Mechanical analysis of elasticity and flexibility of virgin and polymer-treated hair fiber assemblies

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Synopsis

The elasticity and flexibility of virgin and polymer-treated hair fiber assemblies were investigated by employing straight hair tresses or hair shaped into omega loops. Polymer treatment was accomplished by saturating fibers with polymeric solutions, resulting in a deposition of 10–90 mg of polymer per gram of hair. The mechanical testing procedure consisted of subjecting omega-loop-shaped hair or straight hair tresses to multiple bending deformations at 25% strain in a texture analyzer. A total of ten deformations were typically carried out, and elasticity or flexibility parameters were evaluated from data such as (a) the force at 8% deformation, i.e., within the elastic region of bending deformation for hair shaped into an omega loop, (b) maximum force in the first (F₁) and tenth (F₁₀) deformation cycles, (c) elastic modulus in the first (E₁) and tenth (E₁₀) deformation cycles, and (d) the change in hair sample dimensions between the first (H₁) and tenth (H₁₀) deformation cycles. Parameters such as stiffness ratio (₁), F₁₀/F₁, E₁₀/E₁, and H₁₀/H₁ were employed to characterize hair tress rigidity, flexibility or resistance to breakage, and plasticity. Untreated hair was found to be almost perfectly elastic and flexible at 50% RH, evident by the linear dependence of force vs deformation. Flexibility parameters F₁₀/F₁, E₁₀/E₁, and H₁₀/H₁ were in the range of 0.95 to 1.0 at low humidity, while the parameters F₁₀/F₁ and E₁₀/E₁ and were 10% lower at 90% RH. Examination of polymer-modified hair allowed for classification of treatments into categories termed brittle, quite flexible and nonplastic, flexible and plastic, very flexible and very plastic, and very flexible and nonplastic. Poly-(vinyl pyrrolidone) is shown as an example of a quite flexible and nonplastic material, with its flexibility and stiffness dependent upon its molecular weight. The effect of plasticizers on polymer behavior is also discussed.

INTRODUCTION

Elasticity is commonly defined in relation to solid objects as their ability to recover size or shape after deformation. In scientific terms, elasticity implies a linear relationship between the stress (or force) and strain (deformation distance) measured in a sample. A similar term, sometimes used in relation to the mechanical properties of materials is resiliency, which implies free return to a previous position, shape, or condition after deformation. It also describes a material capable of withstanding shock without permanent deformation or rupture. Another term frequently employed to describe mechanical properties is flexibility. According to a dictionary definition, it describes an object that is capable of being flexed, turned, bowed, or twisted without breaking. It may also be characterized by plasticity, which suggests that the material can undergo an irre-
versible change in physical dimensions analogous to the process encountered in molding. Similarly, plasticity is synonymous with pliancy, a term that implies bending or folding with ease.

All of these polymeric properties have been the recent focus of hairspray and styling product manufacturers, who stress a new consumer preference for highly elastic and flexible materials rather than traditional resins characterized by a large degree of stiffness. The elastic/flexible fixatives are advertised as being capable of stabilizing a hairset without making hair feel stiff or rigid, and maintaining the style even after “movement,” i.e., deformation produced by grooming, bodily motion, wind, etc.

The objective of this analysis was to explore the basic mechanical properties of untreated and polymer-modified hair by analyzing stress-strain relationships of bending in multiple deformations. We have explored compression and bending as modes of deformation and have defined and determined parameters related to stiffness, elasticity, flexibility, and plasticity of the fiber assemblies. It should be stressed that while elongation (stretching) or torsion analysis of the mechanical properties of single hair fibers has been discussed in detail (3–5), the bending deformation, especially in the context of multiple fiber assemblies, has not been discussed previously. In this work, a texture analyzer was employed as a tensile meter with the experimental procedure involving the use of hair shaped into “omega loops” (1). Alternatively, hair tresses have also been employed in combination with a three-point bending apparatus (6). Our earlier stiffness measurements of “omega loops” for untreated and treated hair consisted of compressions at low deformations (1 mm penetration—8% of the omega loop height) corresponding to the elastic region of a given stress-strain curve (1). The experimental procedure employed in this work involved the use of a relatively high bending deformation (25%), which produces irreversible changes in the investigated samples as a result of polymer breakage or plastic deformation. Our objective was also to explore factors affecting the elasticity/flexibility of fixative systems, such as the thermomechanical properties of a polymer (glass transition), its molecular weight, and the polymer’s behavior in the presence of low-molecular-weight additives. Throughout the text, we may refer to hair, when in fact this implies the use of hair fiber assemblies in the form of omega-loop-shaped or straight hair tresses.

EXPERIMENTAL

HAIR SAMPLES

Experiments were performed on light brown Caucasian, dark brown Caucasian, Chinese, natural white, and yak hair purchased from International Hair Importers & Products, Inc., Valhalla, NY. All fibers were shampooed twice with ammonium laureth-2 sulfate prior to use in the experiments. Preparation of “omega loops” has been described previously (1). Tresses, employed in the dual cantilever bending experiments, were obtained by gluing hair to plastic tabs, resulting in dimensions of one inch in width and 6.5 inches in length.

POLYMERS AND SURFACTANTS

The samples of poly(vinyl pyrrolidone) were commercial grade products, termed PVP K12 (M_w = 4,000), PVP K15 (M_w = 8,000), PVP K30 (M_w = 60,000), PVP K60


METHODS OF ANALYSIS

Stiffness, elasticity, and flexibility by omega-loop bending. The instrumentation and experimental procedures were similar to those employed in a previous work (1) (Figure 2). Hair treatment was administered by application of a hairspray solution to hair shaped into omega loops, using an Eppendorf pipette. The deposited amount (0.15 g of a hairspray solution per 0.2 g of hair sample) was uniformly distributed over the tress surface.
thoroughly saturating the fibers between the plastic tabs. In order to preserve the circular shape of the omega loops, teflon-coated cylindrical rods were inserted into the loops prior to treatment with the hairspray solution. The hair samples were allowed to dry overnight under conditions of 50% RH and 70°F prior to measurement with a texture analyzer (Model TA-XT2, Texture Technologies Corporation). The texture analyzer has a load sensitivity of 0.1 g and was operated using XTRA dimension software 3.7 from Stable Micro Systems. In addition, humidity resistance measurements were carried out at 90% RH by monitoring the variation of maximum force in each deformation cycle as a function of time for 80 minutes.

A typical experimental trace, portraying force as a function of time, is presented in Figure 3. It shows a series of peaks, each corresponding to one deformation cycle of an omega loop. Flexibility measurements are typically carried out at large deformations of the omega loops. In this work we employed 4-mm deformations, which correspond to a 25% reduction in loop height. It is evident that the maximum force corresponding to the first peak, \( F_1 \), is reduced as a result of the first and subsequent deformations, to eventually reach a value of \( F_{10} \) after ten deformation cycles. The ratio of \( F_{10}/F_1 \) is used as a measure of flexibility for untreated and/or polymer-treated hair assemblies. For polymer-treated hair this ratio reflects the extent of interfiber bond breakage as a result of mechanical deformation of the loops. The same experimental data can be displayed in the form of penetration distance, \( H \), as a function of time, with \( H_{10} \) and \( H_1 \) representing the deformation distance of an omega loop in the first and tenth deformations, respectively (Figure 4). Both distances refer to the original height of the omega loop at time zero of the experiment. This point is automatically established by the instrument when it detects a trigger force equal to 2 grams in the first deformation. In each bending, the deformation distance is constant and equal to 4 mm; however, the reference point (i.e.,
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Figure 3. A typical experimental trace of force as a function of time obtained in a dynamic hairspray analysis experiment. $F_1$, $F_{10}$ = maximum values of force in the first and tenth deformations.

Figure 4. A typical experimental trace of distance as a function of time obtained in a dynamic hairspray analysis experiment. $H_1$, $H_{10}$ = loop height in the first and tenth deformations.

the top of the loop prior to any deformations) is decreased for hair treated with a plastic (flowable) material due to a reduction in the height of the loop. Moreover, $H_1$ is 4 mm while $H_{10}$ will be 4 mm plus the distance resulting from the omega loop geometry change. The ratio, denoted as $H_{10}/H_1$, and calculated as $[(2H_1-H_{10})/H_1]$, is employed in this work to characterize sample plasticity. This parameter scales from 1, corresponding to the case of no change in sample dimensions (no plasticity, $H_{10}=H_1$), and zero, which corresponds to doubling of the deformation ($2H_1=H_{10}$). Finally, experimental
data can also be presented in a plot of force as a function of distance, as shown in Figure 5, for the first deformation (a) and the first ten consecutive deformation cycles (b). The data in these figures correspond to a brittle polymer, discussed later in the text, characterized by an elastic response in the deformation range of 0 to 1 mm. It is in this deformation range that we calculate the ratio of modulae, $E_{10}/E_1$ {modulus is calculated as the slope for the dependence of Force=f(distance) in the linear portion of the curve}, which can be used as a measure of sample (hair treated with a polymer) flexibility. As illustrated by the curves in Figure 5, at a deformation of about 2 mm in the first cycle, the polymer bonds between fibers break, resulting in a reduction of maximum force (F) and modulus (E) in subsequent deformations.

**Stiffness, elasticity, and flexibility by three-point bending of straight hair.** Three-point bending measurements were conducted utilizing a texture analyzer equipped with an accessory shown schematically in Figure 6. In a typical experiment, a hair tress is fastened to a clamp and rests on cantilevers (II and III). The actual testing protocol consists of the following sequence of steps: the probe (I) comes down, touches the hair sample, and when it detects a 2.0 G force, performs a 3-mm, 5-mm, or 10-mm deformation of the fiber assembly. Then it returns to a control height over the sample and repeats the cycle, typically for a total of ten deformations. The final result is a plot of force as a function of time or distance, which can be employed to calculate various mechanical parameters such as $F_1, F(1 \text{ mm}), F_{10}/F_1, E_{10}/E_1$, and $H_{10}/H_1$.

![Figure 5](image_url)  
**Figure 5.** A typical experimental trace of force as a function of distance obtained in a dynamic hairspray analysis experiment. $E_1, E_{10} =$ elastic modulus (slope) in the first and tenth deformations.
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RESULTS AND DISCUSSION

ANALYSIS OF UNTREATED HAIR

Figures 7a and 7b present the experimental traces of multiple deformations of untreated hair at 50% and 90% relative humidity using the omega loop technique. The results of the calculations for various parameters, i.e., $F_1$, $F_{10}/F_{1}$, $E_{10}/E_{1}$, and $H_{10}/H_{1}$, for different types of hair are collected in Table I. The curves shown in Figure 7a

![Figure 7a](a) 50% RH

![Figure 7b](b) 90% RH

Figure 7. Experimental traces of multiple deformations of untreated hair at (a) 50% and (b) 90% RH.
Table I
Flexibility Parameters for Various Types of Untreated Hair at 50% and 90% Relative Humidity

<table>
<thead>
<tr>
<th>Sample</th>
<th>F₁₀/F₁</th>
<th>E₁₀/E₁</th>
<th>H₁₀/H₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caucasian hair</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>50% RH</td>
<td>1.01 ± 0.01</td>
<td>0.96 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>90% RH</td>
<td>1.01 ± 0.01</td>
<td>0.96 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Chinese hair</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% RH</td>
<td>0.97 ± 0.02</td>
<td>0.97 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>90% RH</td>
<td>0.97 ± 0.01</td>
<td>0.97 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Yak hair</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% RH</td>
<td>0.94 ± 0.03</td>
<td>0.94 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>90% RH</td>
<td>0.94 ± 0.03</td>
<td>0.94 ± 0.03</td>
<td></td>
</tr>
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illustrate a nearly linear response to deformation of hair bundles at 50% RH. Also, there is only a small difference in the ascending and descending portions of the curves, which can be related to the process of shape recovery of the sample after the stress is removed in a deformation cycle (sample creep). The shape of the curves obtained at 50% RH suggests that the process of shape recovery is fast and that each deformation cycle starts and ends with only a small shift between the curves. The calculated parameters also indicate nearly perfect elasticity of untreated hair at low humidity with the values of F₁₀/F₁, E₁₀/E₁, and H₁₀/H₁ in the range of 0.95 to 1.0. In contrast to this, the results for untreated hair at 90% RH show a considerable shift between consecutive deformation curves, suggesting a slower shape recovery due to the increased level of moisture in hair. It should be noted, however, that there is no shift between the curves along the distance axis at zero force, signifying that hair has no plasticity under these conditions. These conclusions are further supported by calculated parameters, presented in Table I, which show approximately a 10% reduction in F₁₀/F₁ and E₁₀/E₁, and no change in H₁₀/H₁, as compared to hair at 50% RH.

We have also examined stress relaxation curves for various types of hair subjected to a stress corresponding to 50 G of force at 50% and 90% relative humidity. In the case of 50% humidity, the extent of force relaxation is about 26% after 4500 s, and the process continues beyond this time limit at a very slow rate. For 90% RH, the process of stress relaxation proceeds at a faster rate and reaches a limiting value of 50% conversion after 1000 s of elapsed time. The value of force relaxation remains unchanged even after 4500 s. A more detailed analysis of stress relaxation in hair assemblies will be given in a subsequent paper.

Similar results, in terms of multiple deformation plots and calculated parameters (F₁₀/F₁, E₁₀/E₁, and H₁₀/H₁), were obtained by studying hair tresses subjected to three-point bending deformations. A representative experimental trace for Caucasian hair is shown in Figure 8. The data suggest an evolvement of only small forces, with the F₁₀/F₁ and E₁₀/E₁ parameters showing a small increase while H₁₀/H₁ displays a significant decrease as compared to the ideal value of 1.0. The results imply higher fiber packing as a result of multiple bending deformations, leading to an increase in bending forces and modulae. In addition to this, a reduction in H₁₀/H₁ is probably related to an irreversible change in the sample shape as a result of position shifting of individual fibers in a given hair tress.
TYPES OF MECHANICAL BEHAVIOR OF POLYMER-TREATED HAIR

In contrast to untreated hair, polymer-modified hair tresses generally show irreversible deformations, with a gradual loss of stiffness as a result of the breakage of fiber–polymer–fiber bonds. Various types of behavior for polymer-modified hair are illustrated by the force-vs-distance curves presented in Figure 9. The key distinguishing features are (i) the shape of the plot obtained in the first deformation, (ii) the shift between consecutive deformations along the distance axis, (iii) the values of parameters $F_{10}/F_1$, $E_{10}/E_1$, $H_{10}/H_1$, $F_1$, and $F(1\,\text{mm})$, and (iv) the relaxation times estimated from the shape recovery of an omega loop. Figure 9a portrays the behavior of a brittle polymer, which, as discussed above, shows an elastic and reversible force-deformation profile in the distance range from 0 to 1 mm. The shape of the profile at greater deformation distances suggests breakage of the polymer–polymer or fiber–polymer bonds and a decrease in deformation force. After the first deformation, there is only a small reduction in $F$ values in consecutive cycles, together with a very small shift in the deformation loops, suggesting low plasticity and fast shape recovery (slow stress relaxation). Figure 9b shows...
the plot of force-vs-distance for a polymer termed as "quite flexible and nonplastic." The data indicate a smooth force-vs-distance curve, with little indication for the breakage of polymer bonds between the fibers. In addition to this, a small shift in the consecutive deformation curves along the distance axis suggests low plasticity and relatively fast shape recovery (slow stress relaxation). Figures 9c (acrylates dimethicone copolymer) and 9d (Polymer 1) illustrate the behavior of polymers deposited on the hair that are characterized as flexible and plastic. Both systems are characterized by very high values for the ratios $F_{10}/F_1$ and $E_{10}/E_1$ and relatively low values for the $H_{10}/H_1$ parameter. The deformation curves are shifted along the distance axis, suggesting permanent deformation of hair shape as a result of applied stress. The results also suggest that the stress relaxation is relatively fast while shape recovery (creep) is slow.

It should be emphasized that Figure 9c presents the results of stress-strain analysis for a commercial formulation based on acrylates dimethicone copolymer. The system is termed flexible in the label claim. Indeed, the force increase as a function of distance in the first deformation is given by a monotoneous S-like curve, with only a few shallow dents suggesting possible scissions of polymer-fiber bonds. The subsequent stress-strain cycles produced curves shifted relative to each other by a fraction of a millimeter, suggesting the existence of stress-induced plastic flow resulting in permanent deforma-
tion of the omega loop. Thus, the calculated change in hair loop height after ten deformations is relatively large and amounted to $H_{10}/H_1 = 0.81$. On the other hand, this system provides a good retention of modulus and maximum force with the corresponding parameters of $F_{10}/F_1$ and $E_{10}/E_1$ assuming the values of 0.85 and 0.39, respectively.

The last plot in this series, Figure 9e, illustrates the behavior of a very flexible polymer (Polymer 2) with relatively fast shape recovery kinetics, although not as fast as the polymer treatments presented in Figures 9a and 9b. In this case, the compression of a hair loop produces a smooth deformation curve. A subsequent decrease in stress leaves the sample squashed, with its original shape recovering almost completely within 10 seconds (the time it takes the instrument probe to cycle above the sample). As a result, the sample recovers its shape almost completely (except in the second deformation) and every new deformation cycle starts from the same point.

In general, similar conclusions can be drawn from the analysis of hair tresses treated with polymer solutions (by spraying) and subjected to three-point bending experiments. Figure 10a presents the behavior of hair treated with a brittle polymer (as in Figure 9a), while Figure 10b refers to the same experiment; however, in this case the hair is modified with a low $T_g$ fixative (as in Figure 9c). The plot in Figure 10a clearly demonstrates the brittle character of the polymer treatment. Since the stiffness of this hairset is also very high, corresponding to a maximum force value of about 300 G, the effect of the polymer can be described as “hard, stiff, nonflexible, crispy, and brittle.” On the other hand, analysis of hair treated with a low $T_g$ polymer shows smooth deformation curves progressively extending over larger distances, in effect providing evidence of a relatively minor contribution to plasticity. This polymer can be described as soft (maximum force is about 110 G) and flexible.

![Figure 10](image_url)

Figure 10. Results of three-point bending experiments for (a) hair treated with a brittle polymer and (b) hair modified with a flexible, low $T_g$, fixative. The initial distance of deformation was 5 mm.
EFFECT OF MOLECULAR WEIGHT

Figure 11 presents the force-distance curves for hair treated with PVP solutions at a concentration of 2% w/w and at various molecular weights of the polymer. Low-molecular-weight PVP K12 demonstrates the behavior of a brittle polymer. The first deformation curve contains a linear portion extending from 0 to 1 mm deformation followed by a nonlinear region (from about 1 mm to 4 mm deformation), characterized by a general decrease in force, with superimposed local variations in the form of peaks and valleys. They probably indicate instability in fiber–polymer structure and the stress-induced scission of interfiber polymer linkages. It should also be noted that the maximum force values in the first and tenth deformations were 217.5 G and 148.8 G, respectively. Thus, the percentage stiffness loss was 32%. The change in the modulus of the loop, calculated from the linear portions of force-vs-distance curves, was much larger and amounted to a value of 0.19 for the ratio $E_{10}/E_1$, corresponding to an 81% decrease. The corresponding change in the loop shape was relatively small, resulting in a 7% loss of the loop height after ten deformations, suggesting low plasticity for PVP K12.

An increase in the molecular weight of PVP leads to much more resilient materials. For example, Figure 11d presents the force-distance curves for the higher-molecular-weight analog, PVP K60. In this case, the range of elastic deformation extends to nearly 450 G, followed by a nonlinear increase of force as a function of distance, with local variations.

Figure 11. Effect of molecular weight on the mechanical properties of hair treated with PVP.
indicating some breakage of polymer–hair bonds. The maximum force values in the first and tenth deformations were 596 G and 521 G, respectively, yielding a stiffness loss of about 13%. The modulus loss was larger and resulted in a value of 0.33 for the ratio $E_{10}/E_1$, a 67% decrease. Similar to PVP K12, the change in the dimensions of the hair loop after ten deformations was very small (7%).

Figures 12a–12d present the plots of various mechanical parameters of PVP as a function of molecular weight. They illustrate (i) a large increase in stiffness, as indicated by the maximum in the force-vs-distance curves (a similar although not as pronounced increase in stiffness ratio, i.e., force measured at 1 mm deformation and standardized to untreated hair) (Figure 12a), (ii) an increase of both ratios $F_{10,\text{max}}/F_1,\text{max}$ and $E_{10}/E_1$ as a function of molecular weight (Figures 12b and 12c), and (iii) only a small change in the dimensions of the hair loop treated with a polymer with no dependence on the polymer’s molecular weight, as reflected by the ratio $H_{10}/H_1$, (Figure 12d). Such results suggest that PVP becomes stiffer, more elastic, and more flexible with an increase in its molecular weight. The data also indicate that the elimination of bond breakage and a consequent increase in flexibility occurs without plastic flow of the material, which could inadvertently lead to an irreversible change in the size or shape of the investigated hair loops.

**EFFECT OF POLYMER PLASTICIZERS**

It is also of interest to study the effect of plasticizers on the mechanical properties of hair modified with relatively brittle polymers. Both employed polymers, ethyl ester of PVM/MA copolymer (PVM/MA) and isobutylene/ethylmaleimide/hydroxyethylmaleimide copolymer (IEHC) (Figure 1), are characterized by glass transitions of 102°C and 100°C, respectively. Thus, both hairspray resins are in the glassy state. In addition to this, they are characterized by relatively low molecular weights (ranging from 60,000 dl/g to 80,000 dl/g) and viscosities. These resins were designed for low-VOC aerosol and pump hairsprays and produce fine spray patterns in EtOH or EtOH-water solutions at polymer concentrations in the range from 3% w/w to 6% w/w.

Figures 13a and 14a present the deformation curves obtained for hair treated with IEHC and PVM/MA, respectively. Both polymers display mechanical characteristics intermediate between brittle/nonplastic and quite flexible/nonplastic according to the classification presented in Figure 9. Also, the calculated parameters, $F_{10}/F_1, E_{10}/E_1$, and $H_{10}/H_1$, suggest only a small degree of conservation of maximum force and modulus after multiple deformations as well as low plasticity. For comparison, Figures 13b and 14b show the deformation curves of hair treated with the same polymers containing 41% oleth-10 as a plasticizer. Such a solid film composition is obtained by employing solutions containing 5.71% polymer and 4% of the plasticizer. The glass transition of a polymer blend of PVM/MA (59%)-oleth-10 (41%) was found to be -17°C by differential scanning calorimetry, indicating that such a polymer system is in the rubbery state (8). From the mechanical results, it is evident that both polymer systems become plastic as a result of the addition of a nonionic surfactant as suggested by a shift between subsequent deformation loops along the distance axis. The shift is clearly more pronounced for the ethyl ester of PVM/MA copolymer–oleth-10 system, with a significant proportion of the change in the shape of the loop recovering from deformation.
Figure 12. (a) $F_1$ and $F_{10}$, (b) $F_{10}/F_1$, (c) $E_{10}/E_1$, and (d) $H_{10}/H_1$ as a function of molecular weight for PVP.
within ten seconds of the relaxation time (the time span between consecutive deformation cycles).

Another observation concerns the variation in the ratios of $F_{10}/F_1$ and $E_{10}/E_1$ for brittle and plasticized polymers. In general, one could expect an increase in both parameters for more flexible polymers, as was reported for a series of materials presented in Figures 9a–9e. In contrast to this, for both plasticized IEHC and ethyl ester of PVM/MA copolymer (Figures 12b and 13b), a decrease in the ratios $F_{10}/F_1$ and $E_{10}/E_1$ is evident. This result indicates that a significant energy loss in such systems occurs through plastic flow, which is facilitated by the presence of a low-molecular-weight additive at a high concentration that decreases the $T_g$ below room temperature. Further details concerning the dependence of $F_{10}/F_1$, $E_{10}/E_1$, and $H_{10}/H_1$ as a function of composition were investigated for systems comprised of dimethicone copolylols and oleth-10. The results, not shown in this paper, confirmed a decrease in the values of all three parameters for both blends in the concentration range from 2% to 4% of the plasticizer.

CONCLUSIONS

Mechanical properties of hair fiber assemblies have been measured by (a) compression of omega loops and (b) three-point bending of hair tresses. The results from both experimental procedures were found to be qualitatively similar for both untreated and polymer-treated hair tresses. For untreated tresses, humidity was found to significantly affect the properties of hair in terms of bending forces after multiple deformations. The
calculated parameters showed nearly perfect elasticity for untreated hair tresses at low humidity, with mechanical curves of force-vs-deformation being almost linear and virtually coinciding in repeated deformation cycles. Additional experiments suggested a relatively slow stress relaxation process at 50% RH. At 90% RH, there was a considerable shift between consecutive deformation curves, suggesting faster stress relaxation due to the increased level of moisture in hair, presumably due to higher mobility of the protein chains. These conclusions were further supported by calculated parameters obtained for experiments conducted at 90% RH. They showed an approximately 10% reduction in the flexibility parameters $F_{10}/F_1$ and $E_{10}/E_1$, and no change in the plasticity index $H_{10}/H_1$ as compared to hair at 50% RH.

For polymer-treated hair, we have compared the mechanical behavior of a number of different polymers ranging from brittle to flexible. Based on plots of force-vs-deformation for multiple deformation cycles, the polymers were classified as brittle and nonplastic, quite flexible and nonplastic, flexible and plastic, very flexible and very plastic, and very flexible and nonplastic. Furthermore, we have quantitatively characterized each mechanical behavior with the parameters $F_{10}/F_1$, $E_{10}/E_1$, and $H_{10}/H_1$. The polymers that were found to be very flexible and very plastic as well as very flexible and non-plastic had a glass transition, $T_g$, below room temperature. It was also shown that the mechanical characteristics of a model polymer, poly(vinyl pyrrolidone), depends on the molecular weight. Low-molecular-weight PVP was shown to be brittle and not very stiff. However, an increase in the molecular weight of PVP was coupled with greater stiffness and flexibility, as evident from force-vs-strain relationships and from the calculated values of flexibility parameters. Although the results are not presented in this paper, similar characteristics are displayed by copolymers of vinyl pyrrolidone such as
vinyl pyrrolidone/DMAPMA copolymer or vinyl pyrrolidone/DMAPMA\textsuperscript{+}-
\(C_{12}H_{25}\) Cl\textsuperscript{\Theta} (Polyquaternium-55).

Finally, the measurements of hair tresses treated with plasticized resins have demonstrated a transition from a brittle polymer to a flexible and plastic system. Such an effect is produced by the addition of a relatively high proportion of surfactants (such as oleth-10 or dimethicone copolyol) to polymers characterized by a glass transition of about 100°C such as ethyl ester of PVM/MA copolymer (PVM/MA) and isobutylene/ethylmaleimide/hydroxyethylmaleimide copolymer (IEHC).

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