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Structures and Properties of the Goose Down as a Material for Thermal Insulation

Abstract As a natural filling material, the goose down is well known for its superior thermal insulating properties and is widely used as an insulated filling material for winter outerwear and quilters. However, our understanding of the material is so poor that we still cannot fully explain the mechanisms or the sources for its high thermal insulation. This paper reports an extensive investigation of the chemical compositions, morphological structure and the physical properties, pertaining to thermal resistance of the down and down assemblies compared with other fiber assemblies. Detailed experimental work and data analysis were conducted on the properties influencing the thermal insulation of the down.

Key words compression test, goose down, morphology and configuration, surface hydrophility, thermal conductivity test, thermal insulation

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The downs or down hair from such waterfowl as duck, goose, mallard and swan etc. can be classified based on the color into white and gray. Figure 1, taken with an ordinary optical camera, shows the differences between the feather and the down hair.

Due to the characteristics of light weight, soft touch and warm feeling, the downs have long been considered superior and luxurious as a filling material for beddings and outerwear against cold climates. The intuitive explanation for the excellent thermal insulation of the downs consists of two aspects. One is due to its lofty configuration, which provides a thermal barrier of unusually high effectiveness in trapping still air which is the best insulator. The other has to do with its high resilience, which enables the downs to recover from any squeeze to its original configuration, so as to retain the entrapped air and, thus, the thermal insulation.

In spite of the long history and extensive applications of the down hair, documented knowledge on the material is scarce, fragmented and superficial, and the scientific researches, especially those focused on its unique thermal insulation, have been surprisingly rare. We have only been able to identify a couple of papers [1, 2] specifically devoted to, albeit briefly and qualitatively, the analyses of the structure and properties of the downs and down assembly. In addition, there have been a few studies [3–5] on the structures of poultry feathers in general, on chicken feather [6, 7] and turkey feather [8, 9], in particular. Given the excellent performance and relative abundance of the down material, it was imperative for us to conduct a thorough and extensive investigation about the material for better utilization and even simulation of the properties using synthetic materials.

The Morphological Structure of Down

The first logical step seemed to be the morphological study of the down structure under a scanning electron micro-

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Figures 5, 7, 9, 13 appear in color online: http://trj.sagepub.com

Figure 1 Comparison between feather and the down hair.

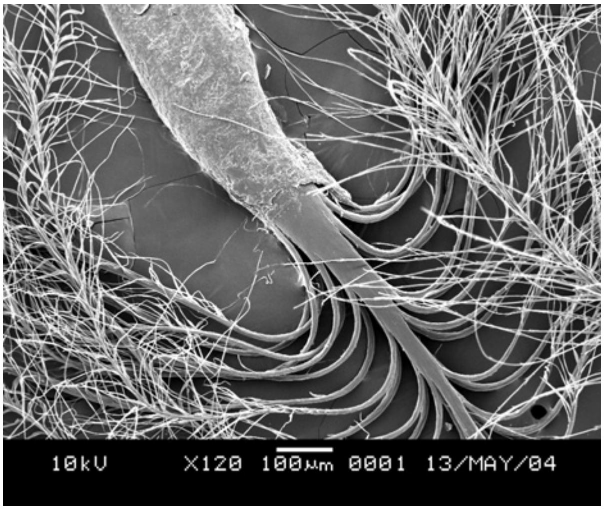

Figure 2 Individual down branch.

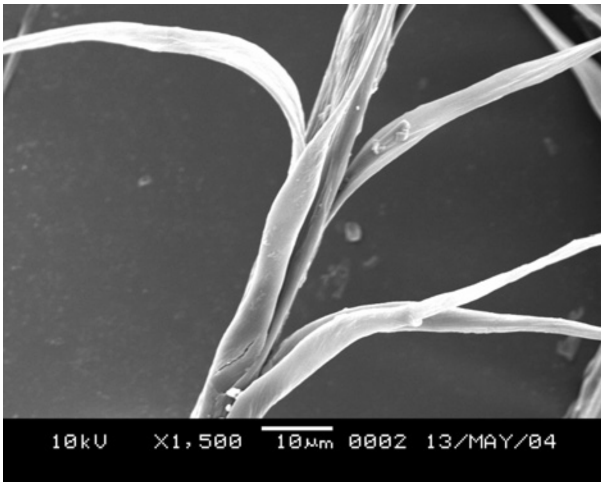

Figure 3 The sub-branches.

scope (SEM). Figure 2 is a SEM picture of a branch of a down cluster magnified by 120 times. The branch consisted of a short central stem from which a number of sub-branches diverged over a wide range of orientations. Each sub-branch carried in turn a large number of fibrils, which protruded from the main branch at approximately 30° to 90° changing from the tip to the root (Figure 3).

Measurements showed that the fibrils' diameter fell within 2 to 6 micron range and the length 100 to 500 micron. Whereas the sub-branch fiber diameter was 8 to 20 micron and the length 0.5 to 3.5 centimeter. The fibrils showed tens of knars, on the tip of which a very unusual morphological form was exhibited, including triangle nodes and crotches located at regular intervals of approximately 20 to 30 microns, as seen in Figure 4. These nodes and crotches had a maximum transverse dimension of 3 to 5 times that of the fibrils themselves.

From the figures we can see one of the major contributors for the superb thermal insulation capacities of the down – its unique structural characteristics. A down cluster is made of a large number of subunits each with appropriate orientation that helps maintain a great loftiness and low volume fraction of a down assembly for thermal insulation purpose. In addition, down fibers provide a valuable feature of recoverable loftiness; the crotches and triangle nodes are so large that they hold in place the crossing fibrils that happen to make contact with each other under compression force.

The Supermolecule Structure of Down

A further study was conducted to examine the supermolecular structure of the down. The down samples were washed in an extraction apparatus with alcohol and ether for no less than 20 circles to ensure complete cleanness. The washed samples were then dyed with osmium tetraoxide for more than 48 h until the samples became fully black, before taking them out and drying naturally. The dyed samples were embedded into an epoxy resin confected at given ratios and then the embedded samples were cured in an oven at 30 for 6 h, 60 for 12 h and 90 for a further 12 h. Finally, the samples were prepared accordingly for observation under a transmission electron microscope.

As Figures 5(a) to 5(d) show, the down had a simpler structure than wool [10], and a down branch could be con-

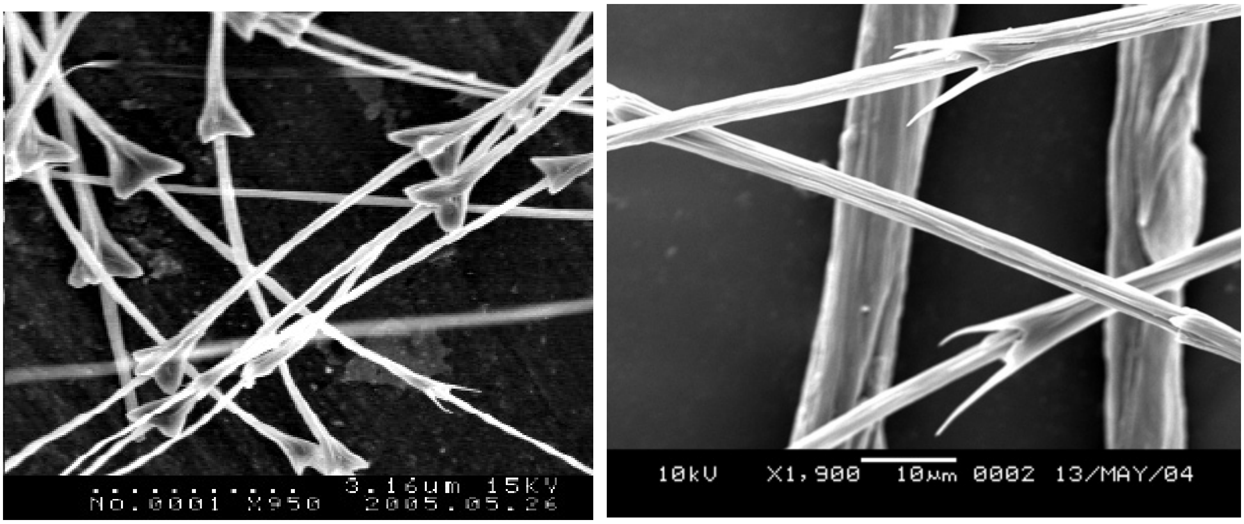

Figure 4 Triangle (a) and crotch (b) nodes on fibrils.

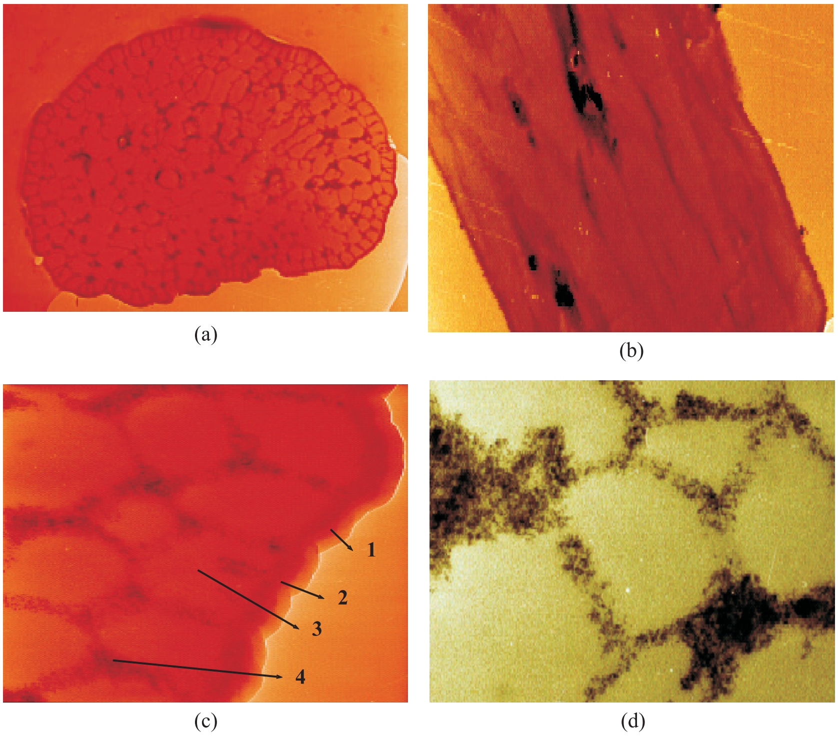

Figure 5 (a) Cross-section of a down branch. (b) Lengthwise structure of down branch. (c) The supermolecular structure of down. 1, epicuticle; 2, cuticle; 3, skin; 4, cortex. (d) Macrofibrils and fibril-matrix.

sidered as one unicellular fiber whose cross sectional shape was approximate ellipse. The down could be divided into four parts from outside inward, which were named as epicuticle film, cuticle layer, skin layer and cortex, of which the epicuticle film was a layer of biologic cell membrane with thickness approximately 0.02–0.10 microns. Inside it there was a cuticle layer with compact structure and 0.05–0.20 micron thickness. The skin layer was approximately 0.2–1.4 microns and regularly packed by a layer of macrofibrils vertically along the cuticle layer. The cortex was a principal part of down and occupied most weights of down, which consisted of numbers of macrofibrils and fibril-matrix.

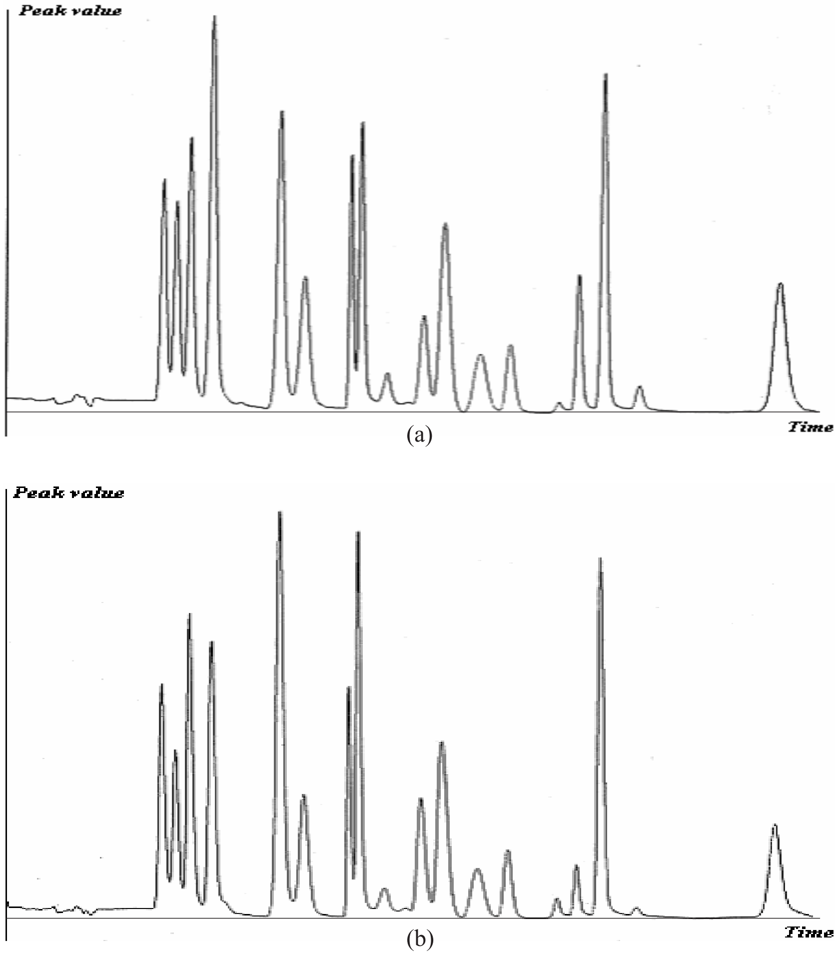

Figure 6 Spectrogram of amino-acid content. (a) Wool. (b) Down.

Through the transmission electron microscope, only one-step fibril structure was found. The macrofibrils arranged much less irregularly than those in skin layer and had various shapes and sizes. However, the structure in cortex was comparatively more compact and coherent than wool, and there were no bigger apertures and pores. Among the macrofibrils there was fibril-matrix which may be the mixtures of high-sulfur-content molecule groups and much more slim fibrils. Such a regularly packed configuration by the macrofibrils resulted in a compact structure and large pores were not among the macrofibrils in the cortex, which decreased the capillary volume and effectively reduced the capillary water inside the downs.

The Internal Chemical Composition of the Down

The down belongs to natural protein fibers and the main component of the down is called the down protein. Down protein is composed of species of alpha-amino-acid and compared with wool keratin as shown Figure 6 and Table 1. These amino-acid molecules link into polypeptide chains to form the primary structure of the down protein. Also, there are many transverse links condensed by most of these alpha-amino-acids among the down protein macromolecules. The main links are salt bond links, amino bond links, ester linkage links, disulfide bond links and hydrogen bond links.

The Surface Chemical Composition of the Down

To further our investigation, we examined in detail the surface chemical compositions of both the down and wool, for it is the surface that determines the energy or heat exchanges of a material with the environment.

The surface matter of the down was washed and distilled with alcohol and aether in an extraction apparatus. Infrared spectrogram of the surface matter was then

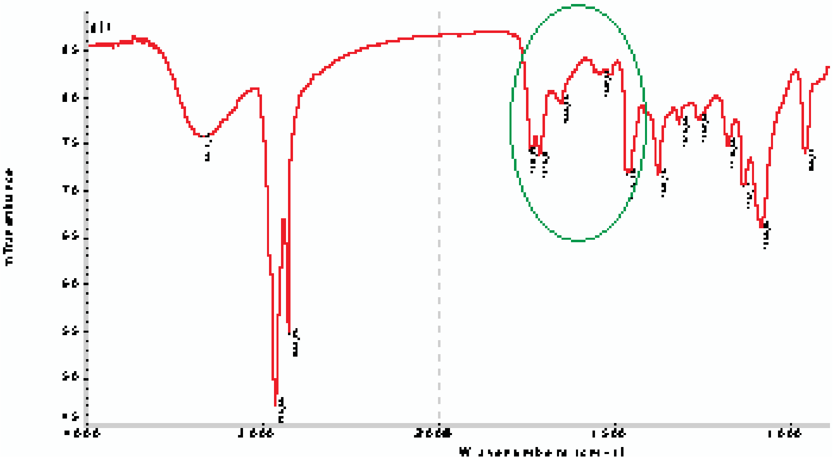

Figure 7 Infrared spectrogram of down surface.

Table 1 Amino-acid sorts and contents of different fibers [2].

Samples / Amino-acid	Down (%)	Wool (%)
Aspartic acid	7.46	6.94
Threonine	4.65	5.08
Serine	6.65	5.64
Glutamic acid	10.15	14.10
Proline	11.01	5.14
Glycine	7.81	5.38
Alanine	3.99	4.09
Cystine	7.23	7.58
Valine	8.08	5.66
Methionine	1.19	1.30
Isoleucine	4.49	3.22
Leucine	8.32	8.41
Tyrosine	4.33	4.96
Phenylalanine	3.96	3.93
Lysine	1.40	3.45
Histidine	0.41	1.05
Arginine	6.81	10.12
Tryptophan	–	–

obtained, as shown in Figure 7. The surface of the down was a layer of biologic cell membrane, which was mainly made of sterol and bimolecular layers of triphosphate ester (Figure 8). The sterol was the phenanthrene compound that was not water soluble and the triphosphate ester was a condensed ester compound of organic alcohol and three molecules of phosphoric acid, which was also a kind of water non-dissolvable organic substance. The whole surface film occupied 10% weight of the whole down, rendering protection and water isolation functions to the down for its excellent water repellency.

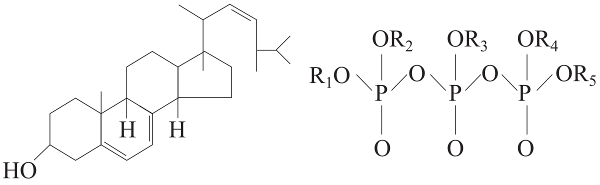

Figure 8 Constitutional formula of steroid (former) and triphosphate ester (latter).

Regarding wool, it is known that the wool epicuticle is made of lipoid structure about 0.9 mm thick, including both β and δ layers. The β layer composes of hydrophobic lipoid and δ layer of hydrophilic protein. The two layers combine through the covalent bond of 18-MEA by thioester and ester linkages. Although the existence of hydrophobic lipoid and the polar group in sulfate bonds prevents wool from interacting with water molecules, water can enter wool through the hydrophilic δ compound in the cell-membrane surface complex [11].

To sum up, the down surface was more hydrophobic than the wool surface and, thus, exhibited a better thermal insulation in humid environment as detailed below.

The Absorbent Quality of the Down

The Moisture Absorbency

The down and down assembly used commercially as filling materials are in fact a mixture of dry material and moistured air; the latter is in turn a mixture of dry air and water.

Since the three substances have vastly different thermal properties, the overall thermal performance of the whole system is apparently a function of the relative proportions of the three constituents. Furthermore, when down becomes wet, the interstitial water can collapse the bulky structure of the down and the assembly, reducing the air trapped and, thus, the assembly thermal resistance. Therefore, the absorbent behavior is an important factor in evaluating the down thermal insulation properties.

The equilibrium moisture regain, M_r, is a primary index reflecting the material absorbent capacity, which is defined as the ratio of the moisture to the total sample weight at equilibrium. Testing the moisture regains of different materials by the torrefaction method in an oven, the samples of various temperatures and moistures were balanced in a WGDSH7015 temperature-moisture-heat tester for equilibrium. Balancing time was 24 h and drying time in oven was more than 2 h. At given ambient relative humidity, RH, (moisture available in the environment) and temperature, M_r was calculated as the percent of absorbed water weight and the total weight of the material.

$$M_r = \frac{W_t - W_d}{W_t} \times 100\% \qquad (1)$$

where W_t is the total or wet weight and W_d is the dry weight of the material. Thus, a material with higher moisture regain represents a greater moisture absorbing capacity at equilibrium.

Figure 9 shows the testing results for the down in comparison with other common fibers as a function of the relative humidity. At a given RH level, the moisture absorbency of the down was lower than either wool or cotton, about half of that of wool; this was likely due to the relatively hydrophobic molecular film on the down skin as discussed in the last section. PET staples retained the lowest M_r due to their lack of hydrophilic groups in their macromolecule structures. The hygrophilicity of various fibers will boost up with increasing relative humidity (Figure 10). In general, a higher M_r value indicates a greater influence of the relative humidity on its thermal insulation.

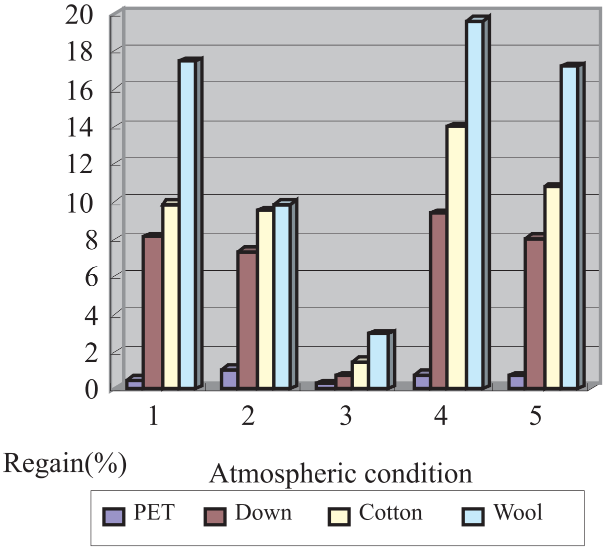

Figure 9 Moisture regains of different fibers.

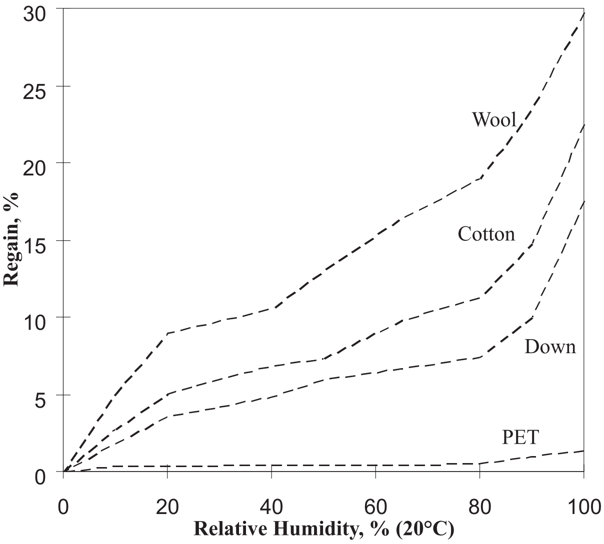

Figure 10 Hydroscopic isotherm at 20 of different fibers.

The Joint Effects of Temperature and Relative Humidity

It is expected that the ambient temperature will impact the thermal insulation properties of the down via two routes; first, the direct influence of the heat energy on the down performance and the secondly, the coupling effects of temperature on the relative humidity. To investigate such joint effects on the down, testing condition was set at five different levels, including standard (S), high-temperature and high-relative humidity (HTHR), high-temperature and low-relative humidity (HTLR), low-temperature and high-relative humidity (LTHR) and low-temperature and low-relative humidity (LTLR), as listed in Table 2.

The testing results are tabulated in Table 3, where the top four rows are the actual moisture regain values of different fibers at the five conditions and for easier comparison the lower four rows are the normalized results by dividing each number with the value tested at the standard condition, S, corresponding to each fiber type.

Table 2 The different condition levels.

Condition level	Code	Temperature (°C)	Relative humidity (%)
1	S	20	65
2	HTHR	80	80
3	HTLR	80	10
4	LTHR	5	80
5	LTLR	10	10

The ranking in terms of the moisture regain values at all five different conditions remained the same i.e. wool > cotton > down > PET, as clearly shown in Figure 9. In other words, the joint effects of ambient temperature and relative humidity did not alter the thermal performance ranking. Further, since our interest was in the thermal insulation performance, only the low temperature case i.e. the two conditions LTHR and LTLR were relevant. In normalized or relative terms, the down was on a par with wool and showed the lowest value of moisture regain. This should be favorable for thermal protection at different humidity conditions.

The branch-like and fractal structure of the down played a critical role in its thermal insulation; such a structure entrapped more air first and then retained more air after compression, accounting to a great degree for the excellent thermal insulation of the down. Also, the hydrophobic molecular film on the down surface prevented the moisture molecules from penetrating into the fiber. Meanwhile, a regularly packed internal configuration by the macrofibrils resulted in a compact structure, so that there were no large pores among the macrofibrils in the cortex, which decreased the capillary volume and effectively reduced the capillary water inside the downs. Finally, in comparison with wool, the lower M_r value at the same RH level and greater reduction in M_r at a decreased RH environment ensured the down assemblies to be much drier, so as to retain their excellent thermal insulation.

Compression and Recovery Properties

We already analyzed above that the down had a unique structure which entrapped more air and retained it after repeated compression via the renewable loftiness, critical features other fibers lack and offers excellent thermal insulation. In this section, we actually tested the compression recovery properties of the down assembly using a test similar to one previously reported [7, 11–13].

A small mass of each material including the down assembly was “sifted” into a cube box of 1,500 cm^3 constructed of plastic board. The exact weight of each fiber mass was measured, but varied because the fiber volume was controlled to fill the cube one-third full, equal to fiber volume of an identical value of 500 cm^3. The box was shaken 20 times to fluff and loosen the fibers. The height (h_1) of the fibers in the box was then measured. Another piece of plastic board of right size was laid on the fiber mass and the height of the fiber mass was then measured again. A 20-gram to 200-gram load was added on the cover board successively and the height was measured each time under each compressive load. When all the loads and the board were removed from the fiber mass, it rose to recover to its original position and the height (h_3) was measured again. Between each load change, five minutes was given to allow the system to reach the equilibrium before measuring the height.

Based on the known volume and the weight obtained, the bulkiness and density, ρ, of different fiber types were calculated in Table 4 as

$$Bulkiness = \frac{V_o}{m} = \frac{1}{\rho} \tag{2}$$

where $V_o = 500\ \text{cm}^3$ is the original volume and m is the mass of fibers. The density, ρ, is the reciprocal of the bulkiness value.

Table 3 The moisture regains of different fibers at different condition levels.

M_r (%)	S	LTLR	LTHR	HTLR	HTHR
PET	0.499	0.701	0.806	0.276	1.076
Down	8.133	8.053	9.339	0.726	7.378
Cotton	9.860	10.786	13.932	1.505	9.529
Wool	17.443	17.208	19.598	2.934	9.883
PET	1.000	1.405	1.615	0.553	2.156
Down	1.000	0.990	1.148	0.089	0.907
Cotton	1.000	1.094	1.413	0.153	0.966
Wool	1.000	0.987	1.124	0.168	0.567

Table 4 Bulkiness and density of different fibers.

Name	V_o (cm^3)	m (g)	Bulkiness (cm^3/g)	ρ Density (g/cm^3)
Down	500	1.43	349.65	0.00286
Wool	500	5.06	98.81	0.01012
Cotton	500	6.48	77.16	0.01296
Polyester	500	5.74	87.11	0.01148

The bulkiness denotes the amount of space a given weight of fibers will occupy under a standard pressure; generally, the larger the bulkiness, the more air trapped, so the better the thermal insulating properties. Table 4 shows that the down assemblies had the highest bulkiness, 3 to 5 times of other fibers and, thus, the lowest density, so they were able to trap the largest amount of air and be propitious to remain the good thermal insulation.

The compression and recovery were also calculated for each fiber type. Compression was reduction in volume when a chosen compressive load (200 g) was applied. Recovery was the degree to which a fiber mass recovered to its original height upon unloading. Both were defined as

$$\text{Compression } (\%) = \frac{(h_1 - h_2)}{h_1} \times 100 \tag{3}$$

$$\text{Recovery } (\%) = \frac{(h_3 - h_2)}{(h_1 - h_2)} \times 100 \tag{4}$$

where h_1 is the original height of the fibers in the container, h_2 is the height of fiber under load of 200-gram and h_3 is the height of fiber with load removed.

The down hair was made of a large number of subunits each with wide orientation and trying to occupy maximal space, so as to maintain great loftiness and bulkiness. Therefore, the down assembly had much higher compression than other fiber assemblies (Figure 11).

When compressive load was removed, the fibers tended to recover toward their original volumes (Figure 12). In order to simulate the practical situation where recovery of a fiber mass is usually accompanied by shacking agitation. The down assembly showed the greatest recovery after one shaking to unlock the nodes and crotches.

Overall, the down assembly possessed the highest bulkiness and recovery from deformation, confirming the explanations above on the superb thermal insulations.

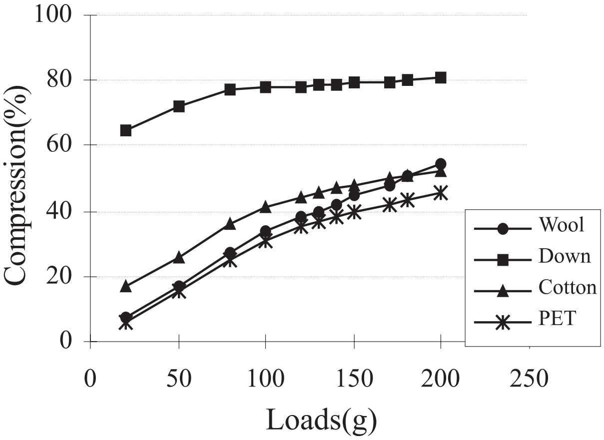

Figure 11 Compression of different fibers.

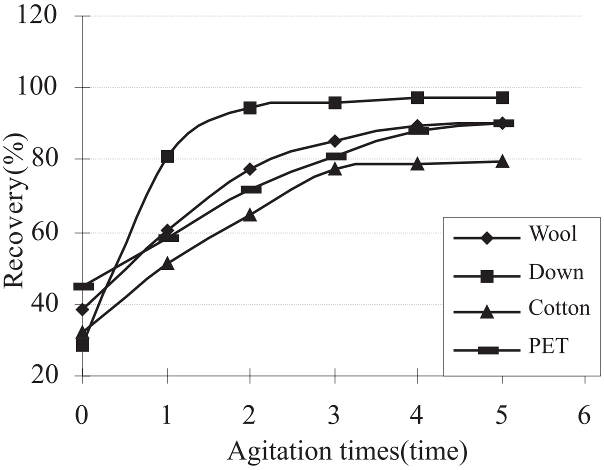

Figure 12 Recovery of different fibers under agitation.

Thermal Insulating Property of the Down and Other Fibers

Finally, we conducted actual experiments to validate the thermal insulation of various fiber masses by measuring their thermal conductivities defined as the heat flow quantity through per unit area of an isothermal surface in unit time, at a temperature difference of 1°C/m (W·m^{-1}·°C^{-1}) [12–14]. Different loose fiber samples at a variety of densities were tested in a YG606 Hot Plate tester (Figure 13).

Figure 13 YG606 plate warmth retaining tester.

Fiber samples were first placed into a nonwoven bag of 30 cm × 30 cm × 30 cm and the bag into the instrument. The thermal conductivity was determined by measuring the heat flowing at a known temperature gradient through a sample of given thickness and the results were read directly from the instrument. As the nonwoven bag was very thin, the effect on the results was minimal.

Thermal insulating materials were used to prevent heat loss, which can occur by conduction, convection, phase change and radiation, individually or collectively. Heat transfer from one side of the fiber assembly to the another side was a complex phenomenon affected by numerous factors, such as density of the assembly, quantity of entrapped air, moisture content and transport and the motion of the contained air. Figure 14 provides the results of the thermal conductivity testing, showing the thermal conductivity as a function of density. Data from this study were similar in both trend and magnitude to results reported in previous work.

The results confirmed once again, at any given density the down possessed the lowest thermal conductivity i.e. the best thermal insulation properties compared with other fibers.

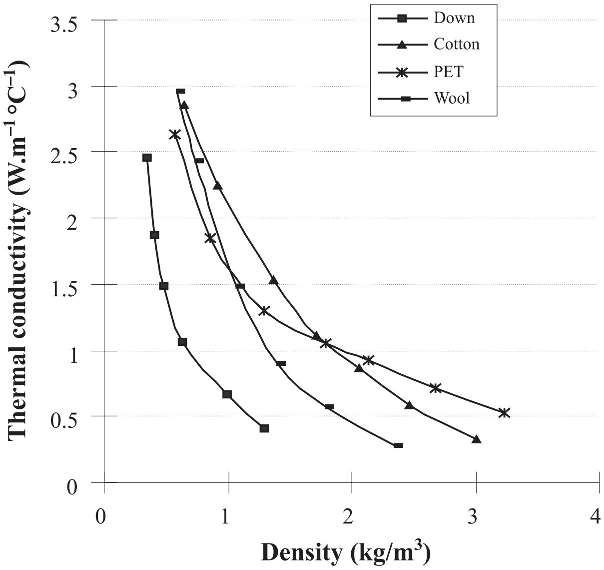

Figure 14 Thermal properties of different fibers under agitation.

Conclusions

Given the excellent performance, relative abundance and our poor understanding of the down material, we conducted a thorough experimental investigation regarding the material, so as to explore the mechanisms behind the performance for better utilization and even simulation of the properties using synthetic materials. We found or confirmed the following.

Down clusters were made of a large number of subunits each with appropriate orientation and crotches and triangle nodes that helped maintain a great loftiness and excellent recovery of a down assembly for thermal insulation purposes.

We also observed that down had a regularly packed internal configuration by the macrofibrils, resulting in a compact structure with no large pores among the macrofibrils in the cortex, which decreased the capillary volume and effectively reduced the capillary water inside the downs.

In comparison with wool, the down surface was more hydrophobic and, thus, exhibited a better thermal insulation in humid environment. Furthermore, down had a lower equilibrium moisture regain, M_r, at the same RH level and a greater reduction in M_r at a decreased RH environment; both ensured the down assemblies to be much drier in a given ambient condition, so as to retain their excellent thermal insulation.

Finally, it was confirmed in this study by the actual testing results that when all other variables remained the same, down assembly possessed the highest bulkiness, greatest recovery from deformation, the lowest thermal conductivity and, hence, the best thermal insulation properties compared with other fibers tested.

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