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Tensile Properties of Thermoplastic Feather Films Grafted with Different Methacrylates

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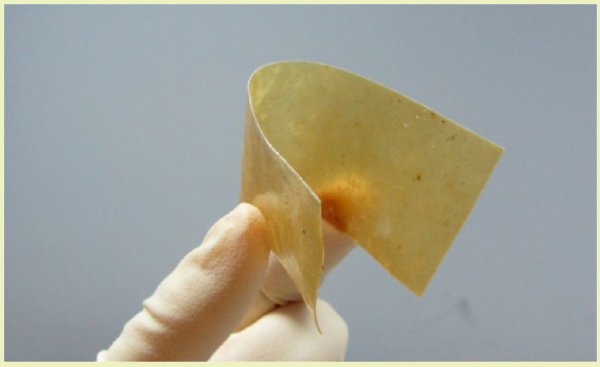
ABSTRACT: Chicken feathers grafted with four different methacrylates show good potential to be made into inexpensive and biodegradable thermoplastics with high strength, excellent flexibility, and water stability. Feathers are available in large quantities and at a low price but have limited applications. Although thermoplastics have been developed from feathers by grafting acrylates and methacrylates, limited information is available on the properties of the thermoplastics and the effects of different methacrylate structures on the properties of thermoplastics. Similarly, the role of homopolymers on the properties of thermoplastics has also not been studied. In this research, feathers were grafted with methyl, ethyl, butyl, and hexyl methacrylates (MMA, EMA, BMA, and HMA, respectively), and the effects of graft polymerization conditions, such as monomer concentrations, temperature, and time of reaction, on the grafting parameters such as monomer conversion, %homopolymer, grafting efficiency, and molar grafting ratio were studied. Methacrylates were successfully grafted onto functional groups on the surfaces of the chicken feathers. Addition of homopolymers was crucial to obtain films with good strength, elongation, and water stability. Transparent feather films with strength up to 3.8 MPa and elongation of 2.5% were developed without the use of homopolymers. Films developed were also stable at high humidities.



KEYWORDS: *Chicken feathers, Thermoplastics, Grafting, Stability, Films*

INTRODUCTION

Considerable efforts have been made to study the potential of using poultry feathers for industrial applications. Feathers are available in large quantities, have unique properties, and are inexpensive, but have limited uses and are mostly discarded in landfills. Mostly (>90%) composed of the protein keratin with a high degree of cysteine cross-linkings, feathers are difficult to dissolve and are inherently nonthermoplastic, making it difficult to process feathers into products. Traditionally, feathers have been hydrolyzed using alkali or extracted to obtain keratin for various applications.[1,2] Recently, feather keratin has been dissolved using ionic liquids that would enable developing various types of products.[3] Similarly, it has been reported that high density steam-flash explosion improves the solubility of feather keratin in various polar solvents.[4] Keratins obtained from feathers have been used in cosmetic and other industries. Studies have also been done to utilize feathers as reinforcement for composites as biopolymers for textile, medical, and other applications.[8] Attempts have also been made to hydrolyze feathers and produce films. Feathers and feather keratin were used as sizing chemicals to replace the nonbiodegradable poly(vinyl alcohol) for polyester, polyester/cotton, and cotton fabrics.[9,10]

The unique architecture, such as the hierarchical arrangement of quill, barbs, and barbules and the hollow honeycomb structures combined with low density and low cost, makes feathers highly attractive for industrial applications, especially for composites. Several studies have been done on using feather and/or parts of feathers as reinforcement for composites. Feather fibers as reinforcement were mixed with polypropylene as the matrix and made into lightweight composites for automotive applications[6] and were found to have properties similar to those of composites reinforced with jute fibers. It was also shown that whole feathers consisting of quills and barbs provided better properties for the composites compared to using quills or barbs separately.[11] Some researchers have blended feather fibers with polyethylene, extruded them in a twin screw extruder, and later compression molded them to form composites.[5] Most studies have attempted to use feathers as reinforcement and synthetic polymers as the matrix, resulting in partially degradable composites. In a unique approach, we have recently demonstrated that feathers can also be used as the

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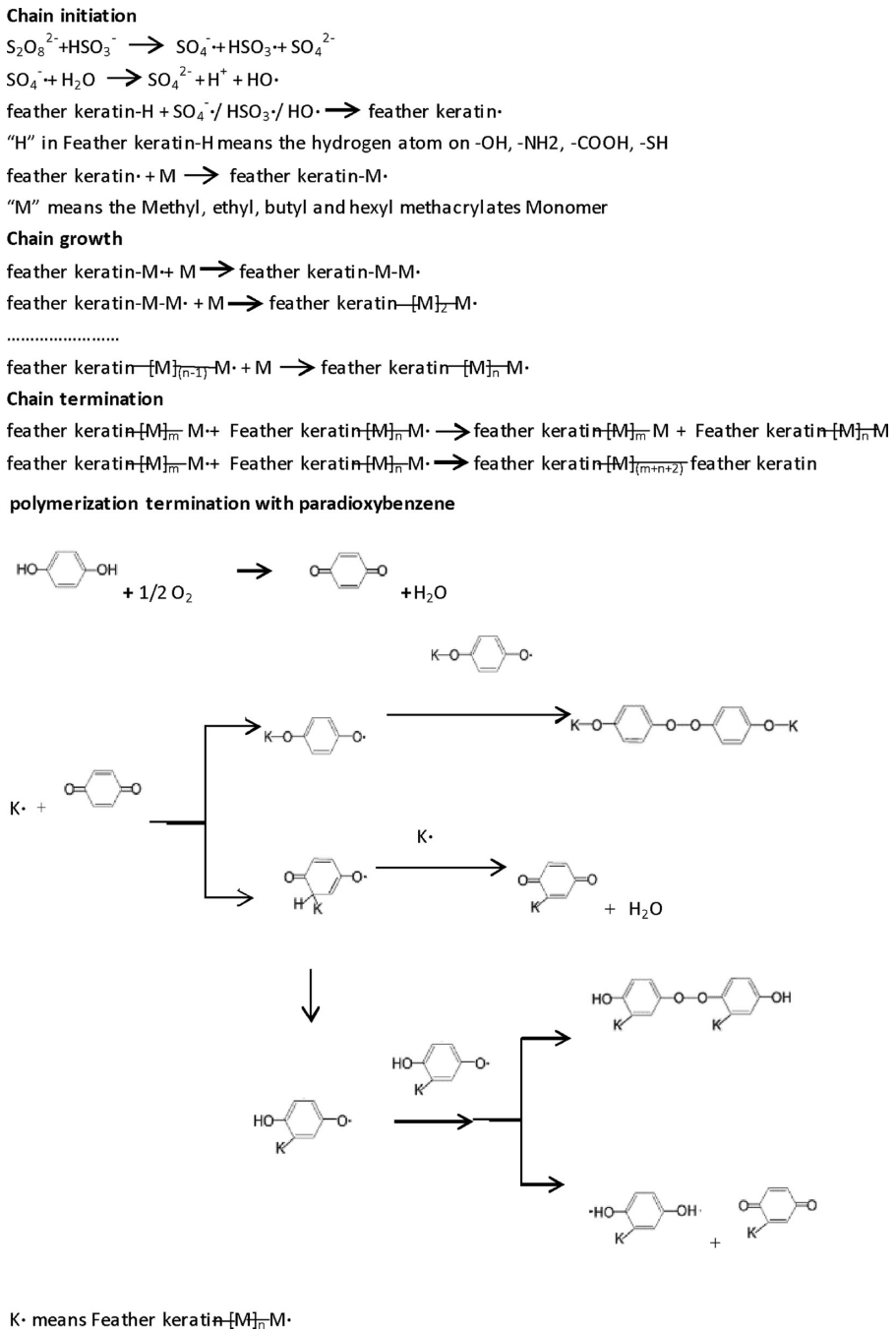
Scheme 1. Schematic of Graft Polymerization of Feather Keratin with Methyl, Ethyl, Butyl, and Hexyl Methacrylates Monomers Using the $NaHSO_3/K_2S_2O_8$ Redox System



K· means Feather keratin-[M]n-M·

matrix with traditional jute fibers as reinforcement.[12] It was found that feathers as the matrix provided similar tensile and flexural properties compared to using polypropylene as the matrix. However, feather-based composites experienced considerable strength loss when exposed to 90% humidity for 24 h. Although several reports are available on developing products from feathers, difficulties in processing feathers in native form and the inability to dissolve feathers in common solvents have restricted large-scale utilization of feathers for industrial applications.

Chemical modifications of biopolymers are common approaches for making biopolymers suitable for thermoplastic applications. Acetylation, etherification, and grafting are some of the common methods used to make biopolymers thermoplastic. Carbohydrates such as starch and cellulose and proteins such as soy proteins have been chemically modified and made into thermoplastic films. Similarly, coproducts of biofuel production such as camelina meal and corn distillers dried grains have been chemically modified and made into thermoplastic films.[13−15] Thermoplastics made from chemically modified biopolymers are shown to have good tensile properties and water stability and are suitable for various applications.

Poultry feathers have also been chemically modified and made into thermoplastics.[16] Feathers were acetylated and made into transparent thermoplastic films after compression molding

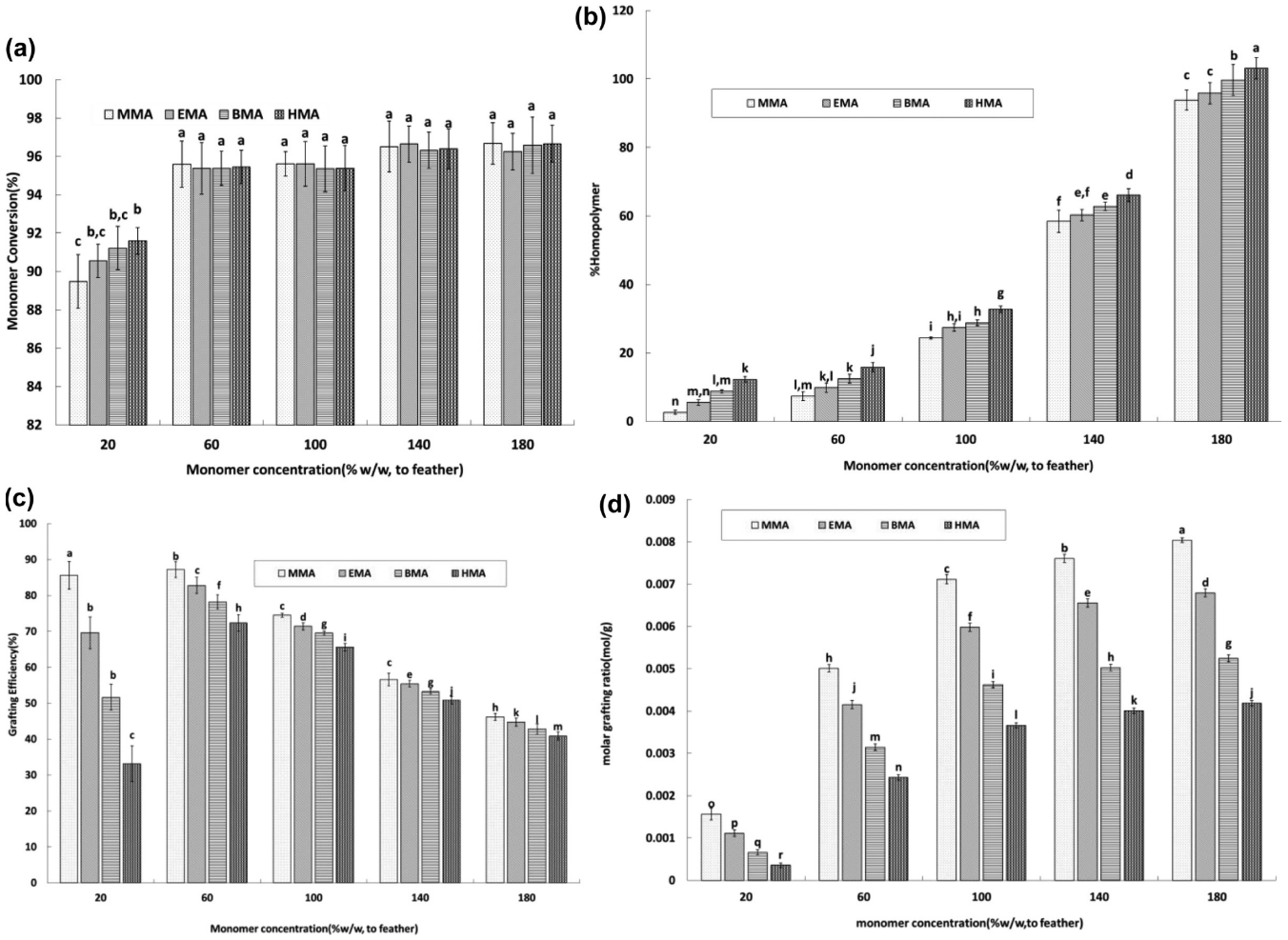


Figure 1. (a) Effect of monomer concentrations on monomer conversion for methyl, ethyl, butyl, and hexyl methacrylates. (b) Effect of monomer concentration during reaction on % homopolymer for methyl, ethyl, butyl, and hexyl methacrylates. (c) Effect of monomer concentration on grafting efficiency for methyl, ethyl, butyl, and hexyl methacrylates. (d) Effect of monomer concentrations during reaction on molar grafting ratio for methyl, ethyl, butyl, and hexyl methacrylates. Grafting reaction temperature was 60 °C. Reaction time was 1 h. Molar ratio of $K_2S_2O_8$/$NaHSO_3$ was 1.0. For each monomer, data points with different letters represent statistically significant difference.

at 170 °C for 15 min.[17] Etherification of feathers with acrylonitrile resulted in feathers that were able to melt and form films when compression molded at 180 °C for 2 min.[18] These films had tensile strengths ranging from 1.6 to 4.2 MPa and elongations ranging from 5.8% to 16.2%.[18] Acrylic monomers such as methyl acrylate and methyl, ethyl, and butyl methacrylates were grafted onto feathers to make feathers thermoplastic.[7,8] It was found that grafting made the feathers thermoplastic and able to form films that were used as scaffolds for tissue engineering. Feathers grafted with methacrylates had considerably higher strength than those grafted with acrylates. When compared to methyl acrylate (MA), butyl acrylate (BA), and butyl methacrylate (BMA), feathers grafted with methyl methacrylate (MMA) provided better dry and wet tensile properties.[8]

Although feathers have been grafted with various acrylic monomers and the grafted feathers have been made into thermoplastic films, a systematic study of the influence of the carbon chain length of the acrylic monomers on the grafting parameters, thermoplasticity of the grafted feathers, and properties of the grafted films have not been done. The type of monomer will not only affect the cost but also the properties and potential applications of the films developed. In addition, previous researches have not studied the influence of homopolymers on the tensile properties of the films obtained. Homopolymers are inevitably formed during the grafting reaction and affect the cost, grafting efficiency, and dry and wet tensile properties of the thermoplastics developed from the grafted feathers.

In this research, we have conducted a systematic study of the influence of the length of the carbon side chain in the acrylic monomers on the grafting parameters and the properties of the thermoplastic films obtained. Influences of hompolymers on the dry and wet tensile properties of the grafted feather films were also studied.

MATERIALS AND METHODS

Materials. Native chicken feather fibers were supplied by Feather Fiber Corp. (Nixa, MO). The feather fibers were cleaned (washed and treated with ethanol) and ground in a Wiley mill. Methyl, ethyl, butyl, and hexyl methacrylates, sodium bisulfite, potassium persulfate, acetone, and other chemicals required for grafting were reagent grade and used as received.

Grafting. Chicken feathers were first soaked by mixing with distilled water. Later, the mixture was transferred into a four-necked flask with the final ratio of feather to water being 1:20. Dilute hydrochloric acid was added to adjust the feather dispersion to a

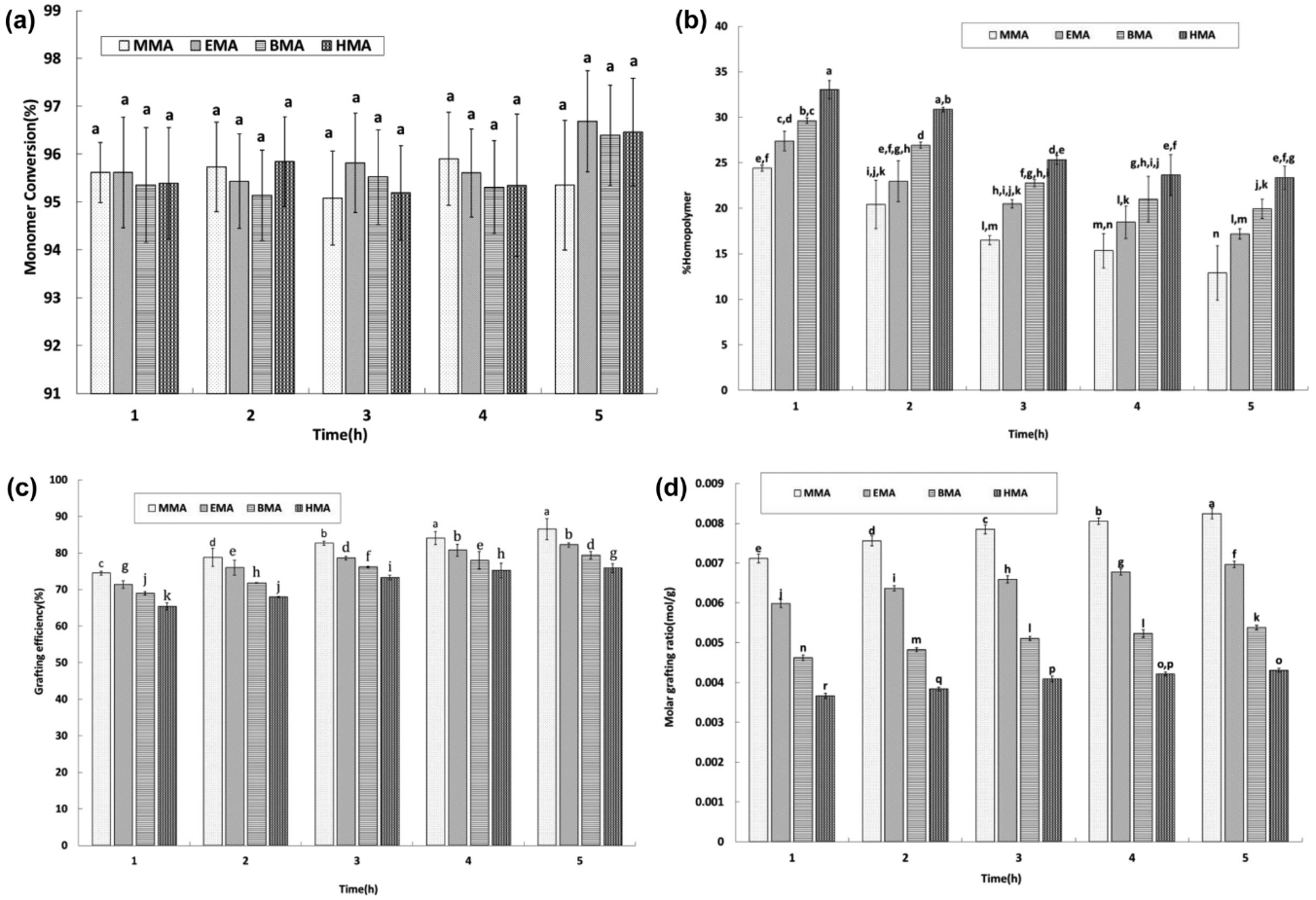


Figure 2. (a) Effect of reaction time on monomer conversion for methyl, ethyl, butyl, and hexyl methacrylates. (b) Effect of reaction time on % homopolymer for the four different methacrylates. (c) Effect of reaction time on grafting. (d) Effect of reaction time on molar grafting ratio for methyl, ethyl, butyl, and hexyl methacrylates. Grafting reaction temperature was 60 °C. Grafting reaction temperature was 60 °C. Monomer concentration was 100% (w/w, to feathers). Molar ratio of $K_2S_2O_8$/$NaHSO_3$ was 1.0. For each monomer, data points with different letters represent statistically significant difference.

desired pH (4.5−6.5), enabling the chemicals to react with the feathers. Different ratios of the monomers ranging from 20% to 180% of the weight of the feathers and initiator including oxidant (potassium persulfate) and reductant (sodium bisulfite) were added, and the flask was deoxygenated using nitrogen gas. Grafting was performed under a nitrogen atmosphere. The grafting reaction was carried out for 1 h at temperatures of 40−80 °C. Finally, 2% paradioxybenzene solution was added to terminate the polymerization. The grafted feathers were collected and first washed with water to remove any unreacted monomers and inorganic salts. After drying at 105 °C for 12 h, the grafted sample was weighed and used to determine the grafting parameters, including % grafting, grafting efficiency, % homopolymers, and molar grafting ratio as described in our previous researches.[7,8] A schematic of the grafting process using the four monomers is given in Scheme 1.

Homopolymers. The homopolymers formed during the reaction influence grafting parameters and also the tensile properties of the thermoplastics developed from the grafted polymers. To investigate the effect of the homopolymers, homopolymers formed during the grafting reaction were extracted by repeated refluxing in Soxhlet with acetone for 48 h. In a separate step, the extracted homopolymers were dissolved in acetone and 25%, 50%, or 75% of the homopolymers based on the weight of the grafted sample was added into the grafted samples. Samples containing the grafted feather and homopolymers were dried at 105 °C for 4 h to remove acetone, and the dried samples were used for compression molding.

Fourier Transform Infrared Spectroscopy (FTIR). FTIR was used to verify the grafting of methacrylates onto the feathers. The grafted feather was extracted by acetone for 48 h, ensuring the complete removal of the homopolymers from the grafted samples. Samples were placed on a diamond cell of a FTIR (model iS10; Thermo Scientific, Columbus, OH), and spectra were collected from 500 to 4000 cm^{-1} in the total attenuated reflectance mode. Each sample was scanned 32 times at a resolution of 8 cm^{-1}. Three spectra were collected for each sample, and the average of the three measurements was used to plot the spectra.

Thermal Analysis. Thermal behaviors of ungrafted feathers and grafted feathers were studied using thermogravimetric analysis (TGA). TGA was performed to determine the degradation temperature (Td) of the ungrafted and grafted samples using a Sigma T300 analyzer. Samples (5−8 mg) were heated to about 600 °C under nitrogen atmosphere. Three samples were analyzed for each condition, and the average of the three readings was used to plot the thermal behavior curves.

Compression Molding Grafted Feathers. The ungrafted and grafted feathers (with and without the homopolymers) were compression molded into films. Grafted samples were powdered on a Wiley mill to pass through a 20 mesh screen. About 10 g of feathers was placed between layers of aluminum foil and compression molded in a Carver press (Carver, Inc., Wabash, IN) between 360 and 390 °F for 10 min at 40,000 PSI to form films. After compression molding, the press was cooled by running cold water, and samples were collected for further analysis. To understand the effect of homopolymers on tensile properties and water stability, a known amount of homopolymers was added into the grafted samples and compression

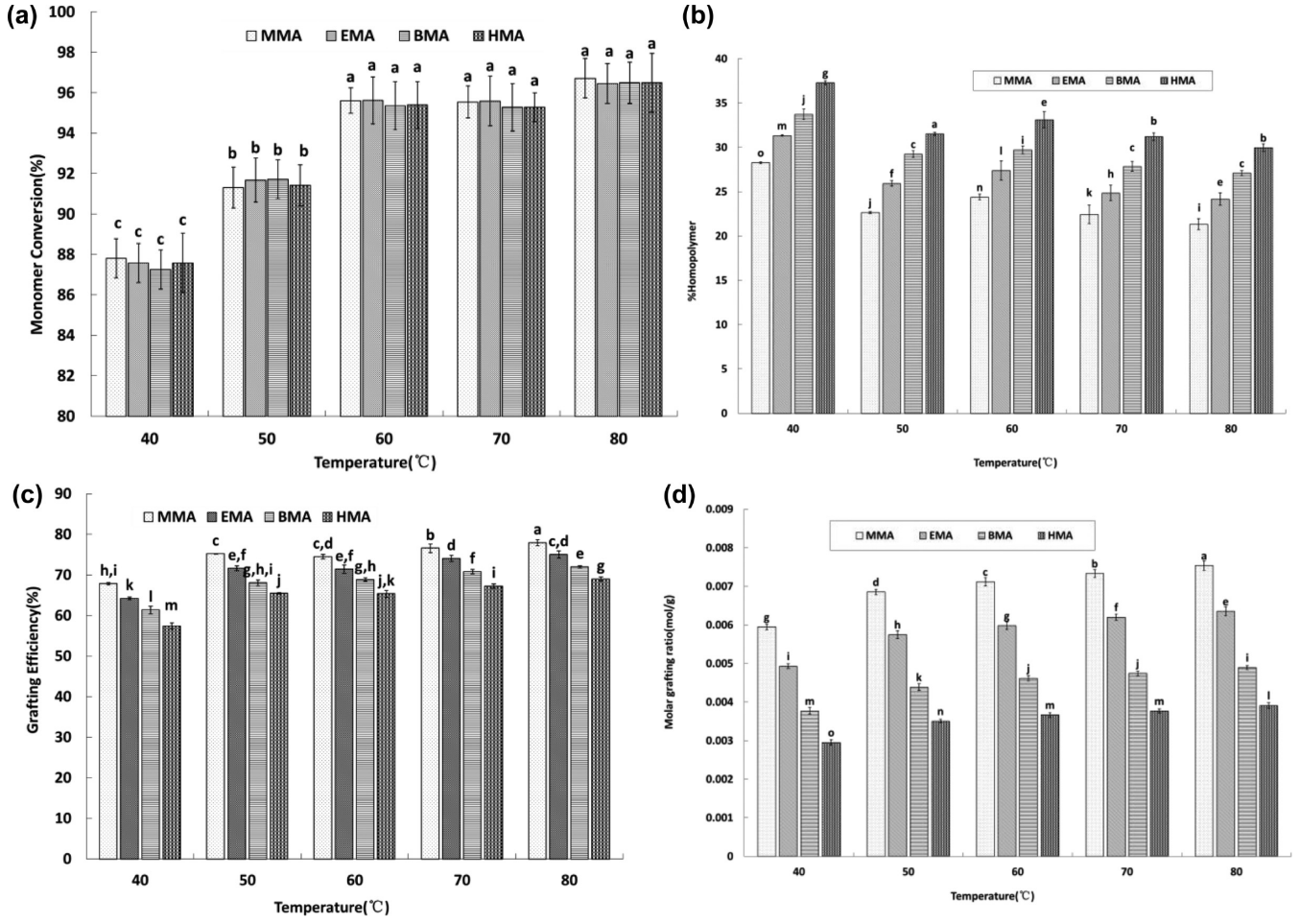


Figure 3. (a) Effect of reaction temperature on monomer conversion. Grafting reaction time was 1 h. Monomer concentration was 100% (w/w, to feathers). (b) Effect of reaction temperature on % homopolymer for methyl, ethyl, butyl, and hexyl methacrylates. (c) Effect of reaction temperature on grafting efficiency for the four different methacrylates. (d) Effect of reaction temperature on molar grafting ratio for methyl, ethyl, butyl, and hexyl methacrylates. Molar ratio of $K_2S_2O_8$/$NaHSO_3$ was 1.0. For each monomer, data points with different letters represent statistically significant difference.

molded into films as described earlier. Photographs of grafted feathers without the homopolymers were taken using a digital camera.

Tensile Testing. The grafted feathers films were cut into strips (8.0 cm × 1.5 cm) and conditioned at 65% relative humidity and 21 °C for 48 h before testing. To determine the stability of the films under high humidities, the grafted feather films were cut into strips (8.0 cm × 1.5 cm) and placed at 90% relative humidity (RH) and 21 °C for 24 h before testing.Tensile strength and breaking elongation of the films were measured on a MTS tester (model Q Test 10; MTS Corp., Eden Prairie, MN). At least 20 samples were tested for each condition, and the average and standard deviations are reported.

Statistics. The data were analyzed using SAS software. The confidence interval was set at 95% with $\alpha = 0.05$, and a p value of <5% was considered to be a statistically significant difference.

RESULTS AND DISCUSSION

Effects of Monomer Concentration. At a low monomer concentration of 20%, the % monomer conversion was considerably lower as shown in Figure 1a. Increasing the monomer concentration to 60% substantially increased the conversion to about 95% for all of the monomers. At low monomer concentration (20%), the monomers with higher chain lengths showed significantly higher conversion compared to the monomer with the smallest carbon chain (MMA). Because MMA is a smaller molecule than HMA, it is probably more mobile and has less of a chance to react with the feathers and with itself to form homopolymers and therefore has a lower % conversion.[8] Figure 1b shows that the amounts of homopolymers almost increase linearly with increases in the amount of monomers. It should also be noted that the amounts of homopolymers formed are higher for the monomers with longer chain lengths. Due to their larger size and steric hindrance to attach to the feathers, BMA and HMA have lower % monomer conversions, and higher levels of homopolymers are formed.[19] Due to these factors, the % grafting efficiency (Figure 1c) was considerably lower for the monomers with longer chain lengths as shown in Figure 1c. When the monomer concentration was 20%, the % grafting efficiency was 85% for MMA compared to 33% for HMA. This difference decreased considerably at higher monomer concentrations. The % grafting efficiency also decreased significantly with increasing monomer concentration because higher amounts of homopolymers were formed and the grafting sites on the feathers were saturated. Because the monomers with longer chains are heavier, the molar grafting ratio decreased with increasing monomer concentration. In addition to being heavier, it should also be emphasized that monomers such as HMA are difficult to be grafted due to their steric structure.[14,20] Overall, an optimum monomer concentration is necessary to avoid

excessive formation of homopolymers, obtain good grafting efficiency, and reduce grafting costs.

Effects of Grafting Time. Varying grafting time from 1 to 5 h did not show any difference in the monomer conversion as shown in Figure 2a, suggesting that 1 h was sufficient to complete the reaction and obtain high conversion. However, increasing grafting time progressively decreased the amount of homopolymers as shown in Figure 2b for all the monomers studied because the monomers had a better opportunity to react with the feathers. Grafting efficiency showed marginal increases with increasing reaction time as shown in Figure 2c. Grafting efficiency was considerably lower (65−75%) when the reaction time was 1 h compared to 75−85% at a reaction time of 5 h. The molar grafting ratio also did not show any major variation with increasing grafting time as shown in Figure 2d, indicating that most of the monomers were able to graft to the feathers within 1 h of reaction.

Effects of Grafting Temperature. Increasing the reaction temperature from 40 to 50 °C and from 50 to 60 °C substantially increased the % monomer conversion as shown in Figure 3a. At low temperatures, there is not enough energy in the system for the monomers to form polymers or react with the feathers or with themselves to form homopolymers leading to a lower conversion. It should be noted that the type of monomer did not show any effect on the monomer conversion when the temperature was varied from 40 to 80 °C. However, increasing temperature decreased the amount of homopolymers as shown in Figure 3b. At low temperatures, the feather structure would not be open, and most of the grafting would have been done on the surface leading to higher tendency for the monomers to react with themselves and form homopolymers.[12,14] Increasing temperature opens the structure of the feathers and provides more sites for the monomers to be grafted, thereby decreasing the % homopolymers formed. Monomers with longer chain lengths forming higher amounts of homopolymers should mainly be due to the steric effect and lesser chance for the monomers to be grafted onto the feathers. Increasing temperature showed a marginal increase in % grafting efficiency and molar grafting ratios for all the monomers studied as shown in Figure 3c and d, respectively.

Thermal Behavior. Grafted feathers generally had higher stability than the ungrafted feathers up to about 380 °C as shown in Figure 4. Although the degradation behavior of the feathers grafted with the four monomers were similar, MMA showed slightly better stability and HMA had the lowest stability. The steep weight loss between 380 and 520 °C is mostly likely due to the degradation of the feathers. Ungrafted and MMA-grafted feathers showed higher weight retention after heating to 600 °C, suggesting that grafting with EMA, BMA, and HMA probably damaged the feathers to a greater extent than MMA and that these monomers were relatively unstable compared to MMA.[21] Figure 5 clearly shows that the rate of degradation of the grafted and ungrafted samples was considerably different. No particular trend was observed in degradation for the four monomers grafted. However, MMA-grafted samples showed the highest degradation rate and at the lowest temperature, whereas EMA had the slowest degradation rate. Differences in the arrangement of the polymers and distribution of the grafted sites on the surface of the grafted samples probably are responsible for the differences in the rate of degradation.

Tensile Properties. A transparent and highly flexible film was compression molded from BMA-grafted films as shown in Figure 6. Tables 1 and 2 compare the tensile properties of the thermoplastic films developed from the four different monomers and containing different levels of homopolymers. When there were no homopolymers, increasing the length of the carbon chain substantially decreased the strength of the

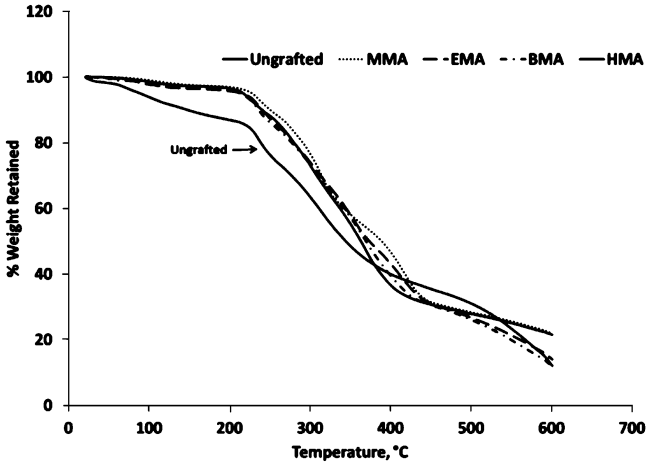


Figure 4. TGA thermograms depicting the % weight loss with increasing temperature for the ungrafted and grafted feathers without homopolymers. Grafting reaction time was 1 h. Monomer concentration was 100% (w/w, to feathers). Temperature was 60 °C. Molar ratio of $K_2S_2O_8/NaHSO_3$ was 1.0.

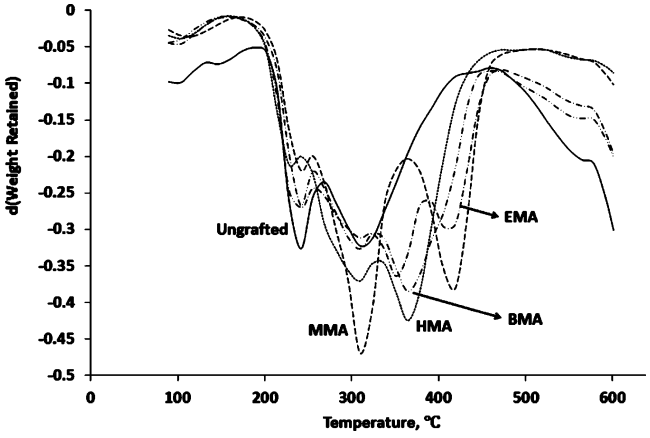


Figure 5. First derivative curves of the ungrafted and grafted samples show considerable differences in the rates of degradation.

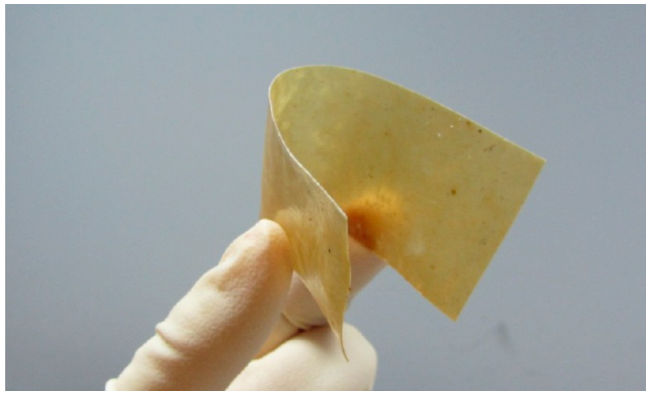


Figure 6. Digital image of a transparent and flexible thermoplastic film developed from BMA-grafted chicken feathers.

Table 1. Dry Tensile Properties of Films Made from Feathers Grafted with Methyl, Ethyl, Butyl, and Hexyl Methacrylates Containing Different Levels of % Homopolymers

	breaking stress (MPa)				breaking elongation (%)			
% homo polymers	MMA	EMA	BMA	HMA[a]	MMA	EMA	BMA	HMA
0	3.0 ± 0.7^{A}	3.8 ± 0.7^{B}	2.4 ± 0.9^{G}	1.9 ± 0.6^{G}	1.5 ± 0.4^{a}	2.3 ± 0.5^{b}	2.5 ± 0.6^{b}	2.9 ± 0.9^{b}
25	4.0 ± 0.8^{B}	4.0 ± 0.9^{B}	2.7 ± 0.8^{G}	2.3 ± 0.5^{G}	1.7 ± 0.3^{a}	2.6 ± 0.8^{b}	2.8 ± 0.8^{b}	9.4 ± 1.0^{e}
50	5.1 ± 0.9^{C}	5.2 ± 0.9^{C}	4.6 ± 0.7^{H}	2.5 ± 0.7^{G}	2.0 ± 0.4^{a,b}	2.0 ± 0.4^{b}	2.8 ± 0.9^{b}	12.4 ± 3.7^{f}
75	7.0 ± 0.7^{D}	6.9 ± 0.9^{D}	5.2 ± 0.8^{C}	2.9 ± 0.9^{G,A}	2.3 ± 0.3^{b}	2.1 ± 0.4^{b}	8.8 ± 0.5^{c}	45.5 ± 3.7^{g}
100	12.8 ± 1.0^{E}	8.5 ± 0.9^{F}	5.8 ± 0.6^{I}	3.0 ± 0.8^{A}	2.3 ± 0.3^{b}	3.4 ± 0.6^{c}	71.3 ± 5.2^{d}	111.3 ± 5.2^{h}

[a]In each column, data with different letters indicate statistically significant difference.

Table 2. Wet Tensile Properties of Films Made from Feathers Grafted with Methyl, Ethyl, Butyl, and Hexyl Methacrylates[a]

	breaking stress (MPa)				breaking elongation (%)			
% homopolymers	MMA	EMA	BMA	HMA	MMA	EMA	BMA	HMA
0	1.6 ± 0.7^{a}	1.2 ± 0.5^{f}	0.8 ± 0.2^{h}	0.7 ± 0.3^{h}	1.0 ± 0.2^{A}	2.8 ± 0.6^{C}	4.6 ± 0.7^{E}	4.9 ± 0.8^{E}
25	2.1 ± 0.8^{b}	1.7 ± 0.5^{a}	1.6 ± 0.3^{a}	1.7 ± 0.5^{a}	1.5 ± 0.2^{B}	3.0 ± 0.8^{C}	5.2 ± 0.8^{F}	19.5 ± 3.0^{I}
50	2.8 ± 0.8^{c}	2.7 ± 0.6^{c}	2.1 ± 0.9^{b}	2.0 ± 0.7^{b}	1.3 ± 0.2^{B}	2.9 ± 0.7^{C}	5.6 ± 0.8^{F}	32.4 ± 5.7^{J}
75	4.1 ± 0.8^{d}	4.8 ± 0.7^{e}	2.5 ± 0.6^{c}	2.0 ± 0.9^{b}	1.5 ± 0.1^{B}	2.4 ± 0.9^{C}	10.7 ± 0.8^{G}	65.5 ± 7.2^{K}
100	5.0 ± 1.2^{e}	5.5 ± 0.7^{g}	2.8 ± 0.4^{c}	2.5 ± 0.6^{c}	1.4 ± 0.3^{B}	3.5 ± 0.5^{D}	129 ± 3.4^{H}	145.3 ± 8.7^{L}

[a]In each column, data with different letters indicate statistically significant difference.

films and provided slightly higher elongation. This is because of the increasing thermoplasticity of the grafted samples. When the samples have lower thermoplasticity, they do not melt completely and form composites that have higher strength. Feathers grafted with monomers such as HMA that provide good thermoplasticity melt better and form films with lower strength but better elongation. In addition, the distribution of the grafted sites and polymer in the grafted sample could also significantly affect tensile properties. For instance, MMA due to its smaller size could enter into the feather, whereas BMA and HMA could be present on the surface to a large extent. Such a distribution could affect the strength and flexibility of the films. At 0% homopolymers, feathers grafted with MMA had a strength of 3 MPa compared to 1.9 MPa for HMA. For all the monomers, addition of homopolymers increased the strength and elongation although to different extents. For MMA, the increase in strength was about 70% when the films contained 50% hompolymers compared to films with 0% homopolymers. There was only about 30% increase in strength when the homopolymers were increased from 0% to 50% for HMA-grafted films mainly because the HMA hompolymer films were themselves considerably weaker than the MMA homopolymer films. However, HMA hompolymers had considerably higher elongation, and the addition of 50% HMA hompolymers increased the elongation of the films to 12.4%, higher than the elongation of the films developed from any other monomer. MMA- and EMA-grafted feathers provided films with higher strength than BMA- and HMA-grafted films without any homopolymers because the BMA- and HMA-grafted films had better thermoplasticity. MMA- and EMA-grafted films do not melt completely and therefore have higher tensile strength but lower elongation. BMA- and HMA-grafted films were considerably more transparent and flexible than the MMA- and EMA-grafted films.

Due to their higher dry strengths, feathers grafted with MMA and EMA also had higher wet strengths compared to BMA and HMA as shown in Table 2. The addition of homopolymers substantially increased the wet strength of the films grafted with all the monomers, although the homopolymers themselves were considerably weaker when wet, except for HMA. Elongation of the films generally increased when wet because the molecules moved easily when water acted as a lubricant. On the basis of the results in Table 2, it is evident (at 50% homopolymer content, 80% strength retention for HMA compared to 46−55% for the other samples) that HMA provides better wet strength retention for the films than the other monomers because HMA is more hydrophobic than MMA or EMA. HMA provided low dry strength but good elongation and strength retention when wet. This indicated that HMA had better thermoplasticity than the other monomers. Because the tensile properties in Tables 1 and 2 are compared at the same % grafting ratios, it may be possible to have feathers grafted with lower levels of HMA and obtain higher tensile properties. Similarly, copolymerization of MMA and HMA may be done to obtain films with the desired properties. Compared to previous researches on developing thermoplastic films from grafted feathers, the films obtained in this research have better elongation and water stability.[8] In addition, glycerol was not used to plasticize the films in this research.

CONCLUSIONS

Grafting of methacrylates is an effective way to develop thermoplastics from feathers with good dry and wet tensile properties. Grafting parameters, especially monomer concentration, play important roles in determining the monomer conversion and molar grafting ratio. A grafting temperature of 60 °C, feather to monomer ratio of 1 to 0.6 and grafting time of 1 h provided optimum grafting efficiency. With increasing alkyl chain length, the % grafting decreased and % homopolymer increased. The grafted feathers showed lower strength but higher elongation with increasing alkyl chain lengths. The films developed from grafted feathers have good dry and wet tensile properties. Therefore, feathers grafted with methacrylates could be useful to develop thermoplastics for commercial applications.

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Notes

The authors declare no competing financial interest.

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