

Fabrication and Processing of Polypropylene - Paraffin Compounds with Enhanced Thermal and Processing Properties: Impact Penetration and Thermal Characterization

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ABSTRACT: The compounds of polypropylene (PP) with paraffin wax (PR) as phase change material were fabricated by extrusion melt compounding. The compounds of PR and PP were brittle and showed PR leakage within its melting point range. The maximum 60 weight percent content of the PR was compounded with the polymer. The high amount of paraffin in the polymer plasticized and significantly decreased the melting point of the polymer. The addition of a linear triblock copolymer based on styrene and ethylene/butylene noticeably ameliorated the workability, impact penetration and paraffin retention properties of the compounds. The compounds were further reinforced by carbon fibers and carbon nanotubes that led to an enhancement of their thermal conductivity and heat transfer efficiency. The material structure and thermophysical properties were studied by microscopy and various characterization techniques. The compounds of polymer with PR show phase change effect due to the solid-liquid phase transition of PR within its melting point range. The experimental time vs. temperature curves of the compounds were recorded within the melting range of PR. The experimental curves were compared with the theoretical calculated results. The results were in agreement except small difference that can be attributed to the experimental errors and the assumptions made during theoretical calculations. The manuscript describes the fabrication of shape enduring compounds, with improved thermal, physical, and mechanical properties and their processing by standard techniques, such as extrusion and blow molding. © 2013 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* **2014**, *131*, 40164.

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INTRODUCTION

In everyday life, the optimization of heat flow is necessary because of the high demand of heat at the right time and in the proper amount in various applications, e.g., storage of solar heat at day to be used at night, cooling of the electronic circuits at peak loads, keeping meals warm for a long time and so on. The thermal energy storage is an outstanding way to store energy when it is available for the time when it is inadequate.

The two types of materials used for thermal energy storage are known as sensible heat storage materials and phase change materials (PCMs). A sensible heat storage material, e.g., water heats up and cools down when the heat is stored or released respectively. However, the drawback here is that the temperature increase causes an increase of thermal energy loss, as well.¹ In contrast to the sensible heat storage materials, a phase change heat storage material stores a large quantity of energy during its phase change while maintaining the temperature constant. Once the phase transition is completed the temperature starts to rise

or fall. The latent heat storage is particularly attractive for the applications where a temperature level needs to be sustained.²

PCMs have several applications in energy storage, thermal protection systems as well as in active and passive cooling of the electronic devices.³ The commonly used materials as PCM are inorganic salts, their mixtures and some organic substances, such as paraffins (PRs). The paraffins are the most promising PCMs due to the reasons that they are available in a large temperature range, have higher heats of fusion, negligible supercooling unlike inorganic PCMs, low vapor pressure, chemical inertness, stability, and they are commercially available at very low cost.^{4,5}

Chemically paraffin waxes consist primarily of straight-chain hydrocarbons with a small amount of branching. Paraffins contain in them one major component called alkanes. The melting point of the alkanes increases with the increasing number of carbon atoms. The alkanes containing 14–40 carbon atoms (C₁₄–C₄₀) possess melting points between 6 and 80°C and are

Table I. Material Properties

Material	Properties
Polypropylene (PP)	Hostalen PP, Lyondell-basell Netherlands, H2250 36, 0.915 g cm ⁻³ , Melting point = 165°C
Styrene-ethylene-butylene-styrene (SEBS)	Kraton polymers GmbH, G1654 ES
Paraffin (PR)	RT31, Rubitherm Technologies GmbH, 0.87 g cm ⁻³ , heat storage capacity = 150 J g ⁻¹ (temperature range 19–35°C), melting point = 27–31°C, flash point = 174°C, thermal conductivity = 0.2 W mK ⁻¹
Carbon fibers (CF)	HTA 5131, Toho-Tenax Europe GmbH, 1.8 g cm ⁻³ , length = 6 mm
Carbon nanotubes (CNT)	Baytubes C150, Bayer Material Science AG, Germany, 1.2–1.7 g cm ⁻³

generally termed as paraffins. Commercial waxes, on the other hand, may have a range of approximately 8–15 carbon atoms. The specific heat capacity of the paraffins is about 2.1 kJ kg K⁻¹ and melting enthalpy lies between 180 and 230 kJ kg⁻¹ which is quite high in organic materials. The combination of these two values means excellent storage density which enables paraffins to have 4–5 times more heat capacity by volume or mass than water.⁶ The paraffins go through solid to liquid transition during their phase change. The leaching of the liquid phase of paraffin is required to be controlled within an application. Therefore, it is essential to enclose them in a way that their liquid phase remains invisible at high temperature. Conventionally, they have been kept in the closed containers or tanks. However a new possibility is to blend them with different polymers.⁷ A polymer fixes the paraffin in a compact form that does not allow the paraffin leakage even if it is in the liquid state.^{8,9}

The motivation for the work presented here comes from the fact that the work done in the past for polymer–PR composites as thermal energy storage materials has provided helpful and promising data.^{10,11} There are some challenges associated with these compounds, such as weak processability by conventional processing techniques like injection molding, extrusion or blow molding, PR leakage from the polymer matrix at its melting point, low thermal conductivity, and mechanical properties. An energy storage system should have sufficient thermal conductivity for the heat transfer. There is still a lack of technical literature about the potential polymers, the processing parameters, thermal conductivity, and mechanical property enhancement of such novel materials. The commercialization of such materials demands intensive study to incorporate them in practical applications. The materials are very attractive for various thermal energy conservation applications and have apparent

advantages as heat storage materials as compared to the sensible heat storage materials. So far, polyethylene is the most commonly used polymer for paraffin encapsulation; however, not much literature is available in polypropylene (PP) as encapsulating matrix for paraffins except some of the previous research has shed light on the PP/paraffin composites as processing agents during extrusion with metal particles and their mechanical properties.^{12–14}

In the present research work, PP has been employed as the encapsulating matrix for PR. The compounds have been altered by the addition of SEBS and carbon fillers for better processability and thermal conductivity. The PR used in this work has a melting point in the range of 27–31°C. Such materials can be very valuable in the thermal energy storage applications within the human comfort zone such as self heating fabrics, shoes or gloves if the challenges associated with their processing and thermal properties are overcome and understood completely.

EXPERIMENTAL

Materials

Table I presents the material characteristics. The data given in the table has been taken from the material data sheets provided by the manufacturer.

Extrusion Melt Compounding

The compounds of PP with PR, SEBS, CF, and CNT were fabricated by melt compounding in Coperton ZSK 18 MEGAlab twin screw extruder. Figure 1 demonstrates the extrusion melt compounding and the temperature profile in the transition and metering zone of extruder for the processing of phase change polymer compounds.

Table II presents the constitution and notation of the fabricated compounds. The compound 1 is a mixture of 40% by weight of PP and 60 % by weight of PR. The percentages are given as percent per weight. The parts of each component of the compounds were weighed before compounding.

The PP granulates, SEBS and carbon fillers were introduced into the extruder through the feeding zone. The PR in liquid state was introduced drop by drop through the transition and metering zone of extruder. The extruded strands of the

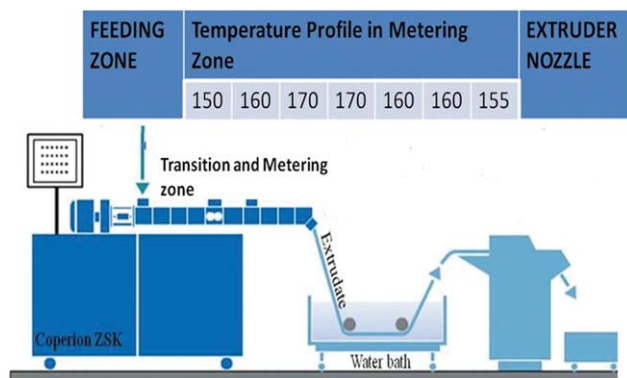


Figure 1. Extrusion melt compounding and temperature profile in extruder heating zones. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table II. Compounds Prepared by Extrusion Melt Compounding

Compositions	Abbreviations
PP	PP
40% PP + 60% PR	PPC1
35% PP + 10% SEBS + 60% PR	PPC2
25% PP + 5% SEBS + 10% CF + 60% PR	PPC3
25% PP + 5% SEBS + 10% CNT + 60% PR	PPC4

compounds were granulated. The granulates were extruded again to ensure homogeneity of the final compound. The pure PP was extruded under the same conditions as for the compounds to keep the similar temperature history. The extrusion melt compounded granulates were used to generate the test samples for differential scanning calorimetry, impact penetration analysis, time temperature study and blow molding.

Material Analysis: Equipment and Methods Used:

1. DSC analysis was done with the help of thermal analyzer DSC-25 Mettler Toledo equipment. The DSC scans for all the compounds were performed in air atmosphere within a temperature range of 25–160°C and a heating rate of 5°C min⁻¹. The thermal properties such as melting enthalpy, latent heat, thermal cycling, and heat capacity of the compounds were investigated. The heat capacity of the composites was measured by DSC according to DIN 51007. The evaluation software STAR SW 8.10 was used to calculate the latent heat of the compounds.
2. Melt volume indices (MVI) of the materials were measured according to DIN EN ISO 1133 standard using the equipment from Göttfert (Schmelzindex, Prüfgerät, Model MP-D).
3. The materials were examined by an instrumented impact penetration machine (Coesfeld GmbH & Co) according to the ISO 6603-2 standards.
4. The thermal conductivity of the composites was measured by LFA 447 Nanoflash according to the DIN EN 821 standard.
5. The experimental time–temperature curves were calculated by tightly packing the finely grounded compound in a test tube (maximum packing fraction $\phi_m \approx 0.54$). The test tube had a diameter of 1 cm, a length of 7.7 cm and the glass thickness of 1 mm. A thermocouple was inserted till the middle of the samples. The open end of the test tubes was sealed with silicone. The sample test tube and a similar test tube filled with water were inserted in the water bath adjusted at 35°C. The temperature rise of the water and test samples as a function of time was recorded using a temperature sensor SE 309.

RESULTS AND DISCUSSION

Paraffin Leakage Test and Microscopy

The PR undergoes solid–liquid phase transition at its melting point. The PR encapsulation has to be efficient enough to keep the liquid phase of PR invisible in an application. The effectiveness of the PP encapsulation was analyzed by keeping the press molded test samples (60 × 60 mm) at 25, 30, and 35°C for 30

min. The melting range of PR lies within the selected temperature interval. The samples wrapped up in the folds of blotting paper were weighed before and after each temperature treatment.

The significant PR leakage was observed from the polymer–PR compound (PPC1) at the melting point of PR. However, the SEBS containing compound PPC2 showed the least PR leakage (Figure 2). SEBS is a triblock copolymer based on styrene-ethylene/butylene-styrene where the saturated soft mid-block is formed by a flexible elastomeric chain of *E/B* (PE/polybutylene) and the two end blocks of polystyrene show hard thermoplastic properties. It is commonly used as an impact modifier for thermoplastics.¹⁵ The reason for reduced PR loss from PPC2 compound could be the chemically different and terminally connected segments of SEBS acting as compatibilizer for the PP and PR. The SEBS improves the miscibility of the compounds.¹⁶

The structure of the compounds was further investigated by the optical and SEM microscopy. It can be seen from Figure 3 that PPC1 compound is a completely immiscible blend of PP and PR. The black holes in the matrix are indicating PR. Whereas the structure of PPC2 compound appears to be more homogeneous and miscible. The microscopy appears to support the observations during leakage tests where it was observed that the presence of SEBS seems to have improved the contact between PP and PR.^{17,18}

The carbon filler containing compounds are presenting an extremely altered matrix morphology. The shape and the orientation of the fillers are important influencing parameters that affect the material structure.¹⁹ It appears that CF has distorted the structure more compared to CNT.

DSC and Thermal Conductivity

DSC measures the heat flow through the sample as a function of temperature. The DSC analysis of the compounds has been demonstrated in Figure 4. The peaks at lower temperatures are the PR melting peaks, whereas, the peaks at higher temperature

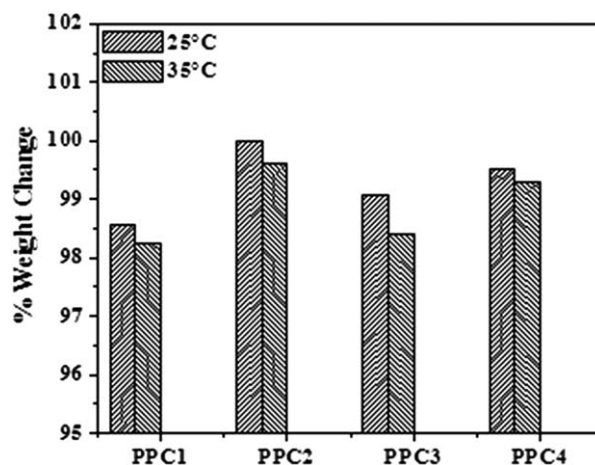


Figure 2. (a) Percent weight change of test samples after 30 min at 25 and 35°C.

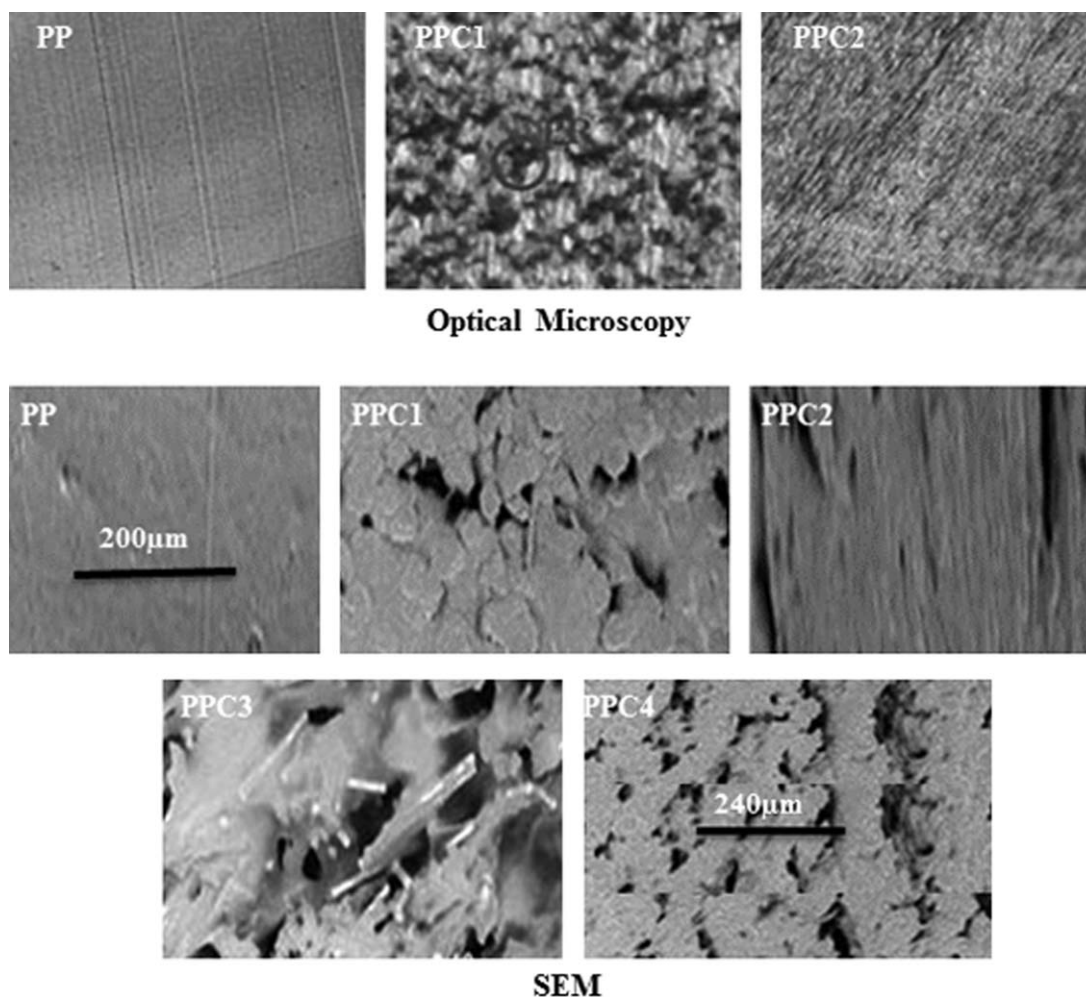


Figure 3. Optical (128×) and SEM microscopy of test samples.

are the polymer melting peaks. The melting point of pure PP is 165°C according to the DSC analysis. The addition of 60 wt % of PR causes approximately 15% decrease in the melting point of PP. However, the melting point of PR is unaffected by the polymer or fillers.

The polymer melting peak for PPC2 compound (with SEBS) is slightly shifted to the higher temperatures indicating that the compound is stable and requires more energy for the melting of crystallites. The polymer melting peak is narrower for PPC4 compound, whereas the polymer melting peak is broadened and lowered for PPC3 compound. The lowering of melting peaks is an indication of fewer crystals in the compound. The effect of fillers at the matrix structure is evident in the microscopic analysis as well that shows significant changes in the matrix structure by the addition of fillers.

The latent heats of the compounds were calculated by the evaluation of the DSC scans. The theoretical calculations were done by the additive rule using eq. (1). The latent heats of the pure PP and PR calculated by DSC analysis were found to be 75 and 122 J g⁻¹, respectively. The experimental and theoretical latent heat of fusion of the compounds is given in Table III.

$$\Delta H_m^{\text{total}} = \Delta H_m^{\text{Polym}} W_{\text{Polym}} + \Delta H_m^{\text{PR}} W_{\text{PR}} \quad (1)$$

where $\Delta H_m^{\text{Polym}}$, melting enthalpy of polymer; W_{Polym} , weight fraction of polymer in compound; ΔH_m^{PR} , melting enthalpy of paraffin; W_{PR} , weight fraction of paraffin in compound.

The samples were heated up and cooled down 20 times by DSC within a temperature range of 22–33°C. The PR phase change takes place within this melting range. After each heat-cool DSC cycle, the latent heat of the PR melting peak was calculated, which was found to be the same after each cycle indicating the stability of PR after repeated charging and discharging by thermal energy.

The thermal conductivity of the compounds increases both as a function of the filler concentration and temperature (Figure 5).

Melt Volume Index

Melt volume index is the touchstone of the ease of polymer flow. MVI (cm⁻³ 10 min) values were recorded for each compound at its respective melting temperatures (determined by DSC). The 4 g of each test sample was taken in the extruder barrel. The materials extrude out of the barrel through a small die hole (Ø 2 mm). The weight of the piston was 2.16 kg. The

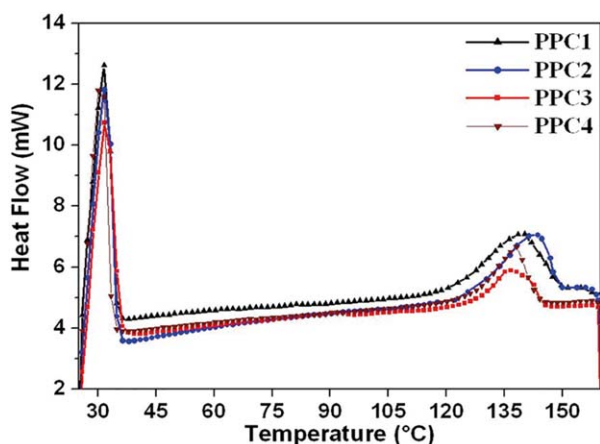


Figure 4. DSC analysis of compounds showing heat flow vs. temperature. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

MFR (melt flow rate) of the compounds was calculated by recording the time taken by the melt to come out of the extruder barrel. The MFR ($\text{g}^{-1} 10 \text{ min}$) for the compounds can be calculated using eq. (2).

$$\text{MFR}(T, m_{\text{nom}}) = 600 \frac{m}{t} \quad (2)$$

m_{nom} , nominal mass (kg); M , mass of the material that comes out of the nozzle; t , time interval for cutting the material that comes out of the nozzle; 600, conversion factor for each g s^{-1} in $\text{g}/10 \text{ min}$ (600 s).

The MFR divided by MVI gives the density of the compounds. The density of the compounds calculated using MVI and MFR data is given in table Table IV.

Theoretical Calculations: Time–Temperature Curves

The designing of a thermal storage unit requires the knowledge of the location of liquid, solid and phase transition temperature, the temperature gradient or all such information. The time–temperature curves of the PCMs were recorded to examine and compare the material data with and without the phase change effect.

Prior to the experimental tests of time–temperature curves of the materials, a theoretical calculation was performed. The heating and cooling of energy storage materials depends upon the surrounding temperature and medium. The numerical solution

Table III. Latent Heat of Compounds by DSC Analysis

	ΔH_m^{PR} Exp./Th. (J g^{-1})	$\Delta H_m^{\text{Polym}}$ Exp./Th. (J g^{-1})	$\Delta H_m^{\text{Total}}$ Exp./Th. (J g^{-1})
PPC1	67/73	27/30	94/103
PPC2	69/73	30/26	99/99
PPC3	69/73	19/19	88/92
PPC4	66/73	20/19	86/92

Exp., experimental; Th., theoretical.

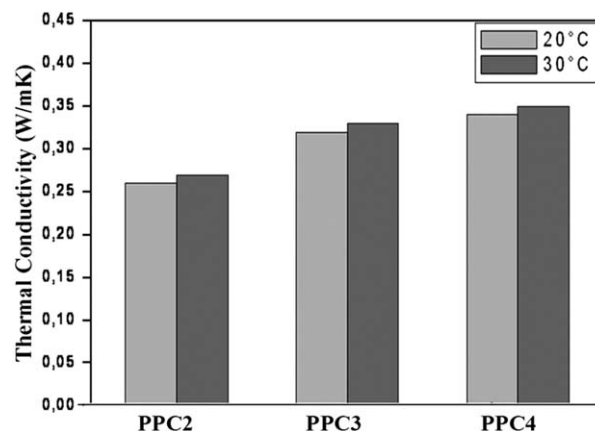


Figure 5. Thermal conductivity of compounds increases by the presence of fillers and as a function of temperature.

for time–temperature curves is based on one-dimensional heat flow in the radial direction. The calculation considers that the sample is a cylinder (1 cm diameter, 7.7 cm long) and the heat is flowing from all sides.

Several fixed-grid methods are available to obtain a numerical solution to the phase change problem.²⁰ In this work, an enthalpy model has been used with a finite solidification temperature interval where enthalpy was determined according to the following equation:

$$H = H_{\text{ref}} + \int_{T_{\text{ref}}}^T \rho C_p(T) dT + \int_{T_{\text{ref}}}^T \rho \frac{dL(T)}{dT} dT \quad (3a)$$

The latent heat is described by a linear function within the mushy zone.

$$L(T) = 0 \quad \text{for } T < T_{\text{solid}}$$

$$L(T) = \Delta H_{\text{lat}} \frac{T - T_{\text{solid}}}{T_{\text{liquid}} - T_{\text{solid}}} \quad \text{for } T_{\text{solid}} < T < T_{\text{liquid}} \quad (3b)$$

$$L(T) = \Delta H_{\text{lat}} \quad \text{for } T > T_{\text{liquid}}$$

Using the above definition for enthalpy the heat equation is written as,

$$\frac{dH}{dt} = \frac{d}{dx} \left(\lambda \frac{dT}{dx} \right) \quad (4)$$

Because enthalpy is assumed to be a function of temperature only, equation (4) is rewritten as,

$$\frac{dH}{dT} \frac{dT}{dt} = \frac{d}{dx} \left(\lambda \frac{dT}{dx} \right) \quad (5a)$$

For one-dimensional heat transfer in the radial direction the following equation is applied.

$$\frac{dH}{dT} \frac{dT}{dt} = \frac{1}{r} \frac{d}{dr} \left(r \lambda \frac{dT}{dr} \right) \quad (5b)$$

Both equations (5a) and (5b) are solved for temperature by applying certain boundary conditions.

Initial Boundary Condition. The initial condition is the temperature distribution at $t = 0$.

Table IV. Density of Compounds by MVI

	°C	MVI (cm ⁻³ 10 min)	MFR (g/10 min)	$\rho = \text{MFR/MVI}$ (g cm ⁻³)
PP	230	0.33	0.30	0.91
PPC1	160	30.33	24.87	0.82
PPC2	160	27.55	24.51	0.89
PPC3	160	60	58.20	0.97
PPC4	160	35	32.55	0.93

$$T(0, x) = T_{\text{init}}(x) \quad (6)$$

Natural Boundary Condition. The natural boundary condition is applied at either $x=0$ or $x=L$ and implies zero heat transfer.

$$\frac{dT}{dx} = 0 \quad (7)$$

Convection Boundary Condition. The convection boundary condition is applied as,

$$-\lambda \frac{dT}{dx} = \pm h(T - T_{\text{inf}}) \quad (8)$$

where the sign of h is positive at $x=L$ and negative at $x=0$.

Dirichlet Boundary Condition. The Dirichlet boundary condition is applied at either end by fixing the value of temperature at the boundary.

$$T(t, 0) = T_L(t) \quad (9a)$$

$$T(t, L) = T_R(t) \quad (9b)$$

In the case of equations (5b), 6–9 are applied with $x=r$ and $L=R$. A list of symbols used in theoretical calculation has been given in the nomenclature at the end of the article.

The heat equations were discretized using a first-order explicit scheme. A computer program written in C++ was used to solve the equations at each time interval. The most important material properties of the compounds such as heat capacity,

density, convection coefficient, latent heat, and thermal conductivity were experimentally determined and the values were used in the computer program within material property files for solving equations. As the program solves the one-dimensional heat equation, it accesses the material property files to perform linear interpolation of the properties according to temperature.

Experimental and Theoretical Calculations: Comparison. The experimentally determined time–temperature curves of the materials have been presented in Figure 6. The figure illustrates a slow temperature change within the melting point range of the PR because of its phase transition. Figure 7 presents a comparison of the theoretical and experimental curves. The results are quite in agreement except certain variations that might be assigned to the experimental errors.

Impact Penetration Testing

The impact penetration test characterizes the ability of an object to resist sudden high loads.²¹ The tests determine the energy absorbed by the sample during high break through. The impact properties of the compounds were analyzed at the press molded test samples with $60 \times 60 \times 5$ mm dimensions.

The falling dart (hemisphere geometry, 4.4 kg, and 20 mm diameter) is accelerated through a guide tube that terminates in the decelerating system, where it stops. The falling height was 300 mm. The speed of the dart is measured by two photoelectric sensors before hitting the sample. The force–displacement

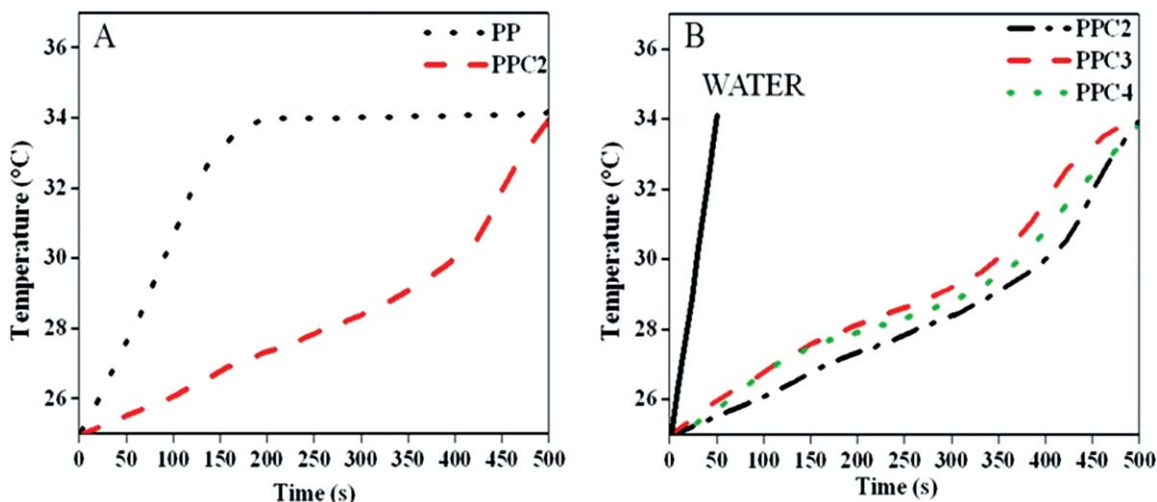


Figure 6. Experimental time–temperature curves of pure PP and compounds. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

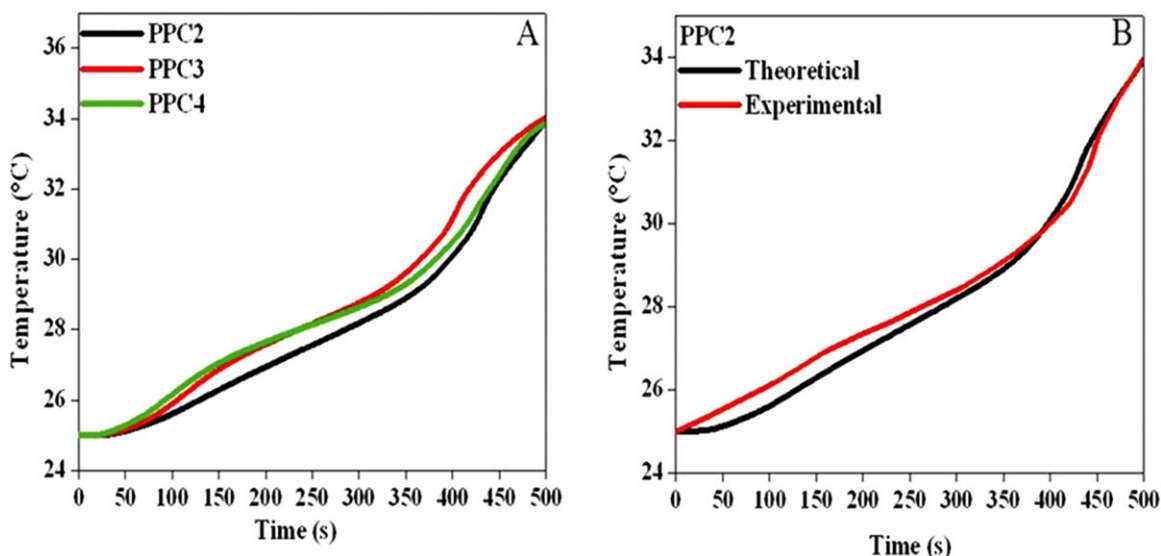


Figure 7. Time–temperature curves: (A) theoretical, (B) comparison. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

curves were obtained after the integration of the measured data. The integration of force–displacement curves calculates the energy.

The results put forth in Figure 8 are showing that the PP is a brittle material, and the brittleness is further enhanced by the addition of PR. However, the addition of SEBS seems to have considerably increased strength and ductility of the compounds. The pictures of cracked specimens are included in the Figure 8, as well. The crack propagation betokens how the material reacts under load.²¹ The analysis of the compounds shows PPC1 compound is brittle that absorbs less energy before the break and shatters into small pieces when the falling dart hit. The PPC2 compound, on the other hand, is manifesting a ductile behavior.

Figure 9 represents the maximum force required to break the sample. The maximum force increases significantly for the PPC2 compound, whereas it has been decreased for the PPC3

and PPC4 compound. The microscopic analysis has shown the distorted structure of the matrix in filler filled compounds. The structural variations due to the fillers might be the reason for low impact properties of these compounds. The PPC2 compound compared to PPC1 compound requires more force to break, ostensibly because of the presence of SEBS.

The crack propagation through CF filled compound is showing brittle behavior, whereas the CNT filled compound are still ductile.

Blow Molding

The blow molding was done at company Roth Werke GmbH, Dautphetal, Germany. The most suitable processing parameters were defined for the blow molding of PPC1 and PPC2 compounds. It was almost impossible to blow mold PPC1 compound. The 60 wt % of paraffin in the polymer plasticized the polymer to the extent that makes it unfit for processing. The preform flows fast and falls along the ground even before the mold closing. Even at the lowest extruder speed and temperature conditions, the material flow was not controllable. The material remained in the mold was not sufficient enough to fill

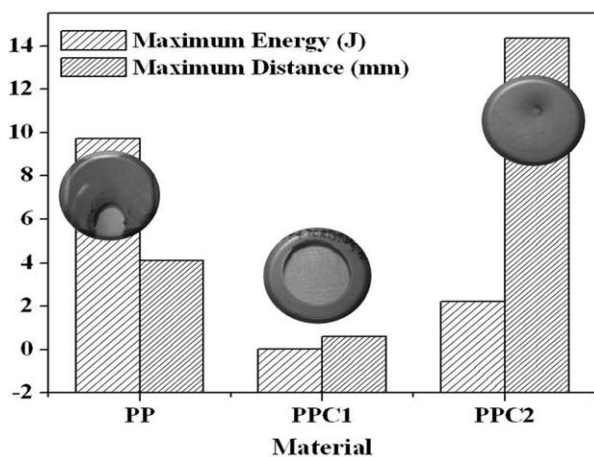


Figure 8. Maximum energy absorbed by PP, PPC1 and PPC2 before break and crack propagation through test samples.

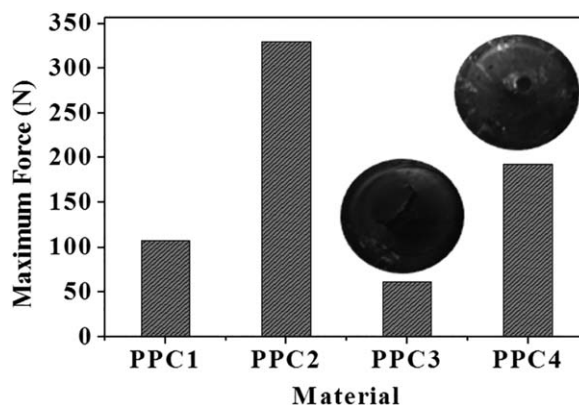


Figure 9. Maximum force needed to break the samples.

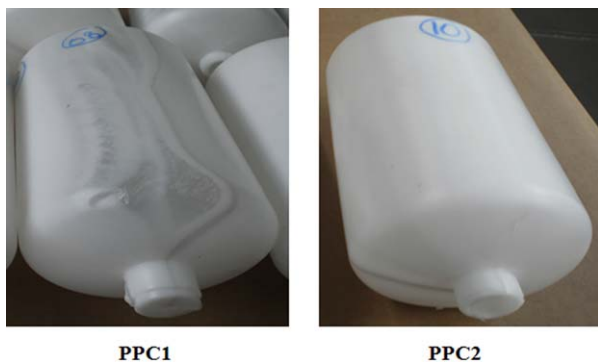


Figure 10. Blow molded parts of PPC1 and PPC2. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the mold completely. The blow molded parts were defective having uneven wall thickness.

The PPC2 compound, on the other hand, had adequate flow rate and filled the mold completely. The outcome was intact blow molded parts with even wall thickness (Figure 10).

The quality of the parts was ensured by measuring the wall thickness of the parts and comparing it to the wall thickness of the pure polymer parts. The compounds with carbon fillers were not blow molded because the industry blow molding setup was not equipped to deal with the carbon fillers. The processing of the materials containing carbon fillers requires intensive cleaning of the equipment after work.

CONCLUSION

The research work presented in this manuscript explains the production of commercially processable, shape stable polymeric phase change compounds for thermal energy conservation applications. The compounds of PP (polymer) with 60 wt % of a commercial paraffin wax (PR) as PCM have been fabricated by extrusion melt compounding. The compounds were further reinforced with a copolymer SEBS and carbon fillers for the enhancement of process ability, impact, and thermal conductivity properties. The processing window has been described for the extrusion melt compounding. The fabricated compounds were analyzed for their thermal and physical properties using different characterization techniques.

The handling of the liquid phase of PR during its phase transition within its melting range is very significant to utilize such materials in an application. The test samples were kept in oven under various temperatures and weighed after each temperature treatment. The compound without SEBS showed most PR leakage. It was observed that the addition of SEBS improves the miscibility of the polymer and PR resulting in the reduction of PR leaching from the matrix. The microscopy was used to study the morphology of the compounds. The structure of compounds with SEBS was homogeneous as compared to the PPC1 compound. The microscopy of carbon filler containing compounds revealed a distorted matrix morphology. The addition of SEBS improved the service temperature, processability and the impact penetration properties of the compounds, as well.

The dynamic scanning calorimetry was used to study the thermal properties such as latent heat storage, heat capacity and melting temperatures of the compounds. The appearance of two peaks in DSC scans of the compounds indicated the encapsulation of PR within the PP matrix. The peak at lower temperatures in the DSC scan appears because of PR melting and at the higher temperature because of the polymer. The thermal conductivity of the compounds increased by the addition of carbon fillers as well as with the increasing temperature. The MVI data was used to calculate density of the compounds. The material behavior under load was observed by the impact penetration analysis. The PPC2 compound showed significantly improved impact properties compared to the rest of the compounds. The CF filled compounds showed brittle crack propagation, whereas CNT filled compounds had crack propagation like a ductile material. The morphology of the matrix is largely affected by the shape and orientation of the fillers resulting in high variations of the material properties. The time–temperature curves of the materials were calculated based on the enthalpy model with finite solidification temperature interval. The comparison of experimental and theoretical calculated time–temperature curves followed the same trend within the range of experimental errors. The PPC1 and PPC2 were blow molded, as well, to test their workability by the commercial processing technique. The PPC2 compound was blow molded to the parts with quality comparable to the standard blow molded parts.

In summary, the work evaluates the production procedure, thermo-physical property analysis by various characterization techniques, blow molding and the theoretical and experimental time–temperature behavior analysis of the polymeric phase change compounds. The materials are a very attractive addition to the energy conservation applications because of their compactness and practicality. The more and more technical literature about processing, potential polymer encapsulants, thermal conductivity enhancement of these materials is needed for their use in commercial applications.

NOMENCLATURE

T	Time (s)
X	Position (m)
Q	Heat flux (W m^{-2})
Λ	Thermal conductivity (W mK^{-1})
P	Density (kg m^{-3})
C_p	Specific heat capacity (J gK^{-3})
T	Temperature (K)
R	Radial position (m)
T_{init}	Initial temperature (K)
L	Total length of specimen (m)
R	Total radius of specimen (m)

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