JOURNAL OF CHEMICAL PROCESS ENGINEERING
p-ISSN : 2527-4457
e-ISSN : 2655-2957

Vol. 9 No. 3 (Special Issue 2024)

Research Paper

Optimization of Polypropylene-Based Polymer Composites Fabrication Using Manual Forming for Automotive and Energy Applications

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Artikel Histori : Submitted 20 October 2024, **Revised** 10 December 2024, **Accepted** 29 December 2024, **Online** 31 December 2024

https://doi.org/10.33096/jcpe.v9i3.1453

ABSTRACT: *Polypropylene (PP)-based polymer composites are extensively utilized in the automotive and energy sectors due to their lightweight, strength, and excellent resistance to corrosion. These properties make them ideal for applications where performance and durability are critical. This study focuses on optimizing the fabrication process of polymer composites using the manual forming method, emphasizing the effects of pressure and heating time on the mechanical properties of the material. The materials employed consist of polypropylene as the matrix and glass fibers as the reinforcing agent. Key process parameters, such as pressure ranging from 150–200 kgf/cm² and heating time between 10–20 minutes, were systematically varied. Mechanical properties were evaluated through tensile tests and impact tests, conducted using a Universal Testing Machine (UTM) and an Izod Impact Tester, adhering to ASTM D638 and ASTM D256 standards, respectively. The findings indicate that the optimal combination of pressure and heating time yielded specimens with an average tensile strength of 35.3 MPa and an impact energy absorption of 0.45 Joules. Despite these promising results, the presence of air voids and uneven pressure distribution affected material homogeneity, which remains a significant challenge. In conclusion, while the manual forming method demonstrates potential for enhancing the quality of polymer composites for industrial applications, further refinement of process parameters is essential to achieve improved material consistency and performance.*

Keywords: *Impact test, Manual forming, Polymer composite, Polypropylene, Tensile test.*

1. INTRODUCTION

Polymer composites have become a vital solution in various industrial applications due to their lightweight, strength, corrosion resistance, and excellent thermal stability. These materials have found widespread use in the automotive and energy sectors, replacing conventional materials like metals owing to their superior mechanical properties and cost efficiency. Polypropylene (PP), a thermoplastic polymer, is among the most widely used materials in composite fabrication because of its high mechanical strength, thermal stability, and low production cost [1] [2].

However, optimizing the fabrication process of polypropylene-based composites to enhance their mechanical performance remains a significant challenge. Previous studies have indicated that combining polypropylene with reinforcement materials such as glass fibers can significantly improve tensile strength and impact resistance, which are crucial for industrial applications like automotive and structural components [3], [4]. The global demand for lightweight materials in the automotive sector, driven by the need for energy-efficient vehicles, has increased at an annual growth rate of 7% [5]. This growing demand highlights the necessity of developing high-performance polymer composites.

Published by
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In addition to glass fibers, recent advancements have explored the use of hybrid reinforcements, including natural fibers such as jute and kenaf, combined with synthetic fibers to achieve superior mechanical properties while promoting sustainability. Studies show that hybrid composites can achieve balanced performance characteristics suitable for automotive and construction applications, with reduced environmental impact compared to fully synthetic alternatives [23] [24]. Furthermore, the incorporation of nanoscale fillers, such as carbon nanotubes and graphene, has been shown to dramatically improve the thermal and electrical conductivity of polypropylene composites, broadening their applicability in energy storage and electronic devices [25].

Manual forming is a fabrication method that combines simultaneous heating and pressing, offering a straightforward and cost-effective approach to producing polymer composites with improved density and strength. Compared to other methods such as injection molding or compression molding, manual forming enables better control over material distribution and structural uniformity. However, challenges such as uneven pressure distribution and air voids during the process remain unresolved, adversely affecting the mechanical properties and homogeneity of the composite [6] [7].

Recent advancements in polymer composite technology have focused on optimizing process parameters, including pressure, heating time, and temperature, to achieve superior mechanical properties [8] [9]. For instance, studies have shown that precise control over these parameters can significantly enhance the tensile strength and impact energy absorption of polypropylene composites [10] [11]. Research on the synergistic effects of reinforcement materials and optimized process parameters has demonstrated that achieving a balance between material composition and process precision is key to developing high-performance composites [26]. Despite these advancements, the manual forming process remains underexplored, particularly concerning its application in polypropylene-based composites for industrial use.

This study aims to address the aforementioned challenges by investigating the effect of pressure and heating time on the mechanical properties of polypropylene-based polymer composites fabricated using the manual forming method. To evaluate the mechanical performance, tensile and impact tests were conducted in accordance with ASTM D638 and ASTM D256 standards. The ASTM D638 standard specifies the procedures for determining the tensile properties of plastics, including tensile strength, modulus, and elongation at break, by subjecting standardized specimens to a uniaxial tensile load. Similarly, the ASTM D256 standard outlines the method for measuring the impact resistance of materials using a pendulum impact tester, providing critical data on the ability of the composite to absorb energy under sudden forces. By adhering to these internationally recognized standards, the study ensures the reliability and comparability of the test results. This research aims to identify the optimal process parameters that yield polymer composites with superior tensile strength and impact resistance. The findings of this study are expected to contribute to the development of cost-efficient and high-performance polymer composites tailored for automotive and energy applications [12] [13].

Furthermore, this research builds upon prior studies that have demonstrated the potential of manual forming as an effective method for polymer composite fabrication [14] [15]. By addressing the gaps in previous research, such as uneven pressure distribution and air void issues, this study introduces a novel approach to optimizing the manual forming process. Additionally, the study explores the potential integration of real-time monitoring systems during the manual forming process to ensure consistent pressure and temperature distribution, a key factor for achieving uniformity in composite properties [27]. The results not only validate the viability of this method for industrial applications but also provide a foundation for future innovations in polymer composite technology.

In conclusion, this research highlights the need for further exploration of manual forming as a fabrication method for polypropylene-based polymer composites. By optimizing process parameters, this study aims to enhance the mechanical performance of the material, thereby meeting the increasing industrial demand for lightweight, strong, and cost-efficient materials [16] [17].

2. RESEARCH METHODOLOGY

2.1. Tools and Materials

The primary materials used in this study included polypropylene (PP) pellets (ExxonMobil Chemicals, 99.5%) and glass fibers (Owens Corning) with an average diameter of 10 µm, which served as reinforcement. To facilitate easy removal of specimens from the mold, a silicone-based mold release agent (Dow Corning, 99%) was applied. The equipment used comprised a manual forming machine capable of applying a maximum pressure of 300 kgf/cm², equipped with a temperature control system, and a stainless-steel mold measuring 200 mm × 200 mm × 2 mm. A hot air oven was utilized to precondition the materials, ensuring moisture removal prior to forming. The prepared specimens were tested for mechanical properties following ASTM D638 for tensile testing and ASTM D256 for impact testing.

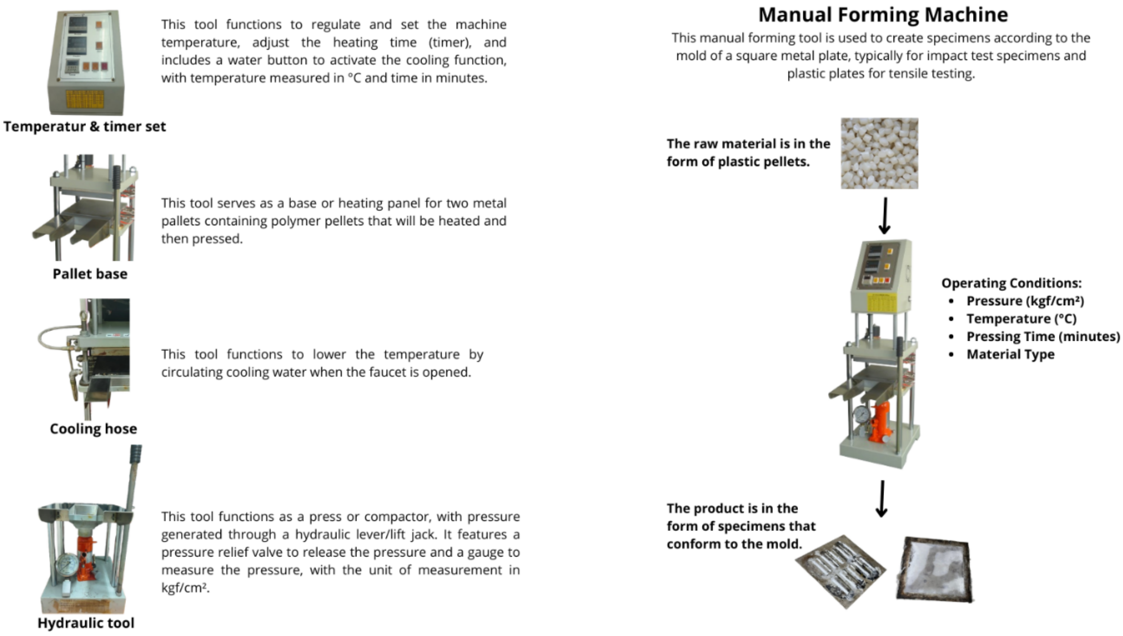

Figure 1. Manual Forming Machine

2.2. Research Methods

The fabrication process began with the mixing of polypropylene and glass fibers in a weight ratio of 90:10 to ensure uniform dispersion. This mixture was preconditioned in a hot air oven at 80°C for two hours to eliminate residual moisture. The material was then placed into a preheated stainless-steel mold, with the mold temperature maintained within the range of 180°C to 200°C. The manual forming process involved gradually applying pressure ranging from 150 kgf/cm² to 200 kgf/cm² over a duration of 10 to 20 minutes. After forming, the mold was cooled to approximately 70°C to ensure dimensional stability before the specimens were removed.

2.3. Test Methods

The mechanical properties of the fabricated specimens were evaluated using tensile and impact tests. Tensile testing was conducted with an Instron 3369 Universal Testing Machine, following ASTM D638 standards, to measure tensile strength, elongation at break, and elastic modulus. Impact testing was carried out using a Tinius Olsen Izod Impact Tester, in accordance with ASTM D256 standards, to assess the energy absorption capacity of the specimens upon fracture. The data obtained from these tests were analyzed to determine the optimal process parameters that enhanced the mechanical performance of the composites. The results were further compared against industry standards to validate the suitability of the fabricated materials for automotive and energy applications.

3. RESULT AND DISCUSSION

3.1. Tensile Test Results

The tensile test was conducted to evaluate the mechanical performance of the polymer composites fabricated using the manual forming method. This test focused on three primary parameters: tensile strength, elongation at break, and elastic modulus. These parameters are critical in determining the suitability of the material for industrial applications, particularly in the automotive and energy sectors, where mechanical reliability is essential. The results of the tensile tests are presented in **Table 1**.

Table 1. Tensile Test Results for Polymer Composite Specimens

No	Tensile Strength (MPa)	Elongation at Break (%)	Elastic Modulus (GPa)
1	35.2	12.1	1.45
2	34.8	12.3	1.43
3	36.0	11.9	1.48
Average	35.3	12.1	1.45

The average tensile strength achieved was 35.3 MPa, which is competitive compared to the tensile strength of pure polypropylene (31–41 MPa) as specified by ASTM D638 standards. The elongation at break averaged 12.1%, exceeding the typical range of 10–11% for unreinforced polypropylene. The elastic modulus averaged 1.45 GPa, indicating sufficient material rigidity for structural applications.

The observed tensile strength can be attributed to the reinforcing effect of the glass fibers, which enhance the load-bearing capability of the composite matrix. The glass fibers serve as stress transfer points, allowing the composite to resist higher tensile forces before failure. Friedrich and Almajid [18] reported similar findings, highlighting the critical role of fiber reinforcement in improving tensile strength in polymer composites.

The slight variation in tensile strength among the specimens is likely due to non-uniform pressure distribution during the manual forming process, leading to inconsistent fiber dispersion and microstructural differences. Hull and Clyne [19] identified that pressure inconsistencies in composite fabrication can result in localized weak points, thereby affecting overall mechanical performance.

The average elongation at break of 12.1% suggests an improvement in the ductility of the composite compared to pure polypropylene. This can be attributed to the controlled temperature and pressure conditions during the manual forming process, which enhance matrix-fiber bonding. Mallick [21] emphasized that maintaining optimal processing parameters is crucial to achieving balanced strength and ductility in composites.

The elastic modulus of 1.45 GPa aligns with previous findings by Yang et al. [22], who reported a similar range for glass fiber-reinforced polypropylene composites. The rigidity provided by the fibers contributes to the composite's suitability for structural applications, such as automotive interior components and lightweight panels.

In comparison to other fabrication methods, such as injection molding or compression molding, the manual forming method achieves competitive tensile properties with simpler equipment and lower costs. Bigg [20] noted that compression molding of similar composites yielded tensile strengths between 30–42 MPa, which closely matches the results of this study. However, manual forming offers greater flexibility for small-scale or custom applications, where large-scale industrial processes may not be feasible.

Overall, the tensile test results confirm that the manual forming process can produce polymer composites with mechanical properties suitable for industrial use. The findings underline the importance of optimizing forming parameters to achieve consistent material performance. Future improvements in mold design and pressure application could further enhance the mechanical properties, ensuring the composites meet higher industrial standards.

3.2. Impact Test Results

The impact test was conducted to evaluate the energy absorption capacity of the polymer composite specimens when subjected to sudden impact forces. This property is critical for applications in the automotive and energy sectors, where materials must withstand dynamic loads or shock without catastrophic failure. The results of the impact test are presented in **Table 2**.

Table 2. Impact Test Results for Polymer Composite Specimens

No	Impact Energy Absorption (Joules)
1	0.45
2	0.47
3	0.44
Average	0.45

The polymer composites demonstrated an average energy absorption of 0.45 Joules, with minimal variation among the specimens. These results are consistent with industry expectations for fiber-reinforced polypropylene composites used in moderate-duty applications, such as interior automotive components or protective panels.

The observed impact resistance is primarily attributed to the energy dissipation mechanisms within the composite matrix. The glass fibers effectively distribute impact energy across the polymer matrix, delaying fracture propagation. This phenomenon aligns with the findings of Friedrich and Almajid [18], who highlighted the role of fiber reinforcement in enhancing impact resistance by improving energy distribution.

Despite the satisfactory results, the presence of air voids in the composite structure, likely caused by uneven pressure during the manual forming process, slightly reduced the material's impact performance. Mallick [21] observed similar trends in fiber-reinforced composites, where porosity introduced during fabrication negatively impacted impact resistance by creating stress concentration points that facilitated crack initiation.

The impact energy absorption achieved in this study falls within the acceptable range for polypropylene-based composites reinforced with 10% glass fibers, as reported by Yang et al. [22]. Their research demonstrated that such composites typically exhibit impact energies between 0.4–0.6 Joules, corroborating the findings of this study.

Compared to composites fabricated using compression molding or injection molding, the impact resistance of specimens produced via manual forming is slightly lower. However, this discrepancy can be attributed to the manual forming process's challenges, such as pressure inconsistencies and the absence of automated temperature regulation. Bigg [20] reported that compression-molded composites generally exhibit higher impact resistance due to better process control, but manual forming remains advantageous for small-scale production due to its simplicity and cost-effectiveness. The results indicate that the polymer composites fabricated using manual forming are suitable for applications where moderate impact resistance is required. These include non-load-bearing automotive components and protective panels, where energy absorption is crucial to enhance safety without significantly increasing weight.

To further improve the impact resistance of the composites, future research should focus on minimizing air voids through optimized pressure application and mold design. Additionally, surface treatments for glass fibers could be explored to enhance matrix-fiber bonding, further improving the composite's ability to dissipate impact energy. Such advancements could enable the manual forming process to produce composites with performance levels comparable to those fabricated using more advanced techniques. The impact test results affirm that the manual forming process can produce polymer composites with adequate energy absorption capacity for targeted industrial applications. With further optimization, the process could achieve even greater competitiveness in high-performance composite fabrication.

3.3. Density Test Results

The density test was conducted to evaluate the structural integrity and material compactness of the polymer composites fabricated using the manual forming method. Density is a critical parameter in assessing the quality of composites, as it directly relates to mechanical properties such as strength, stiffness, and impact resistance. The results of the density test are presented in **Figure 2**.

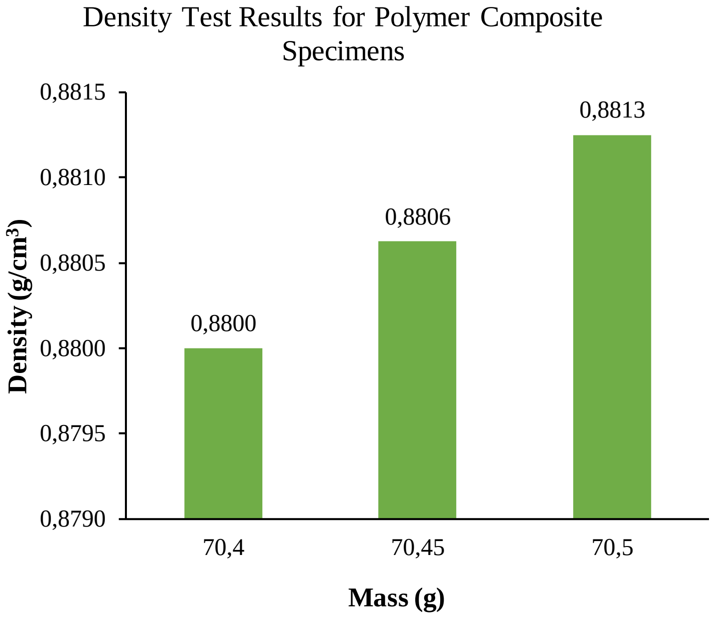

Figure 2. Density Test Results for Polymer Composite Specimens

The average density of the polymer composite specimens was 0.880 g/cm³, which is slightly lower than the theoretical density of pure polypropylene, typically 0.903 g/cm³. This deviation can be attributed to the presence of air voids within the composite structure, which reduce overall compactness.

The reduction in density compared to pure polypropylene is primarily caused by the non-uniform distribution of pressure during the manual forming process. Air voids trapped within the composite act as defects, lowering the material's effective density. Hull and Clyne [19] observed that porosity significantly influences the density and mechanical properties of fiber-reinforced composites, with air voids contributing to lower structural integrity.

Additionally, the integration of glass fibers as reinforcement introduces heterogeneity in the material matrix. While glass fibers enhance mechanical properties, they may also lead to localized density variations if not evenly distributed. Friedrich and Almajid [18] emphasized that achieving homogeneity in fiber dispersion is critical for ensuring consistent density and mechanical performance. The average density achieved in this study aligns with findings reported by Bigg [20], who noted that fiber-reinforced polypropylene composites typically exhibit densities slightly lower than pure polypropylene due to the addition of fibers and the potential for air voids. Yang et al. [22] similarly reported a density range of 0.875–0.895 g/cm³ for polypropylene composites reinforced with 10% glass fibers, confirming the validity of the results obtained in this study.

The slight reduction in density observed in the specimens does not significantly affect their suitability for industrial applications. In fact, the lower density enhances the composite's lightweight properties, making it advantageous for applications requiring a balance between strength and weight, such as automotive interior components and lightweight panels. However, achieving higher density through improved process control could further enhance mechanical properties, particularly tensile strength and impact resistance. This would allow the material to meet stricter industrial standards for load-bearing applications.

To minimize air voids and increase density, future studies should focus on optimizing the pressure application during the manual forming process. Mold designs that ensure even pressure distribution and advanced degassing techniques could be implemented to improve compactness. Furthermore, exploring alternative fiber reinforcement methods, such as treated glass fibers or hybrid composites, may lead to more consistent density and enhanced performance.

In summary, the density test results confirm that the manual forming process produces polymer composites with acceptable density for moderate-duty industrial applications. With further process optimization, the density and related mechanical properties of the composites can be improved, expanding their applicability to more demanding use cases.

4. CONCLUSION

This research demonstrates the potential of the manual forming method for fabricating polypropylene-based polymer composites with mechanical properties suitable for moderate-duty industrial applications, achieving enhanced tensile strength and impact energy absorption through optimal pressure and heating time, with values close to industry standards. Reinforcement with glass fibers improved load transfer and impact energy dissipation, yielding superior performance compared to pure polypropylene, though air voids and uneven pressure distribution slightly reduced density, indicating areas for optimization. Manual forming proved to be a cost-effective and versatile method for producing lightweight, high-strength composites for applications like automotive interiors and protective panels, offering a simpler alternative to techniques like injection or compression molding for small-scale or customized production. This study advances the understanding of process-property relationships in composites and suggests future research into advanced mold designs, enhanced pressure systems, fiber surface treatments, and hybrid reinforcement materials to minimize defects, improve bonding, and expand applications to demanding structural uses. With further optimization, the manual forming method can balance simplicity, cost-efficiency, and performance to meet industrial demands for lightweight, durable, and high-performance materials across sectors.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to Politeknik STMI Jakarta for providing the funding and laboratory facilities that made this research possible. Special thanks are extended to the academic and technical staff of the Chemical Engineering Polymer Study Program for their invaluable guidance and support throughout the research process. Appreciation is also given to colleagues and research team members who contributed to the successful completion of this study through their collaborative efforts and insightful discussions. This research would not have been possible without the collective contributions and support from all involved parties.

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