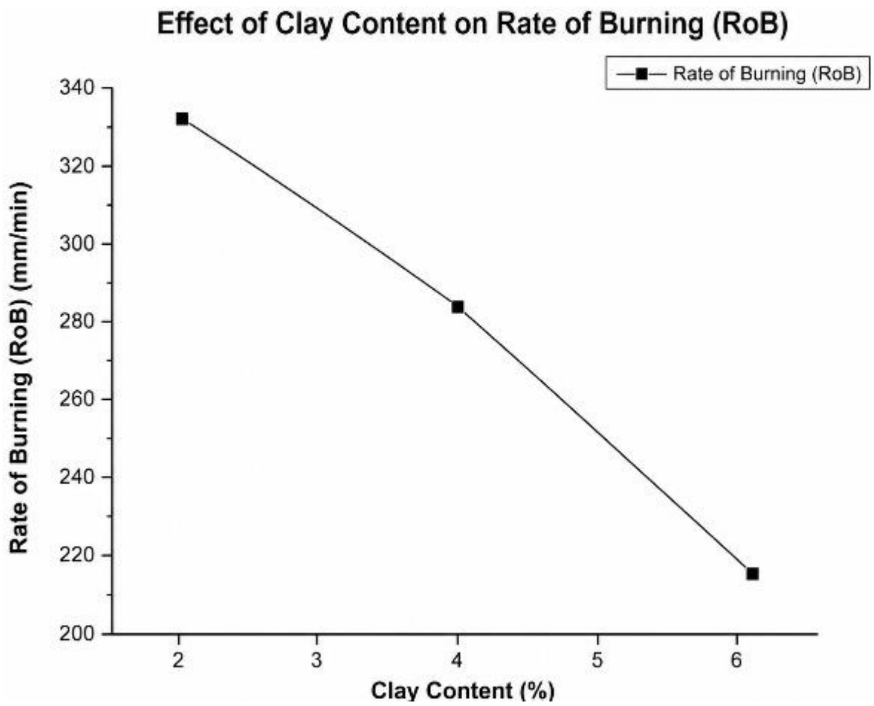
Variation *Clay*	Time of Burning (ToB)	Rate of Burning (RoB)
(%)	(second)	(mm/minute)
2% Clay : 28% SR : 70% PP	18.36	332.94
4% Clay 26% SR : 70% PP	18.71	285.34
6% Clay : 24% SR : 70% PP	23.17	214.27

The averaged values of Time of Burning and Rate of Burning are subsequently presented in graphical form. The graphs for the average absorbed energy and impact toughness are presented in Figure 5.

The burn test results based on the ASTM D635 standard indicate that Sokka roof tile particles (clay) significantly influence the combustion characteristics of the composite. At a composition of 2% MMt : 28% ramie fiber : 70% PP, the composite exhibited low fire resistance, characterized by a Time of Burning (ToB) value of 18.36 seconds and a relatively high Rate of Burning (RoB) of 332.94 mm/minute. This is due to the highly flammable polypropylene matrix, while the contribution of the tile particles as a thermal shield was not yet optimal. Increasing the particle content to 4% MMt : 26% ramie fiber : 70% PP caused the ToB to slightly increase to 18.71 seconds and the RoB to decrease to 285.34 mm/minute. This condition indicates that the particles began to act as a heat retardant that slows down flame propagation. The best combustion resistance was obtained at a composition of 6% MMt : 24% ramie fiber : 70% PP, with the highest ToB of 23.17 seconds and the lowest RoB of 214.27 mm/minute. The higher particle density forms a more effective thermal barrier, thereby reducing the heat transfer rate to the PP matrix and slowing down the spread of the flame.



(A)

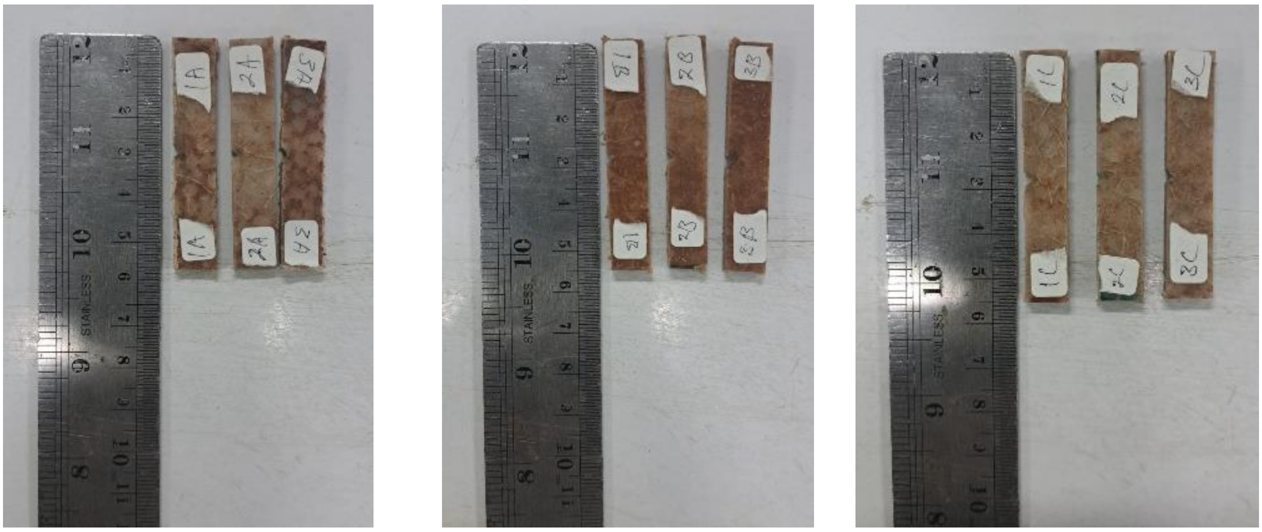


(B)

Figure 5. Burn test graphic, (A). Time of Burning graphic and (B). Rate of Burning Graphic

3.2. Impact Test Result

The impact test was conducted on three types of specimen variations, where each variation was tested three times to obtain data that can be analyzed accurately, Figure 6.. The averaged values of absorbed energy and impact toughness are subsequently presented in graphical form. The graphs for the average absorbed energy and impact toughness are presented in Figure 7.

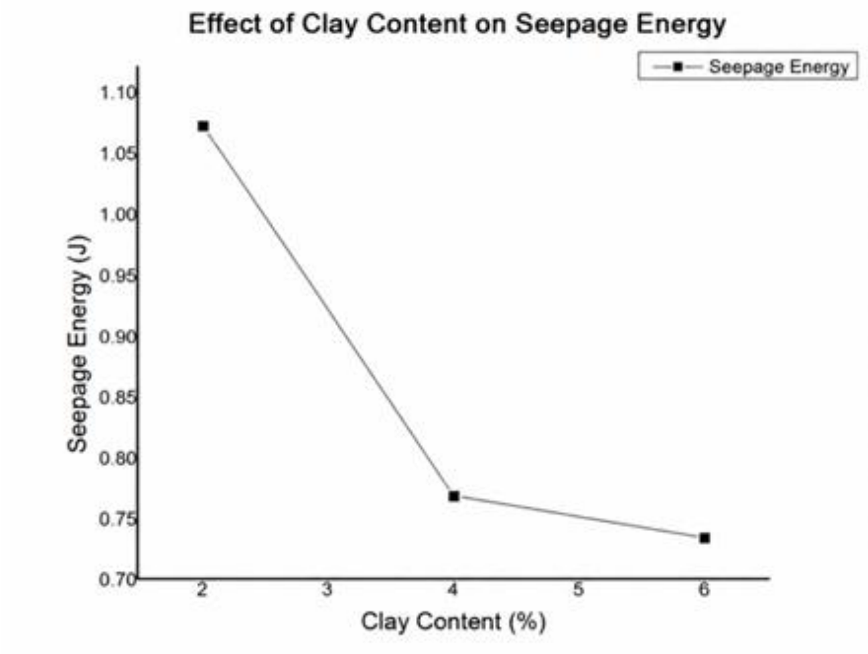


(A) (B) (C)

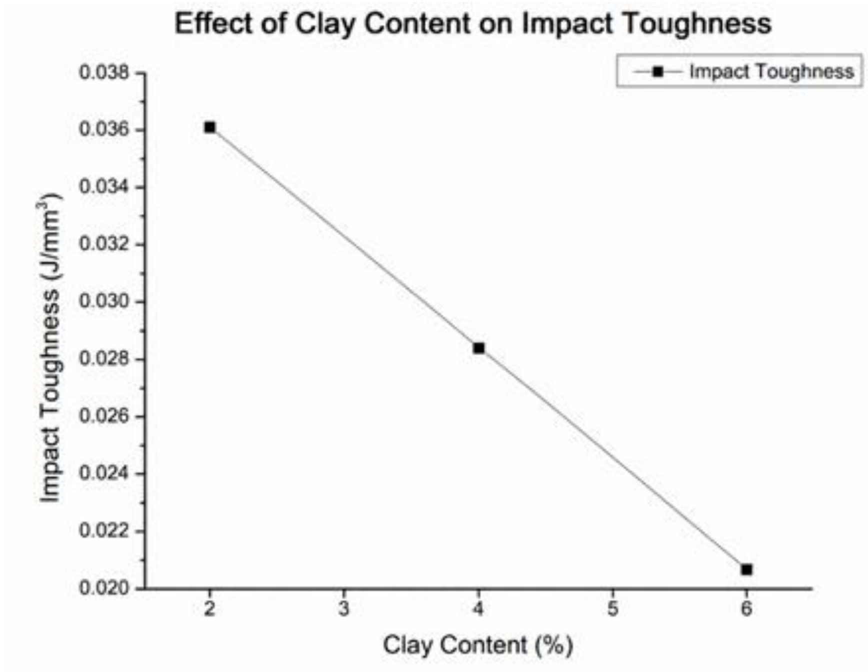
Figure 6. Impact test Specimen, (A) 2% Clay : 28% SR : 70% PP, (B) 4% Clay : 26% SR : 70% PP, (C) 6% Clay : 24% SR : 70% PP

Table 2. Impact Test Result

Variation *Clay* (%)	Absorbed Energy (Joule)	Impact Strength (J/mm²)
2% Clay : 28% SR : 70% PP	1.075	0.0364
4% Clay 26% SR : 70% PP	0.777	0.0285
6% Clay : 24% SR : 70% PP	0.735	0.0204



(A). Absorbed Energy Graphic



(B). Impact Strength Graphic

Figure 7. (A) Absorbed Energy Graphic, (B) Impact Strength Graphic

The material toughness test results show that the increase in Sokka roof tile particle concentration correlates negatively with the composite's absorbed energy. The specimen with the lowest particle content of 2% recorded the best mechanical performance with an absorbed energy of 1.075 Joules and an impact strength of 0.0364 J/mm², indicating a homogeneous particle distribution and the optimal role of ramie fiber as the primary reinforcement. Conversely, the addition of filler loading up to 6% resulted in a reduction of absorbed energy to 0.735 Joules and a decrease in impact strength to 0.0204 J/mm² due to increased brittleness and the emergence of stress concentration points that trigger crack initiation. This phenomenon confirms that the dominance of ramie fiber at low particle fractions is crucial in dampening impact loads, while excessive inorganic particle density actually weakens the interfacial interaction between the polypropylene matrix and the fiber reinforcement .

4. Conclusion

The results of the flammability test based on ASTM D635 indicate that variations in the content of Sokka roof tile particles significantly influence the combustion characteristics of the composite. Increasing the particle fraction from 2% to 6% resulted in an increase in the Time of Burning value and a decrease in the Rate of Burning. Specimens containing 2% particles exhibited a relatively faster flame propagation rate compared to specimens containing 4% and 6%. At the 6% composition, the combustion rate was the lowest, and the burned area length of the specimen was smaller than that of the other variations. These results indicate that increasing the particle fraction contributes to improved flame resistance of the composite.

Meanwhile, the results of the ASTM D5942 impact test showed an opposite trend. An increase in the Sokka roof tile particle fraction led to a reduction in the material’s ability to absorb impact energy. The average absorbed energy decreased from 1.075 Joules at the 2% fraction to 0.735 Joules at the 6% composition. This decrease was proportional to the reduction in impact strength values, which declined from 0.0364 J/mm² to 0.0204 J/mm². Specimens containing 6% particles exhibited more brittle fracture characteristics compared to those with lower particle content.

The improvement in flame resistance at higher particle fractions is associated with the thermal mechanisms occurring within the composite system. Sokka roof tile particles, which contain silica (SiO_2) and alumina (Al_2O_3), exhibit high thermal stability and are non-flammable; therefore, they act as thermal barriers that inhibit the diffusion of heat and oxygen into the polypropylene matrix [11]. Moreover, the increased proportion of the inorganic phase reduces the amount of flammable polymer matrix in the overall composition, thereby slowing the thermal degradation process and decreasing the rate of flame propagation [12].

However, increasing the mineral particle content also leads to a reduction in the impact toughness of the composite. Rigid inorganic particles may act as stress concentration sites under impact loading, particularly when their distribution is non-uniform or when the interfacial bonding between the particles and the matrix is weak [13]. In addition, the difference in elastic modulus between the matrix and the particles limits plastic deformation, reducing the material's ability to absorb impact energy effectively [14]. This phenomenon indicates a trade-off between enhanced flame resistance and decreased mechanical toughness, emphasizing the need for composition optimization to achieve a balanced set of properties [15].

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