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Synthesis of green thermally resistant composite: A review

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Rising demand for the sustainable environment has been enthused interest in the synthesis of a green composite. In the modern era, thermal insulating materials prepared from agro-waste have been concerned globally as they represent a biodegradability and inexpensive alternative to the conventionally derived materials. Nearly 350 million tons of agro-waste is generated through agricultural activity in India which are either land filled or incinerated. The reuse of renewable waste fibers as filler for reinforcement of a polymer composite is a worthwhile option to the environment. This extensive review explores the utilization of agro-waste for synthesis biodegradable thermal resistant composite and methods used for thermal conductivity measurement. Proper utilization of agro-waste is the need of the modern world. In this review, Authors found that agro-waste such as corn cob, corn stalk, rice waste, date palm fiber, durian peel fiber, coconut coir, and straw bales etc. can be blended into the polymer to enhancing its thermal resistant property by lowering their thermal conductivity. This review also investigated an effect of different parameters such as particle size, moisture content, density, and concentration of agro-waste in composite preparation.

Keywords: Agro-waste, Biodegradable, Polymer composite, Reinforcement, Thermal conductivity.

In the last few decades, the world wide consumption of polymer ramped up from 1.5 million ton in 1950 to about 322 million ton in 2015. Polymers are generally used in daily applications such as packaging, manufacturing, automotive, home utilities, and building construction. Some of the reason for increasing use of polymers around the world may be listed as low density, good mouldability, easier preparation of coloured articles, durability and low cost. On the other hand in India, approximately 350 million tons of solid waste is being generated annually as by-products during agricultural activity which is also a severe environment thread[1-2].

This demand is also a remarkable factor for the hike in the production of polymer waste which is either land filled or incinerated. In landfill method, most of the polymer waste takes over hundreds of years to decompose and in incineration process; polymer waste produces large volumes of undesirable gases that affect the atmosphere badly. On the other hand, Burning agro-waste such as trees, leaves, wood, and grasses produces polycyclic aromatic hydrocarbons (PAHs), carbon dioxide (CO2), carbon monoxide (CO) and particulate matter (PM) that are released into the environment around the globe. Since agricultural waste burning is not an environmentally acceptable form of agro-waste management, understanding the proper utilization of agro waste is very imperative[3-5].

As the hike in demand for polymers using, the potential destruction of the environment also increases exponentially. In this decade, there is a main concern towards sustainable environment development and enhancing the usage of a biopolymer. Hence we need to develop materials which utilize the polymeric wastes and are biodegradable[6,7].

Composites are materials composed of two or more different materials with the properties of the resulting material being superior to the properties of the individual materials that make up the composites. Thus we can say that Composites are multifunctional material systems that provide characteristics not obtainable from any discrete material. They are cohesive structures made by physically combining two or more compatible materials, different in composition and characteristics and sometimes in the form as well. Current trends towards a synthesis of green composite, focus on the use of natural fibers as the potential resources for producing biocomposite materials. In general, a biocomposite may be defined as a polymer matrix filled with a reinforcing material such as biomass to serve specific objectives or requirements. Due to the chemical constituent of agro-waste (consisting of cellulose, lignin, and hemicellulose), agro-waste fiber has been received much academic and commercial attention due to its exceptional reinforcement property in polymer composites. The application of green fibers in composite preparation has been grown manifolds due to their excellent properties such as improved mechanical strength, water, oxygen barrier, biodegradable property and dimensional stability. They are also considered to provide better resistance towards heat, wear resistance and many chemicals[8-15].

The current environment aspects encourage the use of agro-waste as filler in polymer composite and preserve the environment from limited landfill space and incineration problem. These unwanted impacts can be minimized by using agro-waste. It has growing interest in the field of producing a green composite.

Renewable agro-waste as a thermal insulator

Agro-waste is known as waste which is produced from various agriculture activities. Thus agro-wastes include manures, bedding, plant stalks, hulls, leaves and vegetable matter. The accumulation of agro-waste might cause health, safety, environmental and esthetic concern. Thus, safe disposal and better utilization of agro-waste is the need of the hour. Several authors have already proposed use of different agricultural residues such as wheat straw, barley straws, date palm fibers, olive stone, coconut and durian mixture as reinforcement in sand concrete, plaster concrete, gypsum, cement lime mortar as matrix to develop new lightweight construction materials with lower thermal conductivity[16-22]. Some of the findings have been described in the subsequent section of this paper (Table 1).

A significant amount of agricultural waste can be utilized by several processes. The Cellular structure of agro waste provides excellent properties such as low weight (density), high mechanical strength (both tensile and compression) and under controlled condition, it can also be used as a fine insulator. It is also a highly versatile material because it can be bent or twisted in particular and complicated shapes and is readily work, fastened and finished. The final shape is pleasant to touch with beautiful patterns at the same time[23-29]. The main advantages of using ligno-cellulosic fibers as reinforcement of polymer matrices may be listed as:

i) high specific mechanical properties,
ii) proper aspect ratios,
iii) low equipment abrasion during preparation and manufacturing,
iv) high availability,
v) low density and
vi) comparatively low cost[30]

Corn cob and corn stalk

Corn-cob, which is a lignocellulosic biomass derived from the maize plant, often causes environmental pollution due to lack of its effective disposal or utilization. The production of the maize grain annually leaves behind an enormous corn cob waste (around 20% corn residue generated annually). Biomass, in which the corn cob is one, provides about 1250 million tons oil equivalent of primary energy (about 14% of world's annual energy consumption), After coal and gas, biomass remains the next primary energy supplier to the world[31- 36].

The agricultural corn stalk is the byproduct of annually renewable crops and abundant volumes are obtained around the world. However, it has normally been utilized in a least efficient way such as burning as compost, which results in haze, one of the most disgusting environmental issues in the current scenario[37-38].

To make good use of the corn coir and corn stalk biomass and convert them into high-value products, a great deal of research has been done to use them as a reinforcing material[39].

During last few years, the use of agro waste in the preparation of composite materials for the construction industry has been the main concern. Aksogan *et al*. (2016) aimed to develop a bio-based composite and investigated its thermal, mechanical and acoustic insulation properties. The biocomposites were prepared with epoxy resin and corn stalk and studied the effect of the ratio of the epoxy/corn stalk particle and stalk particle size on the composite was studied. Reported results reveal that agro waste could be used for the manufacture of commercially feasible and satisfactory insulation material which was of organic origin[40-45].

Several authors had already proposed use of different types of agricultural product such as bagasse, cereal, straw, corn stalk, corn cob, cotton stalks, kenaf, rice-husks, rice-straw, sunflower hulls and stalks, banana stalks, coconut coir, bamboo, durian peel and palm leaves among others for product processing such as fiber board, hardboard and particleboard focusing on their thermal insulation capacity. Other authors also have studied the potential of different kinds of waste such as newspaper, honeycomb and polymeric wastes in different

Table 1 — Reported work on development of ecofriendly thermal insulating material using agro-Waste

References	Raw material	Parameters					Method	Thermal conductivity k (W/m.K.)
		Density of material (kg/m^3)	Agro waste Particle size (mm)	Thickness of material (m)	Moisture content of a material (%)	Agro waste concentraion (wt%)		
Li *et al.*(2016)	Silica/Rice Husk Hybrid, Carbon Black, Titanium Oxide, Polyester	_	_	95×10^{-6}	_	26-36	1-Dry Powder Mixing Method 2-Thermal conductivity Measurement Method	k=5.5
Aksogan *et.al.* (2016)	Corn Stalk, Aluminum Dust, Gypsum, Epoxy Resin, Cement	_	0.5-4	0.02	_	23	ASTMC Thermal Conductivity Meter	k = 0.075
Chen *et al*. (2015)	Rice Straw	200-350	10-30	0.40	10, 14, 18	_	1-Hot Pressing High Frequency 2-Steady State Slab Method For Thermal Conductivity 3-Thickness Swelling Test 4-Modulus of Rapture	k=0.051-0.053
Chaussinan *et al.* (2015)	Straw Bale	_	_	_	_	_	_	k= 0.052-0.12
Avallaneda *et.al* (2015)	Cereals, Barely, Wheat Straw, Corn Stalks, Rice Straw, Rice Husk	_	_	_	_	_	_	_
Balo *et al*. (2015)	Rice Husk Ash +Fly Ash+ Clay+ ETO	1339	39.34×10^{-2}	0.02	_	_	Shortherm QTM Temperature Measurement Gauge	k=0.537 At 165ºC k= 0.256 At 205ºC
Ashour *et al*. (2015)	Wheat & Barely Straw, Clay, Slit, Sand	_	_	0.06	24	1-3	Qtm-500 Thermal Conductivity Meter ASTMC	k=0.310-0.961 (Wheat Straw) k=0.314-0.961 (Barely Straw)
Barlretta *et al*. (2014)	Dried Beech Powder, Diluted Polyurethane	_	_	$109\text{-}123\times10^{-6}$	_	0, 40, 60, 80	1-Multilayer Coating Method 2-Flash Method For Thermal Diffusivity	k Value Decreases by 17%,24%,31%
Agoudjil *et.al.* (2014)	Date Palm Fiber, Sand , Water	1890-722	5	_	_	5, 10, 15	Hot Wire Method(Device)	k= 0.10-0.82
Charoenvai *et. al.* (2014)	Durian Peel Fiber, HDPE	_	5	_	_	5,10,15,20	Extrusion Method	_
Avellaneda *et al.* (2014)	Hemp, Flax, Kneaf, Wood Fiber, Coconut Coir	_	_	_	_	_	_	k = 0.050-0.05
Thomson *et al.* (2014)	Straw Bales (Wheat, Barley, Rice)	_	_	35×10^{-3}	25	_	_	_
Paiva *et.al.* (2012)	Corn Cob	334	_	0.03,0.05,0.06, 0.08	_	_	_	k= 0.101 in centigrade
Padkho *et.al.* (2012)	Rice Straw, Shell Corn	400, 600	_	_	10.54	_	1-ASTMC 177 For Thermal Conductivity	k= 0.03-0.09
Agoudjil *et al.* (2011)	Date Palm Wood	254-276	_	$4.2\text{-}5\times10^{-3}$	_	_	Periodic Method	k= 0.08 (At Atmosphere) k= 0.04 (At Vacuum)
Costa *et.al.* (2011)	Corn Cob	_	_	0.05	_	_	Tabique Construction (Portuguese Traditional Building Technique)	_
Charoenvai *et.al.* (2003)	Durian Peel & Coconut Coir	300-900	_	0.05	(6.8-13.39)	3	_	k= 0.064-0.1513 (Durian Peel) k= 0.0540-0.1430 (Coconut Coir)

manufacturing processes. Paiva *et al*. (2012) fabricated an experimental set up to calculate the thermal insulation property of corn cob particleboards. Testing was done under real thermal and hygrometric conditions and they studied the variation in thermal insulation property of the particleboards with thickness. Reported results showed that thicker corn cob particleboards had smaller thermal transmission coefficient[46-54].

According to Costaa *et al*. (2011), many researchers had focused on the study of application of solid and agro-waste such as durian peel, straw, corn peel, coconut coir, rice hulls, oil palm leaves for thermal insulation. Costa *et al*. (2011) used an agricultural waste, corn cob as sustainable building material for thermal insulation. Their study included the micro-structure and chemical composition. They also concluded that there were significant similarities between the corncob and the extruded polystyrene (XPS) material[48, 49, 50, 55, 56].

Rice waste

India is one of the globally largest producers of white rice and brown rice, accounting for 20% of world's rice production. The rice cultivation leads to the two types of residues: rice straw and rice husk (RH). For every kilogram of harvested paddy rice, between 0.41 and 3.96 kg of rice straw is produced. Rice straw has an ash content of 10–17% of which 75% is silica (SiO_2) content. The RH is the outermost layer of the paddy grain that is separated from the rice grains during the milling process. Both RH and RHA have major components namely, carbon and silica. The silicon element enters rice plants via their root in a soluble form, probably as a silicate or monosilicic acid, which undergoes bio mineralization to form lignocellulose and silica connected network in rice plant[57-59].

Li *et al*. (2016) have been investigated the thermo-physical properties of diverse alternative cheap fillers such as expanded perlite, hollow glass microspheres, house dust , fly ash , xonotlite, pumice and zeolite, as the vacuum insulation panel (VIP) core material, without a sacrifice of their service performance. These fillers were considered as second phase alternative material. Under controlled combustion condition, rice husk ash was also used as a fine insulator. So, the authors prepared powder hybrid core materials (HCMs) using different ratios of rice husk ash (RHA), fumed silica (FS), titanium dioxide, carbon black and polyester using dry powder mixing method and studied their microstructures, thermal conductivity and structural properties. Reported results showed that HCMs and their corresponding vacuum insulation panel (VIP) samples meso/macrostructure had a porosity of 80.5–87.9% and a fine pore size of 150.9–210.3 nm. The most favorable RHA content in the HCMs was 26–36 wt.% that balanced thermal conductivity, cost, structural stability and Green value[60-67].

Dai *et al*. (2015) developed a new thermal insulation material using high frequency hot pressing from rice straw (RSTIB). They also investigated the properties of RSTIB such as high frequency heating, board density, particle size and ambient temperature. They obtained 14% moisture content (MC), 250 kg/m^3 board density, (0.051-0.053) W/(m.K) thermal conductivity and an L-type particle shape which were most favorable physical, thermal and mechanical properties of boards [68].

Today triglyceride-based resins are an attractive alternative to petroleum-based resins because they are inexpensive, easily available, have excellent properties and are derived from renewable sources. Balo *et al*. (2015) manufactured an insulation material by using rice husk ash (RHA), fly ash (FA), clay (C) and epoxidized tall oil (ETO). They also determined the thermal conductivity of these materials experimentally between 0.537 and 0.256 W/(m K) by using Hot Wire Method. The optimum thermal conductivity of the sample was obtained with 30% C ratio+ 50% ETO and 60% FA processed at 205°C. So the composite material made from RHA, ETO, FA and C could be used on roof or wall as insulating materials[69-72].

Padkho *et al*. (2015) fabricated a light wall board from a rice straw and shell corn using heat compression method at a temperature of 120°C with pressure of 150 kg/m^2 and investigated its physical and mechanical properties. The experimental results showed that mixing of agricultural wastes in different proportions according to their features could produce light weight, heat insulation wall panels used for buildings[73].

Natural straw

Natural straw especially straw bales may be considered as novel cellulose based material. These cereal straw, including wheat, rice and barley offer a sustainable and renewable resource for different kind of building products, including thatched roofing, bales and compressed board panels. Straw bales can now be found in many locations around the world, such as Europe, USA, Australia, Canada, China and Japan. They are also used in prefabricated pannelized construction. Currently using natural straw bales in buildings has proved to be significant advantages in terms of long term durability[74-79].

Chaussinanda *et al*. (2015) used natural straws in constructions which are cheaper than those made with traditional materials and their prices could lower in the coming years with the increasing number of professionals in this field. In their paper, the authors aimed to investigate thermal behavior and energy performance of the straw building. They concluded that straw bale building had ability to offer an agreeable summer thermal comfort without using air conditioning and have been provided an improved thermal comfort with less variation in the indoor temperature[80].

Ashour *et al*. (2015) fabricated a sustainable and non-toxic composite reinforced with natural straw fibres and studied the thermal insulation property of the resulting material. Sometimes straw fiber has also been used in cellulose production as an energy resource. Reported results showed that thermal conductivity of a material reinforced with natural straw fiber decreased with increasing fibre content while enhancing with higher cement and gypsum contents. Thus, building materials reinforced with natural straw could be used as thermal insulating building materials[81-87].

Thomson *et al*. (2014) considered cereal straw including wheat, barley and rice as a sustainable renewable source which was used for different types of construction products, such as compressed board panels, thatched roofing and bales. Aerobic degradation of straw might also be limited by the availability of easily metabolised carbon, nitrogen and by prior colonisation by a micro-organism that utilized readily available nutrients. So the authors also investigated the degradation behavior of wheat straw cyclically exposed to elevated humidity levels. Reported results revealed that straw bales could be used for thermal insulation within the external envelope of buildings[88-92].

Date palm fiber

The date palm tree, a member of the palm tree family (phoenix dactylifera), normally exists in the Middle East, the Canary Islands, Northern Africa, Pakistan, India and in the United States (California). There are more than 100 million date palm trees in the world and each tree can grow for more than 100 years. The perfect use of fibers surrounding the stem of date palm trees as reinforcement in polymeric materials has been reported in few studies[93-100].

For last few years, numerous green natural materials (straw, hemp, bamboo, flax, animal hair, cork etc.) have been used as filler in designing and construction of energy thrifty buildings. Agoudjil *et al*. (2014) studied the thermal and mechanical properties of natural mortar reinforced with date palm fibers(DPF). Experimental results showed that increase of DPF concentrations lowered the thermal conductivity of a material and compressive strength while reducing its weight. Thus, natural mortar reinforced with DPF could be used as insulating material in building[101-107].

In present scenario, energy saving can lower the energy consumption up to 50 percent. It also reduces resource depletion. Many researchers have worked on eco-friendly wood based coating. Barletta *et al*. (2014) experimentally analyzed the mechanical response, protective properties, morphological features and thermal insulating property of the wood based coatings by changing their structure and concluded that due to their low intrinsic conductivity, wood particles improved the thermal insulation property of the coating material in the propagation of thermal energy across the coating[108-112].

The efficient utilization of natural source certainly has a positive impact on our environment. In fact, the development of agro-waste reinforced composites is a prominent solution for utilization of such waste as renewable sources. Agoudjil *et al*. (2011) studied the dielectric, chemical and thermo-physical properties of date palm wood (Phoenix dactylifera L) and used this natural material in the manufacture of thermal insulation of buildings. The author used a periodic method for instantaneous determination of diffusivity and thermal conductivity and reported that the date palm wood is very useful for the development of safe and efficient insulating materials[113-118].

Durian peel fiber and coconut coir

Durian Peel Fiber

Durian (Duriozibethinus Murray) is the most popular fruit in South-east Asia, particularly in Thailand, Malaysia, Indonesia, and Philippines and therefore a high amount of durian peel is produced in these countries. Furthermore agricultural waste is anticipated to increase in the future and if we are unable to efficiently dispose off the agriculture waste, it will lead to social and environmental problem. On the other hand Durian peels are rich of soluble fiber (lignin (15.45%), hemicelluloses (13.09%), and celluloses (60.45%) and insoluble fiber (pectin). Thus, to make good use of the durian peel biomass and convert it into high-valuable products, a phenomenal research work has been done to use it as a reinforcement material[119-120].

Charoenvai *et al*. (2014) used recycled high density polyethylene composites with different durian peel fiber content (5%, 10%, 15% and 20%) at different temperatures of 170, 180, 190 and 200°C. The composites were formed by twin screw extrusion and the researchers examined the mechanical properties of the composites viz tensile strength, elasticity modulus, hardness and impact strength. The results showed that modulus of elasticity of the composites were found to increase with increasing fiber content[121].

Coconut coir

The interior structure in between the shell and the outer coating of the coconut seed is known as coconut coir. The chemical constituents of coconut coir have been found to be cellulose, hemicelluloses, lignin, and pectin. It is abundantly available in India. Keeping in view the structural property of coconut coir, it may be used for reinforcement of plastics, rubber clay and cement[122].

Charoenvai *et al*. (2003) used coconut coir and durian peel as a raw material for the manufacture of new particle boards. This would help not only lower the cost but also prevent environment with additional advantages such as in controlling length, thickness, width and density. The authors reported that the mechanical strength of all boards increased with increasing board density. The thermal conductivity of these particle boards was between 0.054 and 0.1854 W/m.K. .Because of low thermal conductivity, these boards could be used for the applications such as in insulating walls and ceiling[123-124].

Thermal properties

Thermal properties are those properties of a material that are based on its conductivity. In other words, these are the properties which are exhibited by a material when heat is passed through it. Thermal conductivity is the most important thermal property

Thermal conductivity and its measurement methods

Thermal Conductivity

Thermal conductivity of a material can be defined as the rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference. The thermal conductivity of a material is a measure of its ability to conduct heat. The molecules are in continuous random motion, colliding with one another and exchanging energy and momentum. If a molecule moves from a high temperature region to a region of lower temperature, it transports kinetic energy to the lower temperature part of the system and gives up this energy through collisions with lower energy molecule[125].

A higher value for thermal conductivity indicates that the material is an excellent heat conductor, and a lower value indicates that the material is a poor heat conductor or insulator.

The basic equation for steady state heat conduction is Fourier equation and the equation is

$$q = -kA\, dT/dx$$

where q= heat conduction rate in x direction only

A= cross sectional area normal to heat flow

dT/dx= temperature gradient in x direction

k = proportionality constant known as the thermal conductivity of conducting medium The Thermal conductivity is a function of the molecular state of the medium; for a single phase system[126,127,129,130].

Measurement methods

Thermal conductivity is a fundamental property of a material that gives a measure of the effectiveness of the material in transmitting heat through it[128]. Different methods have been used for measuring thermal conductivity. Some of the measurement techniques have been described in the next section of this paper.

Hot wire method

The Hot Wire Method is a standard transient dynamic technique based on the measurement of the temperature rise in a defined distance from a linear heat source (hot wire) embedded in the test material. If the heat source is assumed to have a constant and uniform output along the length of test sample, the thermal conductivity can be derived directly from the resulting change in the temperature over a known time interval. In the hot wire probe method, the heating wire as well as the temperature sensor (thermocouple) is encapsulated in a probe that electrically insulates the hot wire and the temperature sensor from the test material[130,131](Fig. 1).

In this method, a wire is integrated into a sample. This can be achieved either by preparing a sandwiched sample/wire/sample system or by filling a chamber that already contains the clamped wire with the powdered or granular material under investigation. At the time of experiment, the wire is heated with a constant electrical power source. It simultaneously acts as a temperature sensor. The temperature is calculated from the increase of the temperature-dependent electrical resistance of the wire with time. The thermal conductivity is determined by evaluating the temperature rise in the wire, which

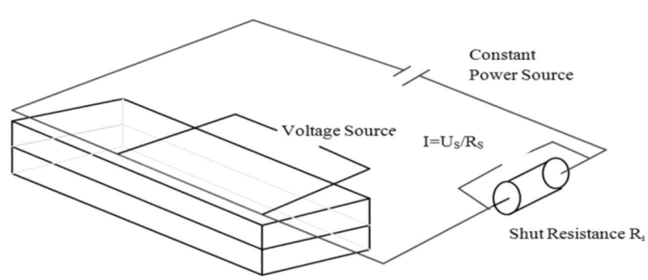

Fig. 1 — Hot wire method

depends on the thermal conductivity of the sample surrounding it[132,133].

Steady state periodic method

Accurate measurement of thermal conductivity is of great importance for materials research and development. Steady state methods determine thermal conductivity directly from the proportionality between heat flow and an applied temperature difference. This method makes use of a simple differential steady state method in which a sample is mounted on an electric heater and a temperature- controlled heat sink. This method calibrates for parasitic heat losses from the electric heater during the measurement by maintaining a constant heater temperature close to environmental temperature while varying the heat sink temperature. This enables a significant signal to noise ratio which permits accurate measurements of samples with small thermal conductance values (Fig. 2). Generally the standard method for the execution of insulation thermal conductivity test is KS L 9016 (Method for Measuring Thermal Conductivity of Insulations), The Heat Flux Method from ISO 8301 and ASTM Test Method C 518: 2004, and thermal conductivity measuring device of Heat Flow Meters HFM 436 Lambda Series from Netzsch are other alternative measurement techniques[134-138].

Thermal diffusivity and its measurement method

Thermal diffusivity

The thermal diffusivity of a material can be viewed as the ratio of the heat conducted (k) through the material to the heat stored (ρCp) per unit volume. The thermal conductivity k represents how well a material conducts heat, and the heat capacity ρCp represents how much energy a material stores per unit volume. A material that has a high thermal conductivity or a low heat capacity will obviously have a large thermal diffusivity[126]. It can be measured using laser flash method that is described below.

Laser flash method

In this method, one side of the sample is heated by using a short laser pulse. The heat diffuses through the sample and results in a rise of the temperature at the back side of the sample that is monitored with an IR-detector (Fig. 3). The change in temperature at the back side of the sample with time is fitted with the solution of the differential equation for the given boundary conditions; the free parameter is the thermal

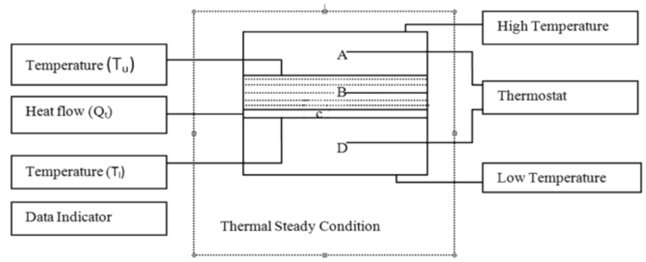

Fig. 2 — Schematic diagram of steady state periodic method: A-High temperature plate B- Test speciman C- Heat flow meter D- Low temperature plate

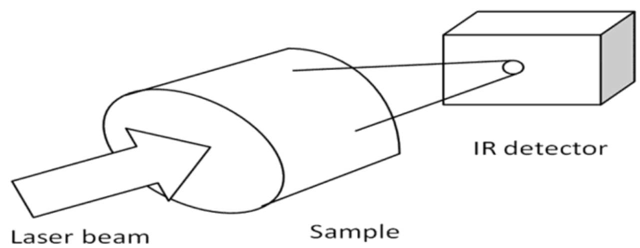

Fig. 3 — Laser flash method

diffusivity α. This quantity is related to the thermal conductivity k by

$\alpha = k/\rho Cp$

ρ = density of the sample

Cp = specific heat of the sample

Sheindlin *et al*. (1998) determined the density from the weight of a degassed sample and its dimensions band ; the specific heat was measured with a differential scanning calorimeter[132, 139].

Conclusion

materials such as corn cob, corn stalk, rice waste, date palm fiber, durian peel fiber, coconut coir, and This review investigated the thermal property of different type of composites reinforced by agro- waste straw bales and we conclude that these natural fibers have many advantages over glass fiber or carbon fiber. They are environmental friendly, renewable, lightweight and low cost materials having high specific mechanical performance.

References

1 Plastic Europe association of plastic manufacturers, *plastic Europe market research group* (2015).

2 Patel A N , Salla S & Pitroda J, *Int J Sci Res*, 2 (2013) 119.

3 Singh R, Singh N, Fabbrocino F, Fraternali F & Ahuja I P S, *Compos Part B*, 105 (2016) 23 .

4 Takoungsakdakun T & Pongstabodee S, *Sep Purif Technol*, 54 (2007) 248.

5 Curtis L, *Biomass Burning* , Burning Issues Special Edition (2002).

6 Mølgaard C, *Resour Conserv Recycl*, 15 (1995) 51.

7 Curlee T R & Das S, *Plastics Wastes (Management, Control, Recycling, and Disposal)*, Noyes Data Corporation, New Jersey (1991).

8 Abba H A, Nur Z & Salit S M, *J Miner Mater Char Eng*, 1 (2013) 271.

9 Jartiz & A E, *Design*, 18 (1965).

10 Kraiem D, Pimber S, Ayadi A & Bradai C, *Compos Part B*, (2013) 368.

11 Mulinari D, Voorwald J, Cioffi M, Silva M, Cruz T & Saron C, *Compos Sci Technol*, (2009) 214 .

12 Charoenvai S, Yingyuen W, Jewyee A, Rattanadecho P & Vongpradubchai S, *Energy Proce*, (2013)479 .

13 Asasutjarit C, Charoenvai S, Hirunlabh J & Khedari J, *Investigations on hygrothermal performance of coconut coir cement boards under Thai climate as determined by field test and simulation*, The sixteenth International Conference on Composite Materials, Kyoto, Japan (2007).

14 Ates S, Ni Y & Tozluoglu A, *Afr J Biotechnol*, 7 (2008) 4153.

15 Mc Gee B, *Folder Corn/Grain Corn: Area and Production*, Ontario by Country (2007).

16 Lim S F, Matu S U, *J Energy Environ Eng*, 6 (2015) 31.

17 Belhadj B, Bederina M, Montrelay N, Houessou J & Queneudec M, *Constr Build Mater*, 66 (2014) 247.

18 Chikhi M, Agoudjil B, Boudenne A & Gherabli A, *Energy Build* , 66 (2013) 267.

19 Barreca F & Fichera C R, *Energy Build*, 62 (2013) 507.

20 Djoudi A, Khenfer M M, Bali A & Bouziani T, *J Adhes Sci Technol*, 28 (2014) 2100.

21 Ashour T, Georg H, Bockisch F J & Wu W, *Mater Des*, 31 (2010) 4676.

22 Khedari J, Suttisonk B, Pratinthong N & Hirunlabh J, *Cem Concr Compos*, 23 (2001) 65.

23 Charoenvai S, Adv *Civ Eng Build Mater*, (2013) 119.

24 Asasutjarit C, Charoenvai S, Hirunlabh J & Khedari J, *Compos Part B: Eng*, 40 (2009) 633.

25 Asasutjarit C, Charoenvai S, Hirunlabh J & Khedari J, *Adv Mater Res*, 47 (2008) 678.

26 Asasutjarit C, Hirunlabh J, Khedari J, Charoenvai S, Zeghmati B & Cheul Shin U, *J constr build Mater*, 21 (2007) 277.

27 Charoenvai S J, Khedari J, Hirunlabh C, Asasutjarit B & Quenard Zeghmati D, *J Solar Energy*, 78 (2005) 543.

28 Khedari J, Charoenvai S & Hirunlabh J, *J Build Environ*, 38 (2003) 435.

29 Cheung H Y, Choy Y S & Lau K T, *J Sound Vib*, 331 (2012) 2348.

30 Espinach F X, Julian F, Lopez J P, Mendez J A, Mutje P & Vilaseca F, *Bioresour*, 7 (2012) 3188.

31 Danje S, Knoetze J H, Görgens J F, *Fast Pyrolysis of Corn Residues for Energy Production*, Stellenbosch University, South Africa (2011).

32 Purohit P, Tripathi A K & Kandpal T C, *Energy*, 31 (2006) 1321.

33 Werther J, Saenger M, Hartge E U, Ogada T & Siagi Z, *Prog Energy Combust Sci*, 26 (2000) 1.

34 Chen L, Xing L & Han L, *Renew Sustain Energy Rev*, 13 (2009)2689.

35 Bapat D W, Kulkarni S V & Bhandarkar V, *Design and operating experience on fluidized bed boiler burning biomass fuels with high alkali ash, in: F.D.S. Preto (Ed.)*, Proceedings of the 14th International Conference on Fluidized Bed Combustion, Vancouver ASME, New York, (1997) 165.

36 Ayeni A O & Daramola M O, *J Environ Chem Eng*, 5 (2017) 1771.

37 Luo Z F, Li P, Cai D, Chen Q C, Qin P Y, Tan T W & Cao H, *Ind Crop Prod*, 95 (2017) 521.

38 Boufi S & Chaker A, *Ind Crop Prod*, 93 (2016) 39.

39 Cheng Z, Yang R, Liu X, Liu X & Chen H, *Bioresour Technol*, 234 (2017) 8

40 Briga-Sa A, Paiva A, Boaventura-Cunha J & Lanzinha J C, *Contribution of the trombe wall to sustainable buildings: Experimental work*, In 38th IAHS world congress on housing science Istanbul, Turkey (2012).

41 Cristel O, Nady P C, Fernando T, Silvio D, Ketty B & Marie-Ange A, *Compos Part A: Appl Sci Manufacture*, 41 (2010) 549.

42 Frydrych I, Dziworsko G & Bilska J, *Fib Textiles Easter Eur*, 3 (2002) 40.

43 Sathre R & González-García S, *Eco-Efficient Constr Build Mater*, 5 (2014) 311.

44 Hou X Z, Zheng F, Li H & Lu C, *Energy Build*, 42 (2010) 1070.

45 Binici H, Aksogan O & Demirhan C, *Sustainable Cities Soc*, 20 (2016) 17.

46 Younquist J, English B, Spelter H & Chow P, *Agricultural fibers in composition panels*, in: Proceedings of the 27th International Particleboard/Composite Materials Symposium, 30–31 March, Pullman, Washington, 133 (1993).

47 Chow P, *Dry Formed Composite Board from Selected Agricultural Residues*, World Consultation on Wood Based Panels, Food and Agriculture Organization of the United Nations, New Delhi, India (1974).

48 Lertsutthiwong P, Khunthon S, Siralertmukul K, Noomun K & Chandrkrachang S, *Bioresour Technol*, 99 (2008) 4841.

49 Khedari J, Nankongnab N & Fotios S, *Agricultural waste materials as thermal insulation for dwellings in Thailand: preliminary results*, in: PLEA 2008: 25th Conference on Passive and Low Energy Architecture, 22–24 October, Dublin, Ireland (2008).

50 Stone N, *Ecol Build Network* (EBNet), (2003) 1 .

51 Soon-Ching N & Kaw-Sai L, *Energy Build*, 42 (2010) 2452 .

52 Hasse C, Grenet M, Bontemps A, Dendievel R & Sallée H, *Energy Build*, 43 (2011) 232.

53 Quaranta N, Caligaris M, López H, Unsen M, Lalla N, Franzoy M, Carrasco M, Cotroni J & Avendano M, *Trans Ecol Environ*, 128 (2010) 447 .

54 Paiva A, Pereira S, Sá A, Cruz D, Varum H & Pinto J, *Energy Build*, 45 (2012) 274 .

55 Khedari J, Nankongnab N & Teekasap S, *Build Environ*, 39 (2004) 59.

56 Pinto J, Paiva A, Varum H, Cost A, Cruz D, Pereira S, Fernandes L, Tavares P & Agarwal J, *Energy Build*, 43 (2011) 1958.

57 Pode R , *Renew Sustain Energy Rev* , 53 (2016) 1468 .

58 Zafar S, Bio Energy Consult., 26 March 2015. ⟨http://www.bioenergyconsult. com/tag/rice-straw/⟩
59 Patel M & Karera A, *Powder Metall Int*, 23 (1991) 30.
60 Alam M, Singh H, Brunner S & Naziris C, *Energy & Build*, 69 (2014) 442.
61 Fine H A, *J Build Phys*, 3 (1989) 183.
62 Li C D, Li B B, Pan N, Chen Z F, Saeed M U, Xu T Z & Yang Y, *Energ Build*, 125 (2016) 298.
63 Wei G, Liu Y, Zhang X, Yu F & Du X, *Int J Heat Mass Transf*, 54 (2011) 2355.
64 Mukhopadhyaya P, Kumaran M K, Normandin N, Van Reenen D & Lackey J, *J Cold Reg Eng*, 4 (2008) 103.
65 Mukhopadhyaya P, Kumaran M K, Normandin N & Van Reenen D, *Fibre-powder composite as core material for vacuum insulation panel*, The 9th International Vacuum Insulation Symposium, London, September (2009).
66 Chindaprasirt P, Rukzon S & Sirivivatnanon V, *Constr Build Mater*, 22 (2008) 932.
67 Dong C, Saeed M U, Pan N, Chen Z F & Xu T Z, *Mater Des*, 107 (2016) 440.
68 Wei K, Lv C, Chen M, Zhou X, Dai Z & Shen D, *Energ Build*, 87 (2015) 116.
69 Liu K, *Soybeans: Chemistry, Technology, and Utilization, Chapman and Hall*, New York, 27 (1997).
70 Ronda J C, Lligadas G, Galià M & Cádiz V, *React Funct Polym*, 73 (2013) 381.
71 Denko S, Shotherm Operation Manual No: 125-2.K.K., Instrument · Products Department 13-9 ShibaDaimon, Tokyo 105 Japan (1981).
72 Balo F, *Energy Build*, 86 (2015) 161.
73 Padkho N, *Proce Eng*, 32 (2012) 1113.
74 Magwood C, Mack C & Therrien T, *New Soc. Publishing* (2005).
75 Holzhueter K & Itonga K, *J Asian Archit Build Eng*, 9 (2010) 495.
76 Egan J, *Rethinking construction: the report of the construction task force*, London, HMSO (1998).
77 Walker P & Thomson A, *In: Proceedings of Central Europe towards sustainable building*, 21 (2013).
78 Yates T, Ferguson A , Binns B, & Hartless R , *IHS BRE Press on behalf of NHBC Foundation*, (2013).
79 Goodhew S, Carfrae J, & De Wilde P, *Eng sustainability*, 163 (2010) 185.
80 Chaussinand A, Scartezzini J L & Nik V, *Energ Proce*, 78 (2015) 297.
81 Johnson R F, Manjreker T G & Halligan J E, *Environ Sci Technol*, 7 (1973) 439.
82 Witka-Jezewska E, Hupka J & Pieniazek P, *Proceedings of the US United Engineering Foundation Conference and 2nd International Conference. Analysis and Utilization of Oily Wastes (AUZO'99)*, Jurata, Poland,1999.
83 Joergensen R G, Figge R M & Kupsch L Z, *Pflanzenernaehr Bodenk*, 160 (1997) 2.
84 Welch I M, Barret P R F, Gibson M T & Ridge I, *J Applied Phycol*, 2 (1990) 231.
85 Pillinger J M, Cooper J A & Ridge I, *J Chem Ecol*, 20(1994) 1557.
86 Witka-Jezewska E, & Hupka J, *Proceedings of the Seventh Polish–Danish Workshop on Biomass for Energy*, Starbienino, 215 (2000).
87 Ashour T, Korjenic A, Korjenic S & Wu W, *Energ Build*, 104(2015) 139.
88 Lacey J, *Wiley-Intersci*, 57 (1979).
89 Knapp E, Elliot L & Campbell G, *Soil Biol Biochem*, 15 (1982) 319.
90 Reinertsen S, Elliott L, Cochran V & Campbell G, *Soil Biol Biochem*, 16 (1982) 459.
91 Cochran V, Horton K & Cole C, *Soil Biol Biochem*, 20 (1982) 293.
92 Thomson A & Walker P, *Constr Build Mater*, 68 (2014) 135.
93 Jimeniez A, *ROMA (IT)*, 15 (1999).
94 Al-Kaabi K, *Graduate Studies Collage. Al-Ain*, United Arab Emirates University (2004).
95 Al-Khanbashi A, Al Kaabi K & Hammami A, *Wiley Intersci Poly Compos*, 486 (2005).
96 Kaddam H, Dufresne A, Khelifi B, Bendahou A, Taourirte M & Raihane M, *Compos: Part A*, 37 (2006) 1413.
97 Abu-sharkh B F & Hamid H, *Polym Degrad Stabil*, 85 (2004) 967.
98 Al-Kaabi K, Al-Khanbashi A & Hammami A, *Natural Fiber Reinforced Composites From Date Palm Fibers*, 11th European conference on composite materials. Greece: Rhodes (2004).
99 Al-Kaabi K, Al-Khanbashi A & Hammami A, *Polym Comp*, 604 (2005).
100 Ahmad A, Hamed M A & Al-Kaabi K, *Adv Mater Res*, (2008)193 .
101 Bouguerra A, Ledhem A, de Barquin F, Dheilly R M & Quéneudec A M, *Cem Concr Res*, 28 (1998) 1179.
102 Ledhem A, Dheilly R M, Benmalek M L & Quéneudec A M, *Constr Build Mater*, 14 (2000) 341.
103 Sedan D, Pagnoux C& Smith A, *J Eur Ceram Soc*, 28 (2008) 183.
104 Bederina M, Marmoret L, Mezreb K, Khenfer M M, Bali A & Quéneudec M, *Constr. and Build. Mater*, 21 (2007) 662.
105 Siddique R, *Cem Concr Res*, 34 (2004) 37.
106 Savastano H & Warden P G, *Constr Build Mater*, 25 (2003) 585.
107 Benmansour N, Agoudjil B, Gherabli A, Kareche A & Boudenne A, *Energ Build*, 81 (2014) 98.
108 Teather P, *Adv Environ Energ Stud*, (2004).
109 Uemoto K L, Sato N M N & John V M, *Energ Build*, 42 (2010) 17.
110 Guo W, Qiao X, Huang Y, Fang M & Han, *Energ Build*, 50 (2012) 196.
111 Prager C, Kohl M, Heck M & Herkel S, *Energ Build*, 38 (2006) 1369.
112 Barletta M, Guarino S, Rubino G, Trovalusci F & Tagliaferri V, *Process Org Coat*, 77 (2014) 701.
113 Barreveld W H, *Date Palm Products, in Food and Agriculture Organization of the United Nations Rome*, FAO Agricultural Services (1993).
114 Al-Sulaiman F A, *Int J Energ Res*, 27 (2003) 1293.
115 Papadopoulos A M, *Energ Build*, 37 (2005) 77.
116 Sanchez C, *J Mater Chem*, 15 (2005) 3557.

117 Kriker A, Bali A, Debicki G, Bouziane M & Chabannet M, *Cem Concr Compos*, 30 (2008) 639.
118 Agoudjil A, Benchabane, Boudenne A, Ibos L & Fois M, *Energ Build*, 43 (2011) 491.
119 Booncherm P, Siriphanich J, *Kasetsart J*, 25 (1991) 119.
120 Charoenvai S, *Adv civil eng build Mater*, 119 (2013).
121 Charoenvai S, *Energ Proc*, 56 (2014) 539.
122 Satyanarayan K G, Kulkarani A G, & Rohotogi P K, *Proc India Academic Sci*, 4 (1981) 419.
123 Thongsumrit T V & Viengsima T, The study of solid content of urea-formaldehyde resin to physical properties and mechanical properties of medium density fiberboards from rubber wood (Heveabrasiliensis, Muell, Arg.) Bachelor of Civil Construction and wood-working Technology, King Mongkut's Institute of Technology, North Bangkok, 99 (1995).
124 Khedari J, Charoenvai S & Hirunlabh J, *Build Environ*, 38 (2003) 435.
125 Holman J P & Bhattacharyya S, *Heat Transfer* (Tata Mcgraw-Hill Publishing Company Limited,New Delhi), 2008.
126 Çengel Y A, *Heat And Mass Transfer A Practical Approach* (Tata Mcgraw-Hill Education) , 2007.
127 Bennett C O & Myers J E, *Momentum, Heat And Mass Transfer* (Tata Mcgraw-Hill Book Company) , 2008.
128 B K Dutta, *heat transfer principles and applications* (PHI Learning Private Limited, New Delhi), 2015.
129 Faghri A., Zhang Y & Howell J, *Adv. Heat and Mass Transfer* (Global Digital Press, Columbia) , 2010.
130 Davis W R , *London Plenum Press*, (1984) 161.
131 Wechsler A E, *London Plenum Press*, (1984) 281.
132 Reichenauer G, Heinemann U & Ebert H P, *Physico chem Eng Aspects*, 300 (2007) 204.
133 Ebert H P, Bock V, Nilsson O & Fricke J, *High Temp High Press*, 25(1993) 391.
134 Kraemer D & Chen G, *Rev Sci Instrum*, 85 (2014) 025108.
135 Korean Standards Association (KSA), KS L 9016:2005, Test methods for thermal transmission properties of thermal insulations (2005).
136 ISO 8301, Thermal Insulation – determination of steady-state thermal resistance and related properties – heat flow meter apparatus (1991).
137 ASTM C 518, Standard test method for steady-state thermal transmission properties by means of the heat flow meter apparatus (2004).
138 Choi G S, Choi J S X, Jeong Y S, Lee S E & Sohn J Y, *Thermochim Acta*, 455 (2007) 75.
139 Sheindlin M, Halton D, Musella M & Ronchi C, *Rev Sci Instrum*, 69 (1998) 1426.