

Article

Understanding the Fundamental Properties of Binder Systems Based on Polyethylene and Waxes for the Metal Injection Molding (MIM) Process

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Abstract

Binder systems based on polyethylene (PE) and wax are widely used in Metal Injection Molding (MIM). However, their application raises environmental concerns related to material waste and the possible alteration of binder properties during repeated processing. This study aims to provide a comprehensive understanding of the behavior and properties of PE–wax systems to establish a reference framework for the evaluation and future development of alternative binder formulations. Model PE–wax blends without metallic powder were characterized using differential scanning calorimetry, tensile testing, and X-ray diffraction. The results showed that polymer and wax type influence the mechanical response of the blends, with the HDPE–octadecane formulation exhibiting a lower Young’s modulus than the HDPE–paraffin wax blend at the same wax content. Thermal analysis revealed distinct transitions associated with the polymer and wax components, together with small variations between successive heating and cooling cycles, indicating thermal-history-dependent behavior. Young’s modulus, Poisson’s ratio, thermal conductivity, and density were also predicted using Digimat software. The predicted Young’s modulus values showed good agreement with the experimental tensile results. The results provide a preliminary framework for screening polyethylene–wax binder formulations.

Keywords: metal injection molding (MIM); binder systems; polyethylene–wax mixtures; multiphysics simulation

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1. Introduction

Metal Injection Molding (MIM) is a manufacturing technology primarily used to produce small metal components with complex geometries. The feedstock consists of a mixture of metal powder and a polymer-based binder system. This mixture is shaped using conventional polymer injection molding equipment to obtain the so-called green part. Subsequently, the binder is removed to produce the brown part, which is finally sintered

to achieve the desired component with properties comparable to those obtained through traditional manufacturing routes [1–3].

Compared with forging and conventional powder metallurgy (pressing and sintering), MIM enables the production of components with significantly more complex geometries [4,5], eliminating the need for secondary machining operations and achieving tight dimensional tolerances (on the order of microns) [6]. Additionally, MIM facilitates the processing of materials that are difficult to handle using conventional methods, such as refractory metals.

MIM is widely applied across various industries, including automotive, electronics, defense, and healthcare [1,3,7–9]. It offers several advantages over other manufacturing processes: it allows the use of advanced materials such as superalloys, precious metals, and cermets, and it supports the fabrication of multi-material components through techniques such as two-color injection molding [10,11]. Furthermore, the high final density of MIM parts enhances their properties [1–4]. The process can also be highly automated, enabling large-scale production while minimizing or eliminating machining and surface finishing steps, thereby reducing manufacturing costs [12].

Binder systems in MIM consist of one or more polymers whose primary function is to bind the metal particles and enable injection molding. They must also provide sufficient strength to the green part for handling [1]. Based on their nature, binders can be classified into thermoplastics, thermosets, gels, water-based systems, and inorganic binders [2]. In practice, MIM binders are typically based on thermoplastic systems, often combining a backbone polymer, such as high-density polyethylene (HDPE), with wax (commonly paraffin) or oils. The polymer ensures structural integrity, while the wax or oil reduces viscosity to facilitate processing [5,9,13–16]. Additional additives may be incorporated depending on specific requirements, such as dispersants to improve powder–binder interaction, plasticizers to enhance flow, and stabilizers to prevent particle agglomeration [1,17,18].

Conventional MIM binders commonly contain petroleum-derived thermoplastics and waxes. Residual feedstock, runners, defective green parts, and polymeric products generated during debinding may contribute to material consumption and waste generation. Reprocessing these materials could reduce waste; however, repeated thermal and shear histories may alter the polymer molecular structure and consequently affect flow, mechanical integrity, and debinding behavior. Recent work on powder-loaded MIM feedstocks has shown that repeated recycling can modify melt-flow behavior, thermal response, wax content, and dimensional shrinkage, highlighting the need for direct reprocessing experiments when evaluating binder recyclability [19]. More sustainable approaches therefore include the use of recyclable, water-removable, bio-based, or biodegradable binder components, together with strategies for recovering and potential reuse of the binder material [6,12,20–22].

From a technological perspective, a MIM binder must provide sufficiently low and stable viscosity during molding, promote homogeneous wetting and dispersion of the metal powder, avoid powder–binder segregation, and maintain sufficient green strength after cooling. It must also remain thermally stable during compounding and injection and allow progressive removal without cracking, blistering, distortion, or excessive residual carbon. Because these requirements are interdependent, binder performance should ultimately be evaluated in highly filled metal–binder feedstocks rather than on the binder system alone [23]. Consequently, this study aims to improve the understanding of thermoplastic–wax binder systems and to provide a reference framework for the future development and evaluation of alternative binder formulations. In parallel, simulation techniques are employed to predict selected mechanical and thermal properties of the binder blends, including Young's modulus, Poisson's ratio, density, and thermal conductivity.

These properties are critical in MIM process design. Mechanical properties must be sufficient to ensure that green parts can be handled without deformation, while thermal properties govern heating and cooling cycles during processing. Density and Poisson's ratio influence mold design and flow behavior during injection and packing stages [1]. Therefore, the present work combines experimental measurements with simulation results to assess the potential of numerical simulation as a preliminary tool for estimating selected properties of new binder formulations.

The present study focuses on polyethylene–wax binder blends without metallic powder in order to isolate the intrinsic thermal and mechanical effects associated with the binder components. Accordingly, the investigated materials should be regarded as model binder systems rather than complete MIM feedstocks. Differential scanning calorimetry (DSC), tensile testing, X-ray diffraction (RXD), and simulation methods were employed to examine the influence of polymer and wax type on selected properties of the blends. The simulations were used as a preliminary tool to estimate Young's modulus, Poisson's ratio, density, and thermal conductivity. However, the results cannot be directly extrapolated to powder-loaded feedstocks, whose behavior is additionally governed by powder concentration, particle morphology, powder–binder interactions, and processing conditions.

This work therefore aims to improve the fundamental understanding of polyethylene–wax binder systems and to provide a reference framework for the preliminary evaluation of alternative binder formulations.

2. Materials and Methods

The binder components used in this study are summarized in Table 1. Two polyethylene grades, high-density polyethylene (HDPE) and linear low-density polyethylene (LDPE), were selected as polymer backbone materials. Paraffin wax (PW) and octadecane (OCT) were used as lower-molecular-weight components. The properties listed in Table 1 correspond to nominal values reported by the suppliers; experimentally determined thermal transitions are presented separately in the Results and Discussion section.

Table 1. Supplier information and nominal properties of the binder components.

Property	HDPE	LDPE	PW	OCT
Supplier	Sigma-Aldrich (St. Louis, MO, USA)	Sigma-Aldrich (St. Louis, MO, USA)	Sigma-Aldrich (St. Louis, MO, USA)	Sigma-Aldrich (St. Louis, MO, USA)
Product No.	547999	428078	327204	O652
Physical form	Pellets	Pellets	Beads or waxy solid	Low-melting solid
Melt flow index	2.2 g·10 min ^{−1} at 190 °C/2.16 kg	1.0 g·10 min ^{−1} at 190 °C/2.16 kg	Not applicable	Not applicable
Molecular weight	Approx. 115,000 g·mol ^{−1}	Not specified	Not applicable	254.49 g·mol ^{−1}
Density	0.95 g·cm ^{−3}	0.918 g·cm ^{−3} at 25 °C	0.79–0.94 g·cm ^{−3}	0.777 g·cm ^{−3} at 25 °C
Nominal thermal property	Vicat softening temperature: 123 °C	Melting range: 100–125 °C	Melting range: 53–58 °C	Melting range: 26–29 °C

Three polymer–wax blends were prepared using an Xplore Micro Compounder MC 15HT mini-extruder (Xplore Instruments B.V., Sittard, The Netherlands) under the processing conditions summarized in Table 2. For mechanical characterization, compression-molded films were prepared using a Collins automatic press (COLLIN Lab & Pilot Solutions GmbH, Maitenbeth, Germany). Type 2 dog-bone-shaped specimens were cut from the films. The specimens had a total length of 75 mm, a gauge length of 25 mm, a width of 4 mm, and an approximate thickness of 0.5 mm. Tensile tests were performed at room

temperature using an Instron 68TM-10 universal testing machine (Instron, Norwood, MA, USA) at a crosshead speed of 10 mm·min⁻¹.

Table 2. Composition and processing parameters of the PE–wax blends prepared for mechanical and thermal characterization under a nitrogen atmosphere.

Polymer Blend	Composition	Mixing Parameters
50LDPE-50PW	50 wt. % of low-density polyethylene and 50 wt. % of paraffin wax	5 min, 40 rpm, 140 °C
50HDPE-50PW	50 wt. % of high-density polyethylene and 50 wt. % of paraffin wax	5 min, 40 rpm, 140 °C
50HDPE-50OCT	50 wt. % of high-density polyethylene and 50 wt. % of octadecane	5 min, 40 rpm, 130 °C

Binder removal (debinding) can be performed under different atmospheres depending on the material. A nitrogen atmosphere is typically employed for oxidation-sensitive materials, such as metals, whereas air is commonly used in ceramic processing. In this study, both atmospheres were considered to assess their influence on the thermal behavior of the binder system. Thermal characterization under a nitrogen atmosphere was conducted using a Discovery DSC 25 Auto differential scanning calorimeter (TA Instruments, New Castle, DE, USA). Samples were heated from −70 °C to 140 °C at a rate of 10 °C/min, followed by cooling at the same rate and a subsequent reheating cycle.

The incorporation of low-melting-point components reduces system viscosity, facilitating mixing and injection while lowering processing temperatures. However, excessive amounts may adversely affect mechanical performance. Therefore, a systematic study on the influence of paraffin wax content on thermal behavior was conducted. In addition, the effect of octadecane as an alternative wax was examined.

For this purpose, small batches were prepared using an overhead stirrer (Thermo Fisher Scientific, Waltham, MA, USA), and their compositions are summarized in Table 3. The 50 wt.% wax formulations were selected as model systems to accentuate the contribution of the wax phase and facilitate comparison between polymer and wax types. This composition was selected because it is representative of formulations commonly reported for this type of MIM binder system [15]. The 30 and 40 wt.% paraffin formulations were additionally studied to evaluate concentration-dependent thermal effects. Thermal analysis in this case was performed under an air atmosphere, representative of ceramic processing conditions, using a PerkinElmer DSC 6 (PerkinElmer, Waltham, MA, USA). Samples were heated from 30 °C to 250 °C at a rate of 10 °C/min.

Samples were placed in sealed aluminium pans. An empty aluminium pan was used as reference. For each DSC measurement, the instrument software (TA Instrument TRIOS V5.6 and Perkin Elmer 6 DSC Pyris v3.7 for Windows) normalized the raw heat-flow signal by the sample mass entered at the time of analysis. Accordingly, all thermograms are reported as specific heat flow in W·g⁻¹. This procedure was used to compare the thermal transitions observed during successive heating and cooling cycles and to evaluate the influence of thermal history on the binder blends.

Table 3. Compositions of the prepared blends used to evaluate the effect of wax content on the thermal behavior of the mixtures.

Polymer Blend	Composition
50HDPE-50PW	50 wt. % of high-density polyethylene and 50 wt. % of paraffin wax
60HDPE-40PW	60 wt. % of high-density polyethylene and 40 wt. % of paraffin wax
70HDPE-30PW	70 wt. % of high-density polyethylene and 30 wt. % of paraffin wax
50HDPE-50OCT	50 wt. % of high-density polyethylene and 50 wt. % of octadecane

Changes in polymer crystallinity arising from thermal cycling and interactions with other components may significantly affect both thermal and mechanical properties. Therefore, both the individual components and their blends were characterized by X-ray diffraction (XRD) to assess whether the degree of crystallinity of PE is influenced by the type and content of wax. XRD profiles were obtained using a PHYWE XR 4.0 X-ray diffractometer (X-ray Expert unit, PHYWE Systeme GmbH & Co. KG, Göttingen, Germany) with CuK α radiation, operating at 30 kV and 1 mA, over a 2θ range of 10° to 30° at a scanning rate of $2^\circ/\text{min}$.

The XRD crystallinity index was estimated using the area-integration method in OriginPro V8. The total diffracted area (A_t) was integrated over the 2θ range from 10° to 30° relative to a straight background line. A baseline following the broad amorphous scattering beneath the crystalline reflections was then defined, and the area above this baseline was integrated as the crystalline area (A_c). The amorphous area was obtained by difference between (A_t) and (A_c) (Equation (1)). The crystallinity index (X_c) was calculated as can be seen in Equation (2), while the amorphous fraction (X_a) was obtained as shown in Equation (3). No mathematical peak deconvolution was performed.

$$A_a = A_t - A_c, \quad (1)$$

$$X_c(\%) = \frac{A_c}{A_t} \cdot 100, \quad (2)$$

$$X_a(\%) = \frac{(A_t - A_c)}{A_t} \cdot 100, \quad (3)$$

In addition, Digimat software was employed to compare experimental results with numerical predictions, with the objective of validating its capability to simulate the mechanical and thermal properties of polymer blends. This approach enables the efficient evaluation of new formulations while reducing the need for extensive experimental testing.

The material model was developed using Digimat (HEXAGON, version 2024.1) [24], specifically the MF (Mean Field) module based on a semi-analytical approach, as reported in previous studies [25]. Modeling was conducted at the microscale to accurately define phase distributions and material parameters. However, direct mechanical analysis at this scale does not adequately represent macroscopic behavior. To bridge this gap, the Mean Field approach employs the concept of a Representative Volume Element (RVE), which links microscopic features to macroscopic properties. Each macroscopic point is associated with an RVE containing a finite number of inclusions that represent the microstructure.

Digimat allows control over the spatial distribution and orientation of inclusions within the matrix. The orientation of each inclusion is defined by a unit vector $\bar{p}$ in three-dimensional space, described by the spherical angles θ and φ . Since inclusion orientations vary, an orientation distribution function (ODF), $\psi(\bar{p})$, is introduced, where $\psi(\bar{p}) d(\bar{p})$ represents the probability of finding inclusions within a given solid angle $[\bar{p}, \bar{p} + d\bar{p}]$. The composite material must satisfy the following conditions:

$$v_0 + \sum_{i=1}^N v_i = 1, \quad (4)$$

where v_0 denotes the volume fraction of the matrix phase, and v_i represents the volume fraction of the i -th inclusion family within the composite, with i indexing each family of inclusions.

The following conditions apply to the inclusions:

$$\psi_i(\bar{p}) = \psi_i(-\bar{p}), \quad (5)$$

$$\oint \psi_i(\bar{p}) d(\bar{p}) = 1, \quad (6)$$

Equations (5) and (6) define the fundamental conditions governing the inclusions. Equation (5) indicates that inclusions with opposite orientations are equivalent, while Equation (6) represents the normalization condition, ensuring that the sum of all orientation probabilities equals unity.

In the present study, a composite material model is adopted in which the matrix consists of either HDPE or LDPE, and the dispersed phase is PW. Based on previous studies [26–28], PW inclusions are assumed to be spherical (aspect ratio = 1) and uniformly distributed within the matrix, consistent with the Mori–Tanaka homogenization approach [29]. A mass fraction of 0.5 is considered for the inclusions.

HDPE is modeled as an isotropic elastic material with a density of $955 \text{ kg}\cdot\text{m}^{-3}$, a Young's modulus of 1050 MPa, and a Poisson's ratio of 0.425. Similarly, LDPE is treated as an isotropic elastic material with a density of $920 \text{ kg}\cdot\text{m}^{-3}$, a Young's modulus of 500 MPa [30], and a Poisson's ratio of 0.439.

PW is also described using an isotropic elastic model, with a density of $893 \text{ kg}\cdot\text{m}^{-3}$, a Young's modulus of 365 MPa, and a Poisson's ratio of 0.495 [31,32].

Once the constituent material properties are defined, a quasi-static tensile load is applied to the composite until a strain of 0.03 is reached.

Regarding thermal properties, the thermal conductivity is assumed to be $0.49 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for HDPE and $0.322 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for LDPE, while a value of $0.21 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ is adopted for PW [33–35].

The formulations selected for modeling in this study are 50HDPE–50PW and 50LDPE–50PW.

3. Results and Discussion

3.1. Mechanical Properties

Table 4 summarizes the results obtained from tensile testing of the polymer–wax samples. Reported values correspond to the mean of five specimens for each formulation, along with the associated standard deviation. The results are consistent with values reported in the literature [26–29].

In terms of stress response, both tensile strength and ultimate stress were evaluated, with the latter being lower than the former. As noted in [29,31], wax crystals dispersed within the amorphous polymer phase act as defect sites, promoting crack initiation and propagation. Furthermore, the wax phase is unable to effectively sustain the stress transferred from the polymer matrix, which limits stress transmission and leads to reduced strength. This behavior is attributed to weak interfacial bonding between the blend components.

Previous studies have reported that increasing wax content can reduce Young's modulus and tensile strength by increasing the proportion of the softer, low-molecular-weight phase [26–28]. In the present study, the experimental results allow the influence of polymer and wax type to be compared at a constant wax fraction. At this fixed wax fraction, the 50HDPE–50OCT blend exhibited a lower Young's modulus and maximum tensile stress than 50HDPE–50PW. This difference may be associated with the lower molecular weight of octadecane and with differences in molecular mobility and polymer–wax interactions [27,28,34,36–38].

Table 4. Mechanical properties of the polymer–wax blends.

Polymer Blend	$E \pm S_E$ [MPa]	$\sigma_{\max} \pm S_{\sigma_{\max}}$ [MPa]	$\sigma_{\text{break}} \pm S_{\sigma_{\text{break}}}$ [MPa]
50HDPE-50PW	632.48 ± 34.78	12.26 ± 0.47	0.53 ± 0.09
50LDPE-50PW	416.47 ± 17.54	9.78 ± 0.93	1.09 ± 0.27
50HDPE-50OCT	375.66 ± 38.98	6.95 ± 0.33	3.55 ± 1.23

E , $\sigma_{\max}$, and σ_{break} , denote for Young's Modulus, maximum tensile stress and breaking stress respectively.

Tensile testing was used here as a comparative method to evaluate the influence of polymer and wax type on the mechanical response of the neat binder blends. These measurements do not provide a complete assessment of injection moldability or green-part performance. Rheological behavior, creep, viscoelasticity, flexural response, and the green strength of powder-loaded feedstocks must be evaluated before practical MIM performance can be established.

3.2. Thermal Behavior

The prepared samples were analyzed by Differential Scanning Calorimetry (DSC). Tests were conducted under both nitrogen and air atmospheres to reflect the most used conditions in MIM processes. In all cases, heating and cooling rates were set to 10 °C/min.

Figures 1 and 2 present the DSC results obtained under a nitrogen atmosphere for HDPE–PW and LDPE–PW blends. Three consecutive stages are observed: initial heating (blue curve, Figure 1), cooling (red curve, Figure 2), and a second heating cycle (pink curve, Figure 1). During heating, two distinct peaks appear at approximately 39.6–40.1 °C and 59.7 °C. The first peak corresponds to a solid–solid transition between different crystalline structures of the wax [32,38], while the second is associated with wax melting [26]. A third peak, observed at 122.7 °C, corresponds to the melting of HDPE. This melting temperature is lower than that of pure PE (≈ 130.7 °C [26]), due to the plasticizing effect of PW [39].

During cooling, crystallization temperatures of approximately 47.8 °C and 107.6 °C are observed, corresponding to the wax and the polymer, respectively, in agreement with literature values [26]. It is also noted that transition temperatures showed small variations between successive heating–cooling cycles. These differences may be associated with thermal history, crystal reorganization, component interactions, or possible degradation, which must be considered when evaluating binder blend recyclability.

For the LDPE–PW system, DSC curves show similar behavior for the wax phase, with peaks appearing at comparable temperatures to those in the HDPE-based blends. The polymer melting temperature during heating is also similar; however, crystallization occurs at a lower temperature, which is consistent with differences in molecular structure, chain branching, and crystallization kinetics between the two polyethylene grades.

Previous microscopy studies on LDPE–paraffin wax blends have shown that increasing the wax content modifies the morphology of the blends and may lead to phase separation at wax contents above 15 wt.% [29]. In the present study, the distinct thermal transitions observed by DSC are consistent with the polymer and wax components retaining distinguishable thermal responses. Previous studies on multicomponent MIM binders have shown that the preferential removal of a low-molecular-weight component can generate pathways for the subsequent elimination of the backbone polymer, while preserving the geometry of the molded part [1,2]. In the present study, the separate thermal transitions detected for polyethylene and wax are compatible with the differentiated thermal behavior required for such staged debinding strategies.

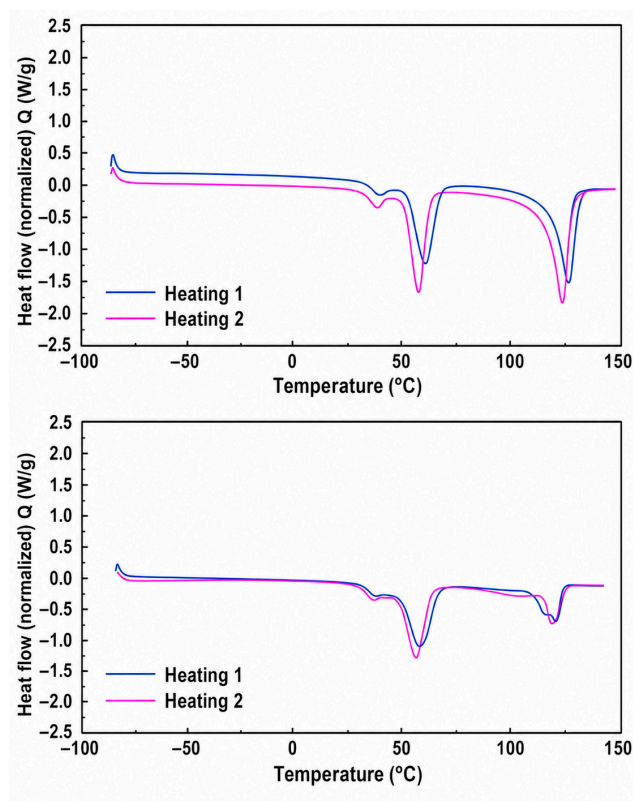


Figure 1. DSC thermograms of the 50HDPE-50PW (**top**) and 50LDPE-50PW (**bottom**) blends obtained under a nitrogen atmosphere: first and second heating scans.

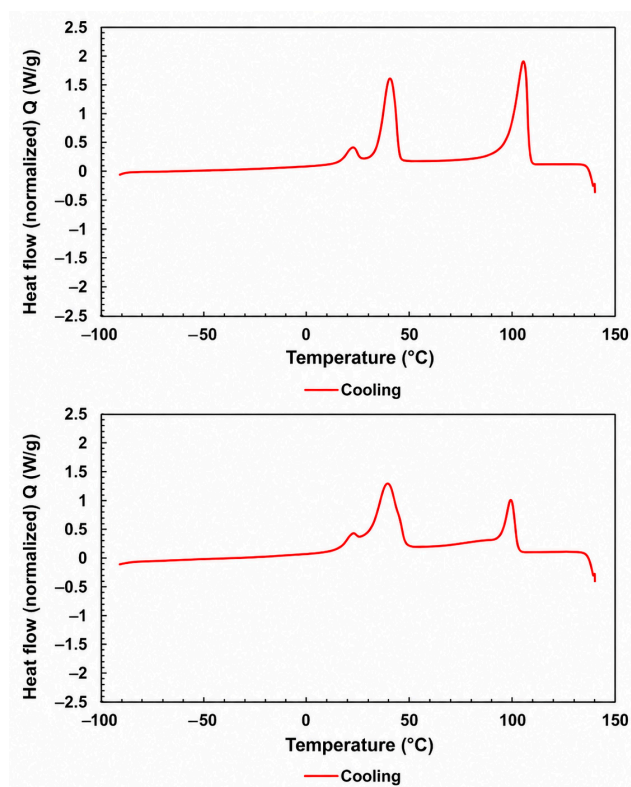


Figure 2. DSC thermograms of the 50HDPE-50PW (**top**) and 50LDPE-50PW (**bottom**) blends obtained under a nitrogen atmosphere: cooling scan.

With respect to the use of octadecane wax, Figures 3 and 4 present the DSC results for the HDPE–octadecane blend. During the first heating cycle (blue curve), wax melting is observed in the temperature range of 31.7–31.9 °C, while polymer melting occurs at 117.2–117.4 °C. This lower melting temperature, compared to the PW-based blends, is consistent with the mechanical results, which showed reduced Young’s modulus and increased ductility in the presence of octadecane.

During the cooling stage (red curve), crystallization peaks corresponding to the wax and the polymer are detected at 18.3 °C and 103.4 °C, respectively. In the subsequent re-heating cycle (pink curve), both components melt at slightly lower temperatures than in the initial heating step, 30.4 °C for the wax and 116.0 °C for PE, possibly due to thermal-history-dependent structural rearrangement or changes in phase interactions during thermal cycling.

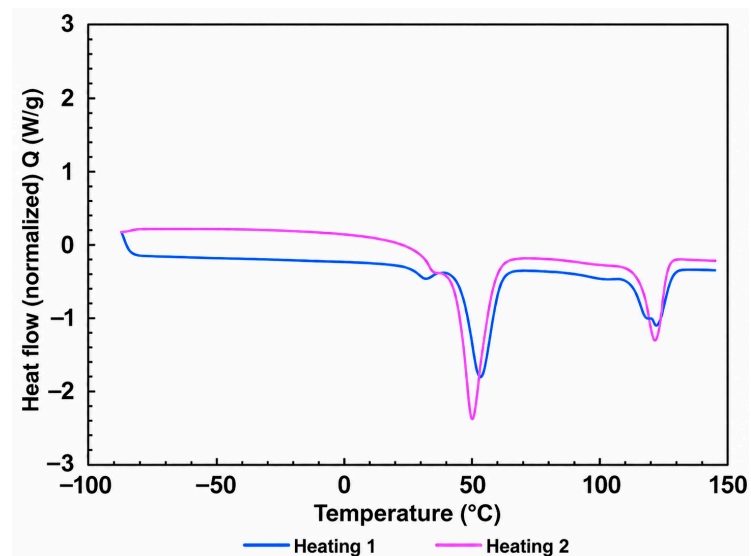


Figure 3. DSC thermogram of the 50HDPE–50OCT blend obtained under a nitrogen atmosphere: first and second heating scans.

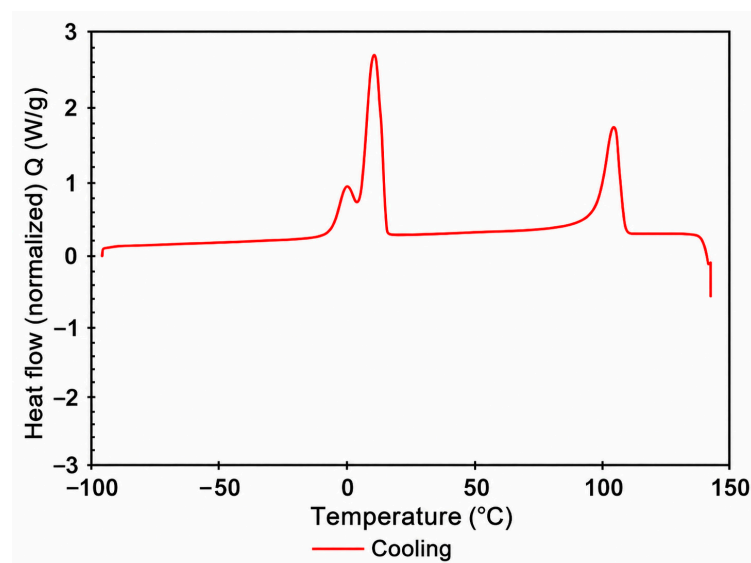


Figure 4. DSC thermogram of the 50HDPE–50OCT blend obtained under a nitrogen atmosphere: cooling scan.

Additionally, as shown in Figure 5, DSC measurements were performed under an air atmosphere. In this case, the analysis aimed to evaluate the influence of both paraffin wax content and composition on the thermal behavior of PE.

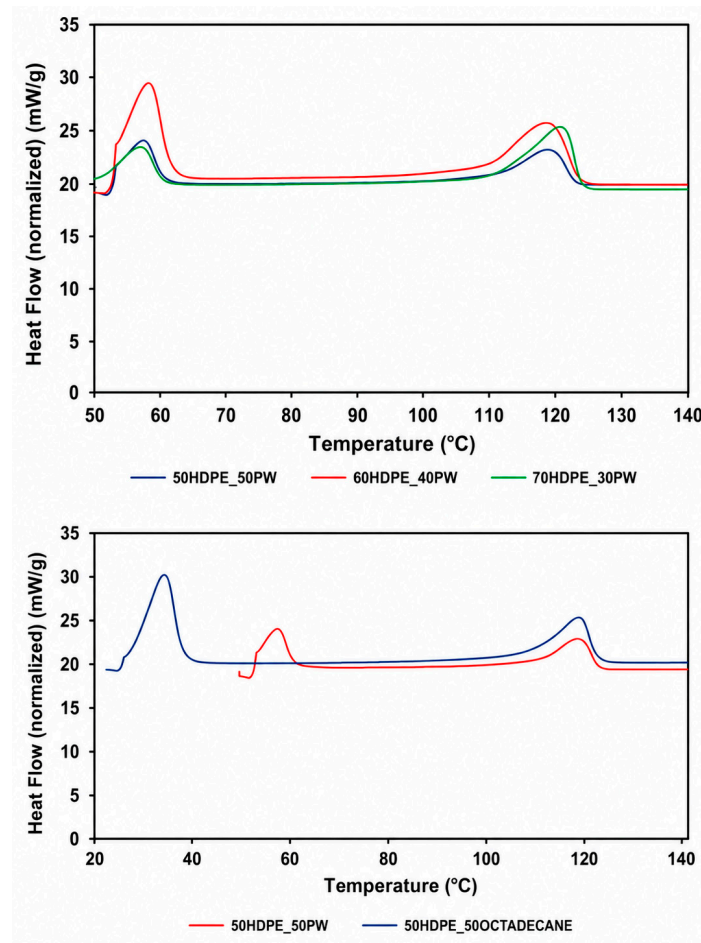


Figure 5. DSC results for HDPE–wax blends obtained under an air atmosphere. HDPE with varying paraffin wax (PW) content (**top**) and HDPE blended with different waxes (paraffin or octadecane) (**bottom**).

The results indicate that wax composition has a negligible effect on the polymer's thermal behavior, as the melting peak of PE appears at a similar temperature (approximately 120 °C) for all samples. In contrast, the wax content has a noticeable impact: increasing the wax fraction in the blend leads to a slight decrease in the PE melting temperature, as illustrated in the upper part of Figure 5. This trend suggests that higher wax concentrations enhance the plasticizing effect within the system.

3.3. X-Ray Diffraction

The crystallinity index and amorphous content of the samples were determined from the XRD data (Figure 6), and the corresponding results are presented in Table 5. The data reveal variations in crystallinity among the different materials, reflecting the influence of both polymer type and blend composition on the resulting microstructure.

The diffraction patterns do not exhibit pronounced crystalline peaks, indicating that the materials are predominantly amorphous. All samples display a broad amorphous halo in the range of approximately 10° to 16° (2 θ). For the 50HDPE–50OCT and 50HDPE–50PW blends, this halo is shifted toward higher 2 θ values compared to pure HDPE.

Additionally, weak diffraction peaks appear at higher angles. A similar trend is observed for the LDPE-based samples.

Table 5. Crystallinity index and amorphous content of the polymers and their blends.

Polymer Blend	Crystallinity Index (%)	Amorphous Content (%)
LDPE	24.85	75.15
50LDPE-50PW	25.83	74.17
HDPE	34.86	65.14
50HDPE-50PW	31.67	68.33
50HDPE-50OCT	29.31	70.69

Experimental results show that pure LDPE exhibits an initial crystallinity of 24.85%, whereas HDPE reaches a higher value of 34.86%. These findings are consistent with literature reports, which attribute the greater crystallinity of HDPE to its higher molecular linearity, facilitating the formation of well-ordered crystalline regions [31].

The incorporation of 50 wt.% PW into LDPE leads to a slight increase in crystallinity, from 24.85% to 25.83%. This behavior can be attributed to the nucleating effect of wax, which promotes the formation of crystalline domains within the mostly amorphous and branched structure of LDPE. Similar effects have been reported for high-molecular-weight waxes acting as nucleating agents in partially amorphous polymer systems [28].

In contrast, blending HDPE with PW results in a decrease in crystallinity, from 34.86% to 31.67%. Although both HDPE and PW are predominantly linear, their interaction appears to hinder the formation of highly ordered crystalline structures. This effect is consistent with previous studies indicating that the incorporation of additional crystalline phases can introduce structural imperfections, ultimately reducing the overall degree of crystallinity in HDPE-based systems [26].

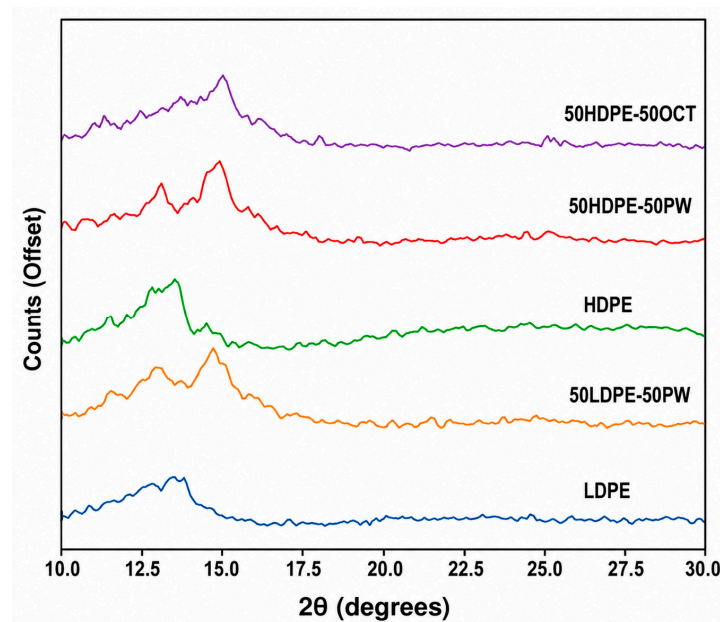


Figure 6. XRD Patterns of LDPE, HDPE, and the corresponding polymer blends.

A more pronounced reduction is observed when octadecane, a lower-molecular-weight wax with 18 carbon atoms, is added to HDPE. In this case, crystallinity decreases to 29.31%. This behavior can be explained by the shorter and more mobile chains of octadecane, which exhibit lower compatibility with the HDPE matrix and disrupt the

formation of ordered crystalline regions. This observation agrees with previous findings, which show that increased molecular mobility in low-molecular-weight waxes can inhibit crystallization in linear polymers such as HDPE [30,39].

These XRD results complement the thermal analysis obtained by DSC. The shifts in melting temperature observed after wax addition are consistent with interactions between the polymer and wax components. However, the apparent crystallinity changes depended on polymer and wax type: a decrease was observed for the HDPE–PW and HDPE–OCT blends, whereas the LDPE–PW blend showed a slight increase. Overall, the results indicate that polymer structure, wax molecular characteristics, and polymer–wax interactions influence the apparent crystallinity and thermal behavior of the blends [30,40,41].

3.4. Simulation Results

This section presents the results obtained from the simulation of the 50HDPE–50PW and 50LDPE–50PW blends using Digimat software.

After performing the simulations, the linear (elastic) response of the materials, corresponding to the initial region of the stress–strain curve, was evaluated. The resulting properties are summarized in Table 6. The density values reported in Table 6 correspond to numerical predictions derived from the constituent properties used in the Digimat model.

Table 6. Properties of the polymer–wax blends predicted using the Digimat model.

	50HDPE-50PW	50LDPE-50PW
Young's modulus (MPa)	649.64	429.24
Poisson's ratio	0.47	0.47
Global density ($\text{kg}\cdot\text{m}^{-3}$)	923	904
Thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	0.33	0.26

As observed, the Young's modulus values obtained from the simulations are consistent with the experimental results presented in Table 4. The predicted Poisson's ratio, density, and thermal conductivity of the blends fall within the ranges defined by the constituent properties. These latter values should be regarded as numerical estimates, since they were not independently measured in the present study. Overall, the results support the use of numerical modeling as a preliminary tool for screening selected properties of binder formulations.

These parameters are critical for the design of injection molding processes. The ability to simulate them provides a valuable tool for preliminary formulation screening. In the context of MIM, accurate knowledge of Poisson's ratio, binder blend density, and thermal conductivity are essential for achieving stable and efficient processing conditions. Poisson's ratio influences material deformation during injection, affecting stress distribution and the formation of defects. Feedstock density governs flow behavior and packing within the mold, which are key factors in minimizing porosity and ensuring dimensional accuracy. Thermal conductivity controls heat transfer during injection and cooling, thereby influencing cycle time, solidification, and the development of residual stresses or warpage. Consequently, the combined experimental–numerical approach adopted in this study provides a preliminary basis for the evaluation of binder formulations prior to their validation in complete MIM feedstocks [1,2,4].

4. Conclusions

The mechanical results show that polymer and wax type influence the stiffness and tensile response of the blends. At the same wax fraction, the 50HDPE–50OCT formulation

exhibited a lower Young's modulus and maximum tensile stress than 50HDPE–50PW. This difference may be associated with the lower molecular weight of octadecane and with differences in polymer–wax interactions; however, the present results do not allow the effect to be attributed exclusively to hydrocarbon chain length. Nevertheless, the mechanical strength of all samples remained sufficient to ensure the mechanical integrity of the neat binder films.

From a thermal perspective, the presence of waxes slightly modifies the melting behavior of PE. Repeated heating and cooling cycles produced small variations in transition temperatures, indicating a thermal-history-dependent response. The distinct thermal transitions associated with the polyethylene and wax components suggest that sequential binder-removal strategies may be feasible.

The area-integration analysis of the XRD patterns indicated changes in the apparent overall crystallinity of the blends. A decrease was observed for the HDPE–PW and HDPE–OCT blends relative to pure HDPE, whereas the LDPE–PW blend showed a slight increase relative to pure LDPE.

The Young's modulus values predicted using Digimat showed good agreement with the experimental tensile results. The predicted Poisson's ratio, density, and thermal conductivity fell within the ranges defined by the constituent properties.

The present results should be regarded as a preliminary characterization of binder constituents rather than a direct prediction of industrial MIM feedstock performance. Nevertheless, the results provide a useful basis for the preliminary screening and design of polyethylene–wax binder formulations prior to their validation in complete MIM feedstocks.

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