



Research Paper

Heat transfer performance of paraffin wax based phase change materials applicable in building industry



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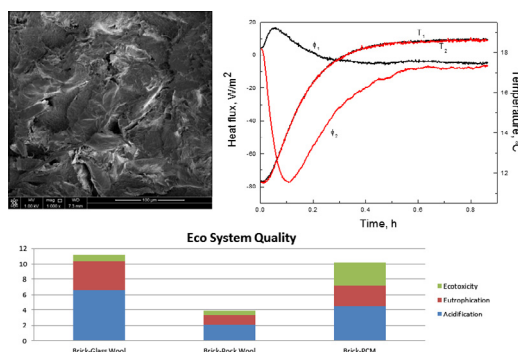
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HIGHLIGHTS

- Thermal characterization of PCMs based on paraffin wax was accomplished.
- PCMs were able to store and release large amount of thermal energy.
- Thermal conductivity of PCMs increases 4 times by adding 15 wt.% of graphite.

GRAPHICAL ABSTRACT



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ABSTRACT

Thermal characterization of phase change materials (PCMs) composed of linear low-density polyethylene (LLDPE), paraffin wax (W) with a melting point of 25 °C, and expanded graphite (EG), that are highly effective in thermal energy storage systems in the building industry, is reported.

Thermal investigation of PCMs with various compositions of LLDPE, W and EG has been performed by nonconventional transient guarded hot plane technique (TGHPT) and compared with conventional differential scanning calorimetry (DSC) measurements. An excellent agreement in determination of thermal characteristics by both methods was found.

Abbreviations: a.u., arbitrary unit; c_p , specific heat capacity of the specimen (kJ/kg·°C); DSC, differential scanning calorimetry; e , thickness of specimen (m); EG, expanded graphite; L_m , latent heat of melting (kJ/kg or J/g); LCA, life cycle assessment; LLDPE, linear low density polyethylene; nd, not determinate; PCM, phase change material; Q_s , heat sensible (kJ/kg or J/g); Q_{total} , heat total (kJ/kg or J/g); SSPCM, shape stabilized phase change materials; W, paraffin wax rt 25; T , temperature (°C or K); T_{init} , initial temperature (°C or K); T_{end} , temperature on the end of measurement (°C or K); T_m , melting temperature; TGHPT, transient guarded hot plate technique; ΔH , melting enthalpy (kJ/kg or J/g); λ , thermal conductivity (W/m·K); ρ , density (kg/cm³).

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The highest values of the total amount of stored energy, sensible heat for solid and liquid states (Q_{total} , $Q_s(\text{solid})$ and $Q_s(\text{liquid})$, respectively) were found for the PCMs with composition LLDPE/W/EG = 40/50/10 and 35/50/15 w/w/w.

Moreover, thermal conductivity and diffusivity of PCMs have been significantly improved by adding EG. Additionally, life cycle assessment was performed to evaluate the environmental impact of three different materials as glass wool, rock wool and PCM used with brick wall.

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1. Introduction

An increasing demand of energy can be observed worldwide and is, so far, mainly satisfied by fossil fuels [1]. However, the conventional fossil energy sources are depleting, and their secondary usage is related to the emission of harmful gases, which rapidly accelerates greenhouse effects [2].

The building industry, in particular, consumes up to 40% of the annual energy production, which is directly related to the release of one-third of the globe's greenhouse gas emissions [3].

One good possibility for minimizing the total amount of energy in order to maintain desirable living temperatures would be based on employing special energy storage materials, such as phase change materials.

Phase change materials (PCM) are substances with a high heat of fusion which, through melting and solidifying at certain temperatures, are capable of storing or releasing large amounts of energy. The main principle of PCMs in terms of thermal energy storage, is based on energy absorption and generation whenever a material undergoes a phase change from solid to liquid, liquid to gas, or vice versa [4].

PCMs have high latent heat values and they are capable of both storing and releasing a large amount of energy during a phase change within minor temperature variations [5,6].

PCMs thermal energy is stored during the off-peak load period. This energy is then released during the peak period. Thus, such thermal energy storage properties for PCMs are intensively investigated to obtain materials with high densities of thermal energy per unit volume/mass which are applicable in various engineering fields for a wider range of temperatures [7–14].

PCMs could be divided into certain categories: organic PCMs, inorganic PCMs and mixtures of them [8,9]. Among them, paraffin produced as by-products in crude oil refineries is known as the most useful PCMs for thermal storage at low temperatures due to their large latent heat (around 200 kJ/kg) and good thermal and chemical stability [10]. Paraffins are saturated mixtures of *N*-alkanes with melting temperatures ranging between 0 °C and 90 °C.

A significant drawback of the paraffins in thermal exchange applications is their low thermal conductivity (0.2 W/m·K). Therefore, fillers with high thermal conductivity are highly advantageous once added into the materials. Hence, expanded graphite is widely used for increasing the thermal conductivity of PCMs [11–13].

Another significant issue to point out is the stability of paraffin blends, knowing the fact that liquid paraffins tend to leak out from blends. There are several approaches to prevent leakage of the paraffins from the blends compact shapes during the solid–liquid phase change transition through blending them with polymers [14–17], encapsulating them within a polymeric or inorganic shell to form microcapsules [18–22] or stabilizing them by adding graphite particles leading to penetration of the paraffins between the graphene layers [23,24].

Recently, Krupa et al. [25] reported the use of linear low-density polyethylene for shape stabilizing PCM blends containing paraffin wax as an active PCM substance supported by expanded graphite

particles which absorbed large quantity of thermal energy caused by melting of paraffin wax within blends, while the polymer matrix retained the material compact on the macroscopic level.

Moreover, thermal and mechanical performance over wide temperature range has been published for these shape stabilized PCMs [26]. Additionally, artificial aging of these PCMs have been tested in order to get information about their stability and degradation over long time. It was found that expanded graphite prevented the leakage of paraffin wax from compact shape as well as retarded photochemical degradation of PCM blends [27].

In addition, intensive investigation of thermal characteristics for phase change systems is considered crucial for larger industrial applications. Differential Scanning Calorimetry (DSC) is a common method mainly used for characterizing the thermal properties of PCMs, providing a “benchmark” required to estimate the melting and crystallization temperatures, the specific heat of melting and crystallization or the specific heat capacity [28,29]. However, DSC measurements provide information about the thermal properties of micro-sized samples that can be significantly influenced by local heterogeneities. Therefore, PCMs constructed by mixing two or more immiscible components need to be characterized as larger pieces of the specimens.

Very recently, new methodologies based on transient guarded hot plane technique have been developed and used for thermal investigation of various PCM systems in large sized samples at long-term performance [30–34].

In this study, PCMs based on LLDPE, W ($T_m = 25\text{ °C}$) and various concentrations of EG have been prepared and their thermal properties have been studied. Investigated PCMs possess a high potential making them suitable in use as effective thermal energy storage system due to optimal phase transition (around 25 °C) close to comfort temperature in residential and commercial buildings. Latent heat of PCMs has been examined by TGHT as well as conventional DSC measurement.

2. Experimental

2.1. Materials

LLDPE (MFI = 1 g/10 min, QAPCO, Qatar), W (Grade RT 25HC, Rubitherm Technologies, Germany) EG (GFG200, SGL Carbon, Germany) having an average size of 200 μm were used for the PCMs preparation.

Thermal characteristics of materials used for SSPCMs preparation are shown in Table 1.

2.2. Samples preparation

Certain amount of LLDPE, W and EG were first blended in the 30-ml mixing chamber of a blending machine (Brabender Plastimeter PLE 331, Germany) at 140 °C for 8 min at a mixing speed of 35 rpm. Specimens of the required shape were then hot pressed using a Fontijne 200 laboratory press (The Netherlands) at constant pressure (50 Mpa) and temperature 140 °C for 5 min.

Table 1

Thermal properties of materials used for SSPCMs preparation.

	T _m (°C)	ΔH (J/g)	λ (W/m·K)
LLDPE ^a	122	100	Around 0.4
W ^b	25	150	Around 0.2
EG ^c	nd	nd	Horizontal 300–2000, vertical 20

^a Measured by DSC.^b www.rubitherm.eu.^c www.sglgroup.com.

Parallelepiped-shaped specimens (45 × 4.5 mm) and thickness 1 or 5 mm were prepared. The thickness of the specimens 1 mm was used for SEM and DSC measurement and thickness of the specimens 5 mm was used for TGHPT and Thermal conductivity and diffusivity measurements.

Fig. 1 shows images of neat LLDPE and PCMs without EG and with 15 wt.% of EG.

The composition of samples investigated in this study, their thickness and their specific density (ρ) are listening in Table 2. Thickness of the specimens was measured at the different place and the average values are presented. Standard deviation of thickness was up to 5%.

2.3. Characterizations

2.3.1. Scanning electron microscopy

The fracture surfaces of the specimens were inspected by a Nova Nano SEM 450 Scanning Electron Microscope at operating voltage 1 kV. Brittle fractures of the specimens were achieved by immersing 1 mm thick specimens to liquid nitrogen for 30 s and subsequent breakage of the specimens.

2.3.2. Differential scanning calorimetry

DSC measurements were carried out by a Perkin Elmer DSC 8500 differential scanning calorimeter. Specimens were precisely weighed (from 3 to 7 mg).

First, the specimen was heated from 10 to 160 °C while keeping constant heating rate 2 °C min⁻¹ and then cooled down at the same heating rate in order to eliminate the influence of sample preparation. The thermal properties were obtained from the second heating run.

All measurements were repeated at least three times.

2.3.3. Transient guarded hot plate technique (TGHPT)

Fig. 2 shows schematic design of experimental device which is projected for the parallelepiped-shaped specimens.

Temperature and heat flow characteristics was inspected on the opposite borders of the specimen. The specimen is set between two parallel aluminum thermal exchanger plates giving a precise regulation of fluid temperature with a (accuracy up to 0.1 °C). Heat flow sensors and thermocouples (type T) are placed on each side of the

Table 2Composition of prepared specimens and their densities (ρ).

Samples	LLDPE/W/EG (w/w/w)	Thickness (mm)	ρ measured (g/cm ³)
S1	100/0/0	4.35	0.9235 (0.001)
S2	60/40/0	4.32	0.8949 (0.004)
S3	50/50/0	4.32	0.8751 (0.002)
S4	45/50/5	4.35	0.8988 (0.002)
S5	40/50/10	4.34	0.9003 (0.002)
S6	35/50/15	4.37	0.9431 (0.002)

Numbers in brackets are standard deviations.

composite (Fig. 2) with the sensitivity around 202 $\mu\text{V/W/m}^2$ flow. The insulation by polyethylene foam prevented heat losses out of the specimen environment. Temperature range between 10 °C and 30 °C was used for TGHPT characterization.

Similarly to this study, TGHPT method for measurement of heat characteristic of various materials has been published previously [34].

2.3.4. Measurement of thermal conductivity and diffusivity

Thermal conductivity and thermal diffusivity was obtained using the periodic temperature ramp method (Fig. 3) by means of a home-made device according methodology already published [31].

Briefly, the method uses small temperature modulation in a parallelepiped-shaped sample while getting thermophysical properties in one measurement together with statistical confidence bounds. The specimens are placed between two metallic plates. The front side of the first metallic plate is heated periodically using a sum of five sinusoidal signals and the temperature is measured with thermocouples placed inside both front and rear metallic plates. The thermophysical parameters of the sample are identified by comparison of the experimental and theoretical heat transfer functions. The system under study is modeled with one-dimensional quadrupole theory. The experimental heat transfer function H is calculated at each excitation frequency as the ratio between the Fourier-transform temperatures of the front and rear plates. Subsequently, thermal conductivity λ and diffusivity α is calculated through a parameter estimation technique by employing the Levenberg - Marquardt method [35].

Recently, this device have been used for characterization of various materials [31,32,34].

3. Results and discussion

3.1. Scanning Electron Microscopy (SEM)

Morphology of prepared PCMs was characterized by SEM. Fig. 4 an illustrates S3 blend and clearly shows separated fractions of LLDPE and W. Fig. 4b and c belongs to S4 and S6 blends

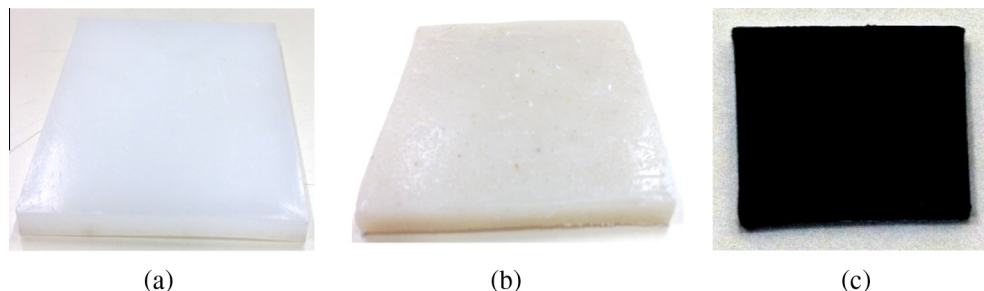


Fig. 1. PCM blends of (a) S1_100/0/0, (b) S2_50/50/0 and (c) S6_35/50/15.

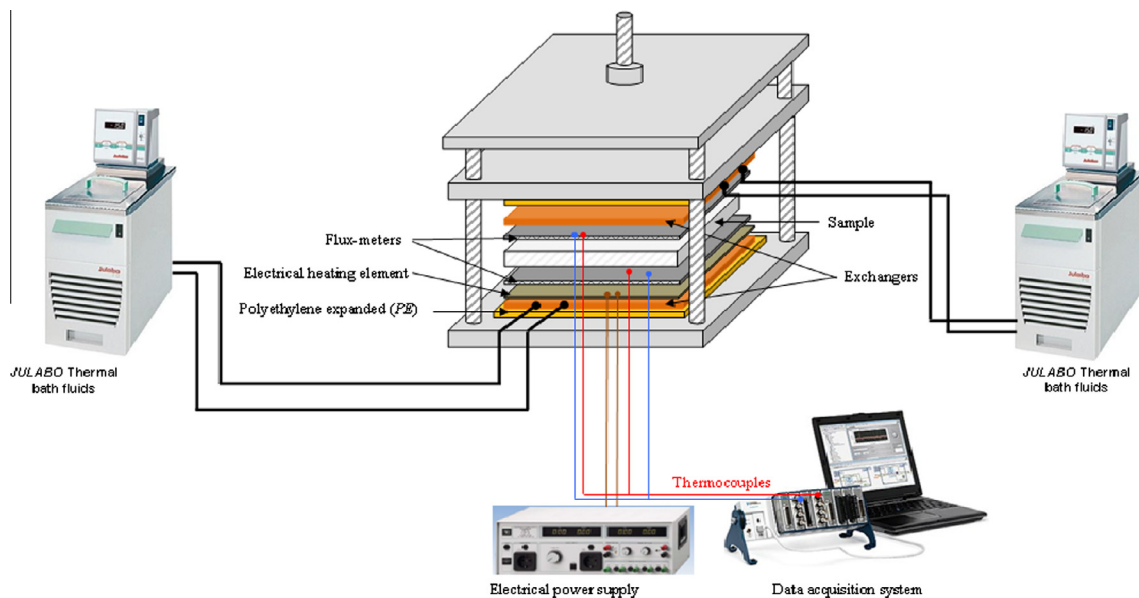


Fig. 2. Experimental set-up of transient guarded hot plate technique.

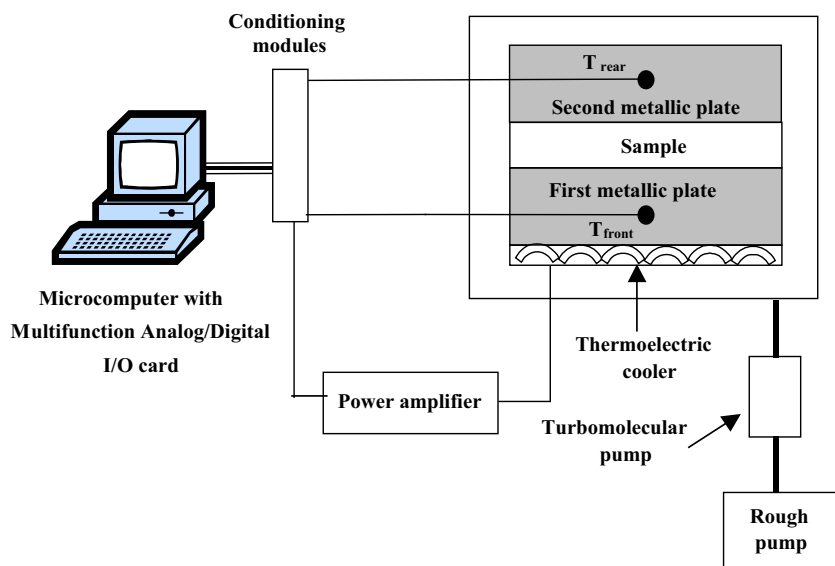


Fig. 3. Schematic representation of the experimental setup.

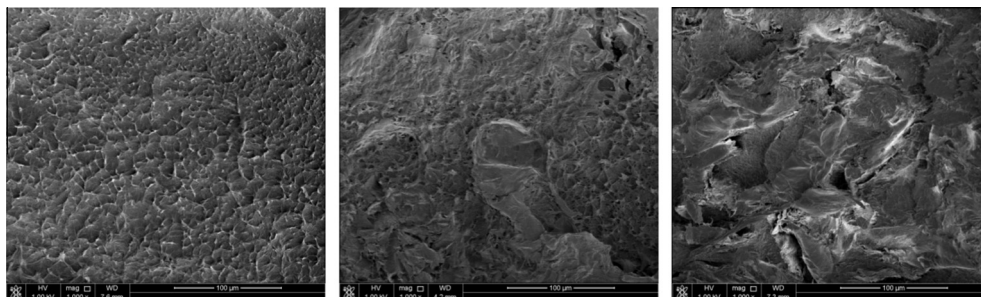


Fig. 4. SEM images of PCMs (a) S3 and (b) S4 and (c) S6.

respectively which contain 5 or 15 wt.% of EG recognizable as whiteness structures on the fracture of specimens. During sample preparation, LLDPE and W are melted and subsequently penetrated between graphene sheets of EG [26].

EG particles are more pronounced in Fig. 4c due to their higher concentration.

Generally, it can be noticed that there is no indication of miscibility between LLDPE and W on the microscopic level. The

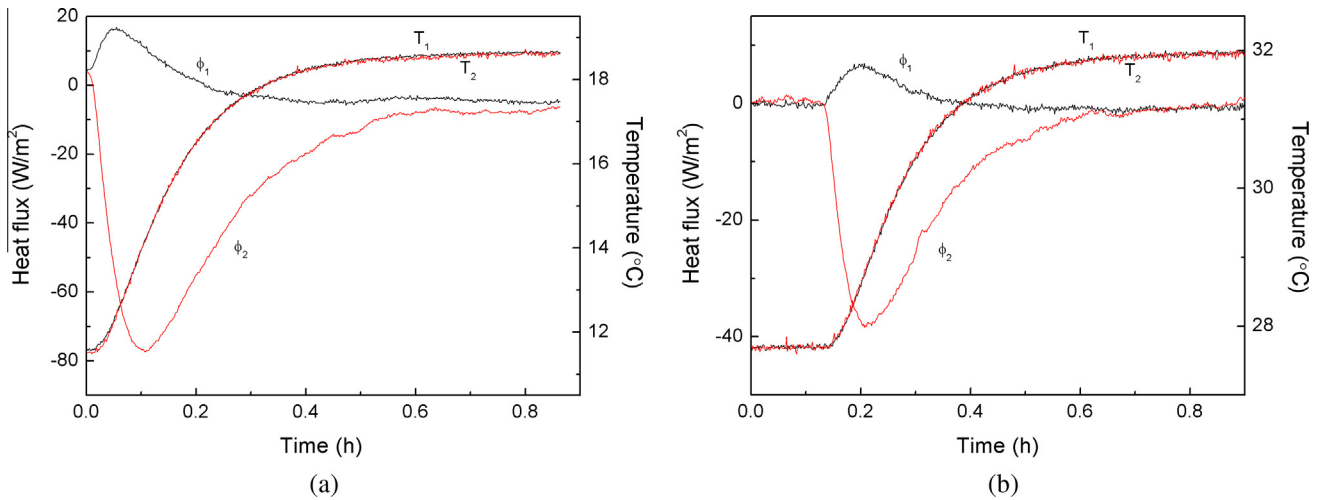


Fig. 5. Typical heat flow and temperature progression for S6_35/50/15: (a) solid phase of W from 11 to 19 °C and (b) liquid phase of W from 28 to 32 °C.

immiscibility is a requirement for PCMs to have well-distinguished melting points for W and LLDPE [36].

3.2. Transient guarded hot plane method (TGHPT)

All investigated PCMs were analyzed in order to obtain information about sensible heat, latent heat, specific heat capacities and total stored or released heat energy. Experiments were done in temperature range from 10 to 30 °C; due to fact that W is an active substance in view of storage properties with a melting point ranging from 22 to 26 °C. Such characteristics make our W well-suitable for applications in the building industry, with a higher utilization capacity of thermal energy in effective energy storage systems.

Fig. 5 illustrates a typical heat flow and temperature evolution for S6_35/50/15 blend in solid state of W (11–19 °C) as well as in liquid phase (from 28 to 32 °C). Similarly, all investigated PCMs have been analyzed over the mentioned temperature range and subsequently sensible heat at solid and liquid states of PCMs has been determined.

Sensible heat has been calculated for solid and liquid state according Eq. (1).

$$Q = \frac{1}{e \cdot \rho} \int_{init}^{end} \Delta \phi \, dt = c_p (T_{end} - T_{init}) \quad (\text{kJ/kg}) \quad (1)$$

where e is the thickness of specimen (m), ρ is the density of specimen (kg/cm^3), c_p is specific heat capacity of the specimen ($\text{kJ}/\text{kg} \cdot ^\circ\text{C}$), T_{init} is initial temperature and T_{end} is the temperature on the end of the measurement.

Values of both evaluated Q_s as well as calculated c_p are clearly listed in Table 3. The variation from 2.42 to 3.05 $\text{kJ}/\text{kg} \cdot ^\circ\text{C}$ for solid state and from 2.36 to 3.07 $\text{kJ}/\text{kg} \cdot ^\circ\text{C}$ for liquid state have been observed.

3.3. Energy storage and release

Since phase change active substance inside the blends is paraffin wax with melting temperature around 25 °C, temperature from 10 to 30 °C was selected to study heat transfer through PCMs. Slight variations in the temperature occurred due to the effect of the surrounding environment, but it is important to point out that such temperature variations have been taken into account during thermal parameters calculations.

Table 3

Sensible heat Q_s and c_p for various compositions of PCMs for solid and liquid state of paraffin wax.

Samples LLDPE/W/EG	TGHPT measurement			
	Q _s (kJ/kg)		c _p (kJ/kg.°C)	
	Solid	Liquid	Temperature range	
	11–18 °C	27–32 °C	11–18 °C	27–32 °C
S1_100/0/0	–	–	1.84	1.92
S2_60/40/0	22.69	11.15	3.02	2.48
S3_50/50/0	18.18	12.30	2.42	3.07
S4_45/50/05	17.85	11.82	2.55	2.36
S5_40/50/10	21.37	12.19	3.05	2.71
S6_35/50/15	19.12	13.45	2.73	2.69

Firstly, the specimens were thermostated to an initial temperature of $T_{init} = 10$ °C. Subsequently, the specimens were heated up to 30 °C. The flow-meters quantified the heat flow exchanged at the borders of the each specimen. Heat flow and temperature evolution of PCM blends with various compositions of LLDPE and W is shown in Fig. 6.

Heat flow and temperature progression of PCMs contain 50 wt.% of W and various concentration of EG is shown in Fig. 7.

Q_{total} stored or released during heating or cooling of specimen can then be calculated according Eq. (1) similarly as in the case of determination of Q_s .

After determination of $c_p(\text{solid})$ and $c_p(\text{liquid})$ state, latent heat of PCMs can be evaluated by means of Eq. (2).

$$Q_{total} = Q_s + L_m = (c_p(\text{solid}) \cdot \Delta T(\text{solid}) + c_p(\text{liquid}) \cdot \Delta T(\text{liquid})) + L_m \quad (\text{kJ/kg}) \quad (2)$$

where, $c_p(\text{solid})$ and $c_p(\text{liquid})$ are the average specific heats for the solid state and the liquid state, $\Delta T(\text{solid})$ and $\Delta T(\text{liquid})$ the temperature variations for the material in the solid and liquid phases are and L_m is the latent heat of melting.

The total amounts of energy per mass stored as well as released, sensible heats and latent heats for PCMs are all listen in Table 4. Calculated L_m of PCMs varied from 55.7 kJ/kg to 69.21 kJ/kg . Noticeable variations of latent heat between PCMs contain the same amount of paraffin wax can be attributed to the leakage of W from LLDPE matrix.

Typical heating curves of PCM contain 15 wt.% of EG is shown in Fig. 8, where solid-solid (minor inflexion point around 15 °C) as well as major solid-liquid transition (around 24 °C) are observed

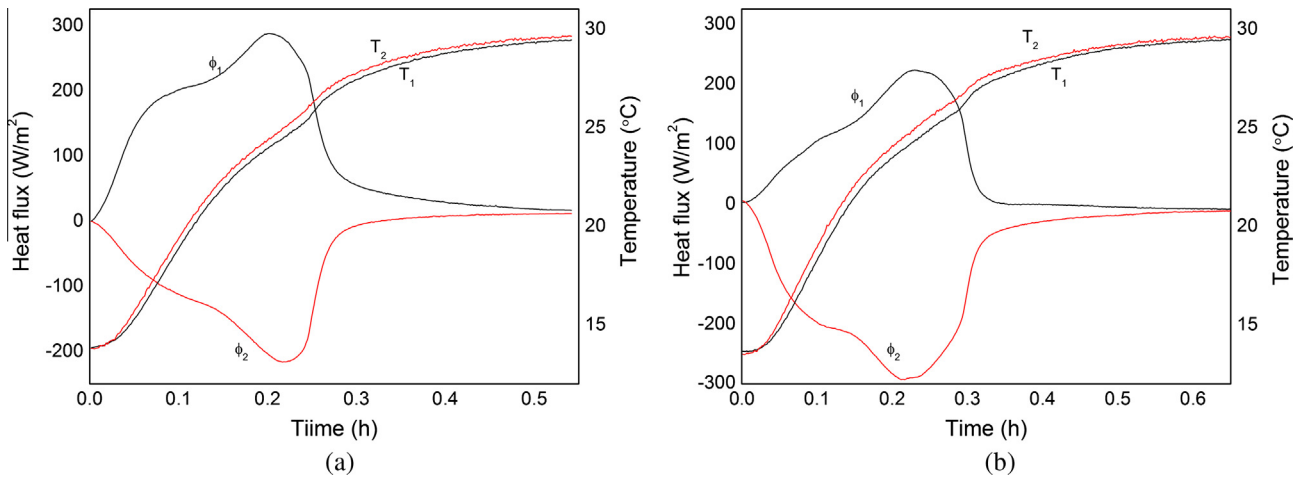


Fig. 6. Typical heat flow and temperature progression for PCMs: (a) S2_60/40/0 and (b) S3_50/50/0.

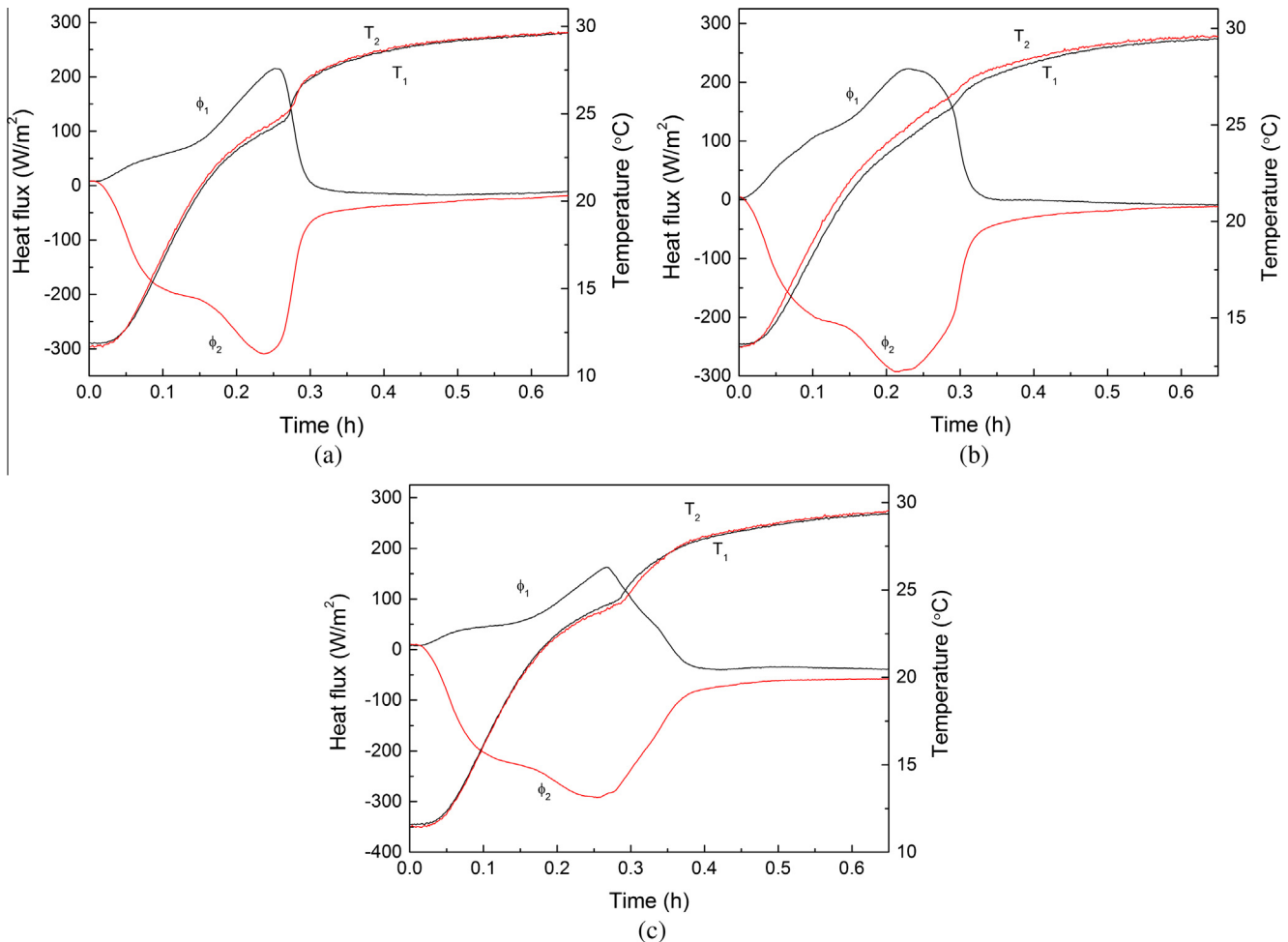


Fig. 7. Typical heat flow and temperature progression for PCMs: (a) S4_45/50/05, (b) S5_40/50/10 and (c) S6_35/50/15.

during heating of specimen. Crystallization peak belongs to solid-liquid transition is shifted to 22.5 °C and minor solid-solid transition is even not visible from crystallization curve.

Table 5 summarizes thermal enthalpies for pure W and various PCMs by using DSC.

Melting enthalpy of W was estimated to be 145 kJ/kg. PCMs contain 40 (S2) and 50 wt.% (S3–S6) of W exhibited melting

enthalpy 60 kJ/kg and for sample S3 65.5 kJ/kg. Melting enthalpy of the samples contain 50 wt.% of W and various concentration of EG varied from 66.1–67.3 kJ/kg.

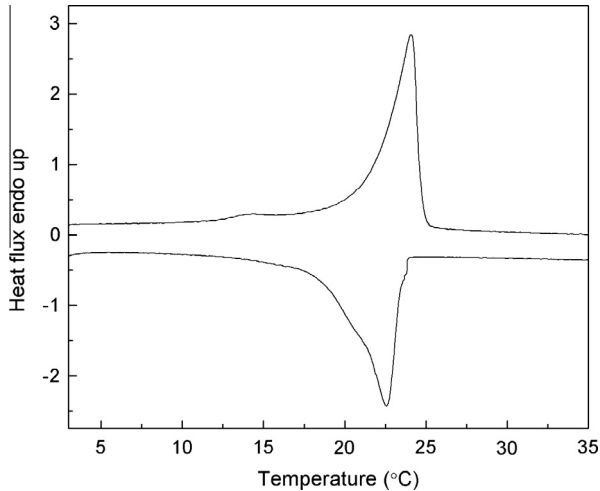
Crystallization enthalpies for PCMs were very close to the values obtain for melting enthalpies.

Fig. 9 shows a comparison of various melting enthalpies of W within mixtures determined by TGHPT and DSC. This shows an

Table 4

The total stored energy per mass, Q_{total} , sensible heat for solid, $Q_s(\text{solid})$, and liquid state, $Q_s(\text{liquid})$, of W and calculated latent heat, L_m , for various composition of PCM blends.

Samples	Q_{total} kJ/kg	$Q_s(\text{solid})$ kJ/kg	$Q_s(\text{liquid})$ kJ/kg	L_m kJ/kg
S1_100/0/0	34.7	–	–	–
S2_60/40/0	88.2	21.2	7.4	59.6
S3_50/50/0	109.9	19.4	12.3	69.2
S4_45/50/05	88.3	25.5	7.1	55.7
S5_40/50/10	97.0	30.5	8.1	58.4
S6_35/50/15	102.8	27.3	8.1	67.4

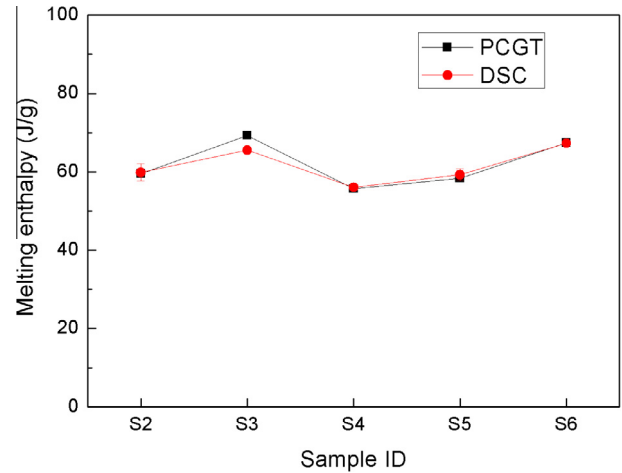
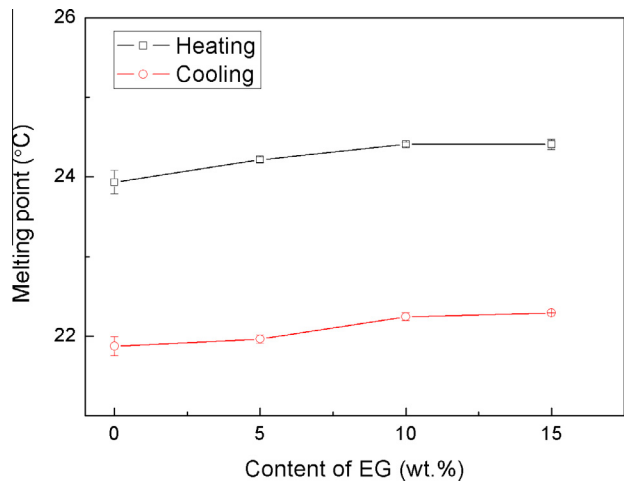
**Fig. 8.** Typical DSC diagram of S5.**Table 5**

Melting and crystallization temperature and enthalpy for W and various PCMs.

	Melting enthalpy (kJ/kg)	Crystallization enthalpy (kJ/kg)
W	145 (2.1)	144 (2.2)
S1	nd	nd
S2	60.0 (2.2)	58.3 (0.8)
S3	65.5 (0.4)	65.9 (1.4)
S4	56.1 (0.4)	60.4 (1.3)
S5	59.0 (1.6)	62.5 (0.6)
S6	67.3 (0.4)	66.6 (0.7)

excellent agreement in determining the melting enthalpy by both employed methods. It is clear that the melting enthalpy of paraffin phase increases with an increase in W content. As for the influence of EG on the melting enthalpy of W, theoretically there should be no influence. On the other hand, EG, as like any filler, influences the melting enthalpy of W as observed in the case of composites based on the semicrystalline matrix. Simply said, the melting enthalpy of any semicrystalline polymer (and this is also valid for paraffin waxes which are short-chains olefinic oligomers) depends on the amount and regularity of the folded chains. The fillers can influence both these phenomena, either positively and negatively, depending on the physical and chemical character of the filler [37]. In our case, no regular tendency in the melting enthalpy on the filler content was observed.

Another interesting point to compare during the melting and solidification of PCMs is fixing the content of W and varying the EG content, as is shown in Fig. 10. A slight increase of transition temperature has been observed, especially for the solidifying temperature. Melting as well as crystallization temperatures of W, similarly as it is in the case of semicrystalline polymers, can be

**Fig. 9.** Comparison of melting enthalpy determined by TGHPT and DSC method for PCM blends.**Fig. 10.** Melting points and solidifying temperature of PCMs contain 50 wt.% of W and various concentration of EG obtained from DSC measurement.

unchanged, increased or decreased by the presence of fillers. Simply said, the filler promotes the formation of bigger crystallites. The melting temperatures of those polymers are found higher than that of neat ones. Conversely, the melting points will be lowered if the filler reduces the sizes of crystallites [36]. This interpretation, based on experiences with composites created from semicrystalline polymers, can be applicable in the case of paraffin waxes. The most reasonable explanation behind the increase of melting and crystallization temperatures of W in a blend is that EG promotes the formation of higher crystallites as they are in neat W.

The cumulative heat of the storage and the release for two different PCMs is shown in Fig. 11. There is an evidence that addition of EG reduces time needed for obtaining heat equilibrium state observed as a slight shift to the lower time for PCM contains 15 wt.% of EG. This expected behavior is caused by present of EG as a filler which significantly increases the thermal conductivity of the PCMs [38].

3.4. Determination of thermal conductivity and diffusivity

The thermal conductivity and thermal diffusivity of PCMs at 18 °C have been measured by home-made DICO device. In case of PCMs without EG, only slight decreasing of thermal conductivity

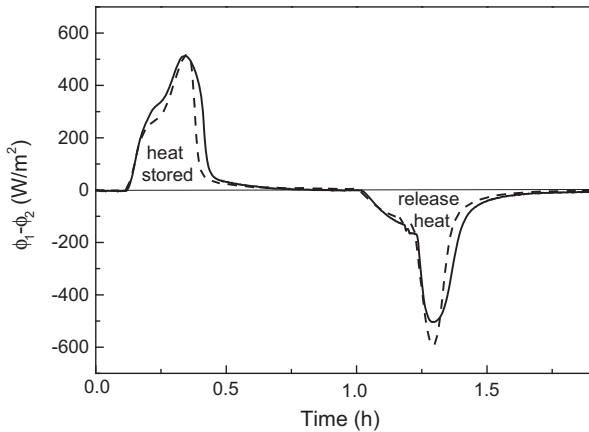


Fig. 11. Cumulated heat flow for heat store and heat release evolution of PCMs S3_50/50/0 (solid line) and S6_35/50/15 (dashed line).

while increasing of W concentration was observed and is caused by variances of the thermal conductivity between neat LLDPE (around 0.4 W/m·K) and W (around 0.2 W/m·K) [39].

Another observation is that thermal conductivity remarkable improves with increasing of EG content due to much higher thermal conductivity of pure EG in contrast to LLDPE and W [39].

Fig. 12a illustrates thermal conductivity and Fig. 12b thermal diffusivity of LLDPE and PCMs with various contents of EG. Addition of W into LLDPE matrix led to decreasing of both, thermal conductivity and thermal diffusivity. Moreover, the increase of W concentration only slightly decreased both thermal conductivity and diffusivity.

More significant effects to thermal properties are caused by addition of EG into PCMs. Thermal conductivity and thermal diffusivity significantly increased with increasing EG content (Fig. 12c and d).

3.5. Life cycle assessment of PCM_Brick wall

Life cycle assessment (LCA) is a widely accepted internationally method used for evaluating the environmental effect of a product, process or activity through the different life cycle stages from cradle to grave. A typical LCA study is compose of the manufacturing phase including processing and extracting raw materials, operational phase and disposal phase (i.e. landfilling, recycling or reusing). When the environmental impacts of the building during its entire lifetime are considered, LCA is a widely used tool since it provides better decision supports [40–43]. In the literature, there are several studies in order to evaluate the environmental effect of equipment, energy supply and insulation materials in the buildings [44–46]. Papadopoulos and Giamia [47] compared the effect of different

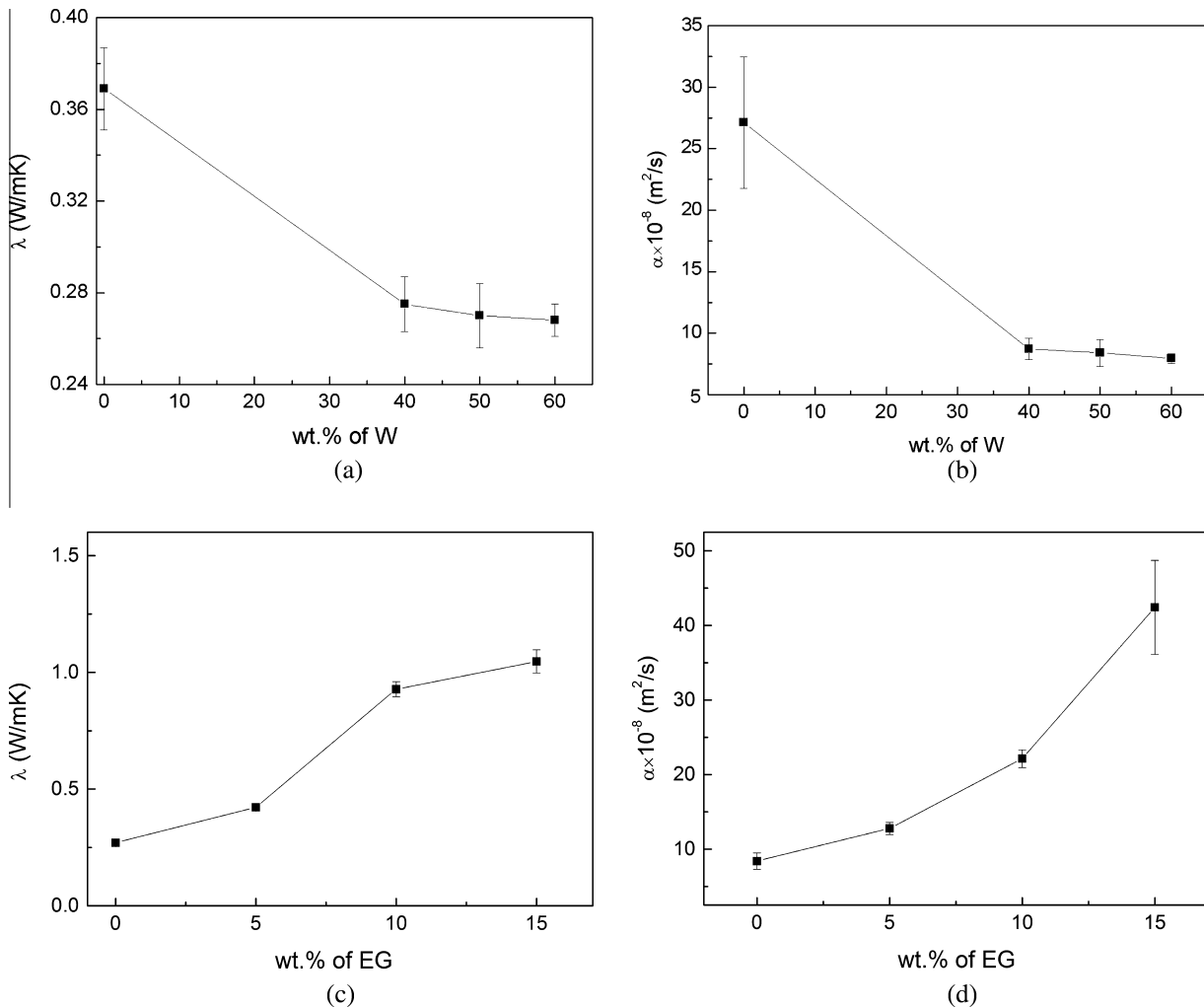


Fig. 12. Influence of W concentration on the (a) and (c) thermal conductivity and (b) and (d) thermal diffusivity of PCMs based on LLDPE, W and EG at 18 °C.

Table 6
Component relation with Ecoinvent database.

Component	Name in the data base Ecoinvent corresponding to the component
Alveolar brick	Brick, at plant, RER, (kg)
Cement mortar	Cement mortar, at plant, CH, (kg)
Concrete	Concrete, normal, at plant, CH, (kg)
Paraffin	Paraffin production, RER, (kg)
LLDPE	Packaging film, LLDPE, RER, (kg)
Graphite	Graphite production, graphite, RER, (kg)
Disposal alveolar bricks	Disposal, building, brick, to final disposal, CH, (kg)
Disposal mortar	Disposal, building, cement (in concrete) and mortar, to final disposal, CH, (kg)
Disposal concrete	Disposal, building, reinforced concrete, to final disposal, CH, (kg)

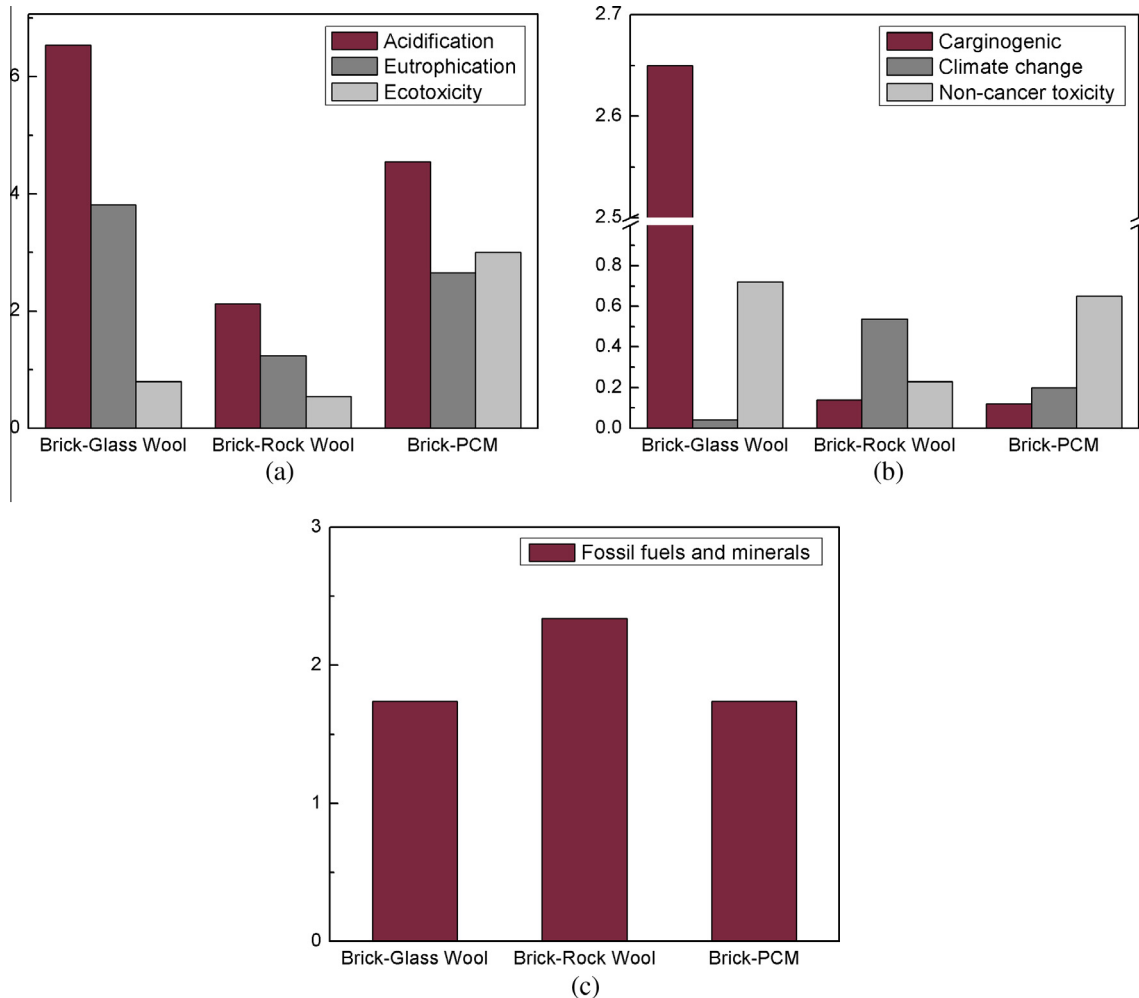


Fig. 13. (a) Eco system quality impact points, (b) human health impact points and (c) resources impact points for various materials.

insulation materials on the environmental performance of the buildings and they concluded that LCA is very useful in order to evaluate the impact of insulation materials on energy consumption. Although these studies prove the importance of using LCA to evaluate and compare the construction solutions, further studies are still needed to evaluate the environmental benefits of PCM used as building material in the construction systems. Herein, LCA was applied to evaluate the environmental impact of three different materials as glass wool, rock wool and PCM used with brick wall using the GaBi LCA software in order to compare the different types of insulation materials based on their sustainability performance. The data required for con-

structing the inventory were retrieved from various supporting database such as Ecoinvent and Buwal 250 found in GaBi impact assessment software with modification for Qatar.

According to the ISO 14040-43 standard series, a typical LCA study is generally applied in four steps [48–51]:

- Goal and Scope definition.
- Life cycle inventory analysis (i.e. identification and quantification of materials usage, energy requirement and environmental releases for the entire life cycle).
- Life cycle impact assessment (i.e. associated with the identified forms of resource use and environmental emissions).

- Interpretation of the results of the inventory analysis and assessing the each option under evaluation in order to determine the best one.

3.5.1. Goal and scope definition

The aim of applying LCA in this study is to evaluate and to compare the environmental impact of different insulation materials. Within the scope of LCA, three brick walls were prepared in the software using glass wool, rock wool and PCM. The PCM is created by using 35 wt.% LLDPE, 50 wt.% W and 15 wt.% of EG, which was considered as an optimal PCMs related to their thermal characteristics such as ability to store and release of thermal energy, thermal transport through material as well as mechanical properties of the blends. The brick walls were built using typical Qatar construction solutions with the following layers on the walls: hollow bricks, plaster and cement mortar and insulating material. Cement mortar designed by using Portland cement, natural sand and water is considered in order to hold the bricks.

The manufacturing and the disposal phase of the brick walls are only considered in this study, since the objective is to compare the insulation materials used in the same constructed walls.

3.5.2. Life cycle inventory analysis

In this step, the inventory list of energy quantity and raw material requirements, atmospheric emissions, solid wastes, waterborne emissions and other releases used in the manufacturing and disposing is shown. The correlation between the brick wall components used in the manufacturing and disposing phase and the Ecoinvent database is shown in Table 6. Since there is no data available for disposal of paraffins in Ecoinvent database, it is estimated.

3.5.3. Impact assessment

The environmental impact categories were determined as ecotoxicity, eutrophication, acidification, cancer and non-cancer toxicity, climate change and resources. Those categories were also aggregated into three main titles as Eco system quality, human health and resources. The life cycle inventory analysis results which consist of the materials that are used through the construction and disposal phase of the brick walls and the impact points of the manufacturing and disposal of the brick walls for each category are presented (Fig. 13).

Stated from the Fig. 13, the brick walls insulated by PCM have the lowest carcinogenic impact and the manufacturing of those mentioned walls consumes the least resources and so they have the lowest impact on fossil fuels and minerals. When the impact of brick walls on the Eco System Quality is highlighted, PCM has the highest impact on ecotoxicity, while it has the higher impact on eutrophication and acidification than the brick walls contain rock wool. However, it can be concluded that the use of PCMs in brick walls reduces the overall impact by more than 15% which is consistent with other study performed by Gracia et al. [52].

4. Conclusions

Thermal investigation of PCMs with various composition of LLDPE, W and EG has been performed by nonconventional TGHPT and compared with conventional DSC measurement. An excellent agreement in determination of thermal characteristics by both methods was found.

TGHPT was applied to determine the total amount of stored energy as well as the sensible heat for solid and liquid states of W for PCM blends. The highest values of Q_{total} , $Q_{\text{s(solid)}}$ and $Q_{\text{s(liquid)}}$ were found for the PCMs with compositions LLDPE/W/EG = 40/50/10 and 35/50/15 w/w/w.

It was found that the addition of W decreases both thermal conductivity and thermal diffusivity of PCMs based on LLDPE/W blends. However, they were also found to be improved by adding EG up to 1.1 W/m·K for PCMs containing 15 wt.% of EG.

Moreover, LCA analysis showed that the use of PCMs in brick walls reduces the overall impact by more than 15% compared to the rock and glass wool brick walls.

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