Assessment of Ichu Fibers as Non-Expensive Thermal Insulation System for the Andean Regions

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Abstract

In the Andean regions, low temperatures (5 to -25ºC) combined with the wind effect give the sensation of extreme cold. Besides, in the rural areas, dwelling structures are very rudimentary, being based on adobe walls and galvanized steel corrugated roofs. The combination of weather issues and construction without thermal insulation considerations put people in extreme living conditions. Using local and cheap natural fibers as thermal insulation is a great alternative especially to upgrade or refurbish rudimentary constructions. In areas above 3000 meters over sea level, natural fibers are vast and cheap (~0.15 USD/kg), especially fibers named "Ichu". In this study thermal properties of natural fibers were characterized according to the ASTM C177. Results show that the thermal conductivity varies from 0.047-0.113 W/m^{2}ºC, for mats with unidirectional oriented fibers, being fine Ichu which have the lowest values. For the fine Ichu fiber to be competitive with glass fiber the mat density should be reduced, this was achieved arranging the fibers randomly, showing a significant reduction in density, without increasing significantly the thermal conductivity. According to these results Ichu fibers have exceptional thermal insulation

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properties, which can be used to increase thermal insulation for dwellings and other applications.

Keywords: Natural fiber, Thermal insulation, Green fibers, SEM micrograph.

1. Introduction

Potentially, natural fibers can be used as replacements of mineral or petrochemical based insulation fibers in a system. Natural fibers can deliver thermal and acoustic insulation in comparison to the common construction materials including a lower negative carbon footprint and fewer health issues during installation, maintenance, removal and disposal after used. Andean region houses are rudimentary, especially in the rural or isolated areas where the thermal considerations for building construction are not considered. Generally, walls are constructed using bricks named Adobe. which is a mix of clay and Ichu fiber (Stipa Ichu, [1]) in fewer percentage (fiber volume fraction less than 5 %). On the other hand, roofs are based on galvanized steel (0.17 to 0.30 mm thick), roof tiling or, less frequently, Ichu fibers. Fig. 1 shows referential rural dwelling commonly built in the Andean regions.

Figure 1: Rural houses (Tahuaccocha – Ayacucho)

Since certain time ago natural fibers have gained notable successes as construction material due to the great physical, mechanical and acoustic properties with low detrimental effect on the environment [2-8] Materials such as hemp, flax (linen), sheep's wool, paper, cotton, coconut fibers and wood fibers are commonly used as single material or combined; however, physical and thermal properties vary considerable from one fiber to others, in which case they should be clearly examined and analyzed to use them in a proper manner and reduce the environmental impact [2, 9]. Frydrych et al. studied and analyzed thermal insulation properties (such as thermal conductivity, absorption and thermal resistance) of fabrics made of cotton and Tencel, showing that Tencel yarn has lower values of thermal conductivity and thermal absorption than fabrics made of cotton yarns, and higher values of thermal diffusion and resistance. The influence of the type of weave on thermal properties was observed for all fabrics made of cotton and Tencel [10]. In the other hand A. Nicolajsen studied thermal transmittance of a cellulose loose-fill insulation material, revealing that cellulose loose-fill insulation had significantly lower thermal performance compared to the stone wool batts [11]. In the area of composite materials Joshi et al. concluded that natural fiber composites are likely to be environmentally superior to glass fiber composites in most cases [12]. Yuhazri et al studied composites with thermal properties based on coconut fibers embedded in natural rubber latex using the cold press technique. The results show that composite materials with 30 wt% of latex provide the best and suitable thermal properties [13]. On the other hand, Alvarez et al, studied coconut fiber filled ferrocement panels as insulation panels for house living in southern Mexico. This material shows lower thermal conductivity than typical building materials such as lightweight concrete bricks, hollow concrete blocks and red clay brick panel walls [14]. Another very interesting research was develop by Petit et al, where they analyze sustainable construction systems at southern region of Chile where they study natural fibers like Sheep's wool, the perennial bamboo or colihue (Chusquea culeou), quila (Chusquea quila), straw from cereal crops and cellulose fiber resulting from forest stewardship and timber production, they concluded that the construction systems should have wall panels insulated with chipped quila bamboo and roof panels insulated with sheep's wool [15].

The work presented here focus in studying and characterizing the thermal conductivity of four different natural fibers: Gross Ichu, fine Ichu, corn stover and wheat stem fibers, aiming to determine optimum fiber and fiber configuration for a better thermal insulation for housing. Natural fibers can be used to upgrade, refurbish or improve thermal insulation characteristic of rural dwellings.

2. Materials and Experimental Setup

As mentioned, four different types of fibers have been characterized (Fig. 2): two different types of Ichu (coarse and fine with average diameter of 0.83 mm and 0.39 mm respectively), corn stover and wheat stem fibers. Natural fibers were obtained, selected and classified in the province of Canchis located at 3480 meters above sea level (Cusco-Peru). The fibers were carefully packaged in order to avoid damage or contamination during transportation to the university laboratories located in Lima-Peru (sea level).

Figure 2: Natural fibers from left to right: a) fine Ichu, b) coarse Ichu, c) corn stover and d) wheat stem fibers.

Ichu (Stipa Ichu) is an Andean feather grass, which grows over 3000 meters above the sea level. Until the second half of the 20th century natural fibers were commonly used as a roofing materials; however, due to the direct contact between the environment (UV radiation, rain water, hail and snow) degradation of the fibers was very fast, consequently, replacement by degradation was very frequent (generally every year), the last condition raised the maintenance costs and reduced the sustainability of the housing. However; if this fiber is free of contact to the degradation agents of environment, its replacement is broadly spread overtime and its maintenance is reduced.

A homemade stable unidirectional thermal conductivity measurement system was designed and manufactured based on the ASTM C177 [16] standard, in this system two measurements can be completed at the same time. Fig. 3 shows a representative diagram of the experimental setup of thermal conductivity measurement. The center plate Ⓐ is an electrical resistance heater which provides heat to the system and guard heaters are located along the edge Ⓒ to avoid that heat generated at Ⓐ transfers laterally. Temperature sensors were placed where the measured material starts and ends, as shown in Fig. 3. Characteristic sample dimensions were 0.4x0.4 m^2 (main heater area Ⓐ). In order to control and measure temperature, NI 9213 module with precision SA1XL-K Omega fine thermocouples were used. In the other hand, the energy consumption in the central plate was measured by single phase power quality analyzers AEMC 8230.

Before being characterized, samples were sized, aligned and weighted; after that they were placed into the system keeping the configuration selected or used and maintaining the thickness to 1 inch. The heating source was set to keep a constant temperature of 65°C and temperatures at the inner and outer part of the Ichu were recorded. The amount of heat (energy) produced by the flexible heater was calculated using the average current and voltage during the steady state period.

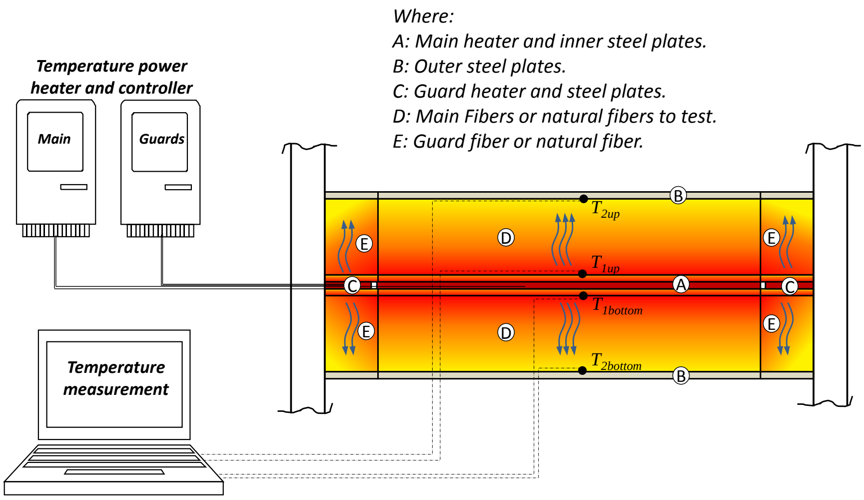

Figure 3: Experimental setup diagram for thermal conductivity measurements.

Thermal conductivity values were obtained using the unidirectional heat transfer equation,

$$\lambda = q * L/(A.\Delta T) \qquad \text{Eq. 1}$$

where λ is the thermal conductivity in W/m K, q is the heat flow through the specimen in W, ΔT is the temperature difference through the specimen in K, L is the thickness of the specimen in m and A is the cross section area in m^2. As the fiber arrangements have a lot of free space between fibers, the λ values obtained are apparent thermal conductivity.

3. Results and discussions.

3.1. Fibers

Depending on how fibers are stacked and organized along the mat, the thermal conductivity of the mats showed a variation. Corn stover has irregular shape as shown in Fig. 1, dimensions varies from ~5 to 100mm in length, ~1 to 10 mm in width and 0.1 to 2 mm in thickness, on the other hand, wheat stem fibers have better regular shape, with variations in length from ~60 to 100 mm, width from ~4 to 7 mm and thickness from 0.05 to 0.10 mm. On the contrary, Ichu fibers have regular shape, having a tubular shape along the length; diameter distribution histogram plots are shown in Fig. 4 (number of classes are determined using the empirical equation $m = 1 + 3.33log(n)$, where n is the number of data points). From the Kolmogorov-Smirnov and Chi-Square test, diameters data fits to Gamma and/or lognormal statistic distributions. As the histograms show, most of fibers have diameters less than average values either for coarse and fine Ichu. Having a higher proportion of small fiber diameters improves the stacking and mats are more compact (fibers with small diameters fill the free spaces located between larger fiber diameters). The structure of Ichu fiber is composed by stems and leaves; both have a tubular shape and can be easily mistaken. The average fiber diameter is 0.39 and 0.83 for fine and coarse Ichu respectively.

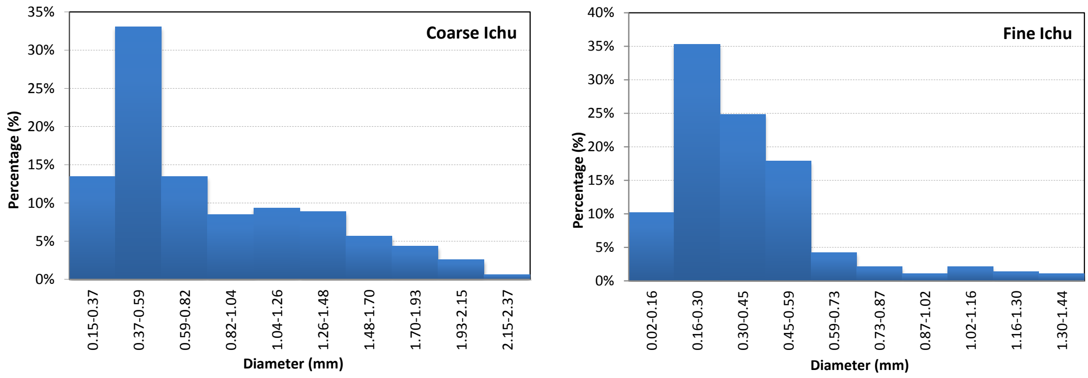

Figure 4: Diameter distribution histogram for coarse and fine Ichu fibers.

3.2. Transient and steady state

After samples were set, energy was supplied to the heater until reaching the needed temperature (65°C). Fig. 5 shows how the temperature gradient and average energy change along the time. When the system started running, the temperature of the heater quickly reached the 65°C temperature that have been set; however, the temperature in the outer part (T_{2up} and $T_{2bottom}$) still remained at room temperature (25°C), as the time kept running the generated heat is diffused in an unidirectional manner until reaching the outer part of the box, and the temperature began to increase, therefore the temperature gradient started to decrease until it reached the equilibrium or steady state (Fig. 5). Equation 1 is limited to steady state conditions; hence, to determine the thermal conductivity, gradient temperature and energy must be taken under steady state conditions, which were reached after 120 minutes approximately.

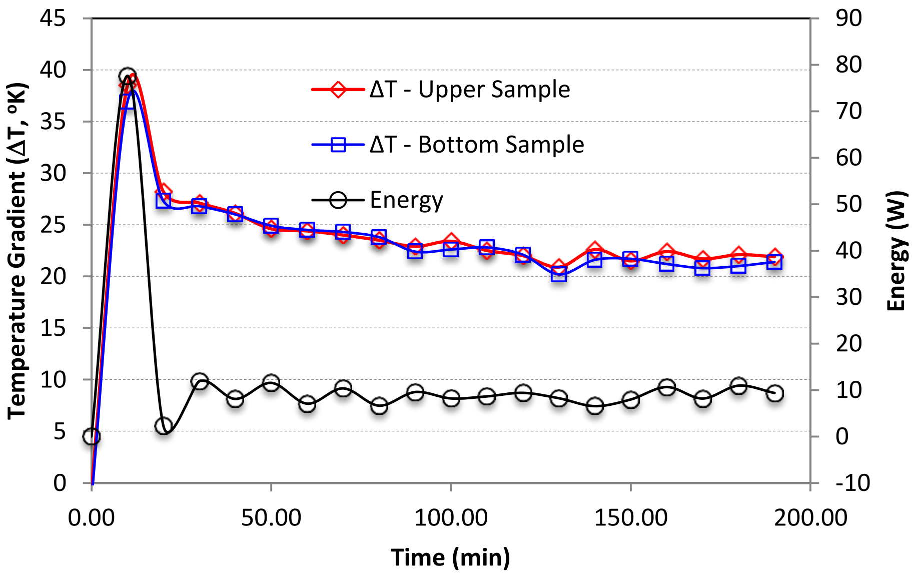

Figure 5: Gradient temperature at the upper and bottom samples and average energy provided to the system.

3.3. Thermal conductivity

3.3.1. Unidirectional fiber arrangement

Table 1 shows the apparent thermal conductivity obtained and the corresponding mat densities for the five different materials. In order to validate the results, glass fiber mats (Aislan Glass®) were tested first, showing that the average value obtained is ~ 3.0% greater than the value specified by the supplier data sheet; besides, experimental standard deviation was in the range of the expected values. A better comparative view of the experimental results is shown in Fig. 6. From these results we can observe that fine Ichu mats have the lowest value of k_{Apparent}, closer to the obtained in glass fiber mats; however, mat densities are three times higher than the density of the glass fiber mat. k_{Apparent} for coarse Ichu mats is considerable higher; this difference basically is due to the structure difference. On the other hand, bundles of fine or coarse Ichu are generally composed by certain amount of stems and leaves. From this approach, we can conclude that the difference lies in the diameter of the stems, thickness of the wall and the proportion of the amount of leaves. In a bundle of coarse Ichu, the amount of stems is considerably higher than the leaves, contrary to what is observed in a bundle of fine Ichu. Measurement performed for stems and leaves shows that the stems diameter varies from ~ 0.6 to 2.37 mm with wall thickness which vary from ~0.15 to 0.35 mm, on the other hand, leaf wall thickness varies from ~0.04 to 0.15 mm approximately.

Micrograph obtained using Scanning Electron Microscope (SEM), show the internal and external structure of the fibers as shown in Fig. 7 a) and b). Stems present a porous hexagonal structure uniformly distributed along the fiber, with higher ratio of porosity in the inner side and presenting a solid structure it the outer side. This form of structure gave to the Ichu stem low density with relatively low thermal conductivity along the transversal direction of the fibers. On the other hand, Ichu leaves have randomly distributed open cell porosity, with low ratio of presence of solid materials along the leaves as shown in Fig. 7 c) and d). A special morphology is observed in the Ichu leaves, a series of trichrome finely dispersed along inside of the leaves. Those characteristics, shown in the SEM micrographs, explain why lower density is observed for the finer Ichu mat compared to the coarse Ichu fibers mat (Table 1). Low density means high density of the porosity which also reflected in the low apparent thermal conductivity (Table 1 and Fig. 6).

Table 1: Apparent thermal conductivity and mat density for unidirectional fiber arrangement of 1 inch thickness.

	$k_{Apparent}$ (W/m°K)	UD Mat Density (Kg/m^3)
Glass	0.0355	32.71
Wheat Fiber	0.0526	45.93
Corn Fiber	0.0557	55.11
Fine Ichu Fiber	0.0473	92.86
Coarse Ichu Fiber	0.1130	122.43

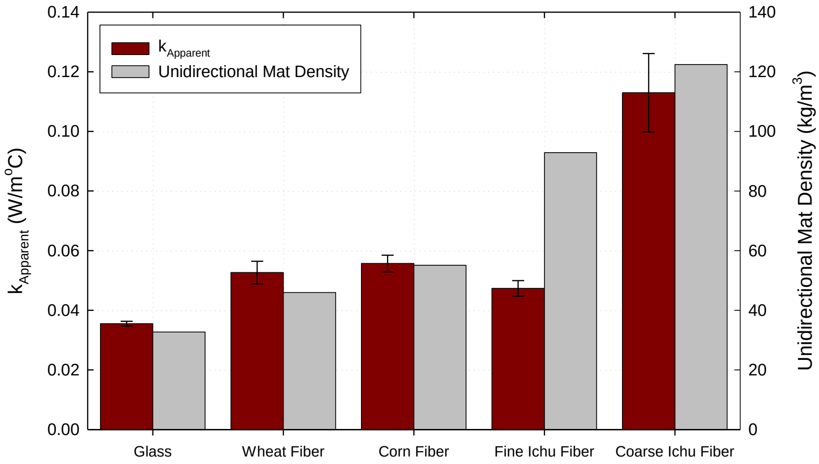

Figure 6: Apparent thermal conductivity and mat density for unidirectional fiber arrangement.

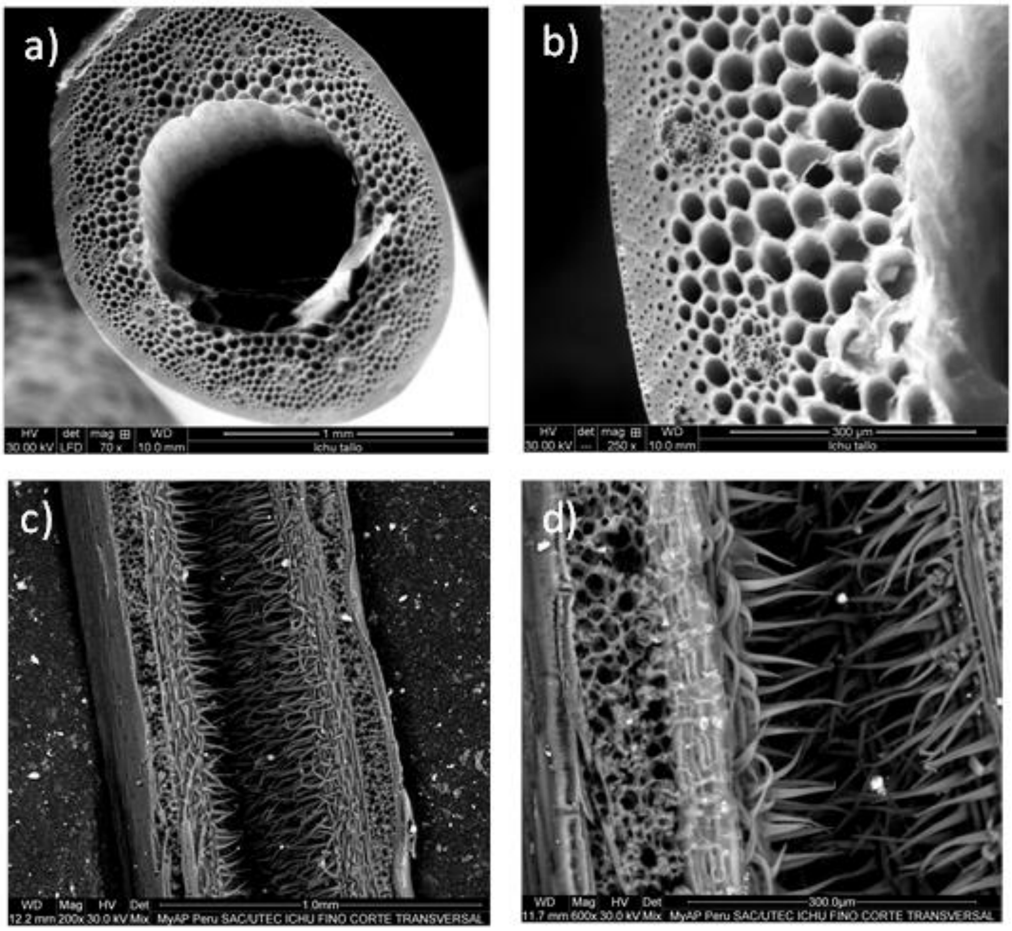

Figure 7: SEM micrography for: a) and b) Ichu fiber stem and c) and d) Ichu fiber leave.

3.3.2. Non-unidirectional fiber arrangement

From the unidirectional fiber arrangement fine Ichu fiber mats have the lowest value of thermal conductivity; however, their density is approximately three times higher than the value observed in glass fibers mat. Based on that, fine Ichu fiber was selected and studied with the purpose to reduce mat density, for that different fiber configurations were tested, furthermore Ichu fibers were modified crushing the fibers in the radial direction; results are shown in Table 2 and Fig. 8; where, "U. Non-Crushed" is the unidirectional non-crushed fiber, "U Crushed" is the unidirectional crushed, "Non-U Non-Crushed" is the non-unidirectional non-crushed and "Non-U Crushed" is the non-unidirectional crushed; non-unidirectional means randomly aligned (Fig. 9). It is evident that the density of non-unidirectional and non-crushed fiber mats decreases significantly, without sacrificing the apparent thermal conductivity. Fig. 9 shows how unidirectional and non-unidirectional non-crushed fiber mats are.

Table 2: Apparent thermal conductivity and mat density for fine Ichu fiber (thickness = 1 inches)

Fine Ichu	$k_{Apparent}$ (W/m^oK)	UD Mat Density (Kg/m^3)
Unidirectional Non-Crushed	0.0473	92.86
Unidirectional Crushed	0.0534	86.75
Non-Unidirectinal Non-Crushed	0.0650	29.59
Non-Unidirectional Crushed	0.1296	32.81

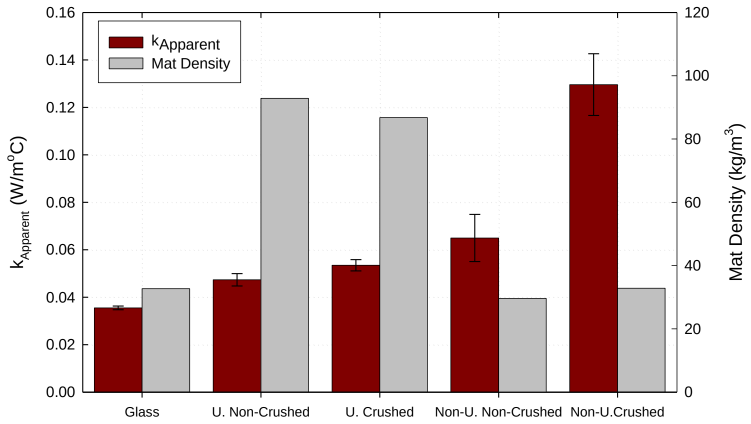

Figure 8: Apparent thermal conductivity and mat density for unidirectional fiber arrangement

Figure 9: Unidirectional and non-unidirectional non-crushed fiber mat for thermal conductivity measurements

For fibers randomly aligned, the amount of volume of free spaces between fibers increases significantly and the number of fibers needed to get the same mat thickness is considerable less (low mat density). Also, the contact area between fibers decreases drastically, one can see that for unidirectional alignment the contact between fibers are lines and for randomly alignment the contact are just points where one fiber cross to others. Based on that scheme, the heat transfer process by conduction decreases drastically, this means the dominant heat transfer process occurs by convection, due to that the apparent thermal conductivity tends to the value observed for air k_{Air} = 0.0259 W/m^{o}C (for atmospheric pressure) [17]. As shown previously by the SEM images (Fig. 7) the internal structure of the fibers is porous; on the other hand, by crushing the fibers, the porous structure was destroyed and the apparent thermal conductivity increased drastically as show Table 2 and Fig. 9.

By the results obtained, Ichu fibers has a great potential to use as a insulation material for walls and roofing due to the low cost, low mat density and excellent apparent thermal conductivity.

4. Conclusions

Natural fibers were characterized with the purpose of using them as a natural thermal insulation system. It has been shown that corn fibers are considerable variable in size and dimensions; however, its apparent thermal conductivity and density are close to the one observed in glass fiber. Similar values were observed for wheat fiber mats, with the only difference that the fibers dimensions are considerablly uniform. A special study was conducted for Ichu fiber, which has tubular shape. This fiber was classified into two different types: coarse and fine Ichu, showing average diameters of 0.83 and 0.39 mm respectively, with the diameter data fitting to Gamma and/or

Lognormal statistical distribution. The tubular shape of Ichu fibers and long length sizes have great advantages due to the possibility to modify the staking orientation obtaining very low-density mats without significant variation in apparent thermal conductivity, especially for fine Ichu. SEM micrography of Ichu fibers (stem and leaves) shows porous internal structure, which reduce the thermal conductivity. For randomly fiber alignment mats density can be reduced to lower values similar to those observed for glass fibers, another advantage is the length size, making it possible to construct large size mats.

5. Acknowledgment

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