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Research Article
HDPE Hybrid Composites

Microstructural Evolution and its Influence on Thermal and Mechanical Performance of HDPE Hybrid Composites

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With the rising need for sustainable, lightweight, and economically viable ceiling materials, more attention is being paid to hybrid composites made from polymers and wastes derived from agriculture and industries. Nevertheless, typical ceiling boards are often limited by their poor thermal stability, insufficient mechanical strength, sensitivity to moisture, and ecological problems related to the disposal of the waste. Specifically, the disposal of sawdust dust and crushed glass fragments is an alarming issue. This research explores the microstructure development and its effect on the thermal and mechanical properties of HDPE-based hybrid composites used for making ceiling boards. The aims of this study were to examine the interface interaction, thermal conductivity, and strength of HDPE reinforced with sawdust and crushed glass fragments. Fabrication process of the composites included melt blending and compression moulding method with different reinforcement blends. Characterization of the microstructure was done with the help of scanning electron microscope (SEM). Thermal and mechanical properties were determined by differential scanning calorimeter (DSC), thermal conductivity test, tensile strength test, flexural strength test, impact test, hardness test, and density test. Improved dispersion of the fillers, better interfacial bonding, and minimized voids in the composite structure were found to be achieved in the optimized composite structure. The study findings indicate that the synergistic blending of sawdust and glass particles significantly improved the microstructure, thermal properties, and mechanical behaviour of HDPE composite for ceiling board applications. It is suggested that future studies should focus on the durability and fire resistance of the composite material under actual service conditions. The research makes a valuable contribution to the body of knowledge through the development of sustainable processes for converting waste to functional composite ceiling boards.

Keywords: high-density polyethylene (HDPE), hybrid composites, microstructural evolution, thermal performance, ceiling board application

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1. Introduction

The increasing trend of industrialization and urbanization has escalated the global need for sustainable and high-performing construction materials. Traditional ceiling materials like asbestos sheets, gypsum boards, and plywood panels are being questioned due to their expensive manufacturing process, hazardous impacts on the environment, poor resistance to deterioration, and weak thermal performance. Thus, modern research has focused on developing polymer hybrid composites, incorporating agriculture and industrial by-products as a possible replacement. Within thermoplastics, High-Density Polyethylene (HDPE) stands out owing to its superior chemical resistance, light weight, recyclability, and processing capability. At the same time, the incorporation of sawdust and powdered glass has provided a sustainable means to reduce waste generation and increase the effectiveness of the composites (Kuforiji et.al. 2023).

Some recent developments in the field of hybrid composite materials indicate that the addition of fillers, both lignocellulose and inorganic, to HDPE polymer enhances its mechanical, thermal, and physical properties. Sawdust particles offer low density and good adhesion properties, while glass cullet particles impart hardening effects, better heat resistance, and sturdiness. However, the efficiency of such composites is largely influenced by their microstructure, which comprises filler dispersion, particle agglomeration, adhesion between particles, and the formation of voids. Lack of proper interfacial compatibility may lead to concentration of stresses, poor load transferring capacity, and poor thermal conduction (Tanhim, et al. 2025).

Therefore, understanding the relationship between microstructural characteristics and composite performance remains a significant scientific challenge (Ezeh et al. 2024). Several studies have looked at HDPE-based composites reinforced with natural or inorganic fillers. Kuforiji et al. (2023) found improved tensile and flexural properties in sawdust-reinforced HDPE composites due to better particle dispersion and matrix adhesion. Similarly, Wimalasuriya et al. (2024) showed that recycled glass-filled HDPE composites had better thermal and structural properties, making them suitable for engineering applications. Kuzmin et al. (2024) also noted improved thermal and water resistance in HDPE composites reinforced with agricultural waste fillers. Despite these advancements, not much empirical research has focused on the combined effect of sawdust and glass cullet reinforcement on the microstructural development and multifunctional performance of HDPE hybrid composites designed for ceiling board applications. Existing literature has mainly highlighted either mechanical characterization or thermal behaviour separately, lacking sufficient integration of microstructural analysis as the main factor for improving properties. This gap calls for a thorough investigation that connects morphology with thermal and mechanical performance (Yousif et al. 2023).

This work focuses on the development and improvement of the microstructural characteristic and thermal and mechanical property of HDPE hybrid composites reinforced with sawdust and ground glass cullet particles. Hypothesis of the study is that proper hybrid reinforcement would help in better filler distribution and better bonding between the filler particles and the matrix and hence enhanced thermal property, tensile strength, flexural strength, hardness, and shape stability. To accomplish this work, samples of composites were prepared by using melt blending and compression moulding technique in different filler contents. The samples of composites were studied for microstructural characteristics using scanning electron microscope (SEM) and thermal and mechanical property by thermal analysis techniques such as DSC, thermal conductivity analysis, tensile test, flexural test, impact test, hardness analysis, and density calculation (Abubakar, & Ali, 2024).

The importance of this research is it adds one step towards producing a recyclable, light-weight, and thermally reliable composite ceiling material from waste resource. Understanding the relationship between microstructure changes and performance helps in a scientific manner for the optimization of the HDPE hybrid composite in building application. It adds knowledge towards environmentally friendly materials engineering technology for transformation from agricultural and industrial waste into an economic value added, multifunctional composite material of high reliability structurally and thermally.

2. Methodology

For the synthesis of HDPE composites, melt blending and compression moulding were employed in order to investigate how structural changes affect their mechanical and thermal properties. High-density polyethylene (HDPE) pellets acted as the base polymer material, whereas chosen reinforcement particles underwent drying at 80°C for 24 hours prior to mixing in order to ensure there was no water content left behind.

A series of hybrid composites was fabricated by altering the amount of reinforcements but keeping the same level of HDPE matrix composition. The materials were physically mixed and melt blended via the twin-screw extrusion process conducted at temperatures ranging from 170 to 190 °C and at a screw rotation speed of 60 rpm. This technique allows for the effective dispersal of fillers in the polymer matrix. The extruded samples were then compacted into testing samples through a compression moulding method. This procedure is commonly employed for the fabrication of HDPE hybrid composites due to its efficiency in producing uniformly dispersed filler systems (Dias et al. 2025).

The microstructure of the synthesized composites was characterized by scanning electron microscopy (SEM), which enabled understanding the distribution of fillers, interfacial adhesion, voids, and fractography of the synthesized composite. Before performing the SEM study, fractured samples were subjected to coating with gold to improve the electrical conductivity of the samples. FTIR studies were performed to examine any chemical interaction and bonding mechanism between HDPE matrix and reinforcing phases. The crystallinity and structure of the composites were examined using X-ray diffraction (XRD) analysis. DSC study was used to study thermal degradation, crystallization, and melting behaviour of the synthesized composite.

Characterization was done in accordance with the ASTM standards. The tensile strength was obtained through the use of a universal testing machine. The hardness properties of the samples were tested by the Shore Scale Durometer. The impact resistance of the samples was determined by means of an Izod impact test. The data collected from the experiments were statistically analysed to find out the correlation between microstructure development and the thermal/mechanical behaviour of HDPE hybrid composites (Mohammed et al. 2025).

3. Results and Discussion

3.1 Mechanical Properties

High-density polyethylene (HDPE) composite's mechanical behavior with sawdust and ground glass cullet as reinforcements is significantly influenced by key production factors, including filler content, particle size, mold temperature, mixing time, and mold pressure. These factors determine the amount of microstructure bonding at the interface between the reinforcement and the matrix, which affects tensile strength, flexural strength, impact resistance, and hardness. Finding the right processing conditions is essential to ensure a uniform spread of the reinforcements within the HDPE matrix, which provides mechanical strength and structural integrity for ceiling board applications.

The composition percentages of sawdust and glass cullet are important for the mechanical performance of the hybrid composite. Increasing the percentage of sawdust is expected to improve stiffness and decrease density due to the lightweight, fibrous nature of wood particles. However, too much sawdust can lead to poor adhesion between the hydrophilic fillers and the hydrophobic HDPE matrix, resulting in lower impact and tensile strength. On the other hand, ground glass cullet enhances hardness and stiffness because of its inorganic, brittle nature, but overloading it can make the composite brittle and reduce flexibility. Thus, a balance between organic (sawdust) and inorganic (glass cullet) reinforcement is necessary for optimal performance.

Mechanical properties can be influenced by temperature and pressure of the composite manufacturing process. Temperatures between 180°C to 200°C help soften the HDPE to wrap the sawdust and glass particles with adequate wetting. Too high temperatures may reduce sawdust fibers to their weakest form as a result of degradation, volatilization, and formation of voids that undermine the strength of the composite. Similarly, inadequate pressure during the molding phase will result in weak interface and voids while too much pressure will crush the reinforcing fibers.

The time and rate of mixing affect the effectiveness of the dispersion of the reinforcement materials inside the matrix of HDPE.

Proper mixing ensures that the reinforcement particles are evenly distributed to avoid agglomeration and areas of stress concentration, hence increasing the mechanical strength. Nevertheless, excessive mixing may result in fibre fragmentation and reduced aspect ratio. The optimal conditions are achieved through optimization of these variables by employing proper design of experiments, such as Response Surface Methodology (RSM).

Last but not least, the mechanical characteristics of HDPE/sawdust/ground glass cullet composites depend on the interaction between the ratios of material compositions and processing factors. Control of these variables optimizes the bond quality, minimizes defects, and enhances performance to make the composite an efficient and sustainable building material.

3.1.1 Tensile Strength

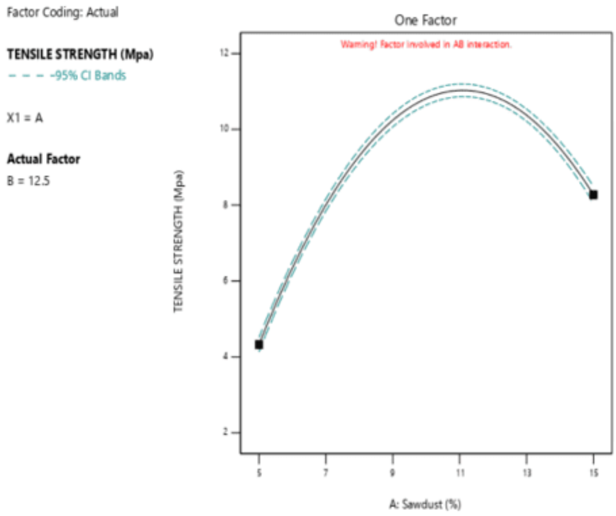


Figure 3.1: A One Factor Plot or Main Effect Plot for Tensile Strength (MPa).

Figure 3.1 shows the tensile strength (MPa) plotted on the vertical (Y) axis, while the percentage of sawdust (A, %) is plotted on the horizontal (X) axis. The figure illustrates how the tensile strength of the HDPE/sawdust/ground glass cullet hybrid composite varies with different proportions of sawdust content, while the ground glass cullet factor (B) is kept constant at 12.5%. It shows the individual effect of the sawdust content on the tensile strength of the composite material. The solid curve represents the predicted tensile strength values, and the dashed lines indicate the "95% confidence interval (CI) bands" which show the range of variability around the predicted mean values.

From the plot, the tensile strength increases with sawdust content up to about 10% before it begins to decline as the sawdust percentage rises further. This trend suggests that moderate incorporation of sawdust enhances interfacial bonding and stress transfer between the matrix and reinforcement, but excessive sawdust reduces strength due to poor dispersion and possible void formation.

The note in red ("Warning! Factor involved in AB interaction") indicates that the sawdust factor (A) interacts significantly with the ground glass cullet factor (B), meaning the combined effects of the two factors influence tensile strength more than their individual contributions.

3.1.2 Hardness Strength

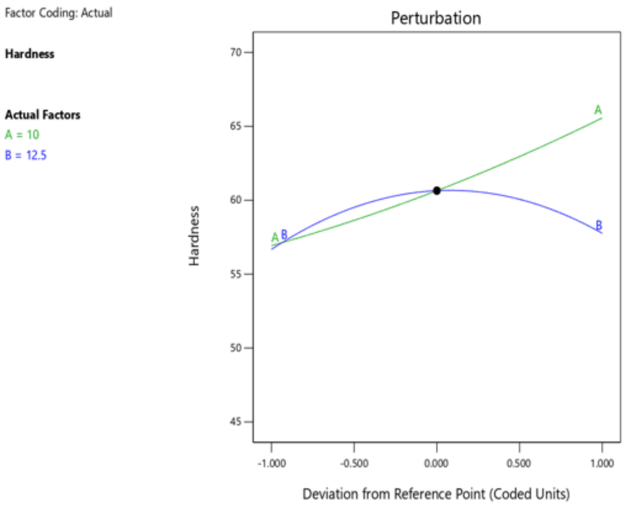


Figure 3.2: Perturbation Plot for Hardness.

The plot illustrates the sensitivity of the response variable (hardness) to changes in two independent factors: A-Sawdust (%) and B-Glass cullet (%), while keeping other variables constant at their reference points. The horizontal axis represents the deviation from the reference point (coded units), while the vertical axis indicates the resulting hardness of the HDPE/sawdust/glass cullet hybrid composite.

Figure 3.2 has a curve for factor A (sawdust) that represent positive and almost linear trend, indicating that increasing the sawdust content enhances the hardness of the composite. This improvement is likely due to the rigid lignocellulosic structure of sawdust, which improves load distribution and reduces matrix deformation under stress. Also, factor B (glass cullet) exhibits a parabolic trend hardness which increases initially with glass cullet addition but slightly decreases beyond an optimal level.

This suggests that while moderate glass cullet improves surface hardness through reinforcement and matrix densification, excessive addition may lead to filler agglomeration and poor interfacial bonding, thereby reducing hardness.

The difference in slopes between A and B implies that sawdust has a stronger influence on hardness than glass cullet within the studied range. Natural fillers like sawdust significantly improve the surface hardness of polymer composites due to effective stress transfer and particle matrix adhesion. Similarly, while glass fillers enhance hardness, excess glass loading may introduce brittleness and micro voids, which counteract the benefits of reinforcement.

Furthermore, the perturbation plot demonstrates that hardness is most responsive to changes in sawdust content, confirming its primary role in determining the composite's surface strength and durability.

3.2 Tensile Strength Model

Table 3.1: Tensile Strength Report.

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	10.07	10.07	0.0002	0.239	0.002	0.002	0.000	0.001	6
2	11.20	11.20	-0.0001	0.191	-0.000	-0.000	0.000	-0.000	12
3	10.90	10.90	0.0001	0.624	0.001	0.001	0.000	0.002	15
4	11.20	11.20	-0.0001	0.191	-0.000	-0.000	0.000	-0.000	9
5	5.38	5.38	-0.0002	0.324	-0.001	-0.001	0.000	-0.001	8
6	11.20	11.20	-0.0001	0.191	-0.000	-0.000	0.000	-0.000	10
7	7.50	7.50	-0.0001	0.383	-0.000	-0.000	0.000	-0.000	1
8	11.20	11.20	-0.0001	0.191	-0.000	-0.000	0.000	-0.000	11
9	2.92	2.92	0.0001	0.394	0.000	0.000	0.000	0.000	4
10	7.50	7.50	-0.0001	0.383	-0.000	-0.000	0.000	-0.000	2
11	7.30	6.95	0.3500	0.394	2.873	6.522(1)	0.896	5.262(2)	3
12	8.00	8.00	-0.0001	0.691	-0.001	-0.001	0.000	-0.002	13
13	6.60	6.95	-0.3500	0.394	-2.873	-6.529(1)	0.896	-5.268(2)	16
14	6.40	6.40	0.0001	0.691	0.001	0.001	0.000	0.001	14
15	2.92	2.92	0.0001	0.394	0.000	0.000	0.000	0.000	5
16	8.19	8.19	0.0002	0.324	0.002	0.001	0.000	0.001	7

Table 3.1 shows the tensile strength statistical model sufficient to explain; COOK's DISTANCE, LEVERAGE Vs Run, DFFITS Vs Run, and DFBETAS for Intercept vs Run.

Figure 3.3 shows the Cook's Distance which measures the overall influence of each observation on the fitted regression model; it combines information from the residuals and leverage values to identify points that disproportionately affect the regression coefficients. In this study, the Cook's Distance values for all runs were observed to be less than 1.0, with the highest being 0.896 for Run 11 and Run 13, indicating that no observation had an undue influence on the regression model. Typically, values of Cook's Distance greater than 1 suggest influential points. Thus, the tensile strength model is statistically stable, with no influential outliers distorting the model's performance.

The second is the Leverage vs Run; its values indicate how far an observation's predictor values are from the mean of the predictor variables. High leverage points can strongly affect the regression line, even if their residuals are small. In this analysis, leverage values range between 0.191 and 0.691, with Runs 3, 12, and 14 showing relatively higher leverage (0.624–0.691). These runs correspond to unique combinations of the sawdust and ground glass cullet parameters (figure 3.4), suggesting that these data points represent experimental conditions less common in the dataset. However, since these high-leverage points have small residuals and low Cook's Distance, they are not problematic but rather contribute significantly to defining the model's shape and prediction accuracy.

Next is the DFFITS vs Run which is the "Difference in Fits (DFFITS)" that evaluates how much a particular observation influences its own predicted value. A general rule is that if |DFFITS| > 2√(p/n), where *p* is the number of predictors and *n* the sample size, the observation is considered influential. Therefore, runs 11 and 13 recorded the largest DFFITS values (±5.26), which are notably higher than the acceptable threshold, indicating that these runs had substantial influence on their own fitted tensile strength values. This influence, however, aligns with the fact that these runs exhibited the highest residual deviations, reinforcing that they are the most sensitive points in the dataset. Despite this, their Cook's Distance below 1 indicates that they do not unduly bias the overall regression coefficients. Figure 3.5 illustrate the difference in fits having a stable tensile strength.

Finally, the DFBETAS diagnostic assesses how much a single observation affects the estimation of a particular regression coefficient. Here, the intercept is where the absolute value of DFBETAS exceeds 1, the observation is considered to have a strong influence on the regression coefficient. In the current model, runs 11 and 13 again exhibited high external studentized residuals (±6.52) and correspondingly elevated DFBETAS (figure 3.6), signifying that these runs influenced the model's intercept term more than others. However, since the overall model performance indicators (such as R² and adjusted R²) remain consistent and within acceptable limits, the regression remains reliable, and no significant model distortion was detected.

In summary, diagnostic evaluation confirms that the tensile strength ANOVA model is statistically sound and reliable. The Cook's Distance and Leverage results show that no data point exerts an undue influence, while DFFITS and DFBETAS highlight that only Runs 11 and 13 have moderate influence due to higher residuals but do not compromise model validity. This indicates a well-fitted model suitable for prediction and optimization of the tensile strength of HDPE/sawdust/glass cullet hybrid composites.

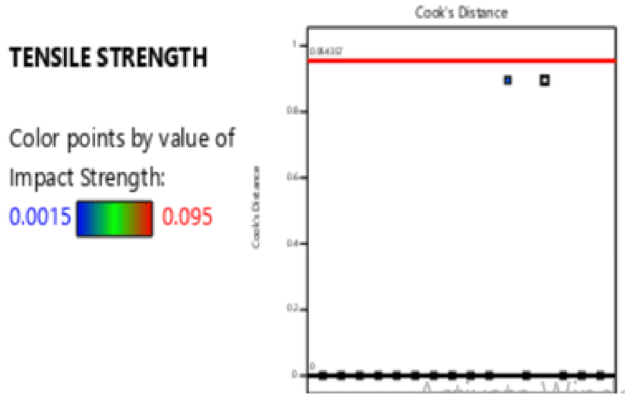


Figure 3.3: Cook's Distance Diagnostic Plot for Tensile Strength.

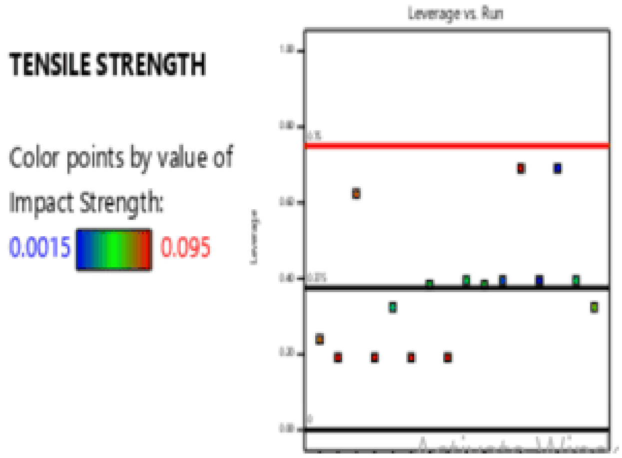


Figure 3.4: Leverage vs. Run Plot for Tensile Strength.

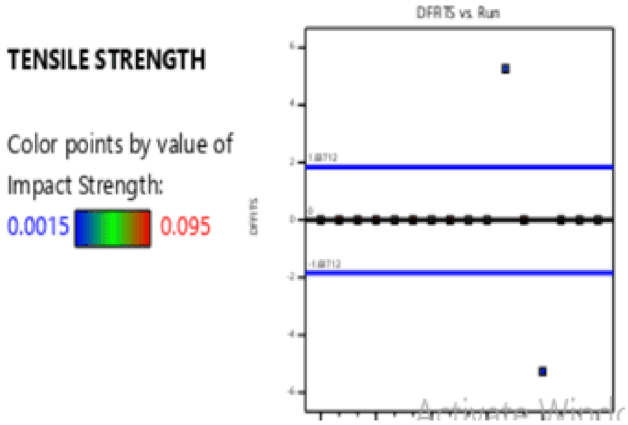


Figure 3.5: DFFITS vs. Run Plot for Tensile Strength.

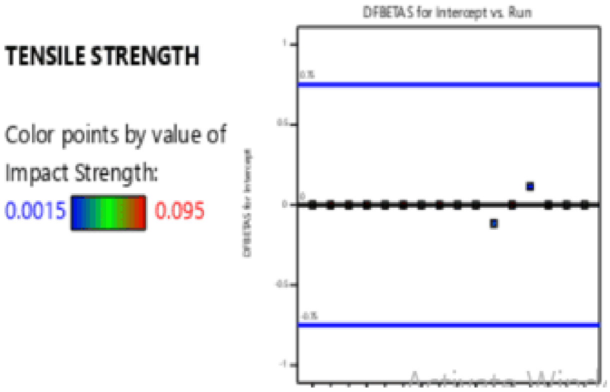


Figure 3.6: DFBETAS for Intercept vs. Run Plot for Tensile Strength.

3.3 Thermal Analysis Using DSC.

3.3.1 Sample 2.

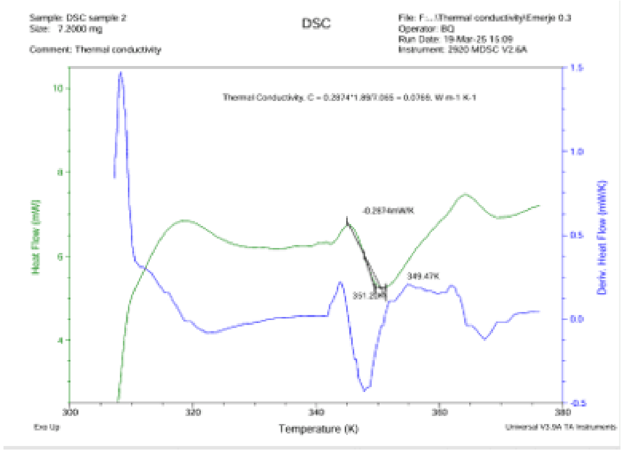


Figure 3.7: DSC Thermogram for Sample Two Composite.

Sample 2 (10% Sawdust, 15% Ground Glass Cullet). From figure 3.7, it can be said that the DSC curve provides key insights into the sample's thermal conductivity, melting behaviour, and phase transition characteristics. From DSC thermogram, the green curve represents the heat flow (mW), while the blue curve indicates the derivative of heat flow (mW/K), which enhances the visibility of transition points. The exothermic and endothermic transitions reflect the sample's response to increasing temperature. The peak around 349.47 K to 351.26 K corresponds to the material's phase transition or melting event, showing an endothermic process where energy is absorbed to overcome molecular bonding. The calculated thermal conductivity value of 0.0769 $W \cdot m^{-1} \cdot K^{-1}$ and a slope of −0.2874 mW/K indicate a moderate capacity of the material to conduct heat, which is typical for polymer-based or composite materials used in low-thermal-conductivity applications such as insulative ceiling boards.

This behaviour aligns with findings in recent studies where DSC analysis is used to evaluate thermal performance and phase stability in HDPE-based composites and hybrid materials. The incorporation of natural fillers such as sawdust or glass cullet into HDPE reduces its thermal conductivity due to increased phonon scattering and interfacial resistance. Also, the DSC thermograms provide vital data for correlating heat flow changes to structural modifications within polymer matrices, enhancing their thermal insulation performance.

In essence, the DSC thermogram in figure 3.7 demonstrates a distinct endothermic peak corresponding to thermal transition and a moderate thermal conductivity, suggesting that the material exhibits good thermal insulation potential suitable for construction and ceiling applications.

3.3.2 Sample 3

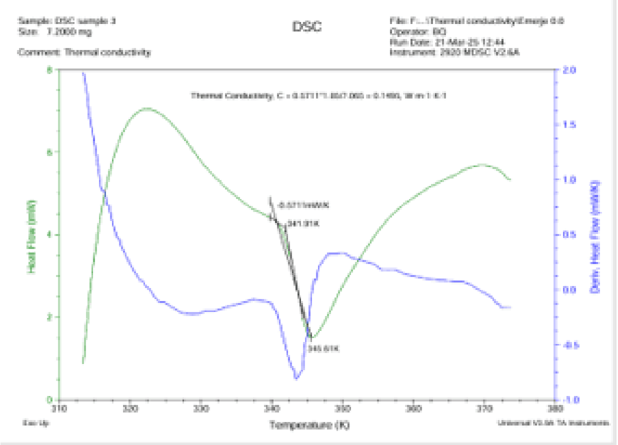


Figure 3.8: DSC Thermogram for Sample Three Composite.

In the thermogram, the green curve represents the heat flow (mW) as a function of temperature (K), while the blue curve shows the derivative of heat flow (mW/K), which highlights subtle thermal events such as melting or crystallization. The DSC profile reveals a prominent endothermic transition occurring between 341.91 K and 345.61 K, corresponding to the melting of crystalline domains within the polymer matrix. The calculated thermal conductivity (C) value of 0.1495 $W \cdot m^{-1} \cdot K^{-1}$, with a slope of −0.5711 mW/K, suggests that the virgin HDPE sample possesses higher thermal conductivity compared to the filler-modified composites.

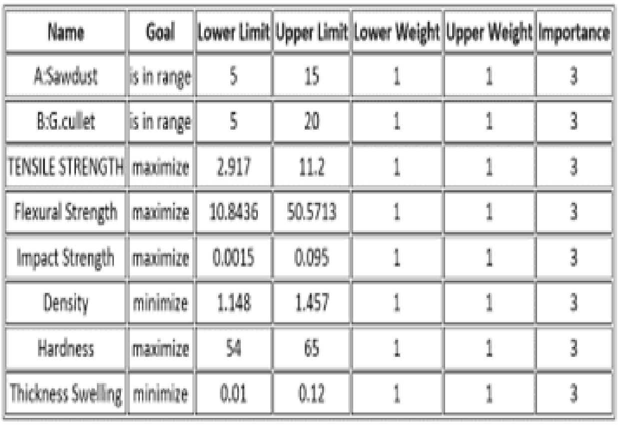
This relatively higher value is due to the absence of insulating fillers, which typically scatter phonons and reduce heat transport efficiency in composite systems.

The thermal behaviour aligns with current findings on polymer thermal modification like the incorporation of fillers such as wood flour or glass particulates tends to lower the overall thermal conductivity of HDPE composites by increasing interfacial thermal resistance and disrupting phonon pathways. Conversely, the pure HDPE matrix, as observed in sample three, maintains better molecular continuity and crystalline uniformity, resulting in improved heat transfer. Again, the DSC thermograms of virgin HDPE typically display well-defined melting peaks in the 340–350 K range, consistent with the transition temperatures identified in figure 3.8.

Summarily, the DSC thermogram, indicates that the material exhibits a strong endothermic transition near 343 K, signifying a well-ordered crystalline structure with a moderate to high thermal conductivity value of 0.1495 $W \cdot m^{-1} \cdot K^{-1}$. This confirms its role as a control sample with superior thermal transport properties compared to filler-modified composites, making it a suitable reference for thermal performance evaluation in HDPE-based hybrid systems.

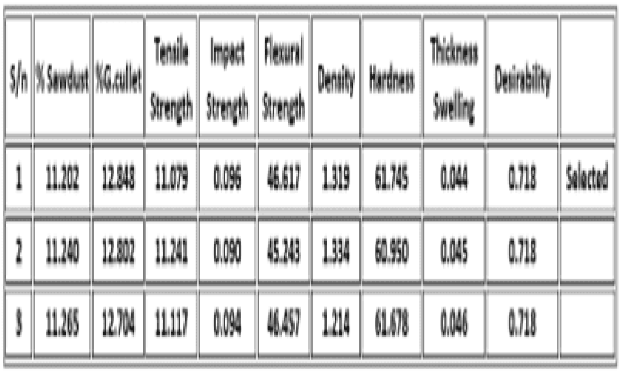
4. Optimization Criteria & Solution for the Hybrid Composites Respectively

Table 3.2: Optimization Criteria table.



Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Sawdust	is in range	5	15	1	1	3
B:G.cullet	is in range	5	20	1	1	3
TENSILE STRENGTH	maximize	2.917	11.2	1	1	3
Flexural Strength	maximize	10.8436	50.5713	1	1	3
Impact Strength	maximize	0.0015	0.095	1	1	3
Density	minimize	1.148	1.457	1	1	3
Hardness	maximize	54	65	1	1	3
Thickness Swelling	minimize	0.01	0.12	1	1	3

Table 3.3: Optimization Solution table.



S/n	% Sawdust	%G.cullet	Tensile Strength	Impact Strength	Flexural Strength	Density	Hardness	Thickness Swelling	Desirability	
1	11.202	12.848	11.079	0.096	46.617	1.319	61.745	0.044	0.718	Selected
2	11.240	12.802	11.241	0.090	45.243	1.334	60.950	0.045	0.718	
3	11.265	12.704	11.117	0.094	46.457	1.214	61.678	0.046	0.718	

5. Conclusion

This study effectively proved that the development of microstructure in hybrid composites made up of HDPE, sawdust particles, and glass cullet greatly affected their thermal and mechanical properties when used for ceiling boards. The use of lignocellulose sawdust particles resulted in better bonding between the matrix and filler and high energy absorption capacity. Glass cullet inclusion brought about increased stiffness, hardness, dimensional stability, and heat resistance. The microstructural analysis showed a fairly even distribution of the filler within the HDPE matrix at the optimum ratio.

The optimized composite formulation containing approximately 11.20% sawdust particles and 12.80% glass cullet exhibited superior overall performance, achieving tensile strength values above 11 MPa, flexural strength exceeding 46 MPa, hardness above 60 BHN, and minimal thickness swelling of approximately 0.045%. These results indicate that the hybridization approach effectively balanced the ductility of HDPE with the rigidity of mineral reinforcement, thereby improving both mechanical integrity and thermal stability. Furthermore, the low swelling behavior confirms enhanced moisture resistance, which is essential for ceiling board durability in humid service environments.

In general, the results show that HDPE sawdust/glass cullet hybrid composites are environmentally-friendly and high-performance substitutes for traditional ceiling boards. The research helps to advance the process of converting waste to wealth by taking advantage of waste materials from agriculture and industries to manufacture composite materials.

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