Correlating Porosity and Tensile Strength of Chemically Modified Hair

Ali N. Syed and Hasan Ayoub
Avlon Industries, Inc., Bedford Park, Illinois USA

Key words
hair porosity, hair tensile strength, hair damage, permanent hair colors, avid permanent waves, hair relaxers, hair bleaches

Abstract
This study validates the porosity method against the widely accepted method of tensile strength for determining the hair damage imparted to hair due to cosmetic treatments.

Over the years, many individual studies have been conducted regarding the extent of damage imparted to hair. These studies deal with the damaging effects of various chemical processes such as permanent waves, permanent colors and hair bleaches.[1-8]

The most commonly employed method to quantify this damage is the measurement of change in tensile properties of the hair. This method takes two to three days in the preparation of samples of hair fibers. It also requires a minimum of 30 to 40 fibers for statistical analysis. Therefore, there is a need for other simpler methods that are equally valid and less time-consuming.

One such method could be the determination of hair porosity or water uptake of hair fibers as described by Valko et al.[9] and by Menkart et al.[1] However, to the best of our knowledge, no study so far has correlated the tensile strength method with the water uptake (swelling/porosity) method following chemical treatments such as permanent waves, permanent colors, hair bleach, and permanent hair relaxers.

Therefore, we have conducted a study whose purpose was to validate the porosity method against the tensile strength method. Another purpose of this study was to use these two methods to compare the magnitude of hair damage between permanent waving, permanent coloring, hair bleaching, and permanent straightening processes. Finally, this study ranked the various chemical processes in terms of their hair damage potential. We believe this is the first comparative damage ranking for various chemical processes in the hair care field.

Swelling or Porosity of Hair

Professionals who are involved in the art of styling hair define the porosity of hair as the capacity of hair to absorb liquids. Hair that absorbs a larger quantity of liquid is said to be more porous than hair that absorbs less liquid. Hair stylists associate higher porosity of hair with higher degree of damage.[10]

Water is able to penetrate into hair after a sufficient contact time. As explained by Feughelman, the absorption of water takes place initially onto the hydrophilic sites of the globular protein matrix and on the surface of the microfibrils. After the initial absorption, more sorption of water builds up on water molecules already attached to the protein structure.[11] According to Chamberlain and Speakman, the total uptake of water is 31.18% at 100% humidity.[12] The uptake of water or swelling of hair can be measured by two methods: the volume method or the weight method.

Volume method: Shansky, in 1963, was the first person to measure the change in the diameter of the individual hair fibers using a microscope.[13] In 1990, Nothen et al. devised a more accurate instrument utilizing an optical unit for sensing the diameter of a single fiber, and an online analyzer for displaying the data in real time.[14] In 1998, Syed et al. measured real time swelling of individual fibers using a laser micrometer that measured the major and minor axis of the fiber simultaneously during the immersion of the fiber in an appropriate solution.[15]

In each of these volume methods, the selection of the fibers takes a long time and then swelling of each fiber has to be measured over a 20-30 minute period. Also many individual fibers have to be used in order to get statistically significant results. Additionally, this method may not be appropriate for measuring the change in diameter of African-descent fibers where the inherent variation in diameter is significant within a single fiber along the hair shaft.[16]

Weight method: The weight method is much less tedious and has the ability

 0361-4387/02/0011-0057$05.00/0

to study the swelling or water uptake of hair fibers using a centrifuge. With this method, a single operator can conduct more than 50 measurements a day.[17] The weight method is also known as the liquid retention or porosity test. Valko and Barnett have defined porosity as the capacity of hair fibers to absorb water.[9] Chemically damaged fibers are considered hydrophilic or porous and therefore would more readily pick up moisture and retain water than the untreated or unmodified hair. Valko and Barnett believed that the greater the porosity of hair, the greater was the damage to the hair fiber. They found the uptake of water for unmodified or normal hair to be 31.10%. Therefore, the porosity technique may become a primary method for determining hair damage due to cosmetic treatments if it correlates with most widely accepted methods for measuring hair damage. One of those methods is the measurement of tensile strength.

Tensile Strength of Hair

The tensile properties of hair fibers play an important role in determining the efficacy of hair treatments such as permanent waves, permanent hair colors, bleaches and permanent hair straighteners. The influence of various hair treatments on the tensile properties of hair can be measured using tensile meters such as Instron[a] and Dia-Stron[b].[18]

One commonly used method to determine if hair fibers have been altered by treatment with cosmetic products is to extend the fibers to 20% of their length before and after treatment and determine the so-called F20 Index. A single fiber is stretched to 20% strain or elongation at a specified constant rate (elongation per minute). The area under the curve (Energy) required to stretch the fiber to 20% strain is used to assess the condition of the fiber. The index values (After/Before Treatment) are calculated and used to assess the extent of hair damage. An Index of less than 1.0 indicates damage to the hair fiber produced by the chemical hair product. This method was first developed by Speakman in 1947 in order to study the effects of physical and chemical processes on keratin properties. Speakman used a percentage to express the changes in the stress for a fixed strain of fibers.[18]

Sookne and Harris coined the term 30% index as the ratio of extension values.[19] This test is similar to the F20 test except that the single fiber is stretched to 30% strain or elongation.

Over the last 50 years, it has become a standard practice to ascertain the F20 Index of the fibers before and after the given treatment in order to determine the positive or negative

[a] *Instron, Instron Corporation, Canton, Massachusetts*
[b] *Dia-Stron, Dia-Stron Ltd, Broomall, Pennsylvania*

Table 1. Hair treatments by commercial cosmetic products prior to determination of porosity and tensile strength of treated hair fibers

Hair treatment	Treatment mixture	Treatment quantity applied	Treatment contact time with hair	Rinse[a]	Shampoo	Rinse[b]
Hair color	28 g Logic[e] Permanent Color Blond-12G 38 g Logic Color Developer (30 vol H_2O_2)	AN	45 min TRP	AN[c]	3 min NCS	
Acid wave	77 g Syntonics[f] Multiplex Acid Wave Lotion 18.5 g Syntonics Waving activator	AN	20 min TRP	2.5 min	5 min CNS	2.5 min
Relaxer SH[j]	Affirm[g] No-Base Relaxer	12 g	18 min	3 min	2 min 2x NCNS	1 min
Relaxer GH[k]	139 g Affirm No-Lye No-Base Relaxer[h] 37 g Affirm Liquid Activator	12 g	18 min	3 min	2 min 2x NCNS	1 min
Hair bleach[l]	7.5 g Logic Powder Bleach 9.0 g Logic Color Generator (30 vol)	AN[d]	45 min TRPH	3 min	1 min NCS	1 min

[a] Rinsed with warm running tap water
[b] Rinsed with running tap water
[c] Rinsed until all excessive Color was gone
[d] Applied by brush to cover entire tress
[e] Logic products are manufactured by Matrix, a part of L'Oréal, France.
[f] Syntonics is a trademark of Syntonics International, Summit, Illinois USA.
[g] Affirm is a trademark of Avlon Industries Inc, Bedford Park, Illinois USA.
[h] Affirm Sensitive Scalp No-Lye No-Base Relaxer Normal Strength
[j] Permanent hair relaxer containing sodium hydroxide
[k] Permanent hair relaxer containing guanidine hydroxide
[l] Permanent hair bleach

AN = as needed
NCS = non-conditioning shampoo
CNS = conditioning neutralizing shampoo
NCNS = non-conditioning neutralizing shampoo
TRP = tress wrapped in plastic
TRPH = tress wrapped in plastic and placed under overhead dryer at 55°C

effect of the treatment on the fibers. In 1966, Menkart et al. compared the F20 Index of hair and wool and found hair to have slightly higher F20 Index than wool.[1]

In addition, many published studies have examined the changes in the tensile strength of cosmetically modified hair in the area of permanent hair colors, permanent hair waves, and hair bleaches.[2-8] The field of permanent hair relaxers is not well researched, although Syed et al. have compared the tensile strength of Caucasian hair against African-American hair using the methods of Speakman[18] and Menkart et al.[1]

Therefore, in order to verify the reliability of the porosity/weight method, we designed a study to correlate the porosity of hair fibers at 100% humidity with the tensile strength of hair fibers at 100% humidity. We hypothesized that a negative correlation would exist between porosity and tensile strength. Additionally, we asserted that if the coefficient of determination (r^2) is at 0.95 or higher, then the porosity/weight method would be considered correlated and thereby established as a reliable method for future use in the laboratory.

This method will enable the hair researcher to obtain results that are both faster and reliable. This method will also allow the hair chemist to compare the degree of damage imparted during various cosmetic treatments.

Experimental

Treating the hair: For the porosity testing, all hair used was Caucasian hair 8 inches long, assembled into six tresses of equal weight. The tresses were accurately weighed on an analytical balance at 4.0 g ±0.1 mg.

For testing the tensile strength of the hair, dark brown European-descent

$$\% \text{ Porosity} = \{[W_a - (W - 0.162W)] / W_a\} \times 100$$

where

W_a = Weight of hair immediately after centrifuging

W = Weight of hair at 65% R.H.

W– 0.162W is described by Menkart et al.[1]

(The average % moisture absorbed from 0% to 65% R.H. for normal hair is approximately 16.2%.)

Figure 1. Calculation of porosity

fibers (Level 2) of 80-90 microns were obtained[c] and separated into six different groups.

Of the six weighed tresses, one was left untreated as a control, and each of the other tresses was subjected to one of the following cosmetic treatments: permanent hair color, acid wave, permanent hair relaxer (sodium hydroxide), permanent hair relaxer (guanidine hydroxide) and hair bleach. Details of these treatments are presented in Table 1. The method of treatment employed in each case was the same as practiced in the market place.

The six sized groups were processed in the same way as the weighed tresses, again according to the details presented in Table 1.

Determining hair porosity: The porosity of the hair was determined utilizing the centrifuge method of Valko and Barnett.[9] Each of the six tresses was divided into eight samples weighing 0.5 gram each. All samples were equilibrated at 65% relative humidity and 21°C for 2 weeks prior to using.

To begin the porosity measurements, each sample was weighed at 65% R.H. using a microbalance[d]. The samples were immersed in 100 ml of deionized water for 30 minutes, removed with stainless steel forceps, and placed into polystyrene centrifuge tubes (28 ml) containing a mesh at the bottom of the tubes to keep the hair separate from the drained water. The tubes were capped and centrifuged[e] at 7,000 rpm for 10 minutes. After centrifuging, the samples were removed and weighed again on the microbalance. This method produced repeatable results for each of the treatments. The porosity of hair was calculated as shown in Figure 1.

Table 2. Porosity of treated hair

Treatment type*	Average porosity (%)
Untreated	31.15 ±0.63 N=6
Hair color with 30 vol developer	32.01 ±0.12 N=8
Acid wave	35.32 ±0.29 N=8
Hair relaxer (NaOH)	36.15 ±1.26 N=8
Hair relaxer (guanidine)	38.00 ±1.17 N=7
Hair bleach with 30 vol developer	54.57 ±2.48 N=5

N = Number of samples
* See Table 1 for specific products tested.

Table 3. Tensile strength of treated hair

Treatment type*	Average tensile strength (mJ)
Untreated	1.210 ±0.18 N=60
Hair color with 30 vol developer	1.138 ±0.20 N=41
Acid wave	0.991 ±0.12 N=55
Hair relaxer (NaOH)	0.776 ±0.11 N=53
Hair relaxer (guanidine)	0.698 ±0.11 N=57
Hair bleach with 30 vol developer	0.480 ±0.08 N=51

N= Number of samples
* See Table 1 for specific products tested.

Determining fiber tensile strength: The untreated fibers and fibers of chemically treated tresses were crimped at 30 mm length from the root tip and then immersed in deionized water at 21°C for 30 minutes. Then the amount of work required to extend the wet fibers by 20% of their original length was determined on the automated tensile tester[f] (Phase 1 = 20%; Maximum Force = 200 gmf; Number of cycles = 1; Gauge = 1).

Results and Discussion

It is apparent from Table 2 that untreated hair has the lowest amount of water uptake (31.15±0.63%, N=6) that is very close to the value of 31.18% found by Chamberlain and Speakman.[12] Our value of 31.15% is also very close to the value of 31.10±1.00% found by Valko and Barnett.[9] Therefore, our method of determining water uptake is in agreement with both of those studies.

[c] *DeMao Brothers, New York, New York USA*[d] *Mettler Microbalance, Mettler Toledo balance model #PC4400, Mettler Toledo Inc, Columbus, Ohio USA*

[d] *Mettler Microbalance, Mettler Toledo balance model #PC4400, Mettler Toledo Inc., Columbus, Ohio USA*

[e] *International Centrifuge Model Centra 4, rotor model 820, IEC International Equipment Company, Needham Heights, Massachusetts USA*

[f] *Dia-Stron Miniature Tensile Tester, Dia-Stron Ltd, Broomall, Pennsylvania USA*

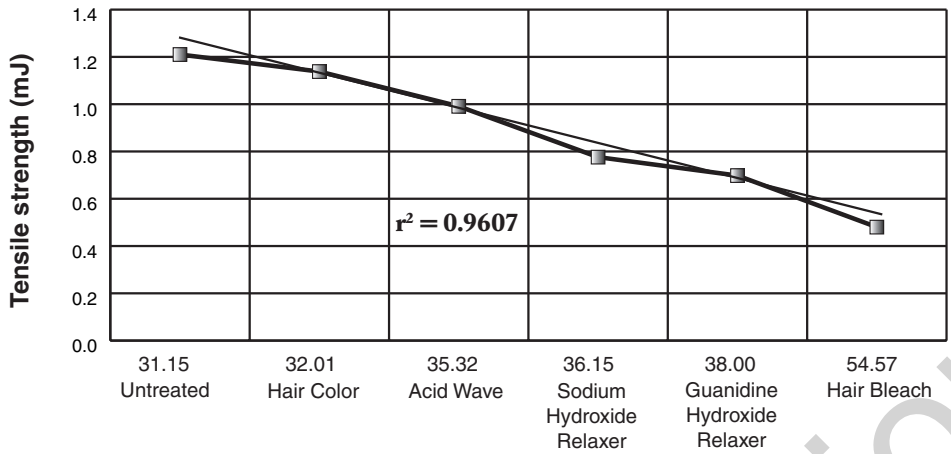

Figure 2. Correlation between porosity and tensile strength of hair treated by selected cosmetic products (see Table 1 for details on the products tested)

The cosmetic treatments such as permanent hair color, acid wave, permanent hair relaxers and hair bleach impart increasingly higher water in that order, as shown in Table 2. It is clear that permanent hair relaxing and hair bleaching are more damaging than processes such as permanent hair colors and acid permanent waves.

As shown in Table 3, untreated hair had the highest average tensile strength (1.210±0.180 mJ, N=60). On the other hand, cosmetic treatments such as permanent hair color, acid wave, permanent hair relaxers and hair bleach produced increasingly greater reductions in tensile strength (to a low of 0.480±0.080 mJ, N=51). The order of damage in terms of tensile strength for each of the cosmetic treatments is shown in Table 3 and it is similar to the order of water uptake for each of the cosmetic treatments in Table 2.

Using a statistical package[g], we correlated the porosity data from Table 2 and tensile strength data from Table 3. The coefficient of determination (r^2) was found to be 0.9607 (Figure 2.), which is statistically significant. Therefore, the water uptake method or porosity method and the tensile strength method are highly correlated.

As shown in Tables 2 and 3, the order of damage caused by the cosmetic treatments is as follows: Untreated hair < Permanent Hair Color (Golden Blonde-Level 12) < Permanent Wave (Acid Wave) < Hair Relaxer containing sodium hydroxide < Hair Relaxer containing guanidine hydroxide < Hair Bleach.

[g] *SPSS, SPSS Inc, Chicago, Illinois USA*

Conclusion

It is clear from this study that Valko and Barnett's weight method (water uptake) or porosity of hair is significantly correlated (r^2= 0.9607) to tensile strength of hair when hair fibers are chemically treated with various cosmetic treatments.

This study also compares the damage imparted to hair fibers from various chemical cosmetic treatments such as permanent hair colors, acid permanent waves, hair relaxers and hair bleaches. The order of magnitude of hair damage is also determined and it is found that permanent hair colors are least damaging followed by acid permanent waves and hair relaxers, whereas the bleaching of hair is the most damaging cosmetic treatment.

The weight method or porosity of hair is a less tedious and less time-consuming method for cosmetic chemists. It can be used instead of the tensile strength method to determine the degree of damage.

The porosity method would seem to be especially convenient to use on excessively curly hair in which the Young's modulus varies significantly within a single hair fiber due to its ever-changing diameter along the hair shaft. The Young's modulus is equal to the stress / strain, where strain is the deformation expressed in length, while stress is equal to the force divided by the cross-sectional area of the fiber. The modulus is usually obtained in the Hookean region (less than 2% strain) where the fiber can be stretched repeatedly without undergoing permanent deformation or damage from extesion.

This study needs to be expanded to many different hair shades in permanent hair colors; this study was limited to only one hair color and only a 30 volume developer. Similarly, this study needs to be expanded to various types of permanent waves, such as alkaline permanent waves.

References

Address correspondence to Ali N. Syed, c/o Editor, *Cosmetics & Toiletries* magazine, 362 South Schmale Road, Carol Stream, IL 60188-2787 USA.

1. J Menkart, LJ Wolfram and I Mao, Caucasian hair, Negro hair, and wool: Similarities and differences, *J Soc Cosmet Chem* 17 769-787 (1966)
2. CE Reese and H Eyring, Mechnical properties and the structure of hair, *Textile Res J* 20 743-750 (1950)
3. YK Kamath, SB Hornby and HD Weigman, Mechanical and fractographic behavior of Negroid hair, J Soc Cosmet Chem 35 21-43 (1984)
4. R Wickett, Kinetic studies of hair reduction using a single fiber technique, J Soc Cosmet Chem 34 301-316 (1983)
5. EG Bendit, There is no Hookean region in the stress-strain curve of keratin, J Macromol Sci-Phys B17(1) 129-140 (1980)
6. W Edman and M Marti, Properties of peroxide-bleached hair, J Soc Cosmet Chem 12 133 (1961)
7. L Wolfram, The reactivity of human hair: A review, in Hair Research, New York: Springer-Verlag (1981) p 497
8. TA Evans, TN Ventura and AB Wayne, The kinetics of hair reduction, J Soc Cosmet Chem 45 279-298 (1994)
9. EI Valko and G Barnett, A study of the swelling of hair in mixed aqueous solvents, J Soc Cosmet Chem 3 108-117 (1952)
10. Milady's Standard Text Book of Cosmetology, Albany, New York: Thomson Learning (2000) p 233
11. M Feughelman, Physical properties of hair, in Hair and Hair Care, DH Johnson, ed, New York: Marcel Dekker (1997) p 17
12. NH Chamberlain and JB Speakman, Z Electrochemie 37 374 (1931)
13. A Shansky, The osmotic behavior of hair during the permanent waving process as explained by swelling measurements, J Soc Cosmet Chem 14 427-432 (1963)
14. J Nothen, V Bollert, G Blankenburg and H Hocker, The influence of the cosmetic swelling behavior on the quality of the permanent wave, Proceedings of the 16th IFSCC Conference, New York, October 8-11, 1990, vol 1 (1990) pp 315-324
15. A Syed, H Ayoub and A Kuhajda, Recent advances in treating excessively curly hair, Cosmet Toil 113(9) 47-55 (1998)
16. A Syed, A Kuhajda, H Ayoub and K Ahmad, African-American Hair: Its physical properties and differences relative to Caucasian hair, Cosmet Toil 110(10) 39-47 (1995)
17. DH Powers and G Barnett, A study of swelling of hair in thioglycolate solutions and its reswelling, J Soc Cosmet Chem 92-100 (1953)
18. JB Speakman, Mechano-chemical methods for use with animal fibers, J Text Inst 38(2) T 102-126 (1947)
19. A Sookne and M Harris, J Res Natl Bur Stand 19 535 (1937)