Light-Weight Polypropylene Composites Reinforced with Whole Chicken Feathers

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ABSTRACT: Light-weight composites reinforced with whole chicken feathers have better flexural strength than composites reinforced with feather fibers (barbs) and nearly thrice higher tensile strength and seven times higher tensile modulus than composites reinforced with powdered chicken feather quill. Chicken feathers are not only inexpensive and abundantly available but also have unique properties such as low density and hollow centers that make them preferable as reinforcement materials, especially for light-weight composites. However, the traditional methods of developing composites do not provide the flexibility of using feathers in their native form as reinforcement. So far, the components in feathers such as barbs or quills have been used separately and/or feathers have been mechanically processed to destroy their native form in order to use feathers as reinforcement in composites. A new method of making composites using nonwoven webs as matrix allows the incorporation of reinforcing materials in their native form such as whole chicken feathers to develop composites. This research shows that whole chicken feathers can be used as reinforcement in composites with better flexural, tensile, and acoustic properties than composites made from processed chicken feathers. © 2010 Wiley Periodicals, Inc. J Appl Polym Sci 116: 3668–3675, 2010

Key words: poultry feathers; composites; light-weight; waste; density

INTRODUCTION

Poultry feathers are abundant, inexpensive, and renewable byproducts that have been studied as potential raw materials for various applications.[1–7] Among various poultry feathers, chicken feathers are currently being commercially processed to separate the quill and barbs. The barbs separated from the quill are commercially sold as "feather fibers."[8] Feathers are preferred as reinforcements in composites due to their unique properties and low cost. The low density (0.89 g/cm^3) of feathers compared with the traditional reinforcing materials used in composites such as natural cellulose fibers make them especially suitable for light-weight composites.[6] The unique structure of feathers, that is, the presence of a hollow center and hierarchical arrangement of the quill, barbs, and barbules gives feathers good mechanical and sound absorption properties desirable in automotive composites.[6] It is difficult to imitate the structure of feathers in man-made reinforcing materials. Therefore, feathers are unique reinforcing materials especially preferable for light-weight composites.[6,9,10]

Light-weight composites are different than the traditional consolidated composites. In traditional consolidated composites, the density of the composite is equal or higher than the sum of the densities of the materials used in the composites. In light-weight composites, the density of the composite will be lower than the combined densities of the reinforcing and matrix materials. This creates voids in the composites leading to composites with inherently inferior properties than the consolidated composites. However, light-weight composites are preferable in automotive applications due to the weight limitations. Feathers would be ideal reinforcing materials for light-weight automotive composites.

Several attempts have been made to use feathers as reinforcements in composites.[1,5–7,11–13] Commercially available feather fibers were mixed with cellulose fiber and polypropylene (PP) matrix in a wet lay paper making process to develop composites. It was reported that feathers fibers provided inferior properties compared with cellulose fibers and modulus of the composites was adversely affected by feather fibers.[14] Medium density fiber boards were made using blends of wood fiber and feather fibers

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in ratios of 20–95% and 5% phenol formaldehyde as the resin. The feather fiber reinforced boards had lower strength and stiffness but had better resistance to swelling and lower water absorption compared with all-wood boards.[7] A bio-based composite was made using feather fibers as reinforcement and soybean oil as the resin. The feather fibers were reported to enhance the mechanical properties of the soy oil based composites.[15] Feather fibers of varying aspect ratio were mixed with low-density polyethylene to develop composites. The density of the composite decreased by about 2% due to the feather fibers and some interaction between the feathers and polyethylene was observed.[1] In another report, feather fibers were reported to improve the stiffness but reduce the breaking stress of polyethylene composites.[5]

All of the above reports have used the commercially available feather fibers with or without further modifications. Although feather fibers are commercially available and have some unique properties, there are several limitations of using feathers fibers compared with using whole feathers. For instance, the processing of the feathers to obtain the feather fibers considerably shortens the length of the feather fibers. Commercially available feather fibers have lengths in the range of 300 μm to 13 mm, whereas the barbs in native feathers can be up to 3 cm in length.[6,16,17] Composites reinforced with shorter length feather fibers will have inferior mechanical properties compared with those reinforced with longer length feather fibers.

However, it is difficult to incorporate longer length barbs or whole feathers as reinforcement using the current methods of composite fabrication. It is difficult to compression or injection mold whole feathers and obtain composites with good properties. Quills that are a major part of the feather are stiff, long, and thick, and prevent whole feathers to be used as reinforcement in injection or compression molded composites. It is not possible to obtain good mixing of the feathers in their native form and matrix polymers to develop compression or injection molded composites. We have recently developed composites by grinding chicken quill and mixing the powdered quill with PP.[6] Ground quill PP composites had similar flexural strength but lower tensile strength and modulus than jute fiber reinforced PP composites.[6]

Recently, we have reported a novel method of making composites using nonwoven webs as matrix.[16] The new method allows the incorporation of reinforcing materials in their native form such as chicken feather, cornhusks, and wheat straw to develop composites. Using reinforcing materials in their native form, not only reduces the cost but also makes it possible to utilize the unique properties of the reinforcing materials. In this research, we have used whole chicken feathers to reinforce PP. The effects of amount of feathers, thickness and density of the composite on the flexural, tensile, and acoustic properties have been studied. A comparison of the properties of the whole feathers composites with that of similar feather fiber and powdered quill reinforced PP composites is also provided.

MATERIALS AND METHODS

Materials

Whole chicken feathers were procured from a farm in India. The feathers were thoroughly washed in water and dried. The mechanical properties of the feather barbs have been reported earlier.[17] Spunbonded PP webs were purchased from Spunfab (Cuyahoga Falls, OH). The web had a weight/area of 11.9 g/m^2 (0.35 oz/yd^2), melting temperature of 162°C, melt flow index (MFI) of 38 g/10 min measured at 230°C, and density of 0.90 g/cm^3. PP was chosen as the matrix due to its low cost and relatively low melting point (160–165°C), which will not degrade the feathers.

Developing composites

Composites were developed using PP web as matrix and whole chicken feathers as reinforcement. The PP web was laid on a large table and a known weight of feathers was spread evenly on the web by hand. The web with feathers on top was cut into 25.4 × 30.5 cm pieces. The PP pieces containing whole feathers were stacked upon each other until the required amount (weight/unit area) of the reinforcing and matrix material was obtained. Additional layers of PP web were placed on the top and bottom depending on the desired ratio of PP and feathers in the composites. The pre-preg was then placed between aluminum foils and compression molded in a Carver press at 380°F for 140 s using spacers (2.8, 3.2, 3.6, and 4.2 mm) to control the thickness of the composites at a pressure of 20,000 PSI. The time and temperature of making feather reinforced composites were optimized in our previous researches.[6,16]

Characterizing the composites

The composites were conditioned in a standard testing atmosphere of 21°C and 65% relative humidity for at least 24 h before testing. Flexural tests were done according to ASTM standard D790-03 on a MTS (Model Q Test 10; MTS Corporation, Eden Prairie , MN) tensile tester equipped with a 500 N load cell. The crosshead speed used was 10 mm/min. Tensile tests were performed on an Instron tensile tester (Model 4000; Instron, Norwood, MA) according to ASTM standard D638-03 using dog–bone-shaped specimens. Crosshead speed was 5 mm/min. Six samples from three different composites were tested for the flexural and tensile properties and the average and ± one standard deviations are reported. The sound absorption properties of the composites were determined in terms of the noise reduction coefficient (NRC) according to ASTM standard C423-99A on a small size Bruel & Kjaer impedance tube. NRC is calculated as the average sound absorption coefficients at 250, 500, 1000, and 2000 Hz frequencies. Three samples from different composites were tested for the sound absorption, and the average readings were used to calculate the NRC and to plot the absorption coefficient curves.

Morphology

A variable pressure scanning electron microscope (Hitachi S 3000N) was used to observe the morphology of the composites. Samples were sputter coated with gold palladium before observing under the SEM.

RESULTS AND DISCUSSION

Morphology of the composites

Figure 1 shows the cross-section of a composite made with 65% feathers. The figure reveals the cross-section of the quill with the characteristic hollow structures. These hollow structures make the feathers light-weight and also facilitate sound absorption. The composite shown in Figure 1 had a density of 1000 g/m^2 and, therefore, has considerable amounts of voids between the reinforcing materials. Although voids could help sound absorption, voids will make the composites to have inferior properties. Figure 2 shows a composite with a density of 2000 g/m^2 containing 50% feathers. When compared with the composite in Figure 1, the high density composite has fewer voids. Most of the feathers have been compressed between the matrix. With fewer voids and more material per unit area, the high density composite will have better properties than the low density composite.

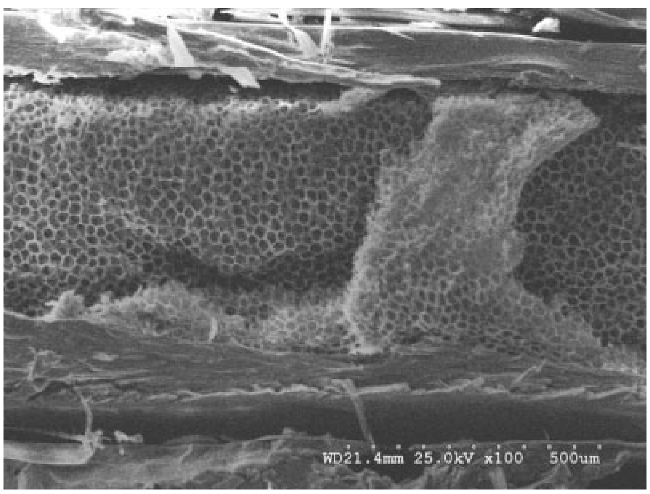

Figure 1 SEM image of the cross-section of a composite reinforced with 65% feathers and 35% polypropylene. The composite had a density of 1000 g/m^2 and thickness of 3.2 mm. The characteristic voids in the quill that provide low density and sound absorption properties can be seen.

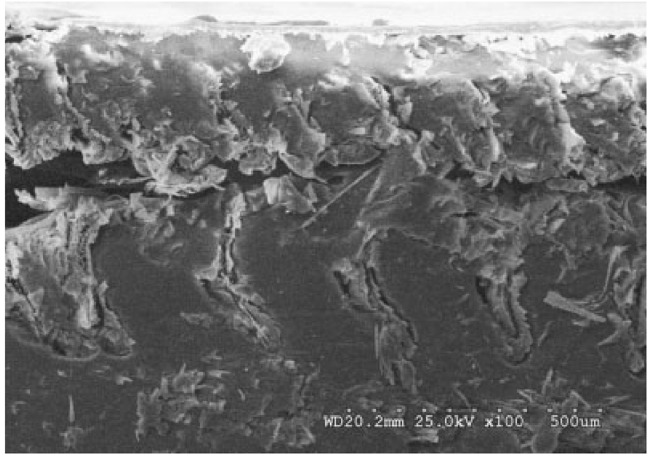

Figure 2 SEM image of the cross-section of a composite reinforced with 50% feathers and 50% polypropylene. The composite had a density of 2000 g/m^2 and thickness of 3.2 mm.

Flexural properties

Effect of thickness of composite on flexural properties

Figure 3 depicts the effect of increasing thickness on the flexural properties of the whole chicken feather reinforced PP composites. Increasing thickness from

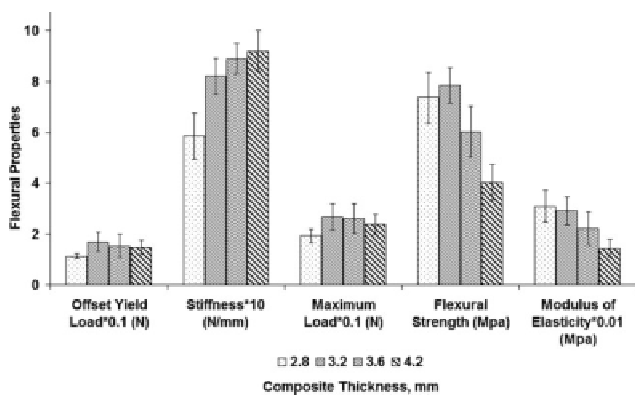

Figure 3 Effect of thickness on the flexural properties of whole feather reinforced polypropylene composites. The composites were made using 35% feather and 65% polypropylene with a density of 1500 g/m^2.

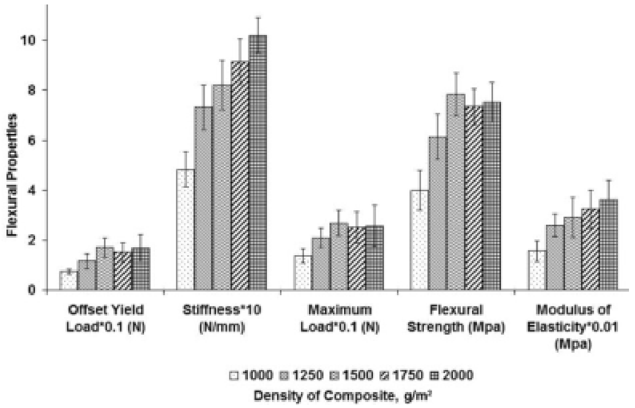

Figure 4 Effect of density of the composite on the flexural properties of whole feather reinforced polypropylene composites. The composites were made using 35% feather and 65% polypropylene with a thickness of 3.2 mm.

2.8 to 3.2 mm leads to a marginal increase in the offset yield load, maximum load, and flexural strength, about 90% increase in stiffness, whereas the modulus of elasticity (MOE) does not change. Above a thickness of 3.2 mm and up to 4.2 mm, the offset yield load, stiffness, and maximum load do not change but the flexural strength and MOE decrease. There is a 50% drop in flexural strength when the thickness is increased to 4.2 mm compared with the flexural strength of the 3.2 mm composite. Increasing thickness without changing the weight per unit area will create more voids or open spaces in the composites. The voids are the weak places that break relatively easily and a composite with more voids will, therefore, have inferior properties. Although the maximum load does not change with increasing thickness, the flexural strength decreases at higher thickness of the composites because the flexural strength is inversely related to the square of the thickness. The MOE is inversely related to the stiffness of the composites and higher stiffness means lower MOE.

Effect of density of composite on flexural properties

Figure 4 shows the effect of increasing the density of the composite without changing the thickness or proportion of reinforcement and matrix materials. Contrary to increasing the thickness, increasing the density of the composite means adding more weight per unit area, and hence, decrease in the voids in the composites. This will lead to improvement in properties as seen from Figure 4. The stiffness and flexural strength of the composite show significant increase when the density is increased from 1000 to 1250 g/m^2. There is no significant increase in the flexural properties of the composites when the density is increased above 1500 g/m^2. Composites with densities from 1250 to 1500 g/m^2 have similar offset yield load, maximum load, and MOE. At a certain thickness, low density composites will not have sufficient material in the composite and there will be a large number of voids leading to poor properties. There is sufficient material in the composite at a density of 1500 g/m^2 and, therefore, the composites have good properties at this density. Up to 1500 g/m^2, the voids in the composites play a predominant role in determining the properties of the composites rather than the properties of the reinforcing materials. At densities of 1500 g/m^2 and higher, the properties of the reinforcing materials probably play a major role in determining the properties of the composites. Although the stiffness and MOE should be inversely related, increasing the amount of feathers in the composites increases both the stiffness and MOE. This should be due to the presence of higher amounts of feathers in the composite. Composites with higher amounts of barbs and quill will be more flexible and, therefore, the MOE does not decrease even though the stiffness increases. The flexural properties of PP composites reinforced with powdered quill were also found to decrease above a density of 1500 g/m^2.

Effect of proportion of feathers on flexural properties

Figure 5 shows the effect of increasing the proportion of feathers on the flexural properties of the composites. Increasing concentration of the feathers does not show considerable change on any of the flexural properties of the composites as shown in Figure 5. Although adding higher quantities of the reinforcing material should increase the flexural properties, the decreasing amount of the matrix material probably results in insufficient matrix material to bind the feathers together leading to poor adhesion between the feathers and hence lack of improvement

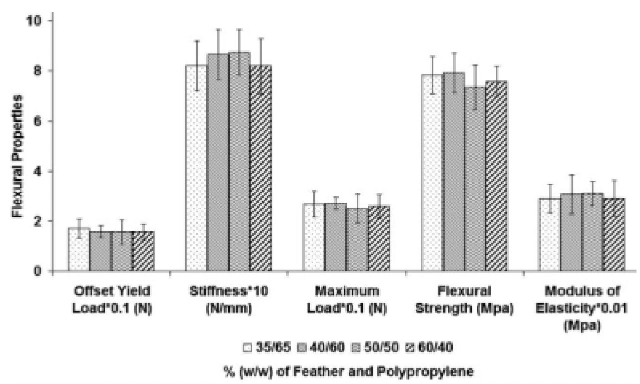

Figure 5 Effect of proportion of feathers on the flexural properties of whole feather reinforced polypropylene composites. The composites were made with a density of 1500 g/m^2 and a thickness of 3.2 mm.

TABLE I
Tensile Properties and Noise Reduction coefficient of Polypropylene Composites Reinforced with Whole Feathers

	Tensile properties		Noise reduction coefficient
	Strength (MPa)	Modulus (MPa)	
Ratio of feather/PP (% w/w)			
35/65	9.0 ± 1.5	1117 ± 57	0.26
40/60	15.9 ± 4.4	1406 ± 235	0.23
50/50	15.6 ± 3.5	1461 ± 270	0.21
60/40	13.4 ± 3.9	1166 ± 308	0.35
Density of composite (g/m^2)			
1000	7.2 ± 1.3	603 ± 240	0.19
1250	8.6 ± 0.9	1005 ± 197	0.28
1500	9.0 ± 1.5	1117 ± 57	0.26
1750	22 ± 1.7	1545 ± 263	0.29
2000	24 ± 1.1	1900 ± 166	0.27
Thickness of composite (mm)			
2.8	13.7 ± 1.9	1400 ± 156	0.18
3.2	9.0 ± 1.5	1117 ± 57	0.26
3.6	10.9 ± 1.8	739 ± 143	0.26
4.2	9.6 ± 1.6	800 ± 77	0.28

The composites with a density of 1500 g/m^2 were made at 380°F for 140 s.

in the flexural properties. The structure of the feathers could also prevent the matrix materials to flow freely and bind the feathers.

Tensile properties

Effect of increasing thickness

Composites with a thickness of 2.8 mm have the highest strength and modulus compared with the composites with higher thickness as seen from Table I. Increasing thickness without adding more material will have an opposite effect compared with increasing the density of the composites without changing the thickness. A composite with higher thickness for the same density of the composite means the creation of voids and, therefore, decrease in the properties of the composites. Therefore, increasing the thickness of the composites without changing the density of the composites will inevitably lead to inferior properties. At a thickness of 2.8 mm, there are fewer voids in the composites, and hence, the composite has better strength and modulus compared with the composites with higher thickness.

Effect of increasing the density of the composite

Increasing the density of the composite without changing the thickness or the proportion of feathers and PP increases the tensile strength and the modulus of the composites. The increase in strength is relatively small when the density is increased from 1000 to 1250 and from 1250 to 1500 g/m^2. However, the tensile strength of the composites increases more than 140% when the density is increased from 1500 to 1750 g/m^2. The modulus of the composites increases more steadily with increasing density than the tensile strength. Increasing density of the composites without changing the thickness means adding more material per unit area, and hence, increase in the strength and modulus of the composites.

Effect of increasing proportion of feathers

Increasing the amount of feathers in the composites from 35% to 40% increases the tensile strength of the composites by about 75% as seen from Table I. Further increase in the amount of feathers to 50% does not increase the tensile strength and in fact, the composites with 60% feather have lower tensile strength than the composites with 40% and 50% feathers. The modulus of the composites also shows a similar trend, that is, decreasing modulus at high proportion of feathers. The lack of sufficient matrix material to bind the feathers should be the major reason for the inferior tensile properties of the composites with higher proportion of feathers.

Sound absorption properties

Effect of composite thickness on sound absorption properties

Increasing the frequency of sound absorption continuously increases the absorption coefficient of the 2.8 and 3.2 mm composites as seen from Figure 6, whereas the sound absorption of the 3.6 and 4.2 mm composite decreases above a frequency of 3.8 kHz. The 3.6 and 4.2 mm have higher sound absorption than the 2.8 and 3.2 mm composites, in the frequency range of 2.4 to 4.3 kHz. The 4.2 mm

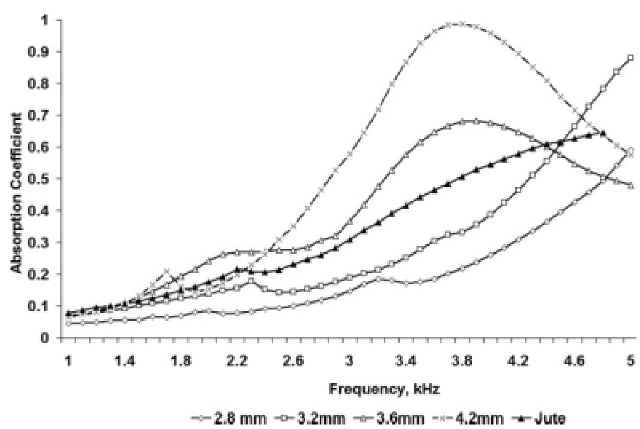

Figure 6 Effect of thickness of composite on the sound absorption of whole feather reinforced polypropylene composites. The composites were made using 35% feather and 65% polypropylene with a density of 1500 g/m^2.

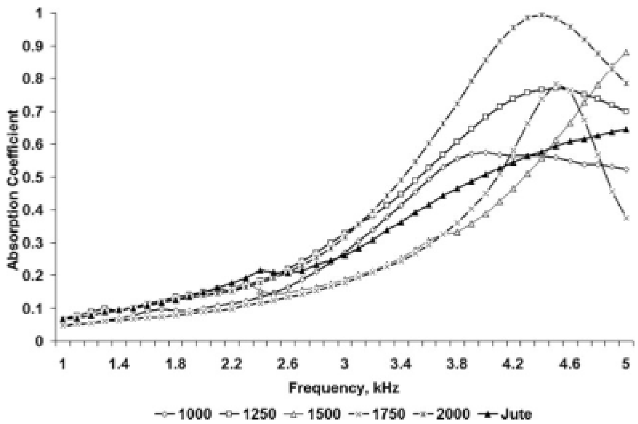

Figure 7 Effect of density of composite on the sound absorption properties of whole feather reinforced polypropylene composites. The composites were made using 35% feather and 65% polypropylene with a thickness of 3.2 mm.

composite absorbs most of the sound in the frequency range of 3.5–3.9 kHz and also has better sound absorption than the other composites shown in Figure 6 in the frequency range of 2.4–4.6 kHz. The 4.2 mm composite also has a peak in sound absorption between 1.5 and 1.8 kHz. The better sound absorption of the 3.6 and 4.2 mm composites compared with the 2.8 and 3.2 m composites should be due to the presence of voids. Increasing thickness without changing the density of the composites means creating voids between the reinforcing and the matrix material. In composites reinforced with conventional fibers, the presence of voids between the reinforcing and matrix material would reduce the sound absorption. However, the unique structure of the feathers, that is, the presence of the barbs and barbules with hollow center reduces the number and size of the voids between the reinforcing and matrix materials and, therefore, leads to better sound absorption. Except for the 2.8-mm thick composite, the other composites have similar NRCs as shown in Table I. Increase in sound absorption with increasing thickness of composites was also reported previously.[18]

Effect of composite density on sound absorption

Increasing density of the composites continuously increases the sound absorption of all the composites up to a frequency of about 4 kHz as shown in Figure 7. With absorption coefficient close to one, the 2000 g/m^2 composite absorbs most of the sound in the frequency range of 4–4.5 kHz. The absorption of the 1250, 1750, and 2000 g/m^2 composites decreases above a frequency of 4.5 kHz, whereas the absorption of the 1500 g/m^2 composite increase continuously throughout the frequency range studied. Increasing density without changing the thickness means adding more material per unit area. This leads to decrease in the voids between the reinforcing and matrix materials but the higher amount of feathers in the composite will provide higher amounts of the hollow structures that absorb the sound and provide better sound absorption to the composites. Except for the composite with a density of 1000 g/m^2, the composites with densities from 1250 to 2000 g/m^2 have similar NRC.

Effect of increasing proportion of feathers

The effect of increasing concentration of the feathers on the sound absorption properties of the composites is shown in Figure 8. The composites made from 35, 40, and 50% feathers have similar sound absorption up to about 3.5 kHz. Above this frequency, the sound absorption of the composite with 40% feathers starts to decrease but that of the composite with 35 and 50% feathers increases further. Small spikes in sound absorption can be observed in the 50 and 35% feather composite between 2.0 and 2.5 kHz. The composite with 60% feather has considerably higher sound absorption than the other composites in the frequency range of 2.5–3.8 kHz. Jute fiber reinforced composites show a steady increase in sound absorption with increasing frequency. The sound absorption of the jute reinforced composites is close to the composites containing 35, 40, and 50% feathers but lower than that of the 60% feather composite up to about 4 kHz. Sound absorption of the composites will depend on the inherent voids in the reinforcing materials, and the voids formed between the reinforcing and matrix polymers. The unique hollow structure in the quill and barbs of feathers provides insulation and, therefore, better sound absorption. At low proportion of feathers, there will be large number of voids between the feather and

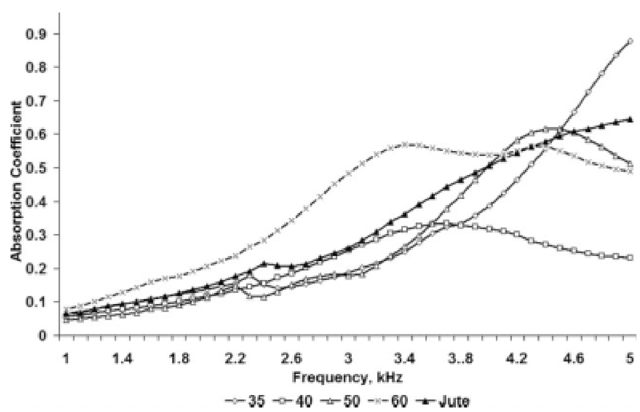

Figure 8 Effect of proportion of feathers on the sound absorption properties of whole feather reinforced polypropylene composites. The composites were made using with a density of 1500 g/m^2 and a thickness of 3.2 mm.

TABLE II
Comparison of the Properties of Whole Feather, Feather Fiber, and Powdered Quill Reinforced Polypropylene Composites

	Stiffness (N/mm)	Flexural strength (MPa)	Modulus of elasticity (MPa)	Tensile strength (MPa)	Tensile modulus (MPa)
Whole feather	0.8 ± 0.1	7.8 ± 0.8	290 ± 56	9.0 ± 1.5	1117 ± 57
Powdered quill	2.2 ± 0.3	10.2 ± 12	779 ± 90	3.4 ± 0.4	160 ± 9
Feather fiber	2.4 ± 0.1	5.6 ± 0.7	548 ± 82	3.2 ± 0.6	158 ± 11

All of the composites were made using 35% reinforcing and 65% matrix material with a density of 1500 g/m^2 and thickness of 3.2 mm. Data for powdered quill and feather fiber are from Refs. 6 and 20, respectively.

PP matrix that leads to relatively poor sound absorption. The higher sound absorption of the composite with 60% feather should be due to the presence of a relatively large number of sound absorbing hollow centers in the feather (quills and barbs). As can be expected, the composites with the highest amount of feathers (60%) have the highest NRC as shown in Table I.

Comparison of whole feather, feather fiber, and powdered quill composites

Table II presents a comparison of light-weight PP composites reinforced with whole feathers, feather barbs (feather fiber), and powdered quill. The whole feather reinforced PP composites have nearly thrice higher tensile strength and seven times higher tensile modulus but lower flexural strength, stiffness, and MOE compared with the PP composites reinforced with powdered quill and feather fiber composites. However, the whole feather composites have higher flexural strength and lower stiffness and MOE than the feather fiber reinforced composites. The lower stiffness and MOE of the whole feather composites compared with the feather fiber and powdered quill composites should be due to the presence of the quill in its native form that provides more flexibility to the composites. Presence of quill and the feathers in their native form also cause uneven distribution of PP leading to inferior properties compared with the powdered quill and feather fiber composites. The higher flexural strength of the whole feather composite compared with the feather fiber composite and nearly thrice higher tensile strength and seven times higher tensile modulus than the feather fiber and quill composites should also be due to the presence of the quill in its native form. Also, aspect ratio of the reinforcing materials is a critical parameter that influences the mechanical properties, especially the modulus of the composites.[19] The whole feathers used in this study had barbs (feather fibers) in the length of 1.5–4.5 cm compared with 300 μm to 13 mm for the feather fibers used in the previous study. The longer barbs in the whole feathers will provide better reinforcement and improve the properties of the composites. The high MOE of the composites reinforced with powdered quill should be due to the high modulus of the quill. Overall, the whole feather reinforced composites have flexural properties between that of feather fiber and powdered quill reinforced composites but have much higher tensile properties than both the feather fiber and quill composites.

CONCLUSIONS

This research shows that whole chicken feathers can be used to reinforce PP composites with good properties. The whole feather composites have higher flexural strength than PP reinforced with feather fibers (barbs) and much higher tensile strength and modulus than composites reinforced with powdered quill. However, the whole feather composites have lower modulus of elasticity than both feather fiber and powdered quill composites mainly due to the stiffness of the quill. The properties of the composites are not affected by the proportion of feathers but increasing the density of the composite improves both the flexural and tensile properties. Composites reinforced with whole feathers have better sound absorption and the higher the amount of feathers the better the sound absorption compared with jute fiber reinforced PP composites. Utilizing whole feathers not only provides good properties but will also eliminate the need for processing the feathers leading to lower costs. The novel method of using nonwoven webs as matrix will be suitable for other reinforcing materials in their native form to develop composites.

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