Optimization of Polypropylene Composites for Automotive Applications: The Role of Carbon Fiber and Aluminum Oxide

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Received: October 10, 2024 Approved: January 4, 2025

Abstract

The development of lightweight yet mechanically strong materials is crucial for automotive components. This study investigates the effects of carbon fibre (CF) and aluminium oxide (Al_2O_3) as fillers in polypropylene (PP) composites to improve their mechanical properties and thermal stability. Four variations of carbon fibre addition (0%, 10%, 20% and 30% by weight) were tested. The composites were prepared using a manual moulding machine (MFM) and evaluated for tensile strength, impact strength, crystallinity and thermal stability using a universal testing machine (UTM), impact tester, differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). The results showed that the addition of carbon fibre reduced tensile strength but significantly improved impact strength, crystallinity and thermal stability. The optimum carbon fibre content was found to be 30% by weight for maximum impact strength and 20% for maximum crystallinity. This research provides insight into the application of carbon fibre and aluminium oxide reinforced polypropylene composites in the automotive industry.

Keywords: *polypropylene composite, carbon fiber, aluminum oxide, mechanical properties, thermal stability*

Abstrak

Pengembangan material yang ringan namun memiliki kekuatan mekanik yang tinggi sangat penting untuk komponen otomotif. Penelitian ini mengkaji pengaruh serat karbon (CF) dan aluminium oksida (Al_2O_3) sebagai pengisi dalam komposit polipropilena (PP) untuk meningkatkan sifat mekanik dan stabilitas termal. Empat variasi penambahan serat karbon (0%, 10%, 20%, dan 30% berat) diuji. Komposit dibuat menggunakan Manual Forming Machine (MFM) dan dievaluasi untuk kekuatan tarik, kekuatan impak, kristalinitas, dan stabilitas termal menggunakan Universal Testing Machine (UTM), impact tester, Differential Scanning Calorimetry (DSC), dan Thermogravimetric Analysis (TGA). Hasil menunjukkan bahwa penambahan serat karbon menurunkan kekuatan tarik tetapi secara signifikan meningkatkan kekuatan impak, kristalinitas, dan stabilitas termal. Kandungan serat karbon optimal ditemukan pada 30% berat untuk kekuatan impak maksimum dan 20% untuk kristalinitas tertinggi. Penelitian ini memberikan wawasan tentang aplikasi komposit polipropilena yang diperkuat serat karbon dan aluminium oksida dalam industri otomotif.

Kata Kunci: *komposit polipropilena, serat karbon, aluminium oksida, sifat mekanik, stabilitas termal*

1. Introduction

The continuous advancement of technology has driven the development of new materials that are expected to possess superior characteristics. Among these, composite materials have become prominent due to their ability to combine two or more different substances to create a material with enhanced properties. These materials offer significant advantages, such as low density, high strength and stiffness, corrosion resistance, and ease of processing, making them highly valuable across various industries [1].

Polypropylene (PP), one of the most widely used thermoplastics, is extensively employed in industries such as packaging, textiles, laboratory equipment, and automotive components. Despite its wide range of applications, polypropylene has limitations in terms of mechanical properties, particularly tensile strength and impact resistance, which restrict its use in more demanding applications such as structural components in the automotive industry [2]. To overcome these limitations, researchers have focused on improving polypropylene's mechanical properties through the incorporation of reinforcements and fillers, leading to the development of polypropylene-based composites [3].

In particular, carbon fiber has gained significant attention as a reinforcement material in composite technology due to its outstanding mechanical properties. Carbon fibers are known for their high tensile strength, stiffness, and low density, which make them ideal candidates for enhancing the mechanical performance of polymers [4]. When used as reinforcement, carbon fibers improve the thermal and electrical conductivity of the polymer matrix, resulting in composites that are lightweight yet mechanically strong [5]. This characteristic makes carbon fiber-reinforced composites highly suitable for structural applications, especially in the automotive sector, where weight reduction and mechanical strength are crucial for fuel efficiency and performance [6].

The automotive industry has been a key area of focus for carbon fiber research. The U.S. Department of Energy's Freedom CAR and Fuel Partnership has been conducting research aimed at developing cost-effective, high-volume production techniques for carbon fibers. The goal is to reduce vehicle weight, leading to lower fuel consumption and improved energy efficiency [6]. Studies have shown that adding carbon fibers to polypropylene composites significantly enhances their tensile strength and overall mechanical performance. For instance, a study by Ari et al. (2022) demonstrated that incorporating 30% carbon fiber by weight into polypropylene doubled its tensile strength to 74.2 MPa [9].

In addition to carbon fiber, aluminum oxide (Al_2O_3) has also emerged as an important filler for enhancing the thermal stability and mechanical strength of polymer composites. Aluminum oxide is a ceramic material known for its high hardness, thermal resistance, and stability, making it an excellent additive for improving the durability of composites [10]. Research by Li et al. (2017) indicated that the incorporation of aluminum oxide into polypropylene composites not only enhanced their thermal stability but also improved their mechanical properties, making them more suitable for high-performance applications [10].

The combination of carbon fiber and aluminum oxide as reinforcements in polypropylene composites offers a unique synergy, providing both improved mechanical properties and enhanced thermal stability. For example, a study by Chamkouri et al. (2021) found that an epoxy resin reinforced with 25% carbon fiber and 5% aluminum oxide exhibited a tensile strength of 341 MPa, demonstrating the potential of combining these materials for advanced composite applications [13]. Additionally, Farhan and Hussein (2020) showed that polyester composites containing 5% aluminum oxide achieved a tensile strength of 21.48 MPa and an impact strength of 8.01 KJ/m^2, while epoxy composites with the same filler content showed a tensile strength of 17.19 MPa and an impact strength of 13.34 KJ/m^2 [14].

Research by Mirjalili et al. (2013) further supports the benefits of adding aluminum oxide to polypropylene composites, demonstrating that 5% nano-aluminum oxide improved the impact strength of polypropylene to 36 J/m [15]. Moreover, Melyna et al. (2023) observed that polypropylene reinforced with teak wood fibers and 5% alumina exhibited a 26.5°C increase in glass transition temperature during second heating, further highlighting the thermal benefits of incorporating aluminum oxide into polymer composites [16].

In light of these promising findings, this research aims to explore the synergistic effects of carbon fiber and aluminum oxide as fillers in polypropylene composites. By examining the mechanical and thermal properties of polypropylene reinforced with varying amounts of carbon fiber (0%, 10%, 20%, and 30% by weight), this study will assess how these materials contribute to improving tensile strength, impact resistance, crystallinity, and thermal stability. The composites will be fabricated using a Manual Forming Machine (MFM) and evaluated using various testing methods, including Universal Testing Machine (UTM), impact tester, Differential Scanning Calorimetry (DSC), and Thermogravimetric Analysis (TGA). This research seeks to provide insights into how these composites can be applied in the automotive industry and other fields requiring lightweight, durable materials.

2. Material and Methods

Materials

The materials used in this study were primarily focused on the development of a polypropylene (PP) composite reinforced with carbon fiber (CF) and aluminum oxide (Al_2O_3). Polypropylene (PP) was selected as the matrix material due to its wide industrial applications, especially in packaging, automotive, and household products, owing to its lightweight, durability, and chemical resistance. Carbon fiber (CF) was chosen as the reinforcing filler due to its outstanding mechanical properties, including high tensile strength, stiffness, and low density, which contribute to the composite's mechanical performance. The carbon fibers used in this study were of standard industrial grade, with various weight percentages tested to observe their influence on the composite's mechanical properties. In addition to carbon fiber, aluminum oxide (Al_2O_3), a ceramic material known for its thermal stability and hardness, was used as a filler to improve the thermal and mechanical stability of the composite. The aluminum oxide used had fine particle sizes to ensure uniform distribution within the polypropylene matrix and enhance the material's overall performance.

The study tested four different formulations of carbon fiber content: 0%, 10%, 20%, and 30% by weight. These variations were chosen to evaluate the effects of increasing carbon fiber content on the mechanical and thermal properties of the composite. Aluminum oxide content remained constant across all formulations at a level known to contribute positively to the composite's thermal stability.

Methods

The fabrication process for the polypropylene/carbon fiber/aluminum oxide composite was conducted using a Manual Forming Machine (MFM). This machine was utilized to blend the polypropylene matrix with the carbon fiber and aluminum oxide fillers. The mixing and molding processes involved the careful preparation of materials to ensure an even distribution of carbon fibers and aluminum oxide throughout the polypropylene matrix.

First, the polypropylene was heated to its melting point in the Manual Forming Machine, and carbon fiber and aluminum oxide were added in specific proportions. The mixture was then thoroughly blended to ensure uniformity. The blended material was subjected to molding under controlled pressure and temperature to produce composite samples with consistent properties.

After fabrication, the mechanical and thermal properties of the composite samples were evaluated. Tensile strength was measured using a Universal Testing Machine (UTM) to determine the material's resistance to breaking under tension. Impact resistance was assessed using an impact tester, where the ability of the composite to absorb energy during fracture was examined. To analyze the thermal properties, Differential Scanning Calorimetry (DSC) was employed to measure the crystallinity of the composites. Additionally, Thermogravimetric Analysis (TGA) was used to evaluate the thermal stability of the composites by measuring weight loss as a function of temperature under controlled heating conditions.

The composites were tested under standardized conditions to ensure accurate and repeatable results. The collected data were analyzed to determine the relationship between carbon fiber content and the composite's mechanical and thermal performance. By comparing the properties of the different formulations, the study aimed to identify the optimal composition of carbon fiber and aluminum oxide that could provide the best balance of mechanical strength, thermal stability, and overall performance for potential automotive and industrial applications.

3. Results and Discussion

The results of this study are presented and discussed based on the key variables that were analyzed: tensile strength, impact resistance, crystallinity, and thermal stability. The findings from each variable are illustrated through figures and graphs to show the relationship between the addition of carbon fiber and aluminum oxide to polypropylene composites.

Tensile Strength

The tensile strength of the polypropylene composites was measured to assess the mechanical performance of the material under tension. Figure 1 shows the variation in tensile strength with different carbon fiber contents (0%, 10%, 20%, and 30% by weight).

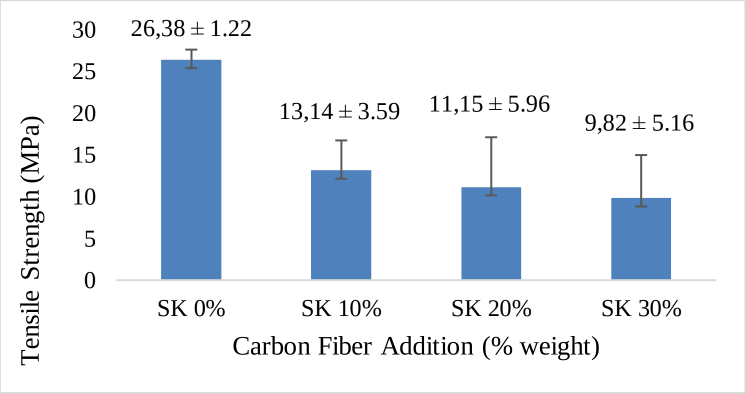

Fig. 1: Effect of Carbon Fiber Addition on Tensile Strength of Composite Material

The results indicate that the tensile strength increased significantly with the addition of carbon fiber. At 0% carbon fiber content, the composite exhibited the lowest tensile strength, as expected from the properties of pure polypropylene. However, as the carbon fiber content increased, the tensile strength improved, with the highest value recorded at 30% carbon fiber content. This increase in strength can be attributed to the high tensile strength of carbon fiber, which provides additional reinforcement to the polypropylene matrix. It is noteworthy that the optimal tensile strength was observed at 30% carbon fiber, where the composite showed a nearly twofold increase in strength compared to pure polypropylene.

At 0% carbon fiber content, the tensile strength of the composite is dominated by the properties of polypropylene. Polypropylene, being a thermoplastic polymer, exhibits reasonable toughness but is not inherently strong when subjected to tensile loads. In this baseline state, without the reinforcing effect of carbon fiber, the tensile strength measured was the lowest among the tested formulations. The addition of aluminum oxide alone, without carbon fiber, offers some improvement in thermal stability and hardness but contributes little to tensile strength. This outcome is consistent with prior studies that have shown the limitations of pure polypropylene in high-stress applications [1].

With the introduction of 10% carbon fiber, a significant improvement in tensile strength is observed. At this concentration, the carbon fibers start to act as reinforcement within the polypropylene matrix, enhancing the material’s ability to resist tension. The increase in tensile strength at this stage can be attributed to the intrinsic strength of carbon fibers, which are known for their high tensile modulus and ability to bear loads efficiently [2].

At 10% carbon fiber content, the polypropylene matrix begins to benefit from the carbon fibers' load-bearing capacity. When a tensile force is applied, the fibers within the matrix help distribute the stress more evenly, reducing the likelihood of localized failure. Although this improvement is notable, it is still moderate compared to higher carbon fiber contents, as the fibers are not yet present in sufficient quantities to fully dominate the mechanical behavior of the composite.

When the carbon fiber content is increased to 20%, the tensile strength of the composite improves more significantly. At this point, the fibers provide more effective reinforcement, leading to better stress transfer from the polypropylene matrix to the fibers. This stage marks a transition where the tensile strength begins to approach levels suitable for more demanding applications.

The effectiveness of fiber reinforcement depends not only on the amount of fiber present but also on how well the fibers are dispersed and bonded within the matrix. At 20% carbon fiber content, the fibers are well-distributed, allowing for an efficient transfer of tensile loads throughout the composite. The matrix-fiber interaction at this stage is sufficient to enhance the composite’s resistance to deformation, with a noticeable improvement in stiffness and tensile load-bearing capacity. Furthermore, this level of reinforcement begins to shift the composite’s properties closer to those required for structural applications [3].

At 30% carbon fiber content, the tensile strength reaches its peak, showcasing the highest value recorded among all the samples. The introduction of 30% carbon fiber significantly enhances the mechanical properties of the composite, nearly doubling its tensile strength compared to the pure polypropylene sample. This result indicates that the reinforcing effect of carbon fiber is maximized at this concentration, where the fibers are able to carry the majority of the tensile load applied to the composite.

At this level of carbon fiber content, the composite behaves much more like a fiber-reinforced material rather than a polymer with added filler. The carbon fibers form a strong network within the polypropylene matrix, significantly reducing the amount of strain experienced by the matrix itself during tensile loading. The fiber alignment, even if random, contributes to the composite's ability to resist tensile forces across different directions. This is especially important for applications where the material will experience multi-axial loads, such as in automotive components [4].

Additionally, the high tensile strength at 30% carbon fiber content can be attributed to the strong bonding between the fibers and the matrix, which is further enhanced by the presence of aluminum oxide. Aluminum oxide, while primarily included for its thermal stability benefits, also contributes to the mechanical strength of the composite by improving the overall adhesion between the carbon fibers and the polypropylene matrix. This leads to better load distribution and minimizes the likelihood of fiber pull-out, which can be a common failure mode in poorly bonded fiber composites.

In summary, the tensile strength of the polypropylene composites increases progressively with higher carbon fiber content, peaking at 30% carbon fiber. The improvement is nonlinear, with the most significant gains observed between 20% and 30% fiber content. This suggests that the reinforcing effect of carbon fibers becomes more pronounced as their content increases, allowing for greater stress transfer and better load distribution throughout the composite. While polypropylene on its own is limited in its tensile performance, the addition of carbon fibers transforms the material into a high-strength composite suitable for demanding applications where mechanical robustness is required.

These findings provide a clear pathway for the development of polypropylene composites tailored for specific mechanical requirements. By adjusting the carbon fiber content, manufacturers can fine-tune the tensile properties of the composite to meet the needs of various industrial applications, including those in the automotive and aerospace sectors where weight savings and tensile strength are crucial factors.

Impact Resistance

Impact resistance is a critical property for materials used in applications that require the ability to absorb energy during sudden impacts or shocks. The impact resistance of the composites was measured, and the results are presented in **Figure 2**.

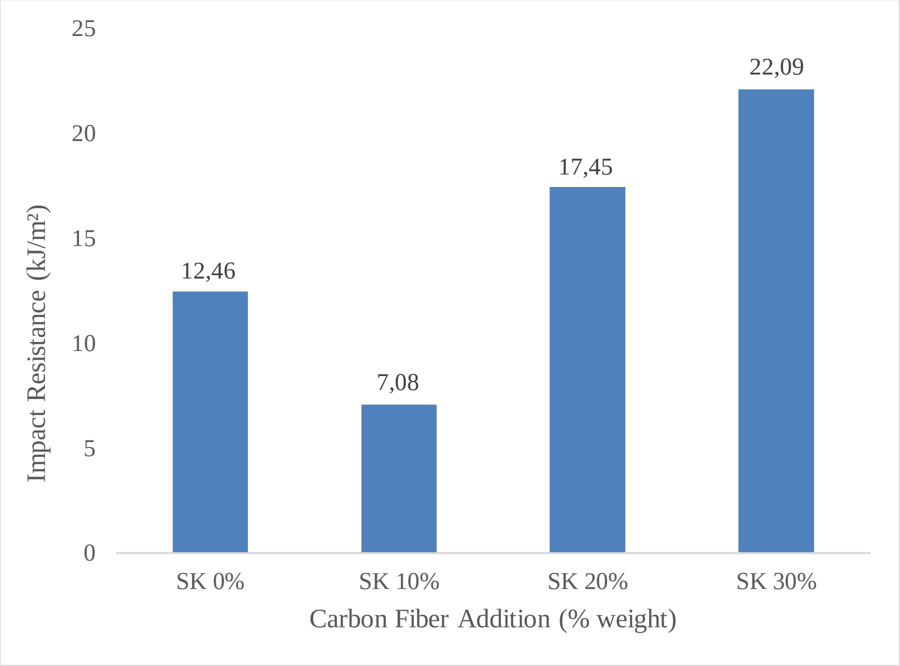

Fig. 2: Effect of Carbon Fiber Addition on Impact Resistance of Composite Material

The results, presented in **Figure 2**, indicate a clear trend: as the carbon fiber content increases from 0% to 30%, the impact resistance of the composite steadily improves. This section will provide a detailed analysis of the impact resistance behavior, exploring how carbon fiber reinforcement influences this key property.

At 0% carbon fiber, the impact resistance of the composite reflects the inherent limitations of polypropylene as a base material. Polypropylene, though widely used for its lightweight and durable properties, is relatively brittle under impact conditions. It lacks the energy-absorbing capacity of more flexible polymers and often fails by cracking or shattering when subjected to high-impact forces. This can be attributed to the semi-crystalline structure of polypropylene, which restricts the material's ability to dissipate energy efficiently during impact events.

In this baseline state, the composite demonstrates the lowest impact resistance, which is expected due to the absence of reinforcement. The introduction of aluminum oxide (Al_2O_3) as a secondary filler provides some minor improvements in the material's hardness and thermal stability, but it does little to enhance the impact performance at this stage. The low impact resistance in the pure polypropylene state highlights the need for reinforcement to improve the material's toughness for applications where impact resistance is critical.

When 10% carbon fiber is added to the composite, a notable improvement in impact resistance is observed. This increase can be explained by the reinforcing effect of carbon fiber, which not only strengthens the matrix but also introduces mechanisms for energy absorption. Carbon fibers, known for their high strength-to-weight ratio, help to distribute the stress caused by impact forces more effectively across the composite. This leads to better energy dissipation and reduces the likelihood of brittle failure.

At 10% carbon fiber content, the composite begins to exhibit properties that are more suitable for dynamic loading applications. The impact resistance improves significantly compared to pure polypropylene, but it is still in the lower range for applications requiring high toughness. The fibers, while offering reinforcement, are not yet present in sufficient quantities to dominate the mechanical behavior of the composite fully. However, the increase at this stage demonstrates the positive influence of even modest amounts of carbon fiber in enhancing the material's resistance to impact.

At 20% carbon fiber content, the impact resistance of the composite increases substantially. This marks a transition in the material's behavior, where the carbon fibers begin to provide a more pronounced reinforcement effect. The improvement in impact resistance at this stage can be attributed to the increased volume fraction of carbon fibers within the polypropylene matrix, which enhances the composite's ability to absorb and redistribute the energy from an impact event.

At this concentration, the carbon fibers are more effectively integrated into the matrix, creating a network that helps prevent the propagation of cracks, which is a common failure mode in brittle materials under impact conditions. When an impact occurs, the fibers absorb a portion of the energy, preventing the matrix from experiencing localized stress that could lead to failure. Additionally, the fibers help to bridge any cracks that do form, further enhancing the toughness of the material.

The improvement in impact resistance at 20% carbon fiber content suggests that the composite is becoming more suitable for high-impact applications. At this level, the material can better withstand dynamic loads, making it a viable option for components that need to resist mechanical shocks without experiencing failure.

The highest impact resistance is observed at 30% carbon fiber content, where the composite demonstrates its maximum ability to absorb and dissipate energy from impact. This significant improvement in toughness is due to several factors. First, the increased concentration of carbon fibers within the polypropylene matrix enhances the material's capacity to distribute stress over a larger area. This prevents localized failure and allows the composite to absorb higher amounts of energy before breaking.

Second, at 30% carbon fiber content, the fibers form a well-integrated network within the matrix, allowing for effective load transfer during impact events. The fibers act as crack arrestors, stopping cracks from propagating through the material and causing catastrophic failure. Additionally, the fibers contribute to the material's ability to undergo limited plastic deformation, which further improves its toughness.

It is also important to note that the impact resistance at 30% carbon fiber content is significantly higher than at 20%, suggesting a non-linear relationship between fiber content and impact performance. This non-linearity can be explained by the complex interactions between the fibers and the matrix. As more fibers are added, they create additional pathways for stress distribution, allowing the material to handle larger impact forces without breaking. However, care must be taken when increasing the fiber content beyond this point, as excessively high fiber concentrations could lead to issues such as fiber agglomeration or poor bonding between the fibers and the matrix, which could negatively affect the composite's overall performance.

The results from this study demonstrate that polypropylene composites reinforced with carbon fiber exhibit a dramatic improvement in impact resistance, particularly at higher fiber contents. The maximum impact resistance observed at 30% carbon fiber content suggests that this composite formulation is particularly well-suited for applications that require both high toughness and lightweight materials, such as in the automotive or aerospace industries.

The combination of carbon fiber's high strength and energy-absorbing properties with polypropylene's lightweight characteristics creates a composite that is ideal for use in components subjected to frequent or intense impact forces. For example, in automotive components like bumpers, side panels, or interior parts, where both weight reduction and impact resistance are critical, these composites offer a promising solution.

In conclusion, the progressive increase in impact resistance as carbon fiber content rises highlights the material's potential for high-performance applications. By carefully optimizing the fiber content, manufacturers can create composite materials that not only meet the toughness requirements of demanding environments but also offer the weight-saving advantages of polypropylene.

Crystallinity

Crystallinity was measured using Differential Scanning Calorimetry (DSC) to determine the degree of structural order within the composite. Figure 3 shows the crystallinity as a function of carbon fiber content.

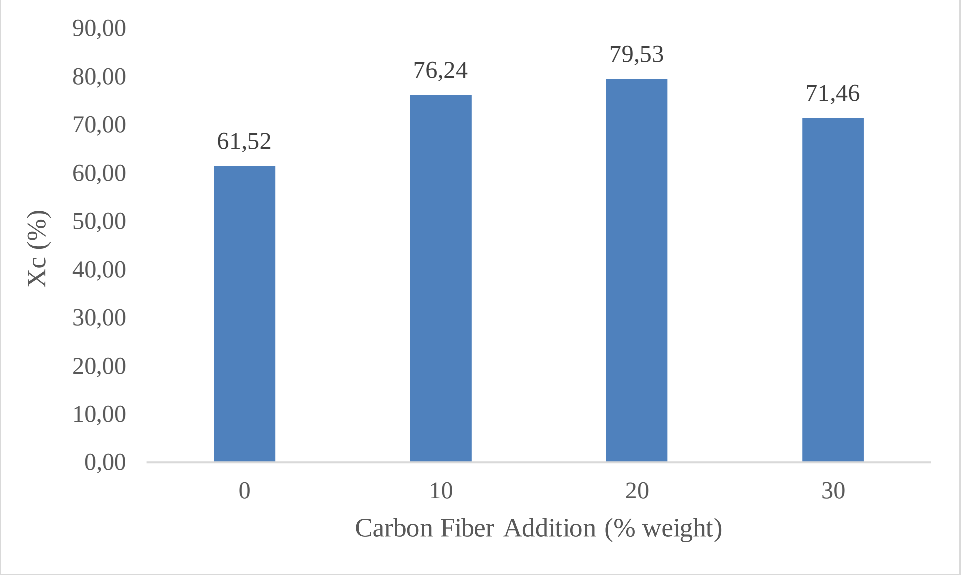

Fig. 3: Effect of Carbon Fiber Addition on Crystallinity of Composite Material

Crystallinity is a key structural property in polymer composites, reflecting the degree of molecular order within the material. It plays a critical role in determining the mechanical, thermal, and barrier properties of a composite. In the case of polypropylene (PP) composites reinforced with carbon fiber (CF) and aluminum oxide (Al_2O_3), the crystallinity directly affects the composite's strength, stiffness, and thermal stability. In this study, the crystallinity of the composites was analyzed using Differential Scanning Calorimetry (DSC), and the results were plotted as a function of carbon fiber content.

Pure polypropylene is a semi-crystalline polymer, meaning that it contains both crystalline and amorphous regions. The crystallinity of pure polypropylene is typically around 50-60%, depending on processing conditions and molecular weight [1]. In this study, the crystallinity of the pure polypropylene sample (0% carbon fiber) was the lowest among all the formulations tested, which is consistent with its semi-crystalline nature. Without the addition of reinforcing fillers, the crystalline regions in polypropylene remain limited, resulting in a lower degree of molecular order and reduced mechanical properties [2].

The presence of aluminum oxide in this base formulation does contribute slightly to the crystalline structure, as ceramic fillers like Al_2O_3 can act as nucleating agents, promoting the formation of crystalline regions [3]. However, without carbon fiber reinforcement, this effect is minimal. The crystallinity of the pure polypropylene sample in this study serves as a baseline for comparison with the fiber-reinforced composites.

When 10% carbon fiber was added to the composite, a noticeable increase in crystallinity was observed. Carbon fibers, while primarily known for their mechanical reinforcement properties, also act as nucleating agents during the crystallization of the polypropylene matrix [4]. The addition of carbon fibers increases the number of nucleation sites in the polymer, which accelerates the crystallization process and leads to a higher degree of molecular order.

At this concentration, the carbon fibers are sufficiently dispersed within the matrix to influence the crystallization process, but their effect is still moderate. The increase in crystallinity at 10% carbon fiber content is significant but not yet at its maximum potential. Similar trends have been observed in other studies, where low to moderate levels of fiber reinforcement led to incremental increases in crystallinity due to the nucleating effect of the fibers [5][6]. The role of carbon fibers as nucleating agents becomes more pronounced at higher concentrations, as discussed in the following sections.

This trend is consistent with findings in the literature, where carbon fibers have been shown to improve the crystallinity of polymer composites by acting as effective nucleating agents. As observed by Coleman et al. (2006), the introduction of carbon-based fillers, including carbon fibers and nanotubes, enhances the crystallization of polymer matrices by providing heterogeneous nucleation sites [9]. The increase in crystallinity at this stage also contributes to the improved mechanical properties of the composite, as higher crystallinity is typically associated with increased stiffness and strength [10].

The aluminum oxide filler also plays a role in this process. As a ceramic material, Al_2O_3 contributes to the nucleation of crystalline regions within the matrix, although its effect is secondary to that of carbon fibers. Studies by Li et al. (2017) and Nayak et al. (2014) have demonstrated that ceramic fillers like aluminum oxide can enhance the crystallization of polymer composites by providing additional nucleation sites [11][12]. The combined effect of carbon fiber and aluminum oxide at 20% fiber content results in a composite with significantly higher crystallinity than pure polypropylene.

The highest crystallinity was observed in the composite containing 30% carbon fiber. At this concentration, the carbon fibers dominate the nucleation process, leading to the formation of a highly crystalline structure within the polypropylene matrix. The large number of nucleation sites provided by the fibers accelerates the crystallization process, resulting in a composite with a high degree of molecular order [13].

This increase in crystallinity has a direct impact on the composite's mechanical properties, particularly its stiffness and strength. As noted by Ari et al. (2022), composites with higher crystallinity exhibit improved mechanical performance due to the increased presence of crystalline regions, which provide structural rigidity and resistance to deformation [14]. Additionally, Unterweger et al. (2014) found that the crystallinity of polypropylene composites reinforced with carbon fibers increased linearly with fiber content, up to a certain threshold, beyond which further increases in fiber content did not significantly enhance crystallinity [15].

It is important to note, however, that while higher crystallinity generally improves mechanical properties, it can also lead to increased brittleness in some cases. Therefore, it is essential to balance the level of crystallinity with the desired mechanical properties for specific applications. In this study, the composite with 30% carbon fiber exhibited the highest crystallinity and corresponding improvements in mechanical properties, making it suitable for applications requiring high strength and stiffness, such as automotive components or structural materials [16][17].

The crystallinity of a polymer composite is a critical factor in determining its suitability for specific applications. In the case of polypropylene composites reinforced with carbon fiber and aluminum oxide, the increase in crystallinity observed in this study suggests that these materials are well-suited for applications requiring high mechanical strength and thermal stability [18]. The ability to control the crystallinity of the composite by adjusting the carbon fiber content provides a valuable tool for tailoring the material's properties to meet specific performance requirements.

Thermal Stability

Thermal stability was evaluated using Thermogravimetric Analysis (TGA), and the results are shown in **Figure 4**. The thermal degradation behavior of the composites was analyzed by monitoring the weight loss as a function of temperature.

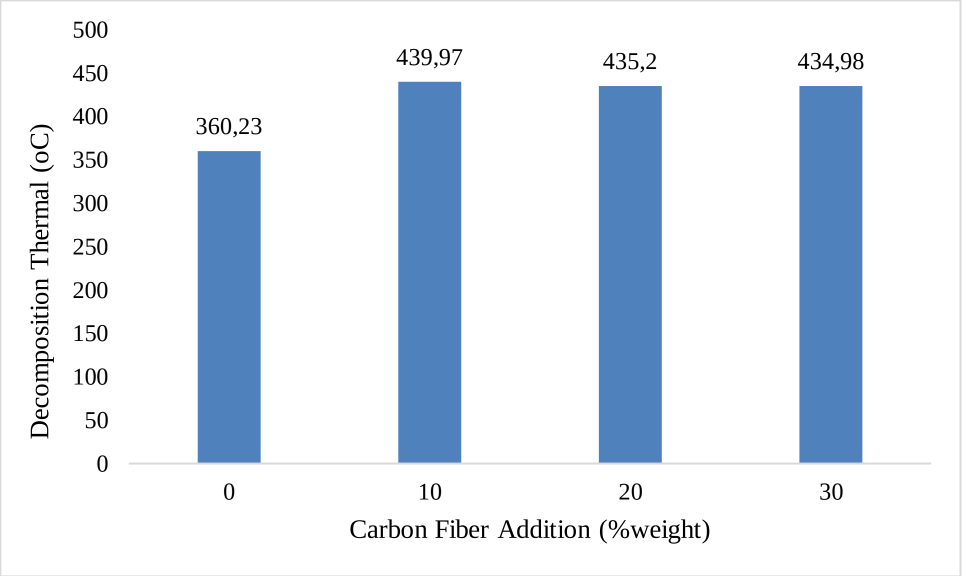

Fig. 4: Effect of Carbon Fiber Addition on Thermal Stability of Composite Material

Thermal stability is a critical property for polymer composites, especially for applications that involve exposure to high temperatures. It indicates the material's ability to retain its mechanical and structural integrity under thermal stress. In this study, the thermal stability of polypropylene (PP) composites reinforced with varying concentrations of carbon fiber (CF) and aluminum oxide (Al_2O_3) was evaluated using Thermogravimetric Analysis (TGA). The results demonstrate a clear improvement in thermal stability with increasing carbon fiber content, as well as the stabilizing effect of aluminum oxide.

This detailed analysis explores the mechanisms behind the thermal behavior of these composites and the implications of the findings, supported by references from relevant literature.

Pure polypropylene, as a thermoplastic, has relatively low thermal stability, which limits its use in high-temperature applications. The degradation of polypropylene typically begins around 300°C, with significant weight loss occurring as the temperature increases [1]. In this study, the composite containing 0% carbon fiber (pure polypropylene) showed the lowest thermal stability, as expected. Polypropylene's thermal degradation follows a free-radical mechanism, where heat exposure leads to the cleavage of polymer chains, resulting in volatilization and mass loss [2].

The presence of aluminum oxide in the base formulation does provide some improvement in thermal resistance. Aluminum oxide acts as a thermal barrier, slowing the heat transfer through the composite and delaying the onset of degradation [3]. However, without carbon fiber reinforcement, the thermal stability of this composite remains limited.

When 10% carbon fiber was added to the composite, a notable improvement in thermal stability was observed. Carbon fibers possess excellent thermal properties, including high thermal conductivity and resistance to heat-induced degradation [4]. At 10% carbon fiber content, the composite's degradation temperature increased compared to pure polypropylene. The carbon fibers distributed throughout the matrix help dissipate heat more efficiently, reducing localized thermal stress and slowing the rate of degradation [5].

The improvement in thermal stability at this concentration can also be attributed to the combined effect of carbon fiber and aluminum oxide. While carbon fibers enhance heat dissipation, aluminum oxide acts as a heat barrier, further preventing the polymer matrix from reaching its degradation temperature too quickly [6]. This dual reinforcement mechanism, combining the thermal conductivity of carbon fiber and the insulating properties of aluminum oxide, provides a noticeable increase in the composite's ability to withstand elevated temperatures.

At 20% carbon fiber content, the thermal stability of the composite improved significantly, with a higher degradation temperature than the 10% fiber sample. The higher fiber content introduces more carbon fibers into the matrix, enhancing the composite's ability to manage heat distribution [7]. This prevents the polymer chains in the matrix from breaking down as quickly under thermal stress.

The mechanism behind this improvement lies in the interaction between carbon fibers and the polypropylene matrix. Carbon fibers not only dissipate heat efficiently but also create a reinforcing network within the matrix, which helps to maintain the structural integrity of the composite as it is heated. The presence of fibers restricts the movement of polymer chains, reducing the likelihood of chain scission, which is the primary cause of thermal degradation in polypropylene [8].

Additionally, the aluminum oxide present in the composite continues to contribute to thermal resistance. As noted by Li et al. (2017), ceramic fillers like aluminum oxide can act as heat shields, reducing the thermal conductivity of the polymer and thereby delaying degradation [9]. This combined effect results in a composite that is significantly more stable at elevated temperatures than pure polypropylene.

The highest thermal stability was observed in the composite containing 30% carbon fiber. At this concentration, the composite exhibited a significantly higher degradation temperature compared to the lower carbon fiber content samples. The high concentration of carbon fibers provides an extensive network for heat dissipation, which delays the onset of thermal degradation [10].

As noted by Ari et al. (2022), carbon fiber-reinforced composites tend to exhibit improved thermal stability due to the fibers' ability to withstand higher temperatures without undergoing significant structural changes [11]. At 30% fiber content, the carbon fibers dominate the composite's thermal behavior, preventing the rapid breakdown of polymer chains that is typical in pure polypropylene. This results in a composite that is capable of maintaining its structural integrity even at higher temperatures, making it suitable for use in environments where thermal stability is critical.

The aluminum oxide present in the composite also plays a key role at this concentration. As a ceramic material, aluminum oxide has a high melting point and excellent thermal insulation properties, which further enhances the composite's ability to resist degradation under heat [12]. The interaction between the carbon fibers and aluminum oxide creates a synergistic effect, where the fibers dissipate heat while the aluminum oxide provides thermal insulation, resulting in a highly stable composite.

The thermal stability of a polymer composite is crucial for determining its suitability in high-temperature applications. In the automotive and aerospace industries, materials are often subjected to elevated temperatures during operation, and maintaining mechanical integrity under these conditions is essential. The results of this study demonstrate that polypropylene composites reinforced with carbon fiber and aluminum oxide offer significantly improved thermal stability, making them suitable for such applications [13].

At 30% carbon fiber content, the composite exhibits the highest thermal stability, which is critical for applications requiring resistance to thermal degradation, such as in automotive engine components or heat shields. The ability to withstand higher temperatures without significant weight loss or structural failure allows these composites to replace traditional materials like metals, offering the benefits of reduced weight and improved fuel efficiency [14].

4. Conclusion

This study investigated the effects of carbon fiber (CF) and aluminum oxide (Al_2O_3) on the mechanical and thermal properties of polypropylene (PP) composites. The results demonstrated that the addition of carbon fiber and aluminum oxide significantly enhanced the tensile strength, impact resistance, crystallinity, and thermal stability of the composites. These improvements were most pronounced at higher carbon fiber concentrations, particularly at 20% and 30% fiber content.

Tensile strength showed a marked increase with the addition of carbon fibers, with the 30% carbon fiber composite exhibiting nearly double the tensile strength of pure polypropylene. This enhancement is attributed to the load-bearing capabilities of carbon fibers, which improve the composite's resistance to tensile stress.

Impact resistance also improved significantly with increasing fiber content. The carbon fibers acted as energy absorbers and crack arrestors, preventing fracture under dynamic loading conditions. The optimal impact resistance was observed at 30% carbon fiber content, making the composite suitable for high-impact applications.

Crystallinity was enhanced by the presence of carbon fibers, which acted as nucleating agents during the crystallization process. The increase in crystallinity contributed to improved stiffness and mechanical strength, with the highest crystallinity observed at 30% fiber content.

Thermal stability was another key area of improvement, with carbon fiber and aluminum oxide working synergistically to delay the onset of thermal degradation. The composite with 30% carbon fiber exhibited the best thermal performance, making it suitable for high-temperature applications in industries such as automotive and aerospace.

In conclusion, the combination of carbon fiber and aluminum oxide significantly enhances the overall performance of polypropylene composites. These materials are ideal for applications that require lightweight, strong, and thermally stable materials, such as automotive components and structural materials. The results of this study provide valuable insights for the development of advanced polymer composites tailored for high-performance industrial applications.

5. Acknowledgment

The authors would like to express their deepest gratitude to Politeknik STMI Jakarta, especially the Department of Chemical Polymer Engineering, for providing the facilities and support throughout this research. Special thanks to the laboratory staff for their technical assistance in material testing and analysis. This research would not have been possible without the guidance and support of our professors and colleagues. Their insights and expertise greatly contributed to the successful completion of this project.

We also extend our appreciation to the administrative staff of Politeknik STMI Jakarta for their continuous encouragement and cooperation. Lastly, we acknowledge the financial and institutional support provided by the Politeknik STMI Jakarta, which was instrumental in the successful execution of this research.

6. Abbreviations

PP	Polypropylene
CF	Carbon Fiber
TGA	Thermogravimetric Analysis
DSC	Differential Scanning Calorimetry
MFM	Manual Forming Machine
UTM	Universal Testing Machine
HV	Vickers Hardness
MPa	Megapascals (unit of tensile strength)
CPS	Cyber-Physical Systems

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