



# Development of thermal enhanced *n*-octadecane/porous nano carbon-based materials using 3-step filtered vacuum impregnation method



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## ABSTRACT

In this study, *n*-octadecane/porous nano carbon-based materials (OPNCs) were thermally enhanced using a 3-step filtered vacuum impregnation method. *n*-octadecane as phase change materials (PCMs) and supporting materials of C-300, C-500, Activated carbon (AC), Expanded graphite (EG) and Exfoliated graphite nanoplatelets (xGnP) made of the same raw material. Through scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FT-IR) analysis, *n*-octadecane was well impregnated in carbon-based materials not a chemical bonding. Thermal conductivities of OPNCs were increased up to 580% compared with *n*-octadecane by TCi. Differential scanning calorimetry (DSC) analysis was used to verify thermal performance of OPNCs, the latent heat capacities of OPNCs were measured from 220J/g to 393J/g. Analysis of thermal stability by thermogravimetric analysis (TGA) showed that the impregnation ratio of OPNCs was about 56% and that of EG was 88.53%. 3-step filtered vacuum impregnation method manufactured a stable and thermally enhanced OPNCs.

## 1. Introduction

The building sector is a major energy consumers with a total contribution toward global energy consumption of about 40% [1,2]. Furthermore, building energy consumption has been rapidly increasing due to population growth and pursuit of enhanced comfort in the buildings [3,4].

Consequently, various techniques have been presented for energy reduction in buildings. The one of techniques, Thermal Energy Storage (TES) is a useful technology for improving energy efficiency and energy saving. When TES apply to buildings, the building could be more stored energy for building energy savings than only use sensible heat [5–8]. TES is applied in buildings by using Phase change materials (PCMs). PCMs provide thermal energy that is stored when it heated by melting and released when it cooled off by solidification. TES thus works in a passive way through these phase changes from solid to liquid or liquid to solid. More energy can be stored using this process compared to the use of sensible heat or latent heat [9–12]. PCMs are divided into three types: organic PCMs, inorganic PCMs, and eutectic PCMs. In this study, *n*-octadecane is selected, which has a melting temperature of 28 °C and is classified as an organic PCM. Organic PCMs have been widely used in thermal energy storage applications due to their large latent heat and good thermal characteristics, such as little or no super cooling, low vapor pressure, good thermal and chemical stability [13–16]. Despite these advantages, PCMs have weaknesses that limit their application to

building materials. Firstly, PCMs incur a leakage problem when in an endothermic or exothermic state. In other words, leakage occurs with the phase change from solid to liquid or liquid to solid. Secondly, PCMs have low thermal conductivity. In order to apply PCMs to building materials for a TES system, high thermal conductivity is essential. To achieve optimal thermal performance of PCMs, they must be stored heat sufficiently, above the sensible heat capacity, which means PCMs are within the state of fusion [17].

Recently, a new type of PCM has been developed, called shape-stabilized PCMs (SSPCMs), composed of PCMs and supporting materials. PCMs need to have congruent supporting materials. If the PCMs are based on paraffin, the supporting material should have a similar skeleton to that of paraffin, such as high-density polyethylene (HDPE), polypropylene (PP), and styrene-butadiene-styrene (SBS). Paraffin can be easily dispersed into the network formed by the supporting material. Providing that the operating temperature is below the melting point of the supporting material, the SSPCMs can maintain their shape even when the paraffin changes from solid to liquid or liquid to solid [18].

Many attempts have been made to enhance the thermal conductivity and mitigate the leakage problem of PCMs. One of the best ways to apply PCMs in a real condition is to impregnate PCMs into high thermal conductivity materials such as carbon materials with porous structures [19–21].

Research by the Drzal group has shown that exfoliated graphite nanoplatelets (xGnP™), which combine the layered structure and low

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Fig. 1. Expanded Graphite.

**Table 1**  
Physical properties of *n*-octadecane.

Melting temperature (°C)	28.0
Latent heat capacity (J/g)	256.5
Specific heat capacity (J/gK)	92.0
Thermal conductivity (W/mK)	0.26

price of nanoclays with the superior mechanical, electrical and thermal properties of carbon nanotubes, are very cost effective and can simultaneously provide a multitude of physical and chemical property enhancements [22–24]. With similar characteristics to those mentioned above, C-300 and C-500 can be made with Exfoliated graphite nanoplatelets (xGnP) through a secondary processing. XG Sciences offers its

**Table 2**  
Different manufacturing methods for SSPCM.

Ref.	PCM	Supporting material	Manufacturing Procedure
[3]	Paraffin-based PCM	Expanded and Exfoliated Graphite (EG)	EG with 97% weight percents of PCM was impregnated until 1 h.
[9]	<i>n</i> -hexadecane	Exfoliated graphite nanoplatelets	5 wt% of xGnP according to weight percentage of Na-MMT was mixed and placed it in filtering flask which was connected water tromp apparatus.
	<i>n</i> -ocatadecane	(xGnP)	Through a vacuum process eliminated air in the pores and turned open to allow to 200 g of PCM, to cover the mixture until 90 min.
			The colloid state of the mixture was filtered 1 µm filter paper, until it seems to be granule shape. Then the mixture was dried in a vacuum drier, at 80 °C for 48 h.
[13]	Technical grade paraffin	Expanded Graphite	Mixed the paraffin which was melted by heating it at 65 °C with the expanded graphite. After being filtered and dried, the paraffin/expanded graphite composite phase change material was obtained.
[16]	<i>n</i> -hexadecane	Exfoliated graphite nanoplatelets (xGnP)	100 g of dried xGnP put inside a filtering flask to draw out air in the pores by using a pump.
			200 g of liquid state of PCM was flowed into the flask to fill the pores until 90 min.
			The samples were dried in a vacuum drier at 80 °C for 48 h.
[18]	High-density polyethylene (HDPE)	Expanded Graphite (EG)	The mass ratio of intumescent flame retardant (IFR) ammonium polyphosphate/pentaerythritol/melamine is 2:1:1. Firstly, HDPE and IFR were dried at 60 °C for 24 h. Secondly, the blends were premixed in a high-speed blender.
			And extruded by a twin-screw extruder that of temperature range was 90–160 °C and screw speed was 250 rpm.
[19]	Technical grade paraffin	Graphite Form (GF)	GFs and paraffin wax were filled into a beaker, and then were heated to 353 K (above the melting point of the paraffin wax 331 K) in a vacuum oven for 3 h.
			When the GFs were submerged in the melted paraffin wax, the system was allowed to cool until the paraffin wax was solidified under normal atmosphere.
			Depending on the bulk density of the GF matrix, mass ratio of the paraffin wax in these composites ranges from 47 to 76%.
[20]	<i>n</i> -hexadecane	Exfoliated graphite nanoplatelets (xGnP)	The composite PCMs were prepared by stirring and sonication of xGnP in liquid paraffin with a mass fraction of 3 and 5 wt%.
	<i>n</i> -ocatadecane		The PCMs were melted by hot plate at over the melting temperature of each PCMs, and the xGnP was then mixed into the liquid PCMs.
	Paraffin wax		After stirring for 20 min and at 1000 rpm, the mixtures were ultrasonicated for 20 min. Lastly the liquid mixtures were injection-molded and cooled.
[26]	Lauric acid (LA)	Activated carbon	The LA and activated carbon that was dried in a vacuum oven at 80 °C for 12 h before, were mixed in a 900 ml beaker with different mass ratios (1:5, 1:4, 1:3, 1:2).
			The composites were heated at 60 °C and stirred at the rate of 500 rpm for 60 min by a constant temperature magnetic stirrer.
[27]	<i>n</i> -octadecane	Activated carbon (AC)	Finally, the composites were dried in an oven at 35 °C for 4 h.
			First, the AC was dried in an oven at 110 °C for 12 h to remove moisture.
			The melted <i>n</i> -octadecane was dissolved in 30 ml of absolute ethanol and then puts dried AC into it with stirred at 600 rpm for 4 h.
			Finally, the mixture was dried in an oven at 80 °C for 48 h or until all of the excess ethanol was evaporated.
[33]	Paraffin wax (PW)	Expanded Graphite (EG)	The composite PCMs were formulated through the mixing method in vacuum condition and at ambient pressure, respectively.
			First, the PW in liquid state with different concentration of EG were mixed by ultrasonic method. Then, each mixture sample was divided into two parts.
			One part was put in the vacuum condition for 32 h, and ultrasound every four hours. The temperature in the vacuum box was kept at 80 °C.
			Another part was put in the thermostatic bath with 80 °C at the ambient pressure for 32 h, and ultrasound every four hours.

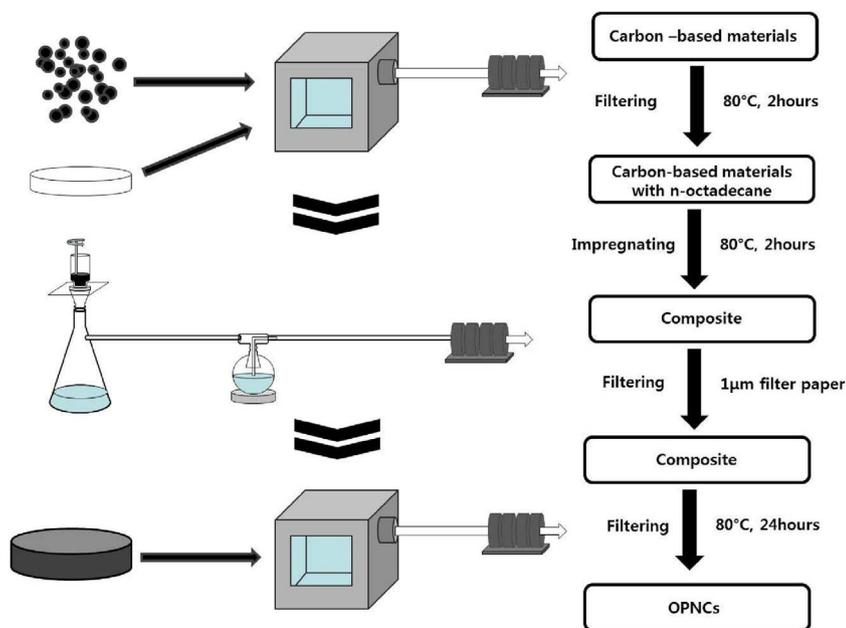


Fig. 2. 3-step filtered vacuum impregnation units.



Fig. 3. Granular images of OPNCs: C-300, C-500, AC, EG, xGnP.

“C-grade” materials in a variety of different surface areas. These materials have a “small flake” morphology, with particle sizes that are larger in the lower surface area materials and smaller in the higher surface area materials [25]. Activated carbon (AC) is another porous nano-sized carbon. While AC is similar to another carbon-based materials, it has a stability of structures and high thermal conductivity. In [26], it was demonstrated that AC is a noteworthy material because it has a large surface area and low density [27]. Lastly, expanded graphite (EG) has been made through the Tryba’s works [28,29]. Using the  $H_2SO_4$ –graphite intercalation compounds (GICs) with thermal treatment, natural graphite can be transformed into graphite, then it has a considerably larger surface area than before treatment one. From this work, EG has an accordion shape as shown Fig. 1 [30,31].

In this study, an attempt is made to address the weaknesses of PCMs such as the leakage problem that causes decay or strength decrease in application and the low thermal conductivity for the application of the TES system in buildings. Porous nano carbon-based materials were therefore used as supporting materials for the purpose of manufacturing SSPCMs. Also, the method of the 3-step filtered vacuum impregnation was conducted as it more precise and has increased productivity in comparison to the methods outlined in [3,9,13,16,18–21,26,27,32–37]. The verification experiments included scanning electron microscopy (SEM) analyze the porous nano-carbon based material characteristics of the micro structure, Fourier transform infrared spectroscopy (FT-IR) for chemical stability, TCI for thermal conductivity, differential scanning calorimetry (DSC) for thermal storage performance and thermogravimetric analysis (TGA) for thermal stability.

## 2. Experimental

### 2.1. Materials

The *n*-octadecane was used in this study as the PCMs. The molecular formula of *n*-octadecane is  $C_{18}H_{38}$ . It is within the alkane group and has a melting temperature of 28 °C, which means its keeps the temperature is maintained in the vicinity of 28 °C, which is acceptable to occupants. Table 1 shows the physical properties of *n*-octadecane.

Supporting materials are needed to create SSPCMs by vacuum impregnation. The criteria for optimal supporting materials are as follows. First, they must be porous because PCMs need to be stored in the pores within the supporting materials, through impregnation. Second, to ensure heat storage, the supporting materials must have high thermal conductivity to improve the thermal conductivity of the PCMs. Porous nano carbon-based materials meet these criteria, and have stable structures. In this study, the experiments were conducted with 5 types of carbon-based materials that have a similar properties since they are manufactured from the same raw material. The xGnP was obtained from Asbury Graphite Mills, Inc., New Jersey, USA. The expandable graphite was obtained from the same company and used as material for EG. C-300 and C-500 were obtained XG science, USA, while AC was obtained from PIUM INNOVATION, Seongnam, Korea.

### 2.2. Preparation

In this study, the 3-step filtered vacuum impregnation method used for manufacturing SSPCMs. As shown in Table 2 summarizes the different methods that have previously been used for manufacturing SSPCMs. Additionally, the references were excluded in which the methods were duplicated [3,9,13,16,18–21,26,27,32–37]. The reference methods were divided according to three weaknesses. First,

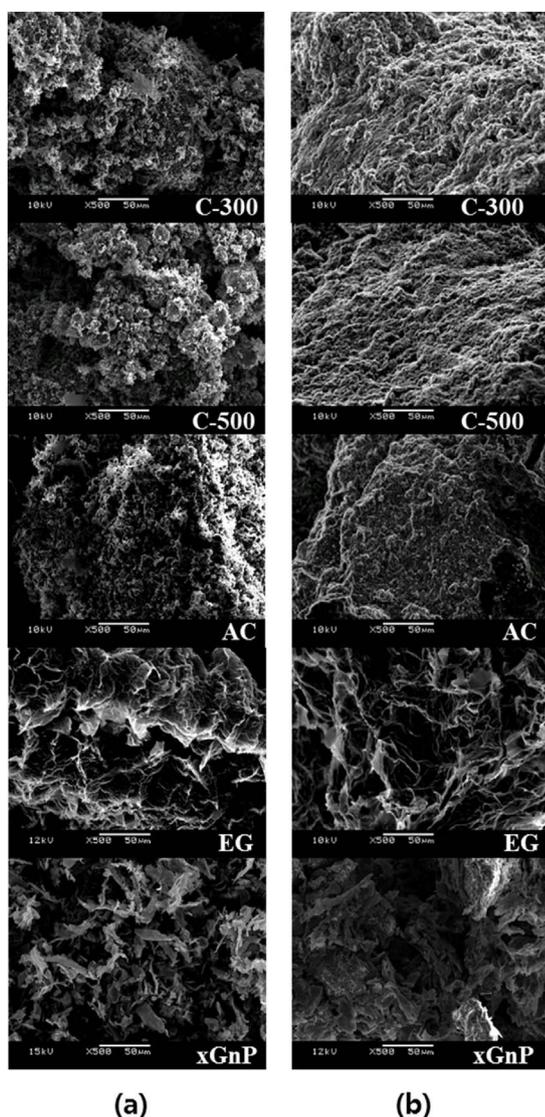


Fig. 4. SEM images of OPNCs: C-300, C-500, AC, EG, xGnP.

reference methods that have a non-filtering process or that have fewer than the 3 filtering process. Second, reference methods in which the outputs are limited to the container size, which is influenced by the number of outputs produced at any one time. Third, reference methods in which it is difficult to penetrate the pores of the supporting materials by a simple mixing process. So, reference methods are faced at risk for leakage problem when applied to a building material. Each reference method showed at least one of above weakness.

*n*-octadecane/porous nano carbon-based materials (OPNCs), the supporting materials is as follows: C-300, C-500, AC, EG and xGnP, were manufactured using the 3-step filtered vacuum impregnation method. Fig. 2 shows a schematic of the 3-step filtered vacuum impregnation. First, the porous nano carbon-based material is prepared on a stainless steel tray and is placed in a vacuum oven for 2 h at 80 °C. Through the first filtering process in first manufacturing process, the air that contained in the cavity and any unexpected residual moisture is eliminated. Second, the porous nano carbon-based material in the tray is placed in the fully melted *n*-octadecane until sufficiently submerged. And the composite is placed in the vacuum oven for 2 h at 80 °C for impregnation. Third, as shown in the middle of Fig. 2, the second filtering process is performed. The OPNCs in a colloidal state are filtered through 1 μm filter paper that connected to a vacuum state flask and stirred until a granular sample appears. The purpose of the second

filtering process is to remove any over-saturated *n*-octadecane from the surface of the OPNCs. Lastly with the third filtering process, the OPNCs are dried in the vacuum oven for 24 h at 80 °C. In order to remove any remaining *n*-octadecane on the surface, the OPNCs are dried completely. The 3-step filtered vacuum impregnation is minimizing might be incur that leakage so that make optimal SSPCMs for building application.

Fig. 3 shows images of the OPNCs in the laboratory at 20.0 °C. As shown, the carbon-based materials consist of a type of black powder and the prepared OPNCs consist of black granules.

### 2.3. Characterization methods

The microstructure of the OPNCs was analyzed through SEM; JSM-6360A, JEOL, Tokyo, Japan, at room temperature. The SEM images of the samples were obtained with a working distance of 12 mm, and the samples were gold coated at a few nanometers in thickness to increase their electrical conductivity [36].

FT-IR; Nicolet 6700, Thermo Scientific, Waltham, MA, USA, was conducted to confirm the chemical bonding of the OPNCs. The OPNCs were analyzed over the range of 650–4000  $\text{cm}^{-1}$ , with a spectrum resolution of 8  $\text{cm}^{-1}$  and all spectra were averaged over 32scans. The measurement was conducted by point-to-point contact with a pressure device.

The TCI thermal conductivity analyzer utilizing the Modified Transient Plane Source (MTPS) was used for measuring thermal conductivity under the following conditions: the diameter of the composite was 20 mm, the thickness of the composite was 10 mm, and the temperature was maintained at 20.0 °C.

The thermal properties of the OPNCs, such as the melting temperature and latent heat capacity, were ascertained using DSC; Q 1000. DSC measurement was operated at 5 °C per a minute during the measurement process for both heating and cooling. Temperature ranges were 0 °C–80 °C for heating and 80 °C–0 °C, for cooling. The onset point and the end point were determined by point of inflection of the curves. Also, the latent heat of the OPNCs was calculated by numerical integration of the area in which the range is from the onset point to the end point. The heating and cooling curves calculated separately. TGA measurements; TA Instruments, TGA Q5000, were conducted under the following conditions: the OPNCs sample size was approximately 2–4 mg, with a the temperature range of 25–600 °C, at a heating rate of 10 °C/min, and under a nitrogen flow of 20 ml/min. TGA was used to analyze the specimen with a high-quality nitrogen atmosphere (99.5% nitrogen, 0.5% oxygen content), to prevent unwanted oxidation [37].

## 3. Results and discussion

### 3.1. Morphology and microstructure of *n*-octadecane/porous nano carbon-based materials

In order to verify impregnation, SEM image analysis was conducted by comparing the pure supporting material to OPNCs. Fig. 4 is SEM images as follows C-300, C-500, AC, EG and xGnP, from top to bottom. Fig. 4(a) and (b) shows SEM images of the OPNCs composed of pure state of supporting material and impregnated state of the material, respectively. As shown in Fig. 4(a), the materials commonly show many pores and particles. On the other hand, Fig. 4(b) are fully filled with *n*-octadecane and are evenly spread. These images confirmed that *n*-octadecane is successfully impregnated in the pores of supporting material. Fig. 3, OPNCs verifies that the granularity of OPNCs is at a stable state at room temperature. Therefore, it is expected that the heat storage capacity of OPNCs was sharply increased than that of the porous nano carbon-based materials and in a building application, this enhances the shape durability of composite.

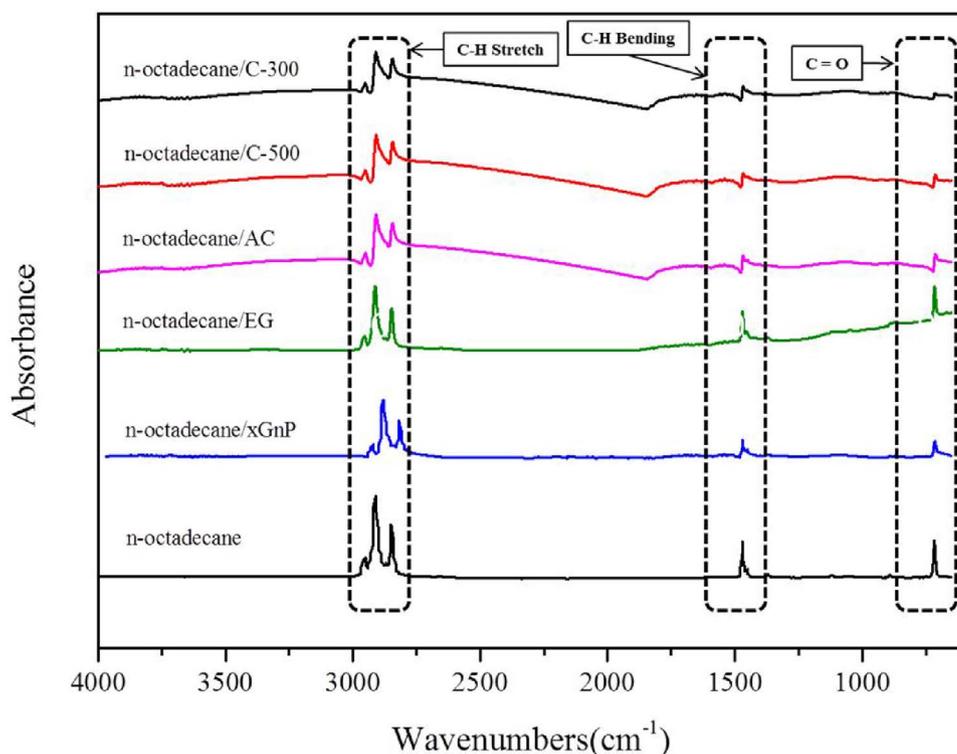


Fig. 5. FT-IR spectrum of manufactured OPNCs.

Table 3

Rate of increase in thermal conductivity compared with *n*-octadecane.

Sample	Thermal conductivity (W/mK)		Rate of increase (%)
	OPNCs	<i>n</i> -octadecane	
<i>n</i> -octadecane/C-300	1.51	0.26	580.77
<i>n</i> -octadecane/C-500	1.31		503.85
<i>n</i> -octadecane/AC	1.01		388.46
<i>n</i> -octadecane/EG	1.11		426.92
<i>n</i> -octadecane/xGnP	1.36		523.08

### 3.2. FT-IR analysis and chemical stability test of *n*-octadecane/porous nano carbon-based materials

FT-IR analysis was conducted for chemical interaction of OPNCs. Fig. 5 indicates the FT-IR spectrum of OPNCs consists of C-300, C-500, AC, EG and xGnP. As shown in Fig. 5, *n*-octadecane FT-IR peaks were observed at  $2910\text{ cm}^{-1}$  (C–H Stretch),  $1470\text{ cm}^{-1}$  (C–H Bending) and  $717\text{ cm}^{-1}$  (C=O) and the OPNCs showed the same peaks as those of *n*-octadecane. Therefore, it is confirmed in this study that the surface tension and capillary force of porous nano carbon-based materials were enhanced when combined with *n*-octadecane through vacuum impregnation. It means that OPNCs maintained porous nano carbon-based materials and *n*-octadecane properties. In other words, this analysis is confirmed that OPNCs have the thermal properties of *n*-octadecane and the thermal conductivity of the porous nano carbon-based materials since nonchemical bonding.

### 3.3. Thermal conductivity analysis of *n*-octadecane/porous nano carbon-based materials

This study was conducted in order to overcome low thermal conductivity of PCMs. The porous nano carbon-based materials used for high thermal conductivity. Pure *n*-octadecane and OPNCs were measured by TCI. The thermal conductivity values of materials were as follows: pure *n*-octadecane, 0.26 W/m K; C-300, 1.51 W/m K; C-500,

1.31 W/m K; AC, 1.01 W/m K; EG, 1.11 W/m K; xGnP, 1.36 W/m K.

Comparing the pure *n*-octadecane and OPNCs, the thermal conductivity of OPNCs increased from 388% to 580% than pure *n*-octadecane. Table 3 shows a comparison of these values of thermal conductivities.

The thermal conductivity degradation typically caused by low thermal conductivity was significantly reduced. Because the thermal conductivity of OPNCs is about four times that of *n*-octadecane. Thus, when OPNCs are applied in buildings as heat storage materials, thermal performance expected to be improved, with to better cope with the external temperature variations.

### 3.4. Thermal performance analysis of *n*-octadecane/porous nano carbon-based materials

To determine the thermal properties of OPNCs, thermal performance analysis was conducted through DSC data analysis. Fig. 6 shows DSC data of OPNCs and *n*-octadecane. In Fig. 6, the DSC graph of OPNCs and *n*-octadecane is similar because OPNCs had thermal properties of *n*-octadecane potentially. Table 4 presents the latent heat capacity of OPNCs. The decrease in the latent heat efficiency of *n*-octadecane was from 59.49% to 23.27% because the latent heat capacity of PCMs is related to the impregnation ratio. Therefore, the use of the 3-step filtered vacuum impregnation was validated by determining the average rate of the remaining latent heat efficiency (ARR) compared with the impregnation ratio. ARR means that PCMs are how much remain and perform in the OPNCs in comparison with PCMs. ARR can be used vacuum impregnated in carbon material in the pores, as OPNCs. Using DSC data in this Eq. (1), there is no complicate calculation method and ARR value indicates that thermal performance of OPNCs in each porous nano carbon-based material. The remaining latent heat was extracted from the DSC data that has endothermic and exothermic curves. Then, two latent heats from endothermic and exothermic was calculated by average that means the remaining latent heat. Lastly, the average rate of the remaining latent heat is compared to the latent heat of PCMs in order to determine the thermal performance efficiency of OPNCs.

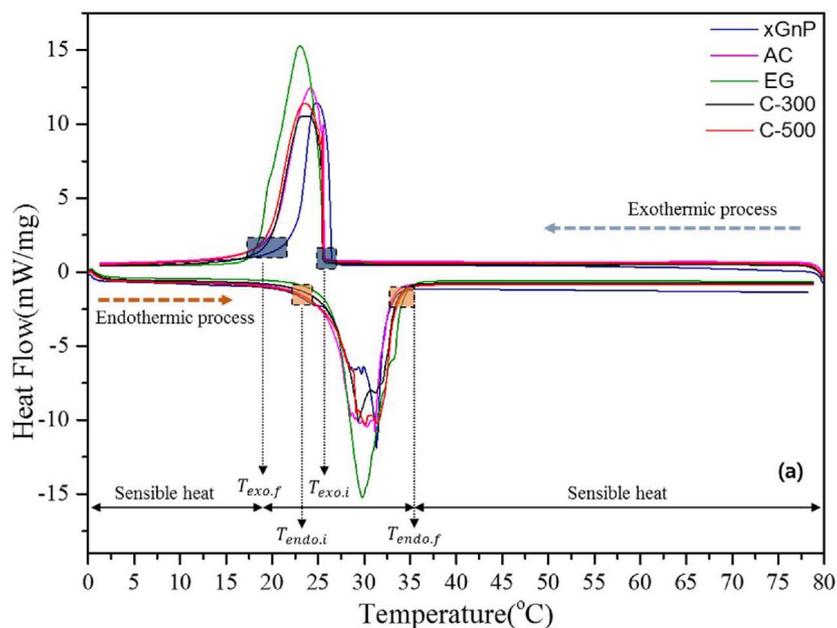
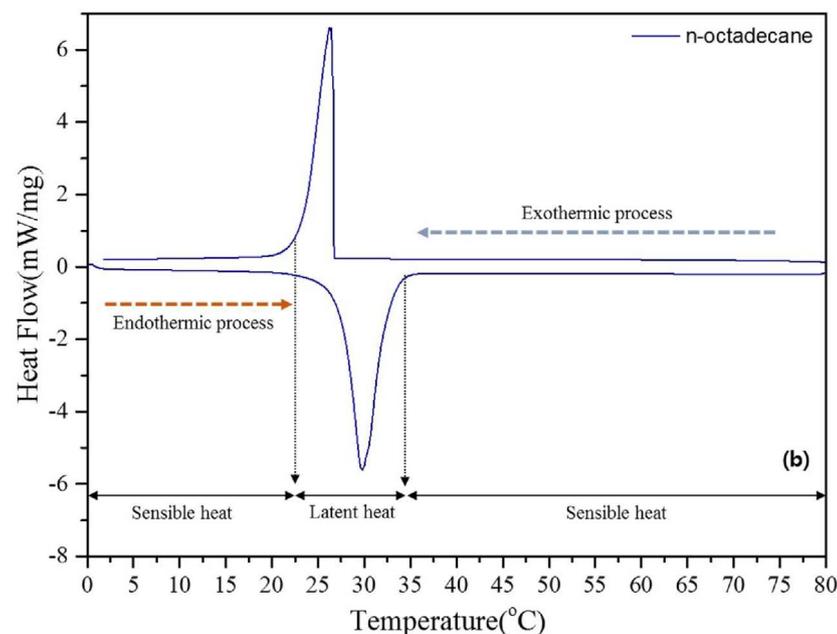


Fig. 6. DSC analysis of OPNCs and *n*-octadecane.



$$L_{OPNCs,avg} = \frac{1}{2} \left( \int_{T_{endo,i}}^{T_{endo,f}} \varphi \Delta T + \int_{T_{exo,i}}^{T_{exo,f}} \varphi \Delta T \right) \tag{1}$$

where,  $L_{OPNCs,avg}$  is obtained from average value that integral value of heat flow for temperature during endothermic and exothermic.  $T_{endo,i}$ ,  $T_{endo,f}$ ,  $T_{exo,i}$  and  $T_{exo,f}$  were shown in Fig. 6(a)

$$ARR(\%) = \frac{L_{OPNCs,avg}}{L_{PCMs}} \times 100 \tag{2}$$

ARR (%) of C-300, C-500, AC, EG and xGnP are 41.27, 43.86, 55.12, 76.63 and 43.51, respectively. This result confirmed that the impregnation ratio and ARR values showed similar tendencies that means more the amount of impregnation of PCMs, the more the proportional relationship that ARR increases was shown. However the difference

between ARR values and the impregnation ratio caused by the experimental difference. Thus ARR can be the index of actual thermal performance of OPNCs. In the OPNCs of each porous nano carbon-based materials, except for EG, the maximum difference of heating latent heat capacity and the maximum difference of cooling latent heat capacity were 10.7J/g and 9.1J/g, respectively. In Fig. 6, the baseline was constant while the temperature was increased from zero to about 25 °C. This explains why the temperatures of the OPNCs were in the sensible heat range. On the other hand, after the 25 °C range, the slopes were rapidly increased. This range is within the range of about from 25 °C to 35 °C. This was due to the initial degree of melting of *n*-octadecane at 28 °C. In other words, *n*-octadecane phase change starts with storage of heating energy in this range. Afterwards, the range in the interval of from 35 °C to 80 °C showed a similar slope to that of the interval of from

**Table 4**  
Latent heat capacity and rate of decrease in latent heat efficiency of OPNCs.

Sample		Latent heat capacity (J/g)		Rate of decrease In Latent heat efficiency (%)
		OPNCs	n-octadecane	
n-octadecane/C-300	Heating	107.80	256.5	57.97
	Cooling	103.90		59.49
n-octadecane/C-500	Heating	114.40		55.40
	Cooling	110.60		56.88
n-octadecane/AC	Heating	118.50		53.80
	Cooling	113.00		55.95
n-octadecane/EG	Heating	196.80		23.27
	Cooling	196.30		23.47
n-octadecane/xGnP	Heating	112.40		56.18
	Cooling	110.80		56.80

**Table 5**  
Peak temperatures during heating and cooling of OPNCs.

Sample	Peak temperature (°C)	
	Heating	Cooling
n-octadecane/C-300	29.34	23.34
n-octadecane/C-500	30.14	23.62
n-octadecane/AC	31.17	24.15
n-octadecane/EG	29.75	23.02
n-octadecane/xGnP	31.34	24.83

0 °C to 25 °C. This means the interval of from 35 °C to 80 °C is also in the sensible heat range also. As shown in the DSC data given in Fig. 6, the graphs show similar shape. Similarly, in Table 5, the maximum difference of peak temperature of heating and cooling were 2 °C and 1.79 °C respectively. In the endothermic data, the peak temperatures of the OPNCs show a similar tendency to that of the n-octadecane melting temperature. In summary, melting temperature and low difference of peak temperature showed similar tendencies that means the non-chemical bonding of OPNCs, indicating successful impregnation.

Therefore, after performing the 3-step filtered vacuum impregnation, it was confirmed that the OPNCs provides superior thermal performance and thermal stability. This is expected to have a beneficial effect in terms of thermal stability for these materials in building applications.

### 3.5. Thermal stability analysis of n-octadecane/porous nano carbon-based materials

The thermal stability of OPNCs was analyzed from the TGA data. TGA tests were conducted at various temperatures rises from 40 °C to 600 °C. Under these conditions, the degree to which OPNCs were impregnated could be determined. The n-octadecane was thermally decomposed, although carbon-based materials were not thermally decomposed. Fig. 7, shows that the first mass loss of OPNCs occurred at 100 °C. It was determined that the thermal decomposition of the n-octadecane occurred in the range of from 197.87 °C to 219.45 °C. Therefore, the TGA graphs for OPNCs showed similar tendencies, regardless of the carbon-based materials. Table 6, show the vacuum impregnation rate, according to the weight ratio, where xGnP shows the lowest impregnation rate of 53.58%, and the case of EG was identified as having the highest impregnation rate of 88.53%. In addition, the impregnation rates, according to the weight ratios indicated similar tendencies, from the experimental values of OPNCs, except for EG. The OPNCs except for EG were slight difference from each value 0.52% to 5%.

### 4. Conclusion

The global concern over the increased energy consumption by buildings has recently increased. Therefore, in this study, a TES system was applied using n-octadecane in order to reduce the building energy consumption. However, the direct application of PCMs in building is difficult because of the problems of leakage and low thermal conductivity of PCMs. In order to address these problems, OPNCs were manufactured by 3-step filtered vacuum impregnation method in this study.

Comparing the SEM images of the pure state of porous nano carbon-based materials with those of the OPNCs, it was confirmed that the morphology of the OPNCs was properly impregnated using the 3-step filtered vacuum impregnation method. FT-IR analysis was identified that OPNCs were bonded by a physical force such as a capillary force without changes occurring to the physical properties. Also, thermal conductivity analysis showed that the thermal conductivity of OPNCs increased more than that of pure n-octadecane from 380% to 580%. DSC analysis of the data, it was confirmed that the heat storage occurs in the specific temperature of the n-octadecane. Also through the ARR values that 41.27%–76.63%, thermal performance of OPNCs figured out in comparison with n-octadecane. Through TGA analysis, OPNCs

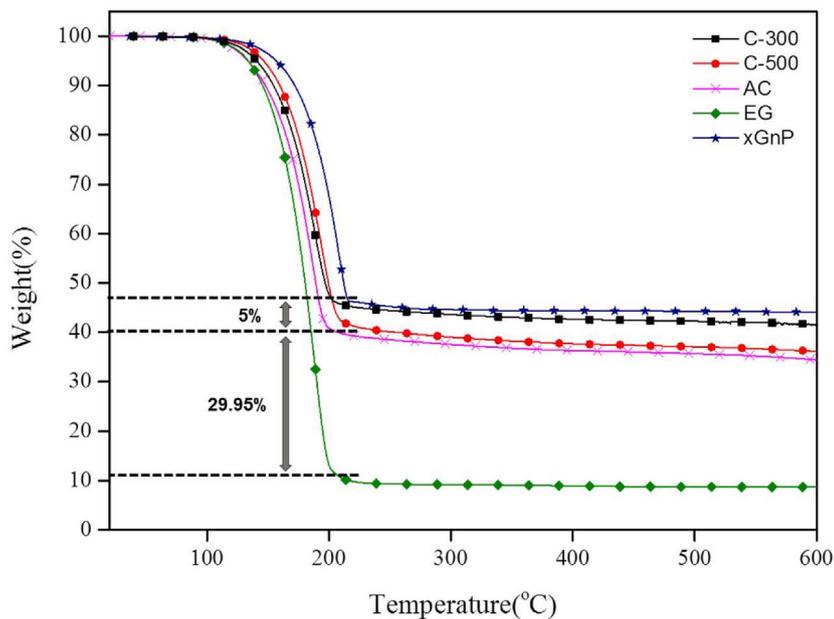


Fig. 7. Thermogravimetric analysis of OPNCs.

**Table 6**  
Impregnation ratios of OPNCs.

Sample	Impregnation ratio (%)
n-octadecane/C-300	54.1
n-octadecane/C-500	57.47
n-octadecane/AC	58.58
n-octadecane/EG	88.53
n-octadecane/xGnP	53.58

have thermal stability due to their thermal decomposition of above 100 °C.

In a summary, the 3-step filtered vacuum impregnation method with the carbon materials, showed similar thermal performance tendencies.

The following three conclusions can be drawn from this study. Firstly, OPNCs can be applied in buildings with low possibility of leakage problem and without the issue of low thermal conductivity. Secondly, porous nano carbon-based materials made from the same raw material showed similar tendencies in all experiments. Finally, 3-step filtered vacuum impregnation method was validated stability of method through OPNCs of similar thermal properties. The 3-step filtered vacuum impregnation method can produce more OPNCs at any given time and more purify by 3 filtered processes. Therefore, this method is recommended for building applications. In the next study, a larger capacity device will be applied.

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