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Sustainable polypropylene nanocomposite for lightweight and low thermal conductivity application

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Abstract

Sustainable polypropylene nanocomposites (PPNCs) were prepared by using melt blending of polypropylene (PP), and nanoclay (NC) in the presence of a compatibilizer, i.e. maleic anhydride grafted polypropylene (MAPP). The characterization of the composite samples was accomplished with tensile tester, x-ray diffractometer, scanning electron microscope, thermo gravimetric analyzer, and thermal conductivity instruments. The improved adhesion between the matrix and the reinforcement enhanced the physical, thermal and mechanical properties of the composites. The result describes how the sustainable product is a function of the process root, material composition and the micro structure. The study focused on the development of a sustainable light weight and low thermal conductive polypropylene nanocomposites for thermal insulation, which can be used in a sustainable environment that may include: alkalinity, fire, moisture, and thermal effects.

Keywords: Sustainable; Polypropylene-nanocomposite; Light weight; Low thermal conductivity.

1. Introduction

Thermal conductivity is the property that describes the ability of a material to transfer heat. An insulator is a material that does not permit the transfer of energy; however materials that are poor thermal conductors can be termed as good thermal insulators [1]. Plastics are poor thermal conductors while metals are good thermal conductors [2]. Any material that conducts heat efficiently will also lose this heat, rather quickly than insulating

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materials [3]. Sustainable heat insulation for energy saving can be useful when energy transfer in form of heat through conduction, convection, and radiation must be minimized in order to reduce heat gain, e.g. in sandwich car body [4]. Energy transfer across engineering materials can be slowed down by insulating material in order to improve energy efficiency in dielectric, refrigerated rail box panel, refrigerated vehicle panel, and building of ceiling [5]. Nowadays, the application of lightweight product design is driven by public regulations associated with environmental impact, carbon or other emissions, and industry factors, *viz*: payload, cost reduction, saving in energy consumption, or increases in product performances [6].

Composite material is defined as a mixture of two or more materials, which are different in composition and they can act as the reinforcement, fillers, or binder [7]. Composite materials are also called composition materials or shortened to composites [8]. They are materials made from two or more materials with considerable differences in physical and chemical properties, that when combined, make a material with appearances and properties, different from the individual components. Composites comprise of weaker materials are known as matrices and strong load-bearing materials are known as reinforcements [9]. Reinforcement provides strength and stiffness which helps to support structural load [10]. Composite materials do not lose their respective identities but still relate their properties to the product. They find applications in: automotive, aerospace, electronic equipment, sport goods, furniture, medical equipment and the packaging industries [11]. Composite materials are used as industrial materials for their outstanding resistance to chemicals and most forms of corrosion. The tools for composite production are considerably cheaper than tools for sheet metal forming [12]. This is because composite processes are one-shot operations or one mold, while sheet metal forming requires five to six separate tools per component line. Composites can be classified on the bases of their matrix types, which include: Polymer Matrix Composites (PMCs), Metal Matrix Composites (MMCs), and Ceramic Matrix Composites (CMCs) [13]. In this study, PP which is a polymer type was used as a matrix material in the composition and this makes the composition a polymer composite. Polymer nanocomposite properties are governed by the incorporation of nanoparticles size, shape, concentration, and interactions with the polymer matrix [14]. Polymer nanoclay composites involve the interaction of polymer matrix with nano-plates of clay formed by the dispersion of low weight percentages of nanoclay into polymer [15].

The aim of this study is to produce a sustainable light weight, low thermal conductive, heat retardant, and thermal insulation material and this will be achieved by melt blending PP and NC with MAPP as compatibilizer. PP is a polyolefin type of thermoplastic made of monomers composed of only carbon and hydrogen atoms and this makes PP an oil loving material known as oleophilic [16]. It is used primarily for thin-wall primary insulations and can be foamed to improve its electrical properties. PP has properties of: low-cost, good solidity, good chemical resistance, high impact strength, high tensile strength, low density, low cost and low thermal conductivity. Application of PP can be seen in: automotive bumpers, wheel housings, air filter housings, side panels, battery case, door trim, crash panel, interior auto parts and other component applications [17]. PP has a good synergy with NC. Clay is a refractory and it has the potentials of sustainable plantation, high surface area, high aspect ratio, cost-effective, environmentally-friendly, naturally occurring and readily available in large quantity [18]. Clay has been used as ceramic for porcelain and this is the standard material for high voltage and radio frequency insulators. However, the addition of maleic anhydride grafted polypropylene to the blend of polypropylene and nanoclay has been confirmed to be effective in the intercalation of the polypropylene nanocomposite. Melt blending technique was used in this study because it is a convenient and popular fabrication technique used in the industry and it has numerous advantages over the other techniques in use for the fabrication of nanocomposites, moreover no solvent is required [19]. This sustainable processing method is environmentally-friendly and it provides a good choice to end-use producers to come up with less capital costs due to its compatibility with existing methods [20].

The heat conduction flow in consecutive layers of different materials is shown in Equation 1 [21].

$$q = \frac{A\Delta T_1 k_1}{x_1} = \frac{A\Delta T_2 k_2}{x_2} = \frac{A\Delta T_3 k_3}{x_3} \quad (1)$$

Where: q is the rate of heat transfer; ΔT is the change in temperature; A is the cross sectional area; x is the thickness of a given material; and k is the thermal conductivity of the medium.
An insulator should be light-weight and stiff with good insulating features. The weight of insulation is a function of the dimensional length (L), dimensional width (W), insulation thickness and the density of the material. The thickness of an insulation material is based on customer's request and specification.
Below are two equations for calculating the weight and density of insulating material.

$$\text{Weight of material (kg)} = \text{length (m)} \times \text{width (m)} \times \text{thickness (m)} \times \text{density } (\mathrm{kg/m^3}) \quad (2)$$

$$\text{Material density } (\mathrm{kg/m^3}) = \frac{\text{weight(kg)}}{\text{Length(m)}\times\text{width(m)}} \quad (3)$$

On the performance of insulating materials, the thickness of an insulation material is a function of the heat transfer rate across the wall layers of the area of application, as shown in **Equations 1, 2, and 3** [22].

2. Experiment

2.1. Materials

Polypropylene CPV340 grade was obtained from Sasol Polymers Product, Sasol Place 50 Katherine Street, Sandton, South Africa. With flexural modulus: 1350 MPa; MFI@ 230^{o}C: 18 g/10min; density: 0.905 g/cm^3; and tensile strength: 33 MPa. Nanoclay Cloisite® 20A type was produced by Southern clay products, Inc. Gonzales, Texas USA. The compatibilizer, maleic-anhydride-grafted-polypropylene (MAPP), with trade name Eastman TM G- 3003 was supplied by Eastman Chemical Company 200 S. Wilcox DR. Kingsport, TN37660, USA. These sustainable products were received and used for melt blending.

2.2. Specimen preparation

NC and MAPP were dried in vacuum oven for 24hours at 80℃. In order to obtain enough materials for characterization tests, melt blending was conducted with rheomixer (HAAKE PolyLab OS) for a homogenous mixture. The rheomixer with total mass of 50g samples rated capacity was set at 190°C processing temperature, with a rotor speed of 60 rpm, for 8mins. The premixed samples from the rheomixer were compression molded in a carver laboratory press (Model – 3851-0, USA) at the temperature of 190°C, with pressure of 10MPa for 8mins by using different characterization molds according to various standards required. After which the molded samples were allowed to cool at room temperature for subsequent characterization. During characterization, each test sample was tested at an average of 5 times. The composite samples blend is shown in **Table 1.**

Table 1. Composite samples blending in weight percentage.

Sample	PP (wt%)	MAPP (wt%)	NC (wt%)
Pure PP	100	0	0
$PPNC_1$	95	4	1
$PPNC_3$	93	4	3
$PPNC_5$	91	4	5
$PPNC_7$	89	4	7

$PPNC_{10}$	86	4	10

3. Characterization

3.1. Mechanical testing

Mechanical properties of PPNC were measured by Instron 5966 tester (Instron Engineering Corporation, USA with a load cell of 10kN in accordance with ASTM D638 standard, in order to investigate the strength and modulus (stiffness) of the composite samples. These tests were performed in tension mode at a single strain rate of 10mm/min and at room temperature. The results presented are the averages of five individual tests per sample.

3.2. Physical testing (SEM, X-ray, and density)

Scanning Electron Microscopy (SEM) analysis was conducted, in order to identify the structure and composition of the samples. It was carried out by using SEM (JEOL JSM-7500F, Germany) instrument with an accelerating voltage of 15Kv. SEM images were taken, in order to study the surface roughness, adhesive failure, fractured surfaces, networks and phase boundaries in blends of the composite samples. X-ray diffraction analysis (XRD) was carried out with PanAnalytical Xpert Pro diffractometer (The Netherlands) to study the crystalline structures of all the samples and nanoparticle. CuKα radiation with a wavelength of 0.154 nm at a voltage of 45 kV and a current of 40 mA. In addition, the densities of the composite samples were calculated and density accounts for weight.

3.3. Thermal analysis (TGA and Thermal conductivity)

This analysis was used to investigate thermal stability, the flame retardant, weight loss or gain, heat conductivity and insulation properties of the composites. Thermogravimetric analysis (TGA) was carried out with Thermogravimetric analyser (Model Q500, TA Instruments, USA) in order to investigate the weight gain or loss of a phase as a result of gas absorbed or released, which is a function of temperature under a controlled atmosphere. The weight of approximately 5 mg of each sample was used to investigate their thermal stability. The TGA heating rate was operated in air and ramped at 10℃/min, from room temperature to 1,000℃. The thermal conductivity analysis of the composite samples was carried out by using Netzsch LFA 427 SOP instruments. Nitrogen was used to stabilize the temperature or cooling in the furnace and argon gas was for the atmosphere inside the furnace. Processing conditions: set temperature range 25℃ – 100℃, sample diameter of 10mm, thickness 4mm, laser voltage 450v, pulse width 0.8ms, Atmosphere of Argon gas, flow rate 100ml/min, heating rate 50K/min, time distance 1min. LFA 427 instruments were operated in accordance with ASTM E1461, ISO 18755 standards.

4. Results and discussion

4.1. Mechanical property

The tensile strength (see **Fig.1a**), and tensile modulus (see **Fig.1b**), show increases in strength and stiffness, respectively at low clay contents of 1% and 3%. Sharp increases were observed at $PPNC_3$ in both tensile strength and modulus. When the clay loading was increased to 5% and above, a decrease was observed due to the fact that the strength of the compatibilizer was exceeded. The mechanical properties of PP with nanoclay contents were enhanced when compared to that of pure PP used as the reference material. This shows that the increases in tensile properties are the functions of clay and compatibilizer.

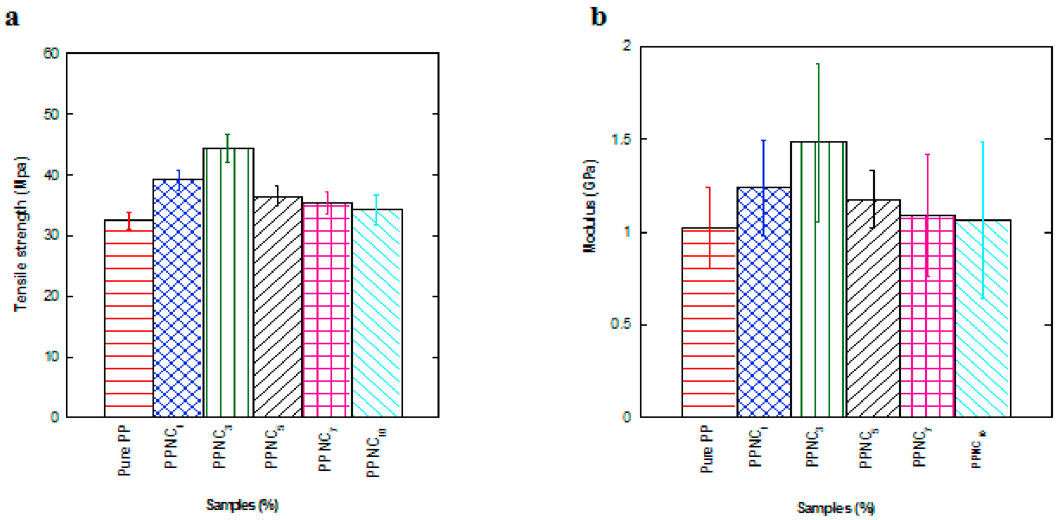

Fig. 1. (a) Tensile strength of samples; (b) Tensile modulus of samples.

4.2. Physical property

SEM micrographs displayed uniform dispersion of NC in the PP matrix with the help of MAPP as compatibilizer, as shown in **Fig .2**. The materials were compatible up to 3% clay content, but from 5% clay loading, poor interfacial adhesion and deboning were observed. Thereafter, at 10% clay content, agglomeration and cracks were observed. This is believed to be the reason for the decreases in strength and modulus of the samples. Moreover, processing route has an effect on the microstructure of the material, by altering the composition and properties of the samples.

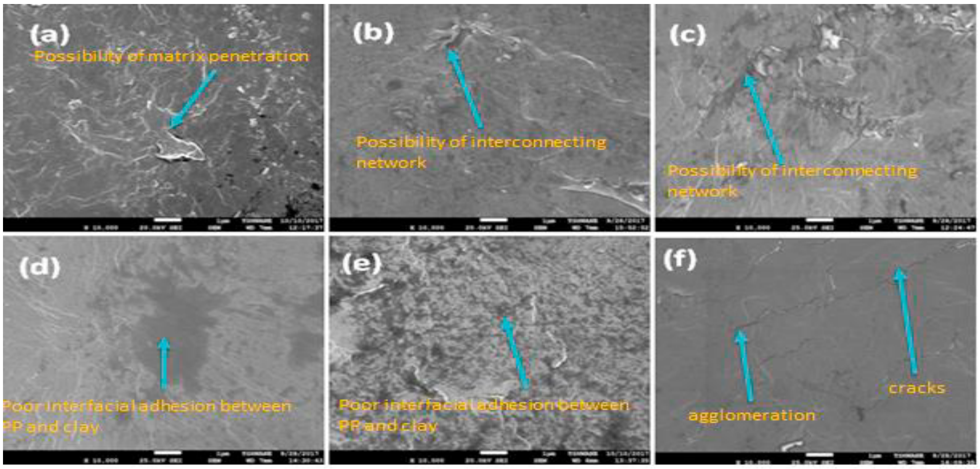

Fig. 2. SEM microgram of : (a) Pure PP; (b) $PPNC_1$; (c) $PPNC_3$; (d) $PPNC_5$; (e) $PPNC_7$; (f) $PPNC_{10}$ with magnification of x10,000.

From the X-ray analysis, the result of the percentage crystallinity shown in **Table 2,** was calculated from the X-ray diffractograms in **Fig 3,** by using the Weidiger and Hermans relation, as stated in Equation 4, below.

$$\%\,X_c = (1 + 9.53(I_a/I_t))^{-1} \times 100 \quad (4)$$

Where: $\%X_c$ is the percentage crystallinity, I_a is the amorphous intensity height, and I_t is the sum total of the intensities of the four main peaks.

It was observed, that there are some amount of crystal in the amorphous polypropylene impact copolymer CPV340 used in this study as the parent material. As the clay content increased, the percentage crystallinity also increased, up to the PPNC3% clay inclusion, and then started to decrease as the clay loading increased. The result corresponds with that of tensile strength and modulus (see **Fig 1**).

Table 2. Main peak intensity, amorphous halo, and percentage crystallinity of composite.

Sample	Peak height (nm)				Intensity total (I_t) of main peaks (a.u.)	Amorphous Intensity (I_a) (a.u.)	$\%X_c$
	$I_{(110)}$	$I_{(040)}$	$I_{(130)}$	$I_{(131)}$			
Pure PP	32.5	56.5	31	24	168	18	49.4
$PPNC_1$	37	46	31	48	162	17	49.9
$PPNC_3$	44	50	30	48	172	18	50.1
$PPNC_5$	39	41	27	44	151	17	48.2
$PPNC_7$	41	36	29	50	156	18	47.6
$PPNC_{10}$	50	37	25	44	162	19	46.2

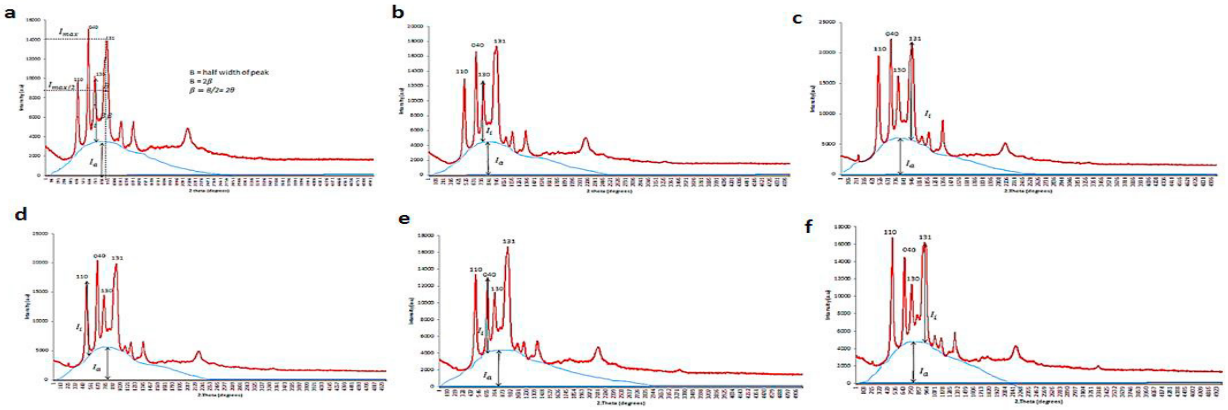

Fig. 3. X-ray diffractograms of: (a) Pure PP; (b) $PPNC_1$; (c) $PPNC_3$; (d) $PPNC_5$; (e) $PPNC_7$; (f) $PPNC_{10}$

4.3. Thermal property

TGA results in **Fig 4,** show the weight loss of samples during degradation process at high temperature due to volatile products in the composite samples. It was found that pure PP degraded faster when compared to PP with clay inclusions. There was an enhancement in the thermal stability due to the incorporation of clay into the polypropylene matrix, which formed char at the end of the experiment. Clay acts as a superior insulator and a barrier to the mass transport of products generated during decomposition. The improvement in thermal stability is due to char formation in the presence of clay reinforcement.

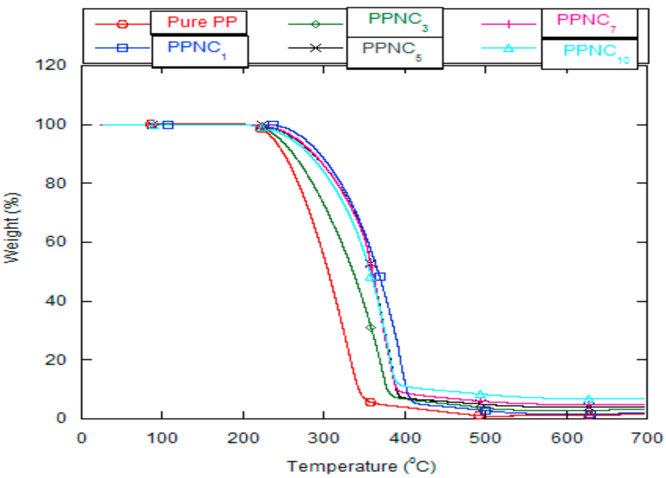

Fig. 4. TGA thermograms of samples.

The thermal conductivity and density data of the samples are shown in **Table 3**. It was observed that the thermal conductivity of the samples decreased as the clay loading increased in the matrix of polypropylene. PPNC with 10% clay gave the best thermal conductivity value. The thermal conductivity of a composite depends on polymer-filler interaction, filler size and shape. Thermal conductivity is also one of the factors used to determine the flame retardant characteristics of a material. Low thermal conductive material is good for flame retardant. The density of the samples which accounts for weight, increased as the clay content in the matrix of PP increased. This means that an increase in clay content caused a slight increase in the weight of the samples.

Table 3. Composite samples blending in weight percentage.

Sample	Density (g/cm^3)	Thermal conductivity (W/m.K)
Pure PP	0.857	0.293
$PPNC_1$	0.886	0.250
$PPNC_3$	0.893	0.2198
$PPNC_5$	0.906	0.2029
$PPNC_7$	0.913	0.I545
$PPNC_{10}$	0.921	0.1230

5. Conclusion

Polypropylene nanocomposite, which offers a new technology and business opportunities for all industry, in addition to being environmentally-friendly is a good candidate of sustainability that has its indicator on: economy, social, and environment. The study showed that the tensile strength and modulus of PP nanocomposites were improved due to the strong interface bonds between matrix and disperse phases. The crystallization, weight reduction, melting behavior, thermal stability and low thermal conductivity of PP nanocomposites were related to compatibilizer and nanoclay contents. The optimum result was observed in PP nanocomposite with 3wt% nanoclay content and since mechanical, physical, and thermal properties are important in this study, PP with 3wt% is recommended for isolation application. Modeling of this composite sample should be considered for future work and also varying different types of clay and compatibilizer in PP matrix.

References

[1] M.S. Al-Homoud, Performance characteristics and practical applications of common building thermal insulation materials, Building and environment 40.3 (2005) 353-366.
[2] G. W. Lee, M. Park, J. Kim, J.I. Lee, H. G. Yoon, Enhanced thermal conductivity of polymer composites filled with hybrid filler. Composites Part A: Applied science and manufacturing 37.5 (2006) 727-734.
[3] B.P. Jelle, Traditional, state-of-the-art and future thermal building insulation materials and solutions–Properties, requirements and possibilities. Energy and buildings 43.10 (2011) 2549-2563.
[4] E. Cuce, S.B. Riffat, A state-of-the-art review on innovative glazing technologies. Renewable and sustainable energy reviews 41 (2015) 695-714.
[5] S.J. James, C. James, 6 Design and operation of frozen cold stores. Fish Canning Handbook (2010) 132-150.
[6] J. S. Damtoft, J. Lukasik, D. Herfort, D. Sorrentino, E.M. Gartner, Sustainable development and climate change initiatives. Cement and concrete research 38.2 (2008) 115-127.
[7] D. Verma, P.C. Gope, A. Shandilya, A. Gupta, M.K. Maheshwari, Coir fibre reinforcement and application in polymer composites: A." Environ. Sci 4.2 (2013): 263-276.
[8] T.W Clyne, D. Hull, An introduction to composite materials. Cambridge university press, 2019.
[9] S. Taj, M.A Munawar, S. Khan, Natural fiber-reinforced polymer composites." Proceedings-Pakistan Academy of Sciences 44.2 (2007) 129.
[10] J. Zhang, K. Chaisombat, S. He, C.H. Wang, Hybrid composite laminates reinforced with glass/carbon woven fabrics for lightweight load bearing structures." Materials & Design (1980-2015) 36 (2012) 75-80.
[11] C. Sanchez, P. Belleville, M. Popall, L. Nicole, Applications of advanced hybrid organic–inorganic nanomaterials: from laboratory to market." Chemical Society Reviews 40.2 (2011) 696-753.
[12] M. Kleiner, M. Geiger, A. Klaus, Manufacturing of lightweight components by metal forming. CIRP annals 52.2 (2003): 521-542.
[13] J.P. Jose, S. Thomas, J. Kuruvilla, S.K Malhotra, K. Goda, M.S Sreekala, Advances in polymer composites: Macro-and microcomposites—State of the art, new challenges, and opportunities. Polymer Composites; Wiley: Weinheim, Germany 1 (2012) 3-16.
[14] I.Y. Jeon, J.B. Baek, Nanocomposites derived from polymers and inorganic nanoparticles. Materials 3.6 (2010) 3654-3674.
[15] N. Saba, M. Jawaid, M. Asim, Recent advances in nanoclay/natural fibers hybrid composites. Nanoclay reinforced polymer composites. Springer, Singapore, (2016) 1-28.
[16] Y. Zheng, E.K. Yanful, A.S. Bassi, A review of plastic waste biodegradation." Critical reviews in biotechnology 25.4 (2005) 243-250.
[17] V. Patel, Y. Mahajan. Polymer nanocomposites: emerging growth driver for the global automotive industry. Handbook of

Polymernanocomposites. Processing, Performance and Application. Springer, Berlin, Heidelberg, (2014) 511-538.
[18] A.J. Jose, M. Alagar, AJITH JAMES, nanotechnology for smart and intelligent food packaging. Biopolymers and Biomaterials (2018).
[19] S.S. Ray, M. Okamoto, Polymer/layered silicate nanocomposites: a review from preparation to processing. Progress in polymer science 28.11 (2003) 1539-1641.
[20] T. Gurunathan, S. Mohanty, S.K. Nayak, A review of the recent developments in biocomposites based on natural fibres and their application perspectives." Composites Part A: Applied Science and Manufacturing 77 (2015) 1-25.
[21] S.S. Mehendale, A. M. Jacobi, R. K. Shah, Fluid flow and heat transfer at micro-and meso-scales with application to heat exchanger design. Applied Mechanics Reviews 53.7 (2000) 175-193.
[22] D.F.A. Abdullah, Theoretical and experimental investigation of natural composite materials as thermal insulation. Al-Qadisiya Journal For Engineering Sciences (2011) 4, 26-36.