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Performance Study of Thermal Properties for Different Types of Evaporator Cooling Local Pad Materials

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Abstract:
The evaporative cooling systems are desirable for their low cost and energy consumption, easy operation, and no pollution. In the present study, the evaporative cooling pads thermo-physical properties were investigated besides the economic perspective because very few insufficient studies addressed this issue. Four natural cooling pads' materials were studied, i.e., straw, corrugated cardboard (COCA), palm fibers (PAFI), and alhagi graecorum (ALHGR). The investigated thermo-physical properties were thermal conductivity, density, porosity, permeability, relative moisture content, and water absorption. The results showed that the ALHGR had the highest thermal conductivity (0.0395 W/m. K), i.e., 23.4% higher than the lowest for the PAFI (0.0320 W/m. K), and water absorption (8.116 g), 136.6% higher than the lowest for the COCA (3.43 g). Also, ALHGR was the cheapest (500 ID) among the studied materials, i.e., 95% cheaper than the most expensive studied material (COCA) (10,000 ID). The straw was the lightest (406.1 kg/m^3), i.e., 89.5% lighter than the heaviest ALHGR (769.6 kg/m^3). The PAFI had the highest porosity (59.8%), permeability (17.8 m^2), and relative moisture content (98.85 %).

Keywords:
Evaporative cooling; Moisture content; Pads; Porosity; Thermo-physical properties.

Highlights:
- Evaporator cooling local pad materials' thermal properties were studied.
- Porosity, permeability, relative moisture content, and water absorption were tested.
- The alhagi graecorum had the highest thermal conductivity (0.0395 W/m. K).
- The alhagi graecorum was the cheapest (500 ID).

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1.INTRODUCTION

In the light of the hot and dry climatic conditions, there is a great tendency to use new alternatives for refrigeration and air conditioning systems in buildings. In the summer season, the traditional refrigeration and air-conditioning systems consume significant energy causing many environmental and economic issues. In addition, statistics indicate that electricity consumption was about 60% for air-conditioning systems higher than other domestic devices [1,2]. Also, the conventional cooler systems are very harmful to the environment due to using chlorofluorocarbons as refrigerants. As a result, efforts must be made to reduce energy use and increase reliance on more environmentally friendly devices. To save electrical energy and avoid environmental risks, the use of direct evaporative cooling has become the preferred solution especially in hot and dry areas because it is one of the most economical and efficient cooling technologies that can be used to cool spaces [3]. The desert cooling systems evaporate water while cooling and humidifying air. They are widely used in regions with hot and dry climates due to the high ability of air to evaporate water. The desert coolers also have many advantages, such as lower energy consumption, easier maintenance, less maintenance experience, and less economical operation than conventional coolers [4]. The core of the evaporative cooling system is the cooling pads. Choosing the best pads' material depends on their thermophysical properties. Therefore, there are various properties of pad's materials that must be recognized when using local desert plants in evaporative cooling, such as thermal conductivity, density, permeability, porosity, and moisture content, to gain high cooling efficiency [5]. The performance of the desert cooler is also affected by climatic conditions, such as air temperature and relative humidity besides the cooler fan flow rate. The high-quality cooling pad provides a larger evaporative area per unit volume, which increases the evaporative cooler's cooling efficiency [6]. Therefore, the high-water retention property of the pad material improves the evaporation rate, enhancing the pad's performance. Researchers worldwide have been searching for new, effective, and inexpensive evaporative cooling pad materials. Basically, the available cooling pad materials are classified into five different categories: organic materials, natural fiber materials, mineral materials, stone materials, and plastic materials [7], see Table 1. The natural fibers materials as cooling pads are a strong contributor to reducing carbon emissions and other pollutants. Natural fibers are an alternative to synthetic fibers, being renewable, environmentally friendly, and biodegradable [8]. Pads made from natural fiber materials are more economical than other pads' materials used so far [7]; therefore, the natural materials attracted many researchers. Jha et al. [9] studied partial, safeda, and root as cooling pads of average real density 1000, 750, and 590 kg/m^3, respectively. The highest surface evaporation of 14.87 g of water per minute was obtained from a partial cooling pad with a thickness of 7 mm. Salam et al. [3] studied date palm fibers as cooling pads. The date palm stem fibers showed good cooling efficiency and cooling capacity. Therefore, palm stem fibers were recommended as an alternative material for a cooling pad in evaporative coolers, especially in hot and dry areas due to its high-water retention capacity and low manufacturing costs. Salem et al. [4] studied the effect of two pad types, i.e., corrugated cardboard and straw, on the efficiency of a direct evaporative air cooler. The straw pads' cooling efficiency was lower than the corrugated cardboard, i.e., 91.4% and 93.1%, respectively. The cardboard pad cooling efficiency increased by 46.6% by increasing the air speed from 2.8 m/s to 4.7 m/s due to faster heat transfer. Abdel Moneim [10] used alhagi graecorum as a natural material in evaporative cooling. The results showed a cooling efficiency of 87% and a dry internal temperature of 22 °C. Due to its significant performance throughout the duration of the experiment, it was recommended to use alhagi graecorum in cooling poultry halls and homes. Alhagi graecorum also had a low preparation and manufacturing cost, i.e., less than ($1) for the size of (40 cm long × 40 cm wide × 9 cm thick). Furthermore, the properties of cooling pads also attracted researchers. Putra et al. [11] measured the permeability of activated carbon from bamboo wood as an alternative pad material. The activated carbon (Betung) made of bamboo was carbonized at a temperature of 400 °C and activated at a temperature of 600 °C with a test time of 60 minutes. The highest permeability found was 13.6 × 10^{-15} m^2. The lowest permeability, i.e., 0.56 × 10^{-15} m^2, was found for the carbonized one at a temperature of 800 °C and activated at an activation temperature of 600 °C with a test time of 60 minutes. Manimaran et al. [8] studied the physical, chemical, mechanical, and thermal properties of the Albizia Liebec bark fibers (ALFs). The fibers' structure was analyzed by FT-IR and X-ray diffraction. The results showed that cellulose content (72.59% by weight) had a density of 905 kg/m^3. The albizia fiber properties and thermal properties were determined using the thermogravimetric analysis and the derivative analysis to determine its heat capacity. It was concluded that the albizia fiber is a good alternative material to promote new industries with green compounds used in numerous fields. The cooling pads' thermo-physical properties significantly impact the evaporative cooling performance. Although, many researchers studied various parameters, such as pad efficiency, cooling capabilities, and economic costs, the pads' thermo-physical properties have received insufficient or no attention especially the local organic materials. The present study investigates the thermo-physical properties of two widely used cooling pads, i.e., straw and corrugated cardboard (COCA), and two local organic materials, i.e., palm fibers (PAFI), and alhagi graecorum (ALHGR). The studied cooling pads' thermo-physical properties were thermal conductivity, density, porosity, permeability, moisture content, and water absorption. The studied materials production expenses were also considered in the present study.

Table 1 Cooling Pads Materials Types

Organic	Aspen Pads [12], rice husk [13], and vermiculate [14].
Metallic	Metallic foams [15].
Natural Fiber's	Eucalyptus [16], coconut coir [17], and Jute [18].
Stone based Materials	Charcoal [19] and roof brick [20].

2.EXPERIMENTAL PART

Due to the development of evaporative cooling methods that use different pad materials, the characteristics of evaporative cooling pads have become very vital due to its impact on the system's efficiency and performance. The studied materials were straw, corrugated cardboard (COCA), palm fiber (PAFI), and alhagi graecorum (ALHGR), as shown in Fig. 1. The materials samples were prepared in a cylindrical shape. Preparation the samples included cleaning, filtering from plankton, separating and cutting, and pressing into Teflon molds, inner diameter= 2.5 cm. Next, the samples were tested, and the results were recorded. The test steps were achieved using different devices, such as a drying oven, a sensitive balance, a graduated vessel, and a thermal conductivity tester. Therefore, the evaporative cooling pads materials' different characteristics were studied including thermal conductivity, porosity, permeability, density, and moisture content for each material. The following sections detail the tests followed. Table 2 shows the studied materials cost in Iraqi dinars at a size of (40×38×9) cm.

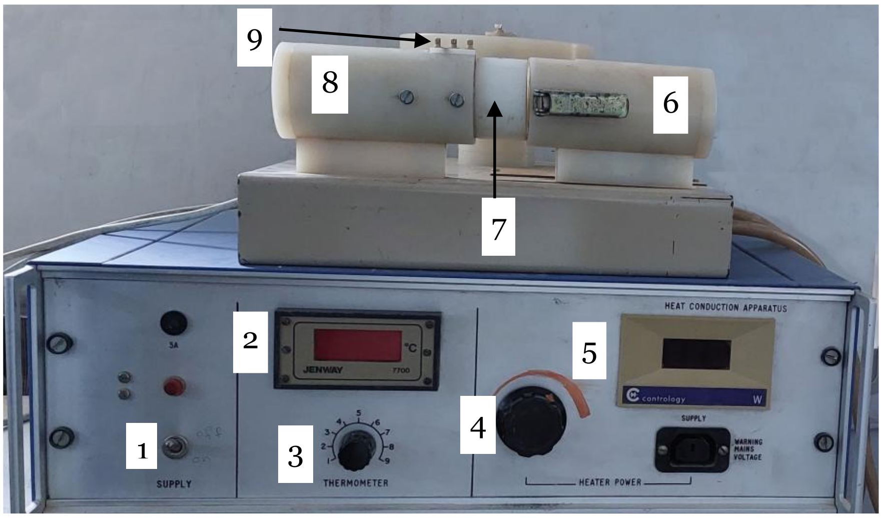
Table 2 Cost of The Studied Materials.

No.	Type of Pad	Cost (ID)
1	straw	2,000
2	COCA	10,000
3	PAFI	750
4	ALHGR	500

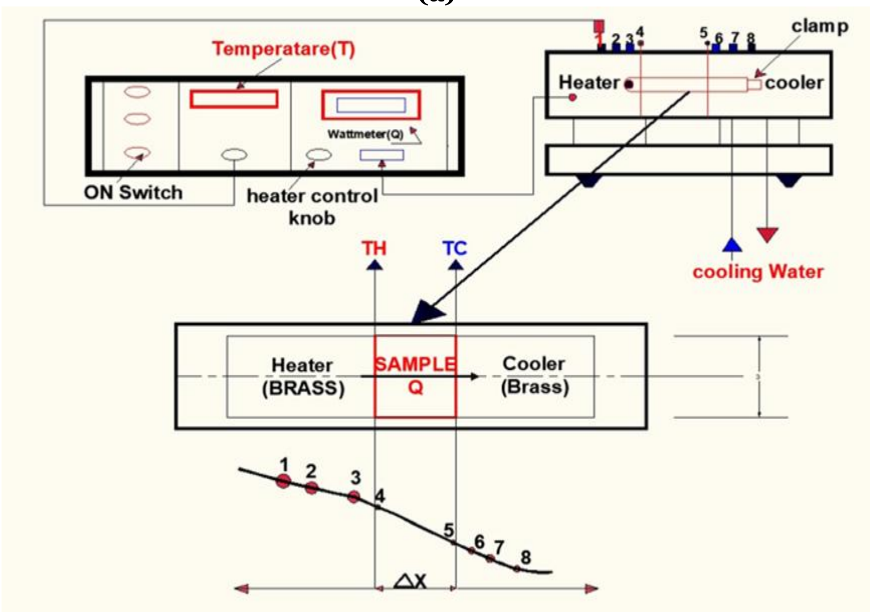
2.1.Thermal Conductivity Measurement

The thermal conductivity measurement device, Fig. 2, consists of two brass solid rods insulated by Teflon. The right rod was attached to an electric heater controlled by a thermostat to heat the right brass rod. The heat transferred through the right brass rod to the test sample that was placed between the two brass rods. The left brass rod was cooled by water, flowed at 25 ml/sec, to generate a temperature difference on each side of the test sample and ensure heat transfer in one direction. The temperatures were measured using eight k-type thermocouples, ±2.5 °C. Three thermocouples were placed on the right rod, three on the left rod, and two on the sample. The samples were pressed inside a Teflon ring, inner diameter= 2.5 cm, under a pressure of 0.5 bar. The Teflon ring's outer diameter was 4.5 cm. The Teflon ring acted as a thermal insulator, 0.3 W/m.K, to reduce the heat loss from the tested samples. The tested evaporative cooling pads were corrugated cardboard (COCA), palm fiber (PAFI), straw, and alhagi graecorum (ALHGR). The electrical power was controlled using a regulator voltage to generate six power values, i.e., 10, 20, 30, 40, 50, and 60 Watts, to accurately calculate the rate of thermal conductivity of the evaporative cooling pad samples. After the experimental measurement started, the steady state was reached in around 60 minutes. Then, the eight thermocouples reading and supplied power were recorded.

Fig. 1 Studied Pad Samples.



(a)



(b)

Fig. 2 Thermal Conductivity Measurement Device **(a)** A photo: 1- The Power Key 2-Temperature Digital Display 3-Thermocouple Selector 4-Voltage Regulator. 5- Electrical Power Digital Display 6-Cold Rod. 7- Test Sample Location 8- Hot Rod. 9- Thermocouples Locations, and **(b)** A Schematic Diagram.

2.1.1.Thermal Conductivity Measurement Procedure

To measure the thermal conductivity of the studied materials, the following steps were followed:

1) The samples were moistened in water for 60 minutes.
2) Before turning on the heater and cooler, all temperature readings (in all points 1-8) were checked.
3) The brass rod on the left was cooled using water at constant flow rate 25 ml/sec for all tests.
4) The brass rod on the right was heated using a heater. The supplied power varied from 10 Watts to 60 Watts.
5) As the steady state was reached, the eight temperatures were recorded, Fig. 2.

2.1.2.Thermal Conductivity Calculation

The thermal energy is transmitted naturally from high temperature to low temperature in forms of conduction, convection, and radiation. The heat transfers through solids by conduction. The rate of conducted heat depends on the material's thermal conductivity. The thermal conductivity (k) is the thermophysical property that describes the rate at which heat flows through an object for a given change in temperature. The thermal conductivity rate across any solid material is directly proportional to the temperature difference (ΔT) and inversely proportional to the material's thickness (Δx) [21]. In an uniaxial thermal conduction, The Fourier law is used to calculate the heat transfer rate (q), as follows [22]:

$$q = kA\frac{\Delta T}{\Delta x} \qquad (1)$$

where A is the cross-sectional area perpendicular to the heat transfers direction.

$$A = \frac{\pi d^2}{4} \qquad (2)$$

where d is the sample diameter.

Therefore, the thermal conductivity can be calculated by re-arranging Eq. (1) to obtain [23].

$$k = \frac{q\,\Delta x}{A\,\Delta T} \qquad (3)$$

where (ΔT/Δx) is the temperature gradient and represents the slope of the temperature curve [24].

2.2. Density

Density is a physical property of a material that expresses the relationship between the unit volume and unit mass of a material. The samples were pressed in a Teflon ring of known size and weight, as shown in Fig. 1. To obtain the accurate weight, the samples were weighed using a sensitive balance (Want® WT3003K, accuracy= 0.001 g and maximum weight= 100 g) after pressing the material inside the ring. To obtain the Teflon ring size, its dimensions were measured using a high accuracy vernier (±0.05 mm), i.e., inner diameter= 25 mm, outer diameter= 45 mm, and height= 20 mm. The sample net volume was the inner Teflon ring volume. Finally, the density (in kg/cm^3) was obtained by dividing the mass (m) of the sample by its net volume (∀).

$$\rho = \frac{m}{\forall} \qquad (4)$$

2.3. Porosity

Porosity is one of the most important properties and characteristics that must be recognized in evaporative cooling pads. The porosity can be defined as the void space in a material. High materials' porosity increases water-holding capacity, which means a proportional relationship between them. In addition, It should be noted that the porosity give no information about the pore's sizes, distribution, and thermal conductivity [11]. The porosity is the ratio of the pores volume ($\forall_p$) to the total volume ($\forall_{total}$), which is calculated from [25].

$$\varphi = \frac{\forall_{total} - \forall_s}{\forall_{total}} \times 100 = \frac{\forall_p}{\forall_{total}} \times 100 \qquad (5)$$

where ∀s is the solid volume.

In the present study, the porosity was measured as follows. The mold and the specimen volumes were measured separately to determine the total volume. The specimen was emersed in water, then its weight was measured using the sensitive balance (Want® WT3003K), and the wet volume was calculated. The pores volume was the difference between the wet and dry specimens. Finally, the porosity was found using Eq. (5).

2.4. Permeability

Permeability is a property of a material that describes how easily liquids and gases can move through a porous medium [26]. Thus, it is dependent on the interdependence of the voids and the pore size of the medium. The high permeability of a material allows fluids to move continuously through it. A liquid enters a material at a certain pressure and permeates at a rate that depends on the material's permeability, porosity, cross-sectional area, and depth. The liquid exits from the second end of the sample at different pressure and discharge rates. Because of the difference in pressure on both sides of the sample, the coefficient of permeability can be used to describe the properties of a porous medium through the rate of absorption and diffusion of liquids and to estimate the pore size. Samples of these materials contain a small hole in the form of pores distributed in the compressed sample. Darcy's law describes the kinetics of fluid flow through porous media in terms of driving force and permeability of the medium. Using Darcy's law, the transmittance of the samples was calculated using the following relationship [27,28].

$$K = \frac{Q * \mu * \Delta x}{\Delta P * A} \qquad (6)$$

where Q is the volume flow rate (= v A), and μ is the viscosity.

To measure the permeability, a flow of air was forced at three speeds, i.e., 4.7, 3.5, and 2.8 m/s. The pressure drop was found through ($\Delta P = \frac{1}{2}\rho v^2$). Then, the permeability was calculated using Eq. (6).

2.5. Relative Moisture Content

The relative moisture content expresses the amount of moisture presented in a material relative to the wet material weight. The relative moisture content can be defined as the mass of water in grams presence in the material tested. To calculate the moisture content of a sample, the weight of the dry sample (m_d) and the weight of the wet sample (m_w) were measured. Finally, the relative moisture content (MC) can be calculated through the following relationship:

$$MC = \frac{m_w - m_d}{m_d} \times 100 \qquad (7)$$

2.6. Water Absorption

One of the key characteristics of cooling pads' materials is their ability to absorb water. To measure the water absorption of the studied samples, the following steps were followed. First, the samples were dried in a microwave oven for 10 minutes at a temperature ranging from 100 °C to 110 °C to remove any moisture. The drying was stopped as the samples moisture reached the ambient humidity. Then, the average weight of the sample was measured using Want® WT3003K balance with an accuracy of 0.001 g in dry conditions. Next, the samples were thoroughly soaked for 15 minutes in water and then weighed under wet conditions. As a result, the weight difference between the wet and dry conditions represented the water absorption ability of each sample [7]. Table 3 presents the accuracy analysis.

Table 3 The uncertainty of measured properties

Parameter	Uncertainty (%)
k (W/m.K)	1.6
ρ (kg/m³)	1.0
φ (%)	2.1
K (m²)	0.03
MC (%)	0.01
water absorption (g)	0.001

3.RESULTS AND DISCUSSION

The experimental thermophysical properties were obtained for straw, COCA, PAFI, and ALHGR, which can be used as pads in direct evaporative cooling desert coolers. The measured thermophysical properties were porosity, permeability, density, thermal conductivity, relative moisture content, and water absorption. Figure 3 shows the studied materials porosity. The PAFI had the highest porosity, i.e., 59.8 %, because of the large spaces between its fibers and its structure is fairly hollow compared to other studied materials [29]. The lowest porosity was for the ALHGR, 31.3 %. It is worth mentioning that the porosity impacts other properties, such as density and thermal conductivity.

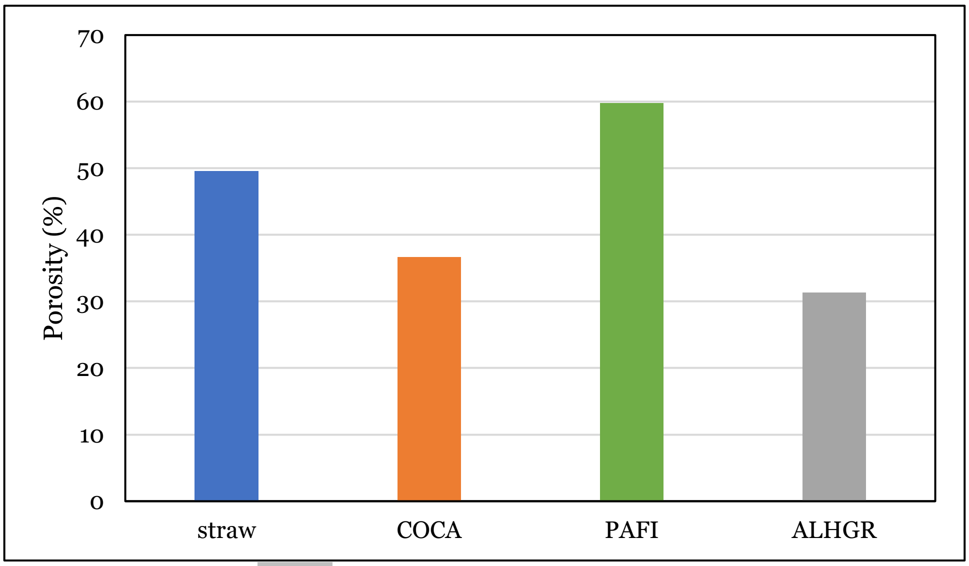


Fig. 3 The Studied Materials Porosity.

The permeability of the studied materials is presented in Fig. 4. The experimental results showed that the PAFI had the highest permeability, i.e., 17.8×10⁻⁵ m², and the ALHGR had the lowest, i. e., 11.2 ×10⁻⁵ m². This result is compatible with the porosity results. The spaces between the PAFI fibers are continues allowing the fluids to pass through them, resulting in high permeability [30].

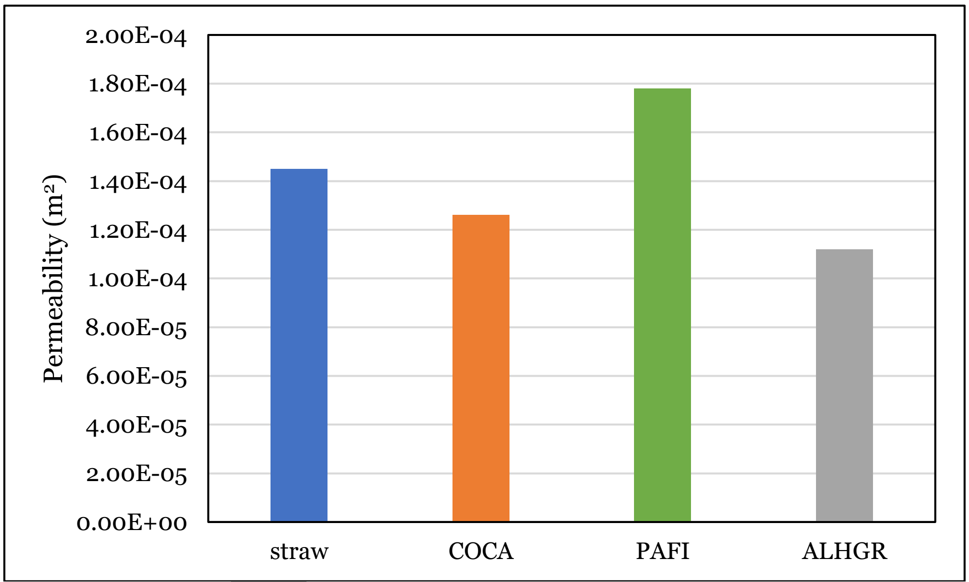


Fig. 4 The Studied Materials Permeability.

Figure 5 shows the density of the studied materials. The results showed that the largest and smallest densities were for ALHGR and straw, i.e., 769.6 kg/m3 and 406.1 kg/m3, respectively. The lack of structural cavities makes the material heavier, and the presence of a hollow tubular structure in its internal structure increases its size resulting in a high porosity and low density [31]. These results are similar to [32].

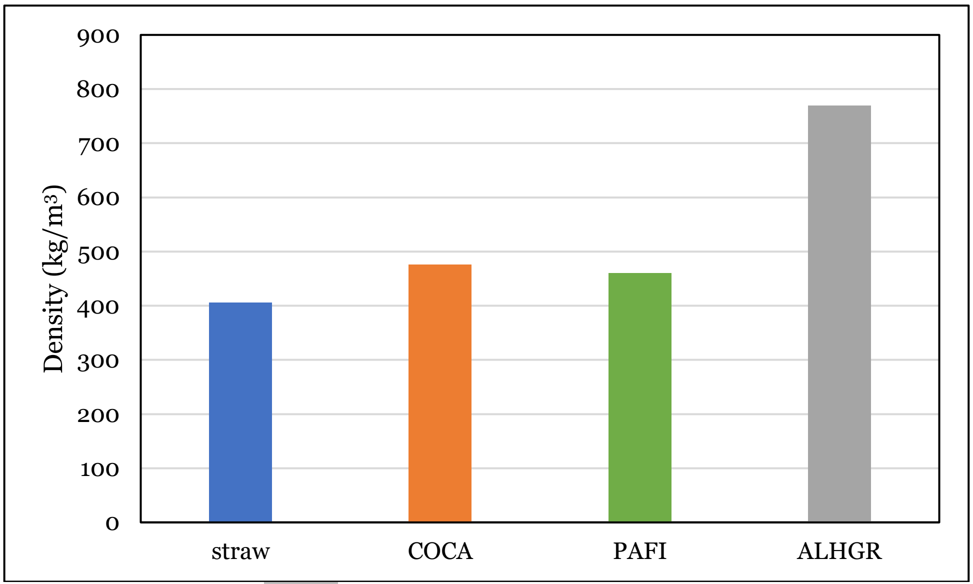


Fig. 5 The Studied Materials Density.

Figure 6 shows the thermal conductivity of the studied materials. The results demonstrated that the ALHGR had the highest thermal conductivity, i.e., 0.0395 W/m·K, and the lowest thermal conductivity was for PAFI, i.e., 0.032 W/m·K. The porosity impacts the thermal conductivity because the pores are filled with air, which has low thermal conductivity [21]. Therefore, low porosity material has high thermal conductivity [33]. Since ALHGR had the lowest porosity compared to other studied materials, Fig. 3, its thermal conductivity was the highest. Consequently, fine and medium fibers conduct more heat [34].

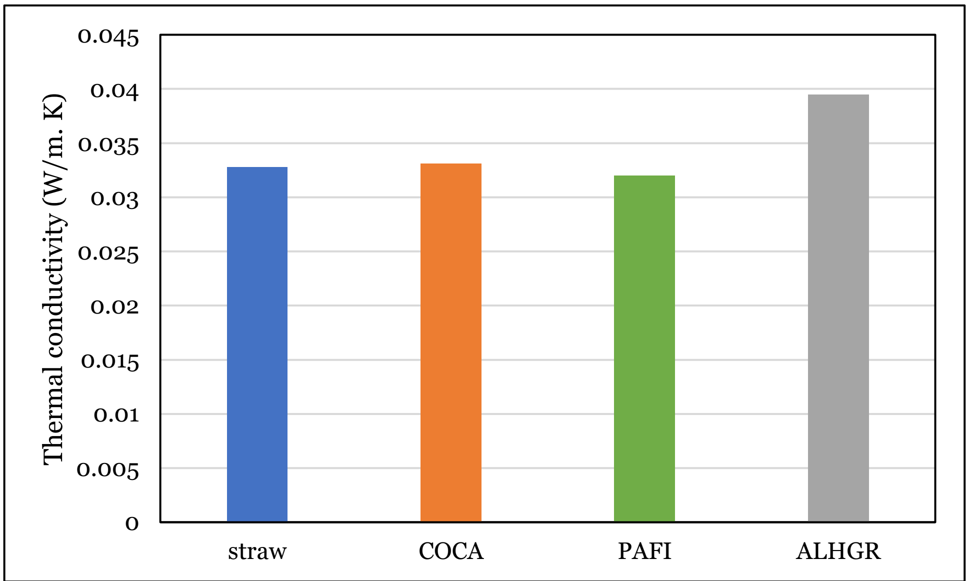


Fig. 6 The Studied Materials Thermal Conductivity.

The relative moisture contents of the studied materials are shown in Fig. 7. The results showed that the highest relative moisture content was for the PAFI, i.e., 98.850%. While the lowest was for the ALHGR, i.e., 46.899%. The PAFI have a hydrophilic nature because it contains hydroxyl groups and other polar groups [35]. Also, the PAFI had higher porosity and permeability than other studied materials, which means that water reaches the PAFI deep structure. As a result, it tends to gain moisture. In addition, the high porosity of PAFI increases its moisture content [36].

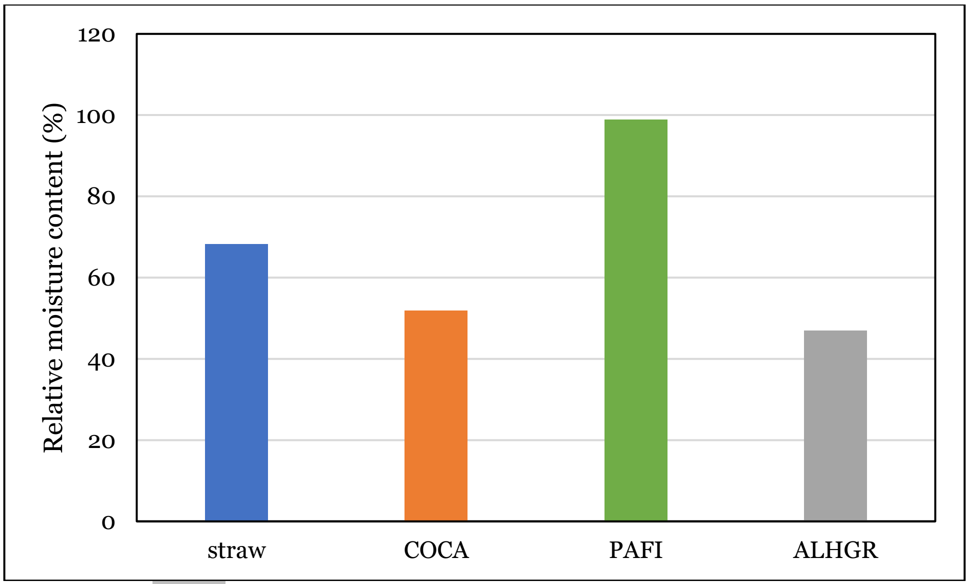


Fig. 7 The Studied Materials Relative Moisture Content.

Finally, Fig. 8 shows the ability of the material to absorb water. It was found that the ALHGR had the highest ability to absorb water, i.e., 8.12 g, while the COCA had the lowest ability to retain water, i.e., 3. 43 g. The natural fibers, as ALHGR, are hydrophillic and tend to absorb water because they are rich with cellulose [37]. Some fibers show good water retention once they are saturated with it [7]. Moisture absorption decreased gradually with time until reaching saturation.

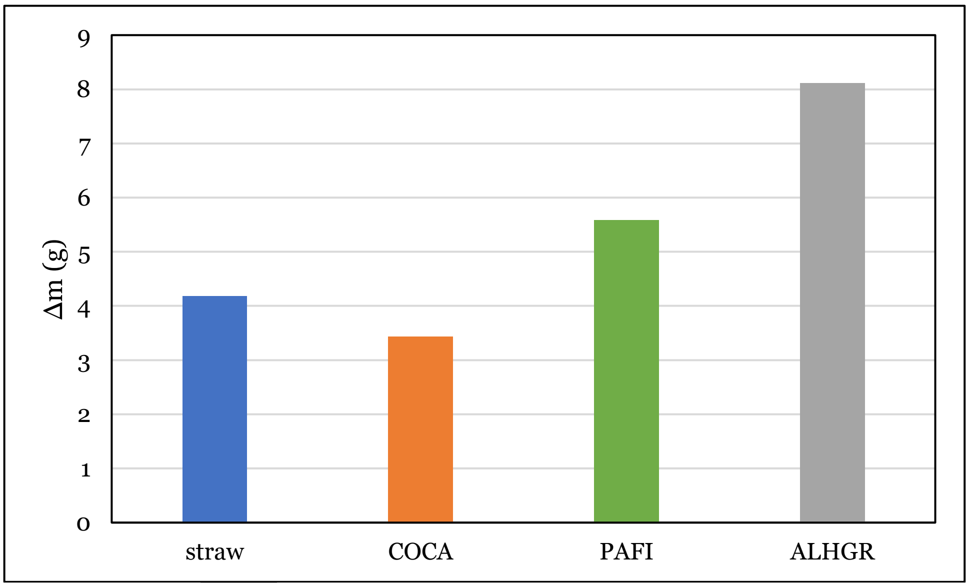


Fig. 8 The Studied Materials Water Absorption.

4.CONCLUSIONS

The present study experimentally investigated the thermophysical properties of different evaporative cooling pad materials, i.e., straw, COCA, PAFI, and ALHGR. The following points represent the key outcomes of the studied materials:

- The highest thermal conductivity recorded was for the ALHGR, while the lowest was for the PAFI. The ALHGR's thermal conductivity was 23.4% higher than the PAFI.
- The highest water absorption recorded was for the ALHGR, while the lowest was for the COCA. The ALHGR's water absorption was 136.6% higher than the COCA.
- The cheapest material was the ALHGR, and the most expensive was the COCA. The ALHGR was 95% cheaper than the COCA.
- The PAFI had the highest porosity, permeability, and relative moisture content. While the ALHGR had the lowest values of these properties. The PAFI had 91.1%, 58.9%, and 110.8% higher porosity, permeability, and relative moisture content than the ALHGR.

- The straw showed moderate properties. Its most significant property was its light weight (406.1 kg/m³).
- Although the COCA is expensive and showed insignificant thermo-physical properties, it is widely used and available because of the cartoon manufacturing.
- As a future study, it is recommended to investigate the evaporative cooling ability of other local plants as trifolium resupinatum.

NOMENCLATURE

A	surface area, (m²)
d	diameter, (m)
k	Thermal conductivity, (W/m.K)
K	Permeability, (m²)
m	Mass, (kg)
MC	Moisture content, (%)
q	Heat transfer rate, (W)
T	Temperature, (°C)
∀	Volume, (m³)
v	Velocity, (m/s)
Q	flow rate (m³/s)
Greek Symbols	
μ	Viscosity, (Pa-s)
ρ	Density, (kg/m³)
ΔT	Temperature difference, (°C)
Δx	Thickness of test sample, (m)
ΔP	Pressure drop or difference, (Pa)
φ	Porosity, (%)
Abbreviations	
ALFs	Albizia Lebbeck fibers
ID	Iraqi dinar
Subscripts	
C	Cold
d	Dry
H	Hot
p	Pore
w	Wet

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