Recycling of Tetra Pak for Space and Water Heating by Blending with Phase Change Materials

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Abstract

A rapid rise in demands for thermal comfort in the building sector necessitates higher energy consumption for air conditioning, ventilation, space, and water heating systems. Recently, phase change materials (PCMs) have gained much attention from researchers for passive heating/cooling of space and water. PCM can store/release thermal energy as latent heat during its phase change process isothermally. Moreover, PCM facilitates solar energy harvesting by photothermal conversion and storage. However, major limitations of PCM include low thermal conductivity, leakage during phase change, and lack of photoabsorbance. Therefore, in this study, the shape-stabilized phase change composites were prepared by melt blending of Paraffin Wax (PW), Tetra Pak (TP), and expanded graphite (EG). PW is an organic PCM, widely being studied due to its high enthalpy, availability at various melting points, and chemical and thermal stability. In addition to providing shape stability and thermal conductivity enhancement of PCM, the usage of TP promotes the recycling of TP waste into useful products. The addition of EG contributes to the thermal conductivity increase of 3.6 times that of pure PW. Moreover, the excellent photoabsorption of EG and TP effectively converted the photo energy to thermal energy and stored it as latent heat by PW in the composite. Two types of composites using PW of melting points 44 °C and 64 °C were exhibited a photothermal conversion and storage efficiency of 80 and 55 %, respectively and which is promising for solar water heating applications.

Keywords: Tetra Pak; Phase change material; Space and water heating; Recycling; Photothermal conversion

1 Introduction

Recently, the global energy demand in the building sector has increased with the rapid social and economic development of society. Heating, ventilation, and air conditioning systems are often used for thermal comfort in buildings that consume conventional energy resources. In order to deal with environmental concerns and the depletion of conventional energy resources, the development of efficient and renewable sources of energy is essential. Solar energy is an important renewable energy source due to its endless reserves (Kannan & Vakeesan, 2016; Shahsavari & Akbari, 2018). Studies on the efficient utilization of solar energy have gained much attention due to its carbon-neutral and renewable characteristics. Solar energy is often transformed into electrical and thermal energy by photovoltaic and photothermal conversion techniques (Boldoo et al., 2020; Rawat et al., 2017). Photothermal conversion is the most efficient and simple solar energy utilization technique for space

and water heating (Arunkumar et al., 2020; Tyagi et al., 2012; Vengadesan & Senthil, 2020), power generation (Zhanget al., 2018b), desalination (Wang, 2018), etc. However, thermal energy storage (TES) systems are required for a continuous supply of heat energy due to the intermittent properties of solar energy. Phase change materials (PCMs) are widely adopted for TES systems to store thermal energy isothermally (Chaturvedi et al., 2021). Among various types of PCMs, paraffin waxes are usually used in practical applications due to the commercial availability of various grades having different phase change temperatures and latent heat, non-corrosiveness, and negligible supercooling (Gulfam et al., 2019). However, low thermal conductivity, shape instability, and poor photoabsorption are the major drawbacks of paraffin in practical applications of energy conversion and storage (Karkri et al., 2015).

There are different strategies adopted to overcome the above limitations, including microencapsulation in the polymeric matrix (Maithya et al., 2021; Yuan et al., 2020; Zhang et al., 2018a), PCMs impregnated in porous materials(Maleki et al., 2019; Umair et al., 2019; Yang et al., 2016), and blending with polymers (Chriaa et al., 2021; Hu, 2020; Mochane & Luyt, 2015a, 2015b; Sobolčiak et al., 2021). Recently, polymeric phase change composites have attracted researchers due to their (i) cost-effectiveness, (ii) high mechanical strength, (iii) efficiency in leakage prevention and heat storage capacity enhancement, (iv) lightweight characteristics with a high strength/weight ratio, and (v) abundance and availability.

Among various polymeric phase change composites, polyethylene and paraffin wax blends have attracted much attention due to their chemical and structural similarities (Hu, 2020; Krupa et al., 2007). They provide good processability, are lightweight, and are low-cost. Krupa et al. (Krupa et al., 2007) examined the energy storage capabilities of low-density polyethylene blends (LDPE) with paraffin wax. The LDPE base provides a compact shape to the composite, while the paraffin wax stores latent heat during melting. The usage of recycled polymer waste in the composite preparation not only improved the thermophysical properties but also provided their sustainable application. Similarly, the tetra Pak waste has gained much attention from researchers to provide an efficient reuse application. Therefore, in this study, PCM composites were prepared by blending PW with recycled tetra Pak and expanded graphite to enhance the PCM shape stability, thermal conductivity, and photo absorbance.

2 Experimental

2.1 Materials

Paraffin wax RT44 and RT64 ((Rubitherm® Technologies GmbH, Germany), and expanded graphite (EG, average particle size of 200 µm, SIGRATHERM®, SGL Carbon, Germany), Tetra Pak (TP) waste consist of 20 % aluminum and 80 % low-density polyethylene (Zlin, Czech Republic) were used for the preparation of the PCM composite.

2.2 Composite Preparation

The components in the required weight fraction were mixed in a Brabender® Plastograph® EC W50 PLE 331 (Duisburg, Germany). The components were melted at 160 °C and mixed at a speed of 35 rpm for 10 minutes (Figure 1). The composite was then hot-pressed at 160 °C for 3 minutes using a hydraulic mounting machine at 3-ton force.
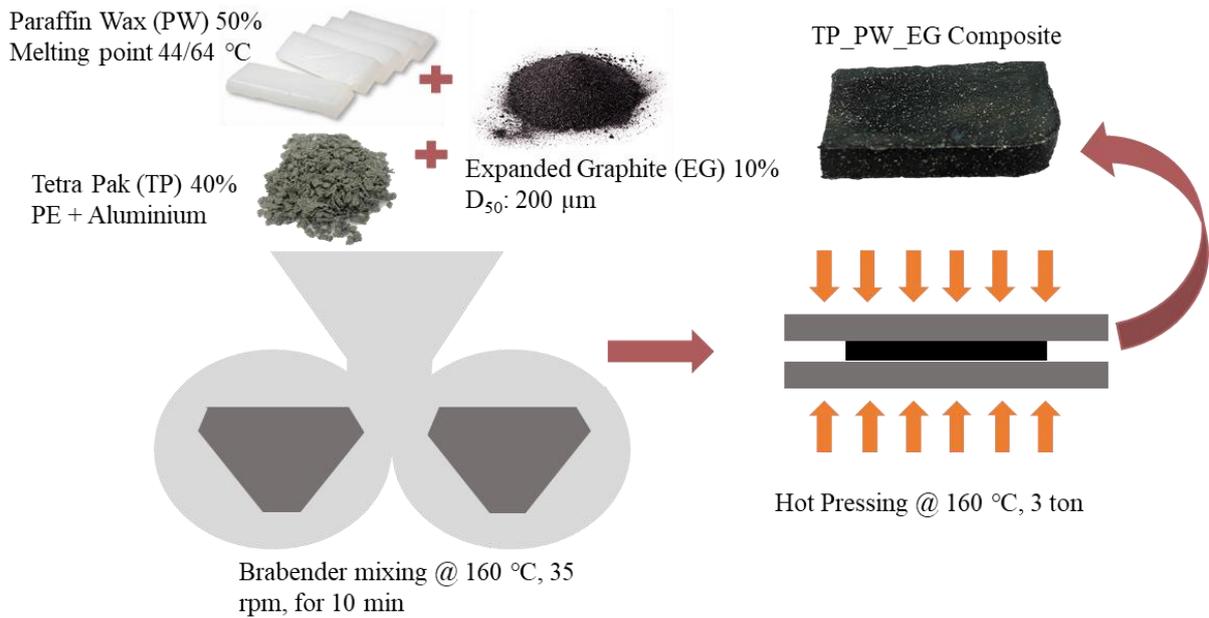
Fig. 1: Schematic representation of TP_PW_EG composite preparation

2.3 Material Characterization

The thermal conductivity of the TP_PW_EG composite was measured on a cylindrical sample of size 7 cm diameter and 9 mm height using the ISOMET apparatus (Applied Precision, Slovakia). The thermal flow in the material was measured using a flat probe at 20 °C. The thermal conductivity measurements were reproducible with an accuracy of 5 % of reading.

The leakage of PW from the composite was measured when the TP_PW_EG composite was placed in an oven at a temperature of 80 °C. The strips of sample specimens with size 60x60x1 mm were placed in the oven for 14 days and the sample weight loss was noted using an analytical balance. The percentage of the PW weight loss in the composite was calculated from the equation:

$$Weight\ loss = \frac{(m_0 - m)}{m_0 \times w} \times 100\ (\%) \tag{1}$$

The thermophysical properties of the composite were measured using differential scanning calorimetry (DSC 8500, Perkin Elmer, USA) at a rate of 10 °C/min. The latent heat and phase transition temperatures were obtained from DSC and the average values at the second heating cycle are presented with an accuracy of ±0.05 °C for the temperature and 0.2 % for the heat flow.

2.4 Photothermal Conversion Testing

The photothermal conversion and storage capacity of the composite were tested under simulated sunlight of intensity 1000 W/m² using a solar simulator (Sunlite, ABET Technologies). The changes in the sample top and bottom temperature and heat flux during the energy conversion and storage process were measured using an infrared thermometer (Testo 845, Germany), a T-type thermocouple, and a heat flux sensor (Captec, France), respectively. The data collection and analysis were carried out using a CR1000X datalogger (CampBell Scientific, USA). A schematic of the photothermal conversion test system is shown in Figure 2.
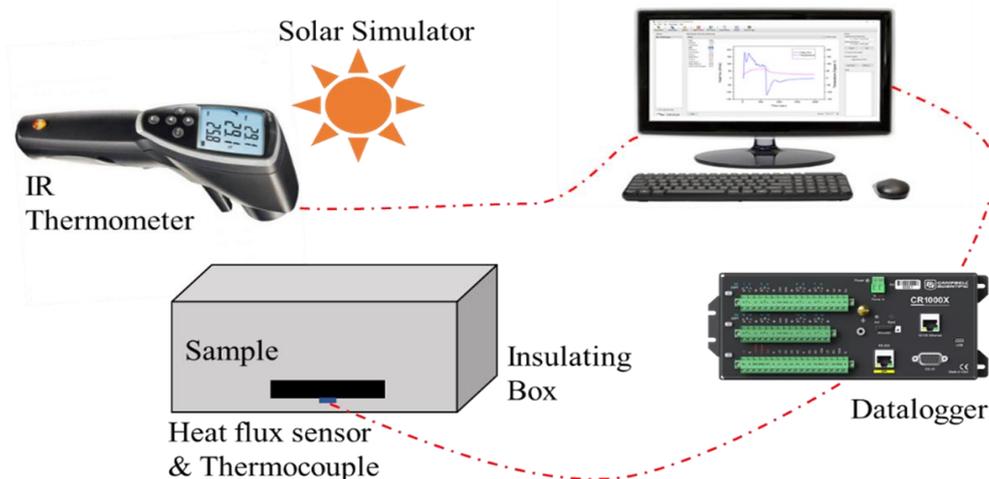
Fig. 2: Schematic representation of photo-thermal energy conversion and storage performance measuring system

3 Results and Discussion

3.1 Thermal Conductivity

The pure TP, RT44, RT64, TP_RT44_EG, and TP_RT64_EG showed thermal conductivities of 0.48, 0.20, 0.19, 0.71, and 0.70 W/m. K, respectively. The introduction of TP and EG into the PW enhanced the thermal conductivity of the TP_PW_EG composite by around 3.6 times that of pure PW.

3.2 Shape Stability

The PW leakage from the TP_PW_EG composite determines the shape stability of the composite. The mass loss of composite over 14 days in the oven at 80 °C was less than 7 %. These results show that the TP matrix effectively encapsulates the PW to prevent the leakage of PW even after melting for a long time. In addition, the porous configuration of EG prevents the leakage of infiltrated PW via the capillary and surface tension forces.

3.3 Thermophysical Properties

The phase change enthalpy and temperatures of pure PWs (i.e., RT44 and RT64) and TP_PW_EG composites attained from DSC analysis are shown in Figure 3. The thermal characteristics estimated from the DSC curves are shown in Table 1. It can be observed from the DSC curves (Figure 3) that RT44, RT64, and their composites have two exothermic and endothermic peaks during the heating and cooling due to an intermediate solid-solid phase change. The temperatures of solid-solid and solid-liquid phase transition processes are close during melting for RT44, RT64, and their composites as seen in Figure 3. However, two distinct peaks for liquid-solid and solid-solid phase change are observed during the crystallization process as shown in Figure 3. The solid-liquid transition peak of the composites (i.e., T_m) was slightly varied from pure PW as shown in Table 1 and Figure 3. However, the liquid-solid transition peak (i.e., T_c) was decreased by 1.8-2.3 °C in the composite than pure PW. This reduced phase change temperature of the composites than pure PW is due to the confinement of PW in the microscopic pores of TP and EG, which prevents molecular motion during the phase transition process (Li et al., 2020).
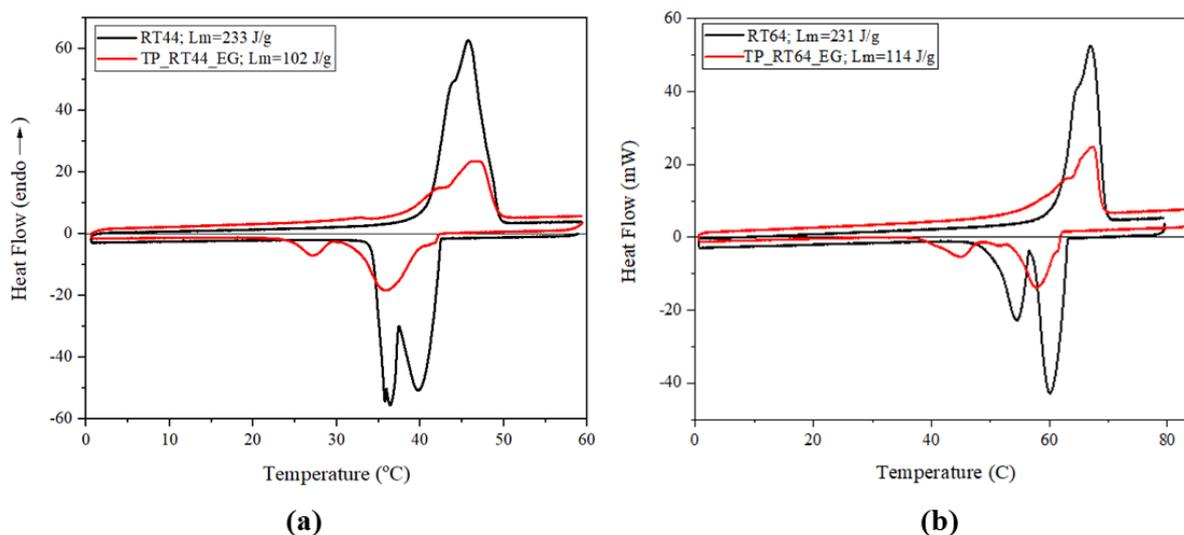
Fig. 3: DSC curves of pure PW and TP_PW_EG composites; (a) RT44, and (b) RT64

Table 1: Thermal properties of PW and TP_PW_EG composites from DSC
(Standard deviations from three samples are shown in parenthesis)

Sample	Heating			Cooling		
	$T_{s\text{-}s}$ (°C)	T_m (°C)	ΔH_m (J/g)	$T_{s\text{-}s}$ (°C)	T_c (°C)	ΔH_c (J/g)
RT44	43.7	45.7	233 (0.1)	36.1	39.5	231.3 (0.1)
TP_RT44_EG	41.9	46.4	102 (0.2)	27	35.7	100.5 (0.1)
RT64	64.5	67.0	231 (0.2)	54.3	60.2	225.9 (0.1)
TP_RT64_EG	62.8	67.2	114 (0.4)	45.1	57.9	112.8 (0.3)

3.4 Photothermal Conversion

Figure 4 shows the sample top and bottom temperature and heat flux evolution plots of the TP_RT44_EG and TP_RT64_EG composites under the simulated solar irradiation of 1000 W/m^2 for 20 or 30 minutes. The sample was placed in an insulation box to avoid heat loss from the bottom and sides of the composite.

As shown in Figure 4, the temperature and heat flux of the composite increase with time during solar irradiation indicating the photothermal conversion capacity of the composite. The heat flux decreases or stabilizes during the phase transition. The conductive heat flux passing through the composite was partially absorbed for the melting of PW which decreases the temperature rise. Therefore, the temperature evolution curve shows a plateau in the PW melting range. After the completion of the phase transition, the heat flux and temperature started to increase rapidly. The time taken for the phase transition of the RT64 composite was higher than the RT44 composite .
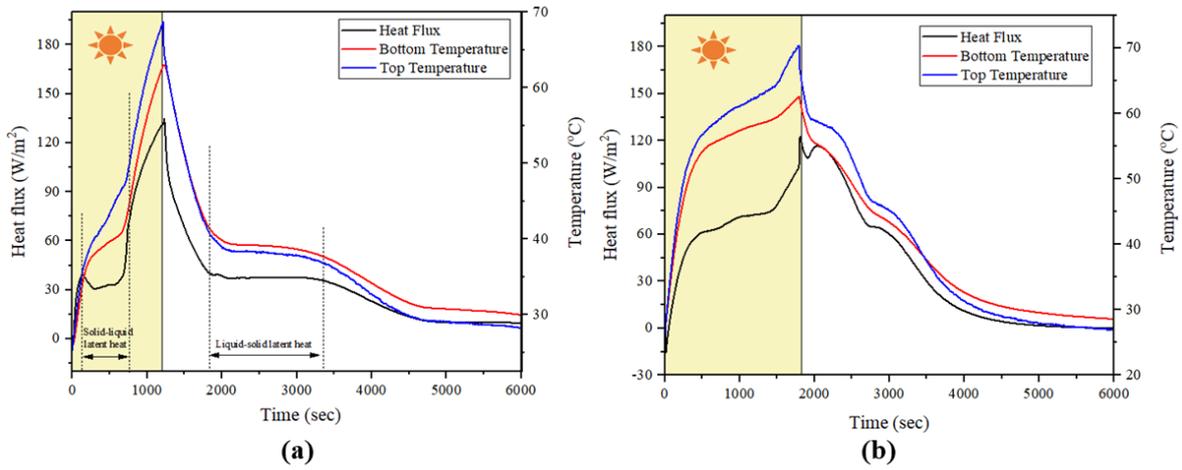
Fig. 4: Temperature and heat flux-time evolution curves of TP_PW_EG composites;
(a) TP_RT44_EG, and **(b)** TP_RT64_EG

The photothermal conversion and storage efficiency (η_p) was calculated by the ratio of the latent heat of the paraffin to the energy of simulated solar light during a phase change Therefore, the storage efficiency is,

$$\eta_p = \frac{m\Delta H}{PS\Delta t} \tag{3}$$

considering all the paraffin in the composite undergone phase transition.

where m is the mass of the composite, ΔH is the latent heat enthalpy, P is the intensity of the light source, S is the surface area of the composite and Δt is the time taken for phase change.

The efficiencies of the composites with RT44 and RT64 were 80 and 55 %, respectively. The reduced efficiency of the TP_RT64_EG composite was due to the increase in time taken for phase change as shown in Figure 4b. This could be due to the increased convective heat loss from the sample surface with the rise in temperature.

4 Conclusion

In this study, a shape-stabilized phase change composite was fabricated by the physical blending and hot pressing of TP, PW, and EG. The integration of TP and EG into the composite significantly enhanced the thermal conductivity and reduced the PCM leakage of the composite. The composite with 10 wt.% EG has a thermal conductivity of 0.71 W/m.°C, which was 3.6 times higher than that of pure PW. The latent heat of the composite varied in the range of 102-112 J/g. The TP provided shape stability to the composite and reduced PW leakage during phase change. In addition to the enhanced physical properties of the composite, usage of TP provides an application for recycled TP from Tetra Pak waste. Two types of composites using PW of melting points 44 °C and 64 °C were exhibited a photothermal conversion and storage efficiency of 80 and 55 %, respectively. The excellent photothermal conversion capacity of the composite can be effectively utilized for solar thermal energy conversions and used for space and water heating applications in the building industry.

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