ADMI IJST International Journal Science and Technology

OPEN ACCESS

IJST Vol 4 No. 3 | November 2025 | ISSN: 2828-7223 (print), ISSN: 2828-7045 (online), Page 118-131

The Effect of Temperature Variations on Sheet Press Machines on the Hardness and Toughness of PP (Polypropylene) and HDPE (High Density Polyethylene) Materials

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Article History
Received : November 24, 2025
Accepted : December 30, 2025
Published : December 31, 2025
Available Online :
December 31, 2025

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Cite This Article:
Slat, W. S., Runtuwene, S. J., Djefry Hosang, Agnes Wakkary, & Yenni Sigalingging. (2025). 082189496975 The Effect of Temperature Variations on Sheet Press Machines on the Hardness and Toughness of PP (Polypropylene) and HDPE (High Density Polyethylene) Materials. International Journal Science and Technology, 4(3), 118–131.

DOI:
https://doi.org/10.56127/ijst.v4i3.2376

Abstract: Global plastic waste continues to grow, making recycling essential for supporting a circular economy. Process parameters, especially heating temperature during sheet pressing, strongly influence the quality of recycled products. **Objective**: This study investigates how heating temperature affects the impact toughness and hardness of recycled Polypropylene (PP) and High-Density Polyethylene (HDPE) produced using a sheet press machine, and identifies the optimal processing temperature for improved mechanical performance. **Methodology**: This research used a quantitative experimental approach. Recycled PP and HDPE were shredded, then heated at 160°C, 170°C, 180°C, and 190°C for 120 minutes, and molded into sheet specimens using a sheet press machine. Mechanical properties were evaluated using Charpy impact testing in accordance with ASTM D6110 and Rockwell hardness testing (M scale) following ASTM D785. Results were compared across temperature variations to determine performance trends. **Findings**: Both materials showed improved impact toughness and hardness as temperature increased up to 180°C, indicating better melt uniformity, fewer voids, and stronger molecular bonding. For HDPE, impact toughness increased from 2.3 J at 160°C to 8.675 J at 170°C, reaching its peak at 180°C, then decreased at 190°C, suggesting early thermal degradation. For PP, the highest average hardness was 15.52 HRM at 180°C, followed by a decline at 190°C, consistent with structural softening and reduced crystallinity. **Implications**: The results suggest that controlling heating temperature particularly around 180°C can enhance the manufacturing efficiency and product quality of recycled plastic sheets, supporting more reliable and sustainable material utilization. **Originality**: This study provides practical evidence on the temperature–property relationship for sheet-pressed recycled PP and HDPE under controlled heating conditions and confirms 180°C as an optimal temperature before thermal damage reduces structural integrity.

Keywords: Hardness, Toughness, Polypropylene Materials, High Density Polyethylene, Sheet Press Machines, Temperature Variations

INTRODUCTION

Plastic waste has emerged as one of the most urgent environmental challenges of our time. Global production and consumption of plastics continue to rise: for example, production hit approximately 400 million tones in 2022, yet only about 9.5 % of that came from recycled materials (Houssini et al., 2025). Between 2000 and 2019, plastic production more than doubled, increasing from 234 million tonnes to around 460 million tonnes, and plastic waste also more than doubled during the same period. Without significant intervention, annual plastic waste could approach 1 billion tonnes by 2060 (*Global Plastics Outlook*, 2022). The most common types of post-consumer plastic waste worldwide include Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), and Polypropylene (PP) (Zheng et al., 2023). Plastic recycling effectively reduces plastic waste while promoting the circular economy, where materials are reused sustainably (J & V, 2023).

In recycling and reprocessing, the parameters of the process are crucial for ensuring product quality (Guan et al., 2020). The sheet press machine, which uses heat and pressure to create recycled plastic sheets, relies heavily on three main factors: heating temperature, heating duration, and material thickness (Lyutyy et al., 2024). Variations in these parameters directly affect the polymer's mechanical properties, including hardness, toughness, and elasticity (Prociak et al., 2021).

Several previous studies have examined the influence of thermal parameters on the mechanical characteristics of recycled plastics. Research by Jamirul Hakim and Johanes Wawan Joharwan (2020) investigated the effect of heating temperature on PP within the range of 220–260°C. The study revealed that the optimum mechanical performance specifically, hardness and compressive strength was achieved at 240°C, whereas temperatures exceeding 260°C led to over-degradation and decreased strength (Hakim et al., 2020). Similarly, Zainuddin (2022) analyzed the effect of heating duration at a constant temperature of 250°C with variations of 60, 80, and 100 seconds. The highest hardness value (21.3 HV) was obtained at 60 seconds, but declined at longer durations due to uneven melting and molecular degradation (Zainudin & Suwantri, 2022). A more recent study by Sitanggang et al. (2024) employed a factorial design (RAL) approach to examine the interaction between heating temperature and duration. The results showed that both parameters significantly affect the surface morphology and mechanical behavior, including hardness (Sitanggang et al., 2024).

The findings highlight that temperature and heating time are crucial for the mechanical performance of recycled polymer sheets, with optimal values varying by plastic type and machine configuration. Further research is needed to explore how these factors affect the toughness and hardness of PP and HDPE during sheet press processing. This research aims to enhance production efficiency and product quality in the recycled plastic industry while promoting sustainable waste management.

RESEARCH METHOD

This study utilized an experimental research method with a quantitative approach. The experimental procedure aimed to investigate how variations in heating temperature and duration affect the mechanical properties of plastic materials, specifically toughness and hardness, during the sheet press process. A quantitative approach was employed to gather measurable numerical data from laboratory tests, which were subsequently analyzed statistically to objectively identify relationships and trends between the variables (Sheard, 2018).

The primary quantitative data were collected from the results of hardness and impact toughness tests conducted on plastic samples processed using a sheet press machine. Data collection involved direct observation and documentation during the heating and molding processes. The research utilized essential tools to ensure precise processing and characterization of recycled plastic materials. Key equipment included a caliper for dimensional measurements, a stopwatch for timing, and machines for grinding, shredding, pressing, and testing hardness and impact. These tools were selected to enable meticulous fabrication, preparation, and mechanical testing of samples under controlled laboratory conditions, reflecting our commitment to advancing recycling technology (Keskisaari et al., 2019).

The study examined two widely recycled thermoplastics, Polypropylene (PP) and High-Density Polyethylene (HDPE). Each material has a distinct melting temperature HDPE between 125°C and 135°C, and PP around 160°C to 165°C (Babaei et al., 2024). These variations in melting thresholds are crucial considerations when setting temperature parameters during sheet press processing to prevent incomplete melting or excessive thermal degradation (Zhang et al., 2024).

One significant advantage of the sheet press method is its ability to produce composite sheets with improved mechanical strength and durability (Arendra & Akhmad, 2017). The sheet press machine operates by applying both heat and pressure to recycled plastic particles, melting them into a homogeneous form before pressing into thin sheets (Woods et al., 2024). These sheets can later be utilized for structural or functional components in applications such as packaging, furniture, or automotive interior parts. Temperature and heating duration are among the key processing factors that strongly influence product quality; inappropriate settings may result in defects, reduced strength, and material degradation.

Research Design

This research begins by identifying a key issue related to the varying mechanical properties, specifically toughness and hardness, of recycled thermoplastics such as Polypropylene (PP) and High-Density Polyethylene (HDPE) when processed using a sheet press machine. These variations are often influenced by differences in processing temperature and heating duration, which in turn affect the thermal degradation and molecular alignment of the recycled polymers. To address this issue, we conducted a comprehensive review of previous studies and relevant international standards, including ASTM D785 and ASTM D6110, to gain a better understanding of the factors influencing the thermal and mechanical behavior of PP and HDPE during reprocessing.

The experimental design was based on insights from existing literature, focusing on heating temperature as the independent variable, while maintaining a constant heating duration of 120 minutes. The dependent variables in this study were impact toughness and hardness. The materials used comprised recycled polypropylene (PP) and high-density polyethylene (HDPE) waste, which were collected, cleaned, and crushed into smaller, uniform particles using a plastic shredding machine. These prepared particles were then subjected to heating and compression in a sheet press machine under controlled temperature and pressure conditions, resulting in the production of uniform plastic sheets.

After the sheets were formed, they were cut into modified specimens for mechanical testing, measuring 55 mm x 10 mm x 10 mm, in accordance with established testing protocols. The same specimens were utilized for both impact and hardness tests. For consistency in material properties, samples used for hardness testing were taken directly from the impact test specimens. Mechanical testing was conducted using two primary methods: the Charpy impact test, following ASTM D6110 standards, to measure the material's resistance to sudden loads, and the Rockwell Hardness test (M scale), in accordance with ASTM D785, to assess surface hardness.

The experimental data obtained from both tests were tabulated and averaged to assess the influence of temperature and heating time variations on the mechanical performance of the recycled materials. The results were analyzed both graphically and statistically to identify trends and determine the correlation between processing parameters and resulting mechanical properties. Finally, the findings were synthesized to draw conclusions regarding the optimal processing conditions that enhance the toughness and hardness of recycled PP and HDPE. The study concludes with recommendations for further research focused on refining process parameters such as pressure, cooling rate, or additive use to improve the performance and durability of recycled thermoplastic materials. The more concise research design can be seen in the research flowchart shown in Figure 1.

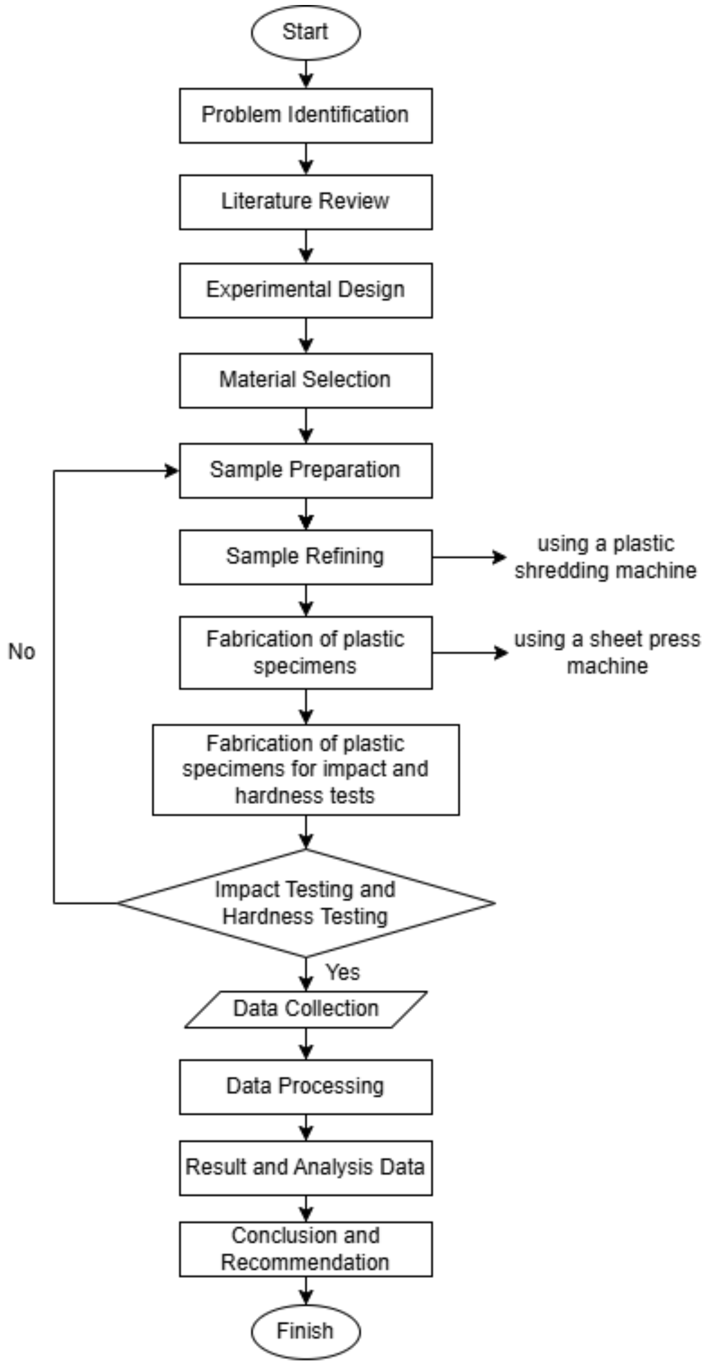

Figure 1. Research Flowchart

RESULT AND DISCUSSION

Impact Test

The testing was conducted on four HDPE plastic specimens, each subjected to four different heating temperatures: 160°C, 170°C, 180°C, and 190°C, with a duration of 120 minutes at each temperature, as illustrated in Figure 2. At 160°C, the impact values ranged from 1.5 to 3.1 J, yielding an average impact toughness of 2.3 J. This indicates that HDPE exhibited low impact toughness at this temperature.

Table 1. Impact Value of HDPE

	Impact Value (Joule)			
HDPE Specimens	**160°C**	**170°C**	**180°C**	**190°C**
HDPE 1	2.1	7.5	10.2	6.5
HDPE 2	1.5	10	11	8.2
HDPE 3	3.1	9.8	9	6.7
HDPE 4	2.5	7.4	10	8.8

The low impact values can be attributed to the incomplete melting of the HDPE, resulting in defects such as uneven fusion. Such defects created weak points in the material, making it more susceptible to fracture or cracking under impact. As shown in Table 1, although the variation among the specimens was not highly significant, one specimen recorded the lowest value of 1.5 J, while another achieved the highest value of 3.1 J. This variation suggests slight differences in structural integrity or material response to the applied temperature.

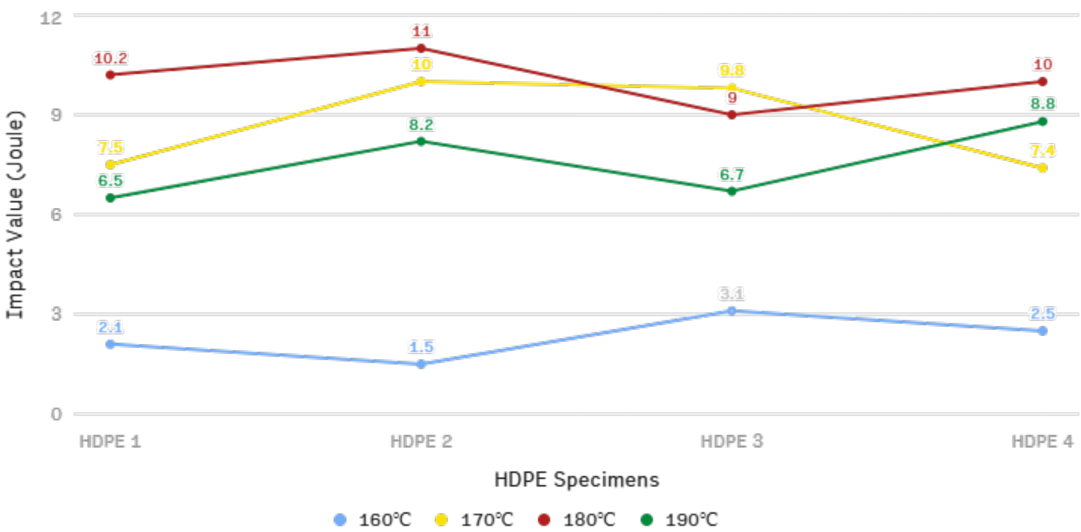

Figure 2. Impact Value of HDPE by Temperature

A significant increase in impact value was observed when HDPE was heated to 170°C. This temperature produced a high impact value, resulting in an average value of 8.675 J, despite noticeable variations among the four samples. The improvement can be attributed to the complete melting of the HDPE, which led to a more homogeneous structure with fewer voids or air bubbles. However, the impact values at this temperature exhibited greater inconsistency between samples. This inconsistency could be due to the presence of foreign contaminants, such as fragments of other plastic types or impurities. Additionally, since this temperature is close to the optimal threshold, some specimens may have begun to experience thermal degradation.

The impact value of HDPE plastic increases steadily with rising temperatures, peaking at 180 °C. Beyond this point, specifically at 190 °C, the impact value begins to decline. This trend shows that HDPE performs optimally in resisting impact loading at 180 °C. At this temperature, the polymer chains become sufficiently mobile to absorb and dissipate impact energy without undergoing excessive softening or structural weakening, which leads to enhanced toughness.

This behavior aligns with existing literature on the thermal processing of HDPE. As the processing temperature rises from a lower range toward an optimal window typically reported to be around 170 to 185°C for many hot-press and molding operations the polymer melt becomes more homogeneous, leading to improved flow and a reduction in entrapped air and voids (Akhmad et al., 2018). These changes generally enhance impact toughness, as demonstrated in this studies that show improved consolidation and mechanical performance within the 170 to 185°C range.

At 190 °C, thermal degradation becomes more pronounced. Previous studies have reported similar findings, indicating that overheating during processing can weaken intermolecular bonding, create micro-cracks, and destabilize crystalline structures, ultimately reducing impact value. Additionally, other research highlights that prolonged exposure to temperatures near the degradation threshold accelerates chain scission and oxidation, which contributes to brittleness and decreased mechanical performance. This alignment with existing literature emphasizes the importance of temperature control during HDPE processing to maintain mechanical integrity and prevent property loss due to degradation.

Similar to the HDPE specimen testing, the polypropylene (PP) specimens were tested under four different thermal conditions, specifically at 160°C, 170°C, 180°C, and 190°C for 120 minutes, as shown in Figure 3. Based on the obtained data, a trend of increasing impact value is observed with rising temperature, reaching a maximum impact value at 180°C. At this temperature, one specimen exhibited a significantly higher impact value compared to the other three specimens.

Table 2. Impact Value of PP

Impact Value (Joule)				
PP Specimens	**160°C**	**170°C**	**180°C**	**190°C**
PP 1	1.9	3.1	4.1	2.5
PP 2	2.1	3	5	3.9
PP 3	2.7	3.5	7.3	4.8
PP 4	4	4.5	6.6	6

This notable deviation in a single specimen may be attributed to several factors, including non-uniform melting, localized reduction of voids, or better compaction during molding, which can lead to increased toughness. Additionally, the presence of inconsistencies in recycled PP feedstock such as differences in polymer grade, varying molecular weight distribution, residual additives, or contamination with compatible copolymers can cause mechanical property variations between specimens. Such heterogeneity is common in recycled polypropylene materials and has been reported in prior studies to produce outlier mechanical performance when heating enhances bonding or crystallinity in only certain samples.

Based on Table 2, the lowest impact test value occurs at the heating condition of 160°C. This is caused by incomplete melting, which results in weak bonding between polymer chains and therefore produces a significantly lower impact value compared to the specimens heated at higher temperatures. The impact value at 170°C is higher than at 160°C, and the values at this temperature tend to be more stable across the specimens. The increase and stability of impact value at 170°C can be attributed to enhanced softening and partial homogenization of the polypropylene structure. This improvement reduces internal defects like voids and microcracks. At this temperature, the polymer fuses more effectively without excessive degradation, allowing for better energy absorption during impact. Additionally, the formation of more uniform crystallinity and decreased residual stress contributes to the consistent mechanical behavior observed in the specimens.

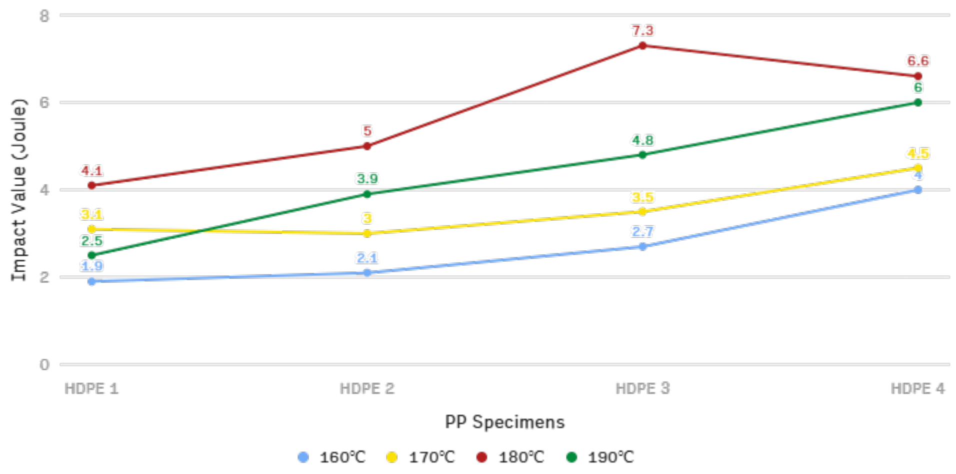

Figure 3. Impact Value of PP

Hardness Test

Hardness testing was carried out on four HDPE specimens. The hardness values were expressed in HRM (Rockwell Hardness M-scale), where the results varied among samples but remained relatively stable. Based on the graph shown in Figure 4, the hardness test results for the four HDPE specimens exhibit the same pattern as the previous impact test, in which the hardness values increased with rising temperature but began to decline when reaching the heating temperature of 190°C.

Table 3. Hardness Value of HDPE

Hardness Value (HRM)				
HDPE Specimens	**160°C**	**170°C**	**180°C**	**190°C**
HDPE 1	12.4	14.1	17.08	15.81
HDPE 2	11.24	14.22	16.3	14.84
HDPE 3	9.12	10.3	15.6	14
HDPE 4	12.1	16.04	17.38	14.82
Average	**11.215**	**13.665**	**16.59**	**14.8675**

As shown in Table 3, the hardness value increased significantly from 170 °C to 180 °C, rising from 13.665 HRM to 16.59 HRM. The notable increase in hardness from 13.665 HRM at 170 °C to 16.59 HRM at 180 °C can be explained by enhanced crystallinity and lamellar reorganization caused by annealing. According to Suwanprateeb et al., raising the annealing temperature improves crystallinity, raises the melting point, and increases the tensile modulus of HDPE (Suwanprateeb, 2004). Moreover, in a comparative study on polyethylene, Song and colleagues reported that annealing reorganizes and thickens lamellae, leading to a more tightly packed crystalline structure and greater resistance to deformation (Hedesiu et al., 2007). This structural densification reduces amorphous regions and residual stresses, thereby significantly increasing hardness under indentation.

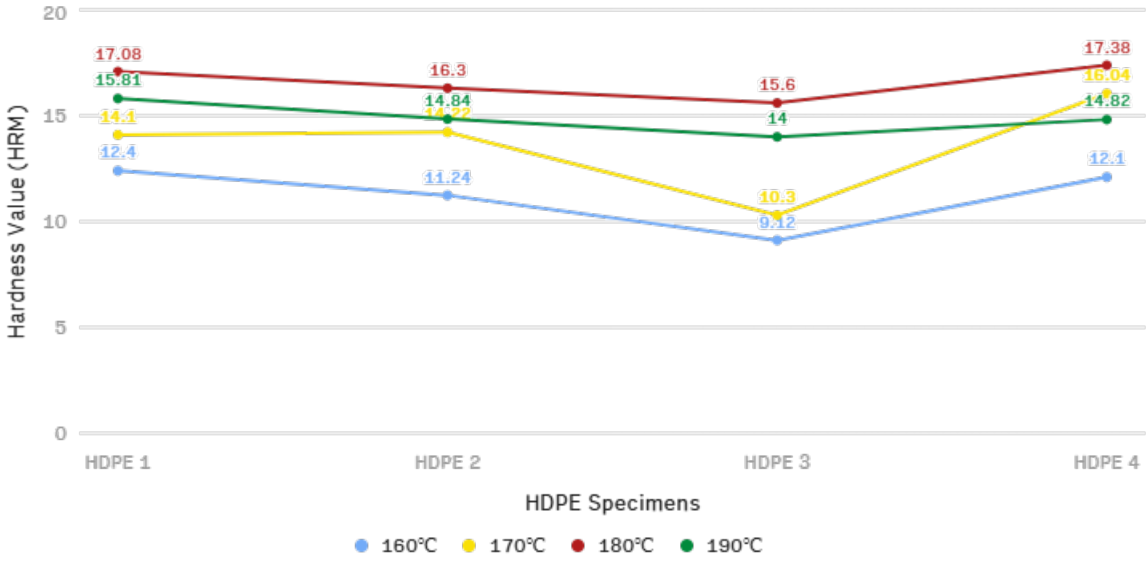

Figure 4. Hardness Value of HDPE

As shown in Table 4, the increase in hardness from 160 °C to 170 °C indicates how the material responds to initial heating. The average hardness rises from 9.37 HRM to 12.225 HRM during this temperature range. This increase suggests that, as the temperature rises, the polypropylene structure begins to show greater molecular orientation and a reduction in amorphous regions. Consequently, the material becomes stiffer and exhibits a higher resistance to indentation. Although there are still variations among the specimens at this temperature, all samples demonstrate a consistent upward trend. This reinforces the idea that the heating process provides an initial homogenizing effect on the internal structure of the material.

Table 4. Hardness Value of PP

Hardness Value (HRM)				
PP Specimens	**160°C**	**170°C**	**180°C**	**190°C**
PP 1	9.66	11.9	15.24	13.12
PP 2	8.57	12.16	15.63	13.54
PP 3	9.04	11.4	14.64	12.86
PP 4	10.21	13.44	16.58	12.24
Average	**9.37**	**12.225**	**15.5225**	**12.94**

Based on the graph shown in Figure 5, at 180 °C, the hardness value reaches its peak with an average of 15.5225 HRM, representing the highest point in the entire testing sequence. Under these conditions, PP is within an optimal thermal processing zone, where polymer chain mobility promotes higher crystallinity formation and refinement of lamellar structures. The reduction of microvoids, increased structural density, and lower residual stress make the material more resistant to deformation under indentation load. The consistency of values among specimens at this temperature demonstrates mechanical stability, and therefore can be interpreted as the most effective heating temperature for increasing hardness.

However, when the temperature is increased to 190 °C, the hardness value decreases to an average of 12.94 HRM, although it remains higher than at 160 °C. This decrease indicates the occurrence of over-softening or the onset of thermal degradation, where portions of the polymer chains begin to lose integrity, resulting in reduced resistance to pressure. In addition, at this temperature the crystalline structure may begin to remelt, increasing the proportion of amorphous phases that tend to be softer. Thus, the data confirms that after surpassing the optimum point at 180 °C, the mechanical properties of the material begin to decline, meaning that higher temperatures no longer provide benefits for increasing hardness.

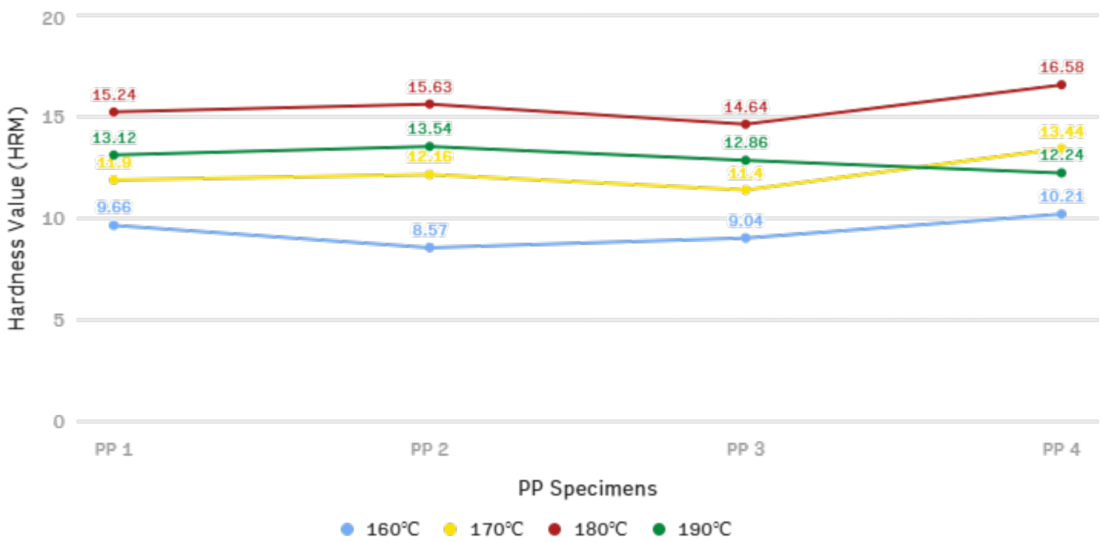

Figure 5. Hardness Value of PP by Temperature

CONCLUSION

The experimental results demonstrate that heating temperature plays a critical role in determining the mechanical performance of both HDPE and PP, as reflected through impact value and hardness measurements. At 160°C, both materials exhibit the lowest impact values due to incomplete melting, weak intermolecular bonding, and the presence of voids and fusion defects, which reduce their ability to withstand sudden loading. As the temperature increases to 170°C, a substantial improvement in impact resistance is observed, attributed to better homogenization, reduced internal defects, and enhanced molecular mobility, although some variation among samples indicates minor inconsistencies in material purity and melt behavior.

The results show that the optimal mechanical performance for both HDPE and PP occurs at 180°C, where impact value reaches its highest level and hardness values peak significantly. At this temperature, increased chain mobility enables improved crystallinity, lamellar thickening, structural densification, and reduced residual stress, resulting in greater toughness and resistance to deformation. These findings align with existing literature, which identifies the 170–185°C range as the ideal thermal processing window for maximizing mechanical integrity in thermoplastic polymers.

When the temperature is further increased to 190°C, both impact value and hardness decline, indicating the onset of thermal degradation, chain scission, micro-crack formation, void generation, and partial melting of crystalline regions. Although the mechanical values at 190°C remain higher than those observed at 160°C, the downward trend confirms that overheating reduces mechanical stability and compromises structural performance. Overall, the study concludes that controlled heating is essential, and 180°C represents the most effective processing temperature for improving toughness and hardness in recycled HDPE and PP while avoiding degradation-related property loss.

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