Impact of Personal Care Products on Tensile Strength and Structure of Hair

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Abstract

Currently, there is a lot of debate over hair products and the components within them. While sulfates and parabens have been the two most controversial components within hair products, there is very little public knowledge regarding how other chemical components can impact hair. The purpose of this research is to explore the three chemical components (citric acid, hydrogen peroxide, and sodium chloride) found in shampoo, and evaluate the impacts that each of these chemical components can have on hair. The impact of these chemicals will be quantified through testing changes and differences in the mass, tensile strength, and hair diameter. Based on the results of this study, it appears that DI water has is a significant impact on hair, which impacts how clear the other results are. While the way each of these chemicals interacts with hair seems significant, further research needs to be done to get a clearer understanding of how the other chemical treatments impact hair and how significant the impacts are.

Introduction

The purpose of this study is to examine the impact that specific chemicals have on hair. The chemicals being studied are citric acid, hydrogen peroxide, and sodium chloride. These chemicals are commonly found in hair products such as shampoo, conditioner, and hair lighteners. To compare the impact that these chemicals have on hair, stress-strain analysis was completed on treatment groups as well as a control group that used DI water. DI water refers to deionized water, which is free of contaminants such as ions or minerals. This involved subjecting hair samples to a set treatment and completing a pull test on each treated hair to measure the force that it took to break the hair, as well as the amount that the length of the hair changes before it breaks. These measured values were then used to calculate stress and strain using the following equations:

$$Stress = \frac{Break\ Force}{Cross\ Sectional\ Area} \qquad Strain = \frac{Change\ in\ Length}{Original\ Length}$$

The primary reason to study the impacts that these chemicals have on hair is to better understand the chemicals that are commonly used in hair products, as there

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is not currently a lot of published knowledge on this topic. By understanding these impacts, we can better inform people's decisions on what products to use based on the chemicals that are in them. For example, if one of the studied chemicals shows a strong negative impact on hair, understanding this impact may lead people to avoid products with this chemical.

The main chemicals of focus for this study are citric acid, sodium chloride, and hydrogen peroxide. While there does not appear to be published data on how these chemicals directly impact the mechanical properties of hair, there are anecdotal claims on the impacts that these chemicals have. According to multiple sources, citric acid can be beneficial to hair in multiple ways. The two main ways that citric acid benefits hair are by removing product buildup in hair making the hair appear brighter, and by lowering the pH of hair products to a pH that is better for hair. Some of these claims can be seen in sources such as anveya.com and other blogs. In the case of sodium chloride, the consensus appears to be that it is harmful to hair. There are a variety of explanations for why sodium chloride is harmful to hair, but the most common explanation is that it dries out hair, leaving it brittle. This claim can be seen on multiple sources such as naturallycurly.com, but there does not appear to be published research on the topic. In the case of hydrogen peroxide, it is believed that it is highly damaging to hair according to many sources. However, the extent to which hair is impacted by these chemicals does not seem to be publicly known, and beginning to determine this is the primary focus of this study.

According to Franbourg et al., there are measurable differences between the physical properties of hair from different ethnicities.[2] The article found that while there are some similarities between hair from different ethnicities, there are very notable differences between the radial swelling, geometric characteristics, and the mechanical characteristics. Because of the observed measurable difference in physical properties based on ethnicity, hair samples for this study were taken all from one source, a 21-year-old Caucasian female, to limit the number of variables and allow all samples to be compared to one another. Furthermore, this study relies on "Human Hair: A Unique Physicochemical Composite" by L.J. Wolfram, which describes the chemical, physical, and mechanical characteristics of hair. While this source included a large amount of information, the most relevant piece is a table of the amino acid composition of human hair and how it differs between different ethnicities (Appendix A). This table will be used as a reference point in this study because understanding the typical amino acid composition of hair is highly beneficial when examining why certain chemicals impact hair the way they do, as different amino acids react differently with certain chemicals.

Another component to consider when evaluating chemical impact on hair is hair growth.[3] Hair growth consists of three phases: anagen, catagen, and telogen. While this article does not discuss how the mechanical behaviors of hair may differ in different stages, it is possible that hair may behave differently at different stages. If according to this source, an average of 84% of hairs are in the anagen phase—which is when the hair is actively growing—and 16% are in either catagen or telogen, then it is possible that roughly 16% of the sample could be outliers due to being in a

2 *Current Research on Ethnic Hair by A. Franbourg, P. Hallegot, F. Baltenneck, C. Toutain, and F. Leroy.*

3 *Structure and Function of Skin, Hair and Nails by J.E. Lai-Cheong, and J.A. McGrath.*

different stage of growth. This piece of information may be useful when examining the results of the hair trials, because if the amount of outliers is close to 16% that may indicate that the mechanical properties of hair change during different phases of growth.

The hair alone does not account for the possible external conditions, like weather, that can predispose the hair to be impacted in a certain way by the chemical components. The structure and mechanical properties of hair vary under external environmental conditions. For this study, the tensile properties of hair under different strain rates, relative humidities, and temperatures were studied and examined. Multiple figures from this study are used as reference points in the procedure, including the 3D structure of hair, images showing the fracture surfaces at different strain rates, and a plot of how stress and strain vary with relative humidity (Appendices B, C, and D). These figures help to provide a clearer understanding of factors that impact the stress and strain of hair as well as a better understanding of the way that hair fractures. Because the hair sample is coming from a single source, the environmental impact on the hair can be controlled effectively.

Using this information, the goal of this study is to determine how citric acid, hydrogen peroxide, and sodium chloride impact hair by answering the following questions:

Is there a significant difference between the average stress and strain for hair samples in different treatment groups?

If there is a significant difference in the stress and strain, does there appear to be a clear indication why this difference occurs, based on existing knowledge of hair?

Based on differences that may be observed, should hair products containing any of these chemicals be avoided?

Methods

Sample Collection

All samples were donated from one source to limit variables that could impact results such as age or ethnic background. The student researcher volunteered to donate the hair samples, and IRB approval was obtained to use these hair samples for research purposes. Each sample was cut to 5-8 inches in length and was cut from the source by a professional hairdresser. The samples were allowed to dry thoroughly before any testing was done.

Sample Prep

Multiple treatment groups were done with the primary difference being the identity of the chemical used in the treatment solution. The identities of these chemicals are citric acid, hydrogen peroxide, and sodium chloride (salt). Two different control groups were also done, with one set not being soaked in any solution, and one using DI water in place of a chemical solution.

For each treatment group, a solution was made with the designated chemical. The desired number of hairs were inserted into a scintillation vial (10 hairs for the main treatment groups), and the solution was added. In the case that the hairs floated to the top of the solution, they were pushed down into the solution with a pair of forceps. Additional solution was then added to reach the top of the vial. The filled vials were then capped and stored for multiple days. Once the desired amount of time passed (four days for the main treatment groups), the hair samples were carefully removed from the solution with a pair of forceps, placed on a piece of paper towel, rinsed thoroughly with DI water, patted dry with more paper towel, and placed in a clean beaker which was put in a desiccator for multiple days to allow the hairs to dry thoroughly.

Sample Examination

After each sample was subjected to a particular treatment, the sample examination began. The sample examination consisted primarily of measuring stress and strain of the hair. For this process, all the data and measurements were recorded in an Excel spreadsheet. An example of this is shown below in Figure 1.

Starting Length (mm)	63.9
Break Length (mm)	104.5
Delta Length (mm)	40.6
Break Force (N)	1.043
Measured Diameter	0.08519
Average Hair Radius(mm)	0.04260
Cross Sectional Area (mm^2)	0.005700
Area (mm^3)	0.3642
Stress (N/mm^2)	183.0
Strain	0.635

Figure 1: Example Data.

Before beginning the testing process, the hair diameter was measured using a ProScope portable digital microscope with the m200 lens. To do this, an image of the hair was taken using the portable microscope connected to a laptop, and the diameter of the hair was determined using ImageJ. Once the diameter was determined, the hair was then loaded into the testing apparatus which is shown in Appendix E and F. The hair was first clamped onto the force gauge, after the hair was clamped to the force gauge, the force was zeroed in Logger Pro, a data logging software compatible with the sensors used. The hair was then clamped to the apparatus and pulled taught, to the point just before a force reading began to register. Once the hair was clamped on both ends and pulled taught the start length was measured using a digital caliper, the length measured is the length of the hair from tip of clamp to tip of clamp.

Once the hair is fully loaded and the start length is measured, Open Broadcaster Software (OBS) is prepared to record the pull test. This recording includes a video of the caliper showing a change in length, a recording of the hair as it was being pulled, and a screen recording of the force reading in Logger Pro. Logger Pro was prepared by making sure it had been zeroed as described above, and that the duration was set to 1000s to prevent the data recording from cutting off early. The duration is set to 1000s by going to experiment, data collection, and entering 1000 into the duration box.

Once OBS and Logger Pro were prepared, the pull test was ready to begin. To do this, the caliper was set up to record the change in distance as shown in Appendix G, collection was started in Logger Pro, and recording was initiated in OBS. Once all of this was ready the pull could begin. The apparatus was cranked slowly to pull the hair and was cranked until the hair broke. Once the hair broke, collection was ended in Logger Pro, and recording was ended in OBS. The video taken using OBS was then examined to collect the final change in length and the break force. Using this data and the data collected before the pull test, stress and strain were calculated.

$$Stress = \frac{Break\ Force\ (N)}{Cross\ Sectional\ Area\ (mm^2)}$$

$$Cross\ Sectional\ Area = \pi * Radius^2 = \pi * \left(\frac{Diameter}{2}\right)^2$$

$$Strain = \frac{\Delta Length}{Start\ Length}$$

These steps were repeated for each individual hair and all data was recorded into Excel spreadsheets.

Results

When comparing the results of the chemical trials to the two control groups, there appears to be varying significance. In comparison to the no soak control group, the DI water soak, Peroxide soak, and citric acid soak all appear to have a significant difference in both stress and strain. But when comparing to the DI water soak control group, it appears that only peroxide and sodium chloride have a significant difference, but they only have a significant difference in the strain, not the stress.

Hair	Stress (N/mm^2)	Strain
1	199.4853735	0.474
2	201.473739	0.478
3	178.2535363	0.471
4	158.1615222	1.150
5	184.3650861	0.348
6	183.4408085	0.525
7	180.6726914	0.753
8	219.1229537	0.550
9	212.8697364	0.474
10	216.6079127	0.550
11	181.2376914	0.386
12	196.0367993	0.520
13	185.8929735	0.529
14	175.9617051	0.532
Average	190.9701806	0.553
ST Dev	17.38301157	0.195
% dev	9.102474279	35.24

Table 1: No Soak Control Data.

Table 1 includes the stress and strain values for the no soak control. These samples were tested after the hair samples were collected and dried, and no soak was done.

Hair	Stress (N/mm^2)	Strain
1	182.99	1.5739
2	180.19	1.6933
3	196.49	2.0637
4	158.01	2.1137
5	156.18	1.7582
6	223.81	1.5719
7	157.82	2.1143
8	138.37	1.8479
9	170.86	1.8275
10	189.42	0.9896
Average	175.41	1.76
ST Dev	24.58	0.34
% Deviation	14.01	19.21

Table 2a: DI Water Control Set 1.

Hair	Stress (N/mm^2)	Strain
1	160.47	1.7604
2	189.75	1.9084
3	178.91	2.8870
4	161.24	2.0324
5	165.72	1.7820
6	185.25	1.6356
7	110.28	1.8671
8	148.71	1.7055
9	170.59	1.8648
10	138.35	2.0844
Average	160.93	1.95
ST Dev	23.77	0.36
% Deviation	14.77	18.24

Table 2b: DI Water Control Set 2.

Hair	Stress (N/mm^2)	Strain
Average	168.1705	1.85408
ST Dev	24.68114	0.352367
% Deviation	14.67626	19.00493

Table 2c: DI Water Data Combined.

Table 2 includes the stress and strain values for the DI water control. These samples were subjected to a DI water soak for a total four days. Two sets of ten hairs were subjected to this treatment and split into set 1 and set 2. Table 2 is split into three tables, Table 2a, 2b, and 2c. Table 2a includes the stress and strain values for set 1, Table 2b includes the stress and strain values for set 2, and Table 2c includes the average, standard deviation, and % deviation for set 1 and 2 combined.

Hair	Stress (N/mm^2)	Strain
1	150.99	0.7195
2	148.83	0.6534
3	135.11	0.6949
4	146.69	0.6698
5	125.34	0.5347
6	178.97	0.6995
7	149.03	0.9628
8	146.95	0.5679
9	134.80	0.5116
10	207.73	0.6116
Average	152.45	0.6600
ST Dev	24.03	0.1300
% Deviation	15.76	19.27

Table 3a: Peroxide Set 1.

Hair	Stress (N/mm^2)	Strain
1	146.96	1.5612
2	89.67	1.8136
3	171.48	1.6129
4	161.21	1.6788
5	162.10	1.5590
6	151.41	1.5611
7	188.59	1.5492
8	143.10	1.3037
9	167.39	1.5020
10	161.11	1.6030
Average	154.30	1.57
ST Dev	26.16	0.13
% Deviation	16.96	8.20

Table 3b: Peroxide Set 2.

Hair	Stress (N/mm^2)	Strain
Average	153.373	1.11851
ST Dev	24.46903	0.484193
% Deviation	15.95393	43.2891

Table 3c: Peroxide Data Combined.

Table 3 includes the stress and strain values for the peroxide chemical treatment. Two sets of ten hairs were subjected to this treatment and split into set 1 and set 2. These samples were run with a 3% hydrogen peroxide solution for a total of four days. Table 3 is split into three tables, Table 3a, 3b, and 3c. Table 3a includes the stress and strain values for set 1, Table 3b includes the stress and strain values for set 2, and Table 3c includes the average, standard deviation, and % deviation for set 1 and 2 combined.

Hair	Stress (N/mm^2)	Strain
1	180.04	1.3901
2	142.86	1.7917
3	119.49	1.7591
4	127.24	1.7034
5	152.12	1.8217
6	148.85	1.7042
7	122.23	1.8490
8	131.85	1.6943
9	151.65	1.7324
10	134.61	1.5597
Average	141.09	1.70
ST Dev	18.12	0.14
% Deviation	12.84	7.98

Table 4a: Citric Acid Set 1.

Hair	Stress (N/mm^2)	Strain
1	179.65	2.0619
2	175.26	1.7732
3	143.74	1.8388
4	191.29	2.0741
5	173.71	2.0397
6	148.20	1.9218
7	129.13	2.3945
8	198.94	1.9210
9	165.21	1.8885
10	171.18	1.8842
Average	167.63	1.98
ST Dev	21.68	0.18
% Deviation	12.93	8.88

Table 4b: Citric Acid Set 2.

Hair	Stress (N/mm^2)	Strain
Average	154.3625	1.840165
ST Dev	23.73636	0.20946
% Deviation	15.37702	11.38265

Table 4c: Citric Acid Set 3.

Table 4 includes the stress and strain values for the citric acid chemical treatment. Two sets of ten hairs were subjected to this treatment and split into set 1 and set 2. These samples were run with a 50.128% w/w citric acid solution for a total of four days. Table 4 is split into three tables, Table 4a, 4b, and 4c. Table 4a includes the stress and strain values for set 1, Table 4b includes the stress and strain values for set 2, and Table 4c includes the average, standard deviation, and % deviation for set 1 and 2 combined.

Hair	Stress (N/mm^2)	Strain
1	195.6	0.439
2	235.8	0.469
3	198.9	0.543
4	171.7	0.511
Average	200.5	0.490
ST Dev	26.5	0.053
% Dev	13.2	10.85

Table 5: Sodium Chloride Pre-Trial.

Table 5 includes the stress and strain values for the sodium chloride treatment. These samples were run with a 25.098% sodium chloride solution for a total of four days. The sodium chloride treatment data is more limited than the other treatments as only a pre-trial including four samples was run.

Discussion

Table 6 compares the stress and strain values of each treatment to the no-soak control group. Table 7 compares the stress and strain values of each treatment to the DI water control group. These comparisons were done by running a two-sample t-test assuming unequal variances for each treatment group using the data from Tables 1-5; the Excel spreadsheet showing these calculations is in Appendix H. In both tables, the p-values that show significance are highlighted in green, and the p-values that don't show significance are highlighted in red. At a 95% significance level, alpha (α) is 0.05, so a p-value less than 0.05 shows significance, and a p-value higher than 0.05 shows that there is no significance. Significance in this value means that there is a significant difference between the control value and the treatment value.

From Table 6 it can be determined that the DI water soak, hydrogen peroxide soak, and citric acid soak all appear to have a significant difference in both stress and strain from the no soak control. This means that all these treatments had some measurable impact on the hair. When examining the significance, it appears that all three of these treatments had a negative significance in the stress and positive significance in the strain. This means that the force required to break the hair decreased. It also means that the amount that the hair stretched before breaking increased. While the sodium chloride values do not appear to show significance in this table, it is possible that the lack of significant results is due to a small sample size and more data should be collected to determine if there are any significant impacts on hair from sodium chloride.

From Table 7 it can be determined that only the stress values for peroxide and sodium chloride have significance in comparison to the DI water control. Both peroxide and sodium chloride show a negative significance in the strain value, which means that the strain values for both peroxide and sodium chloride were significantly lower than strain values for the DI water control samples. Because Strain=(Change in Length)/(Original Length), this means that peroxide and sodium chloride seem to make the hair less stretchy in comparison to DI water, but more stretchy in comparison to the no soak control. This could be for many reasons, such as potentially breaking bonds in the hair, allowing it to stretch more easily. However, to determine why the hair becomes more stretchy, further research needs to be done. When compared to the DI water control, citric acid does not appear to have any significance.

When comparing the two tables, there appears to be a substantial difference in what treatments have a significant impact on hair. This may be due to the significant impact that DI water appears to have on hair in comparison to the no soak control. Because of this significant difference seen from DI water, it is difficult to determine how many of the changes seen from the treatments are due to the DI water in the solution. Further research is needed.

Figures 2 and 3 provide a visual comparison of the stress and strain values for every treatment to better understand why there is a difference between whether a treatment has a positive or negative significance between the no soak and DI water soak statistical comparison.

Group	Stress		Strain	
	t-value	p-value	t-value	p-value
No Soak Control	Control (Table 1)			
DI Water Control	2.036933343	-0.00343333	2.03951345	+9.3073E-15
Peroxide	2.036933343	-9.9425E-06	2.05183052	+6.6802E-05
Citric Acid	2.036933343	-1.1438E-05	2.04522964	+1.6116E-17
Sodium Chloride Pre-Trial	2.776445105	+0.53417312	2.1199053	-0.28943219

Table 6: All Stress and Strain Data Compared to No Soak Control.

Group	Stress		Strain	
	t-value	p-value	t-value	p-value
DI Water Control	Control			
Peroxide	2.024394164	-0.064489673	2.030107928	-3.59703E-06
Citric Acid	2.024394164	-0.079269531	2.039513446	-0.880321243
Sodium Chloride Pre-Trial	2.776445105	+0.08720836	2.079613845	-1.46802E-13

Table 7: All Stress and Strain Data Compared to DI Water Soak Control.

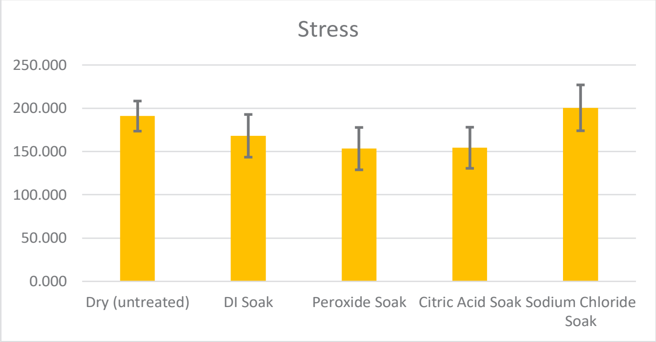

Figure 2: Average Stress with Standard Deviation.

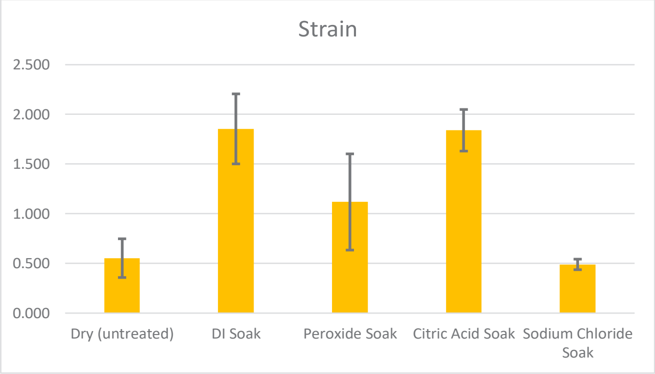

Figure 3: Average Strain with Standard Deviation.

Conclusion

The primary goal of this study was to determine if there is a significant impact on hair due to the chemical treatments (citric acid, peroxide, and sodium chloride). Based on the results of this study, it appears that there is a significant impact on hair by DI water, which impacts how clear the other results are. While it does appear that there may be some significance to how each of these chemicals interacts with hair, further research needs to be done to get a clearer understanding of how the other chemical treatments impact hair and how significant the impacts are.

There are a few limitations to this study. The primary limitation to note is that DI water appears to have a significant impact on hair. Because DI water is the solvent for the other chemical treatment solutions, this may impact the results of the study. Another limitation is small sample sizes. While the main treatments do have a fair number of samples (20 per treatment) the sodium chloride treatment has only had a pretrial of four samples completed.

There are multiple potential future directions. The first would be to complete a full trial of the sodium chloride treatment because only a pretrial was completed for this study. Another potential future direction would be to test other solvents that may have less of an impact on hair than DI water does so that a clearer analysis of the other chemical treatments can be completed. It may also be worthwhile to further study the impact that DI water has on hair to determine why it has the impact that it does. This study provides an introductory glance into the ways hair can be affected by various chemicals, but it also shows the need for further research into the topic.

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Appendices

Table I. Amino acid composition of human hair of various ethnic origins (μM/g)

	Hair type		
Amino acid	**African**	**Brown/Caucasian**	**Asian**
Alanine	370-509	345-475	370-415
Arginine	482-540	466-534	492-510
Aspartic acid	436-452	407-455	456-500
Cysteic acid	10-30	22-58	35-41
1/2 Cystine	1310-1420	1268-1608	1175-1357
Glutamic acid	915-1017	868-1053	1026-1082
Glycine	467-542	450-544	454-498
Histidine	60-85	56-70	57-63
Isoleucine	224-282	188-255	205-244
Leucine	484-573	442-558	515-546
Lysine	198-236	178-220	182-196
Methionine	6-42	8-54	21-37
Phenylalanine	139-181	124-150	129-143
Proline	642-697	588-753	615-683
Serine	672-1130	851-1076	986-1101
Threonine	580-618	542-654	568-593
Tyrosine	179-202	126-194	131-170
Valine	442-573	405-542	421-493

Appendix A: Human Hair: A Unique Physicochemical Composite by L.J. Wolfram.

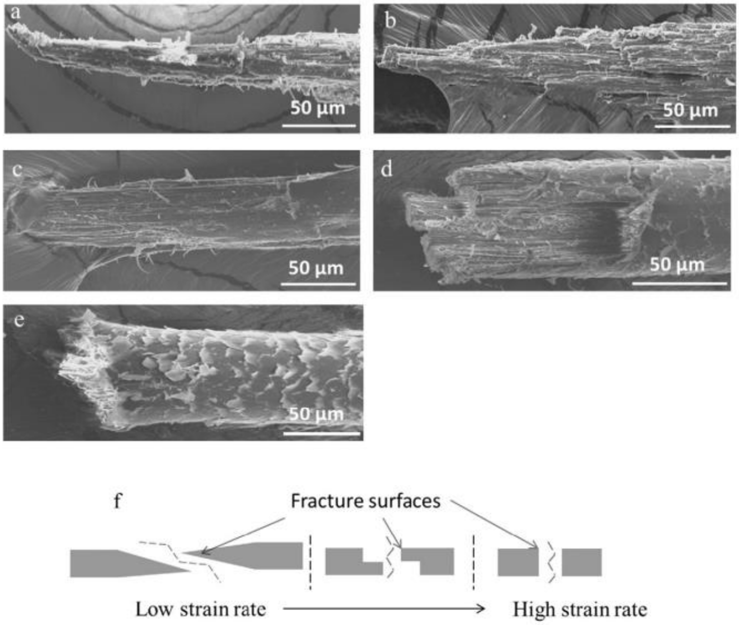


Fig. 10. Fracture surface of hair specimen tested at (a) 10^{-4}, (b) 10^{-3}, (c) 10^{-2}, (d) 10^{-1}, and (e) 10^{0} s^{-1} strain rates and (f) schematic representations of fracture modes from low strain rate to high strain rate (at low strain rates, fiber pulling and inter-fiber sliding is more prominent. At high strain rates, fracture surface is flat).

Appendix B: Structure and Mechanical Behavior of Human Hair by Y. Yu, W. Yang, B. Wang, and M.A Meyers.

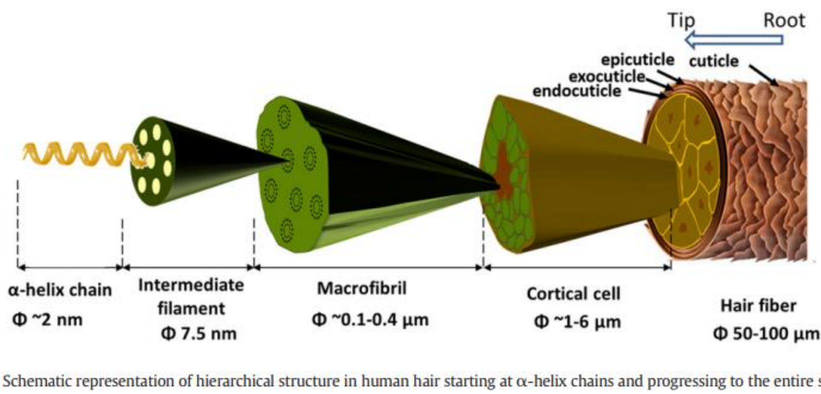


Fig. 1. Schematic representation of hierarchical structure in human hair starting at α-helix chains and progressing to the entire section.

Appendix C: Structure and Mechanical Behavior of Human Hair by Y. Yu, W. Yang, B. Wang, and M.A Meyers.

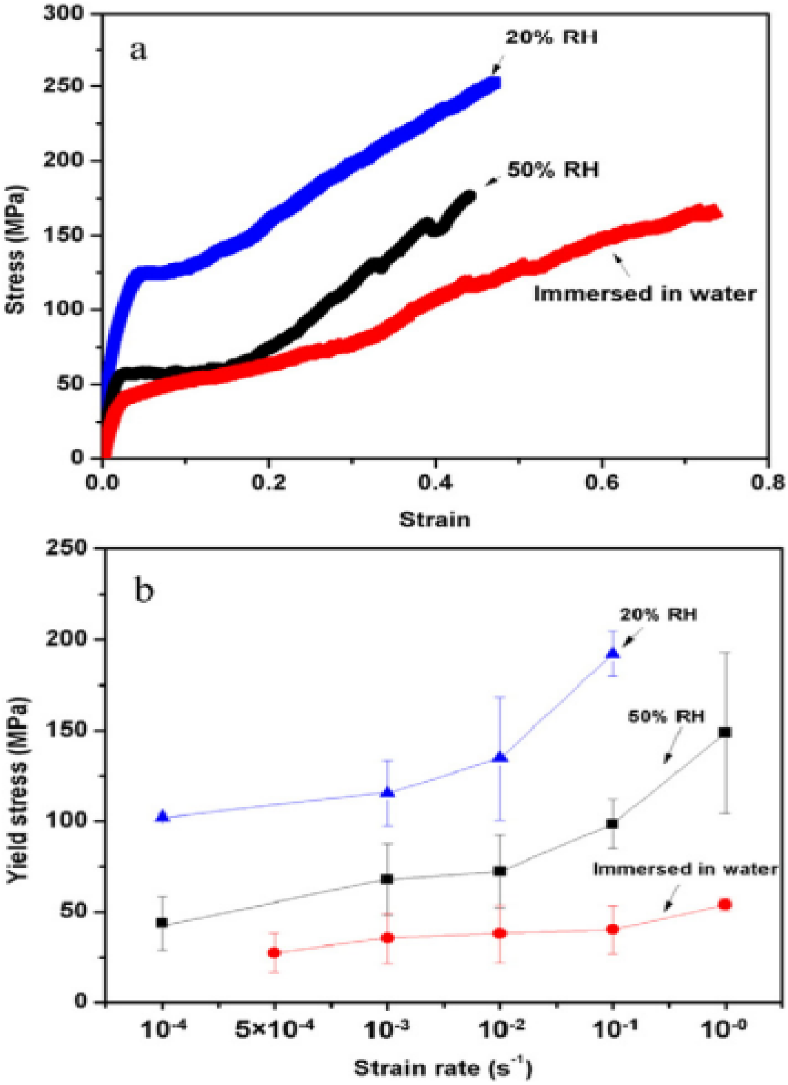
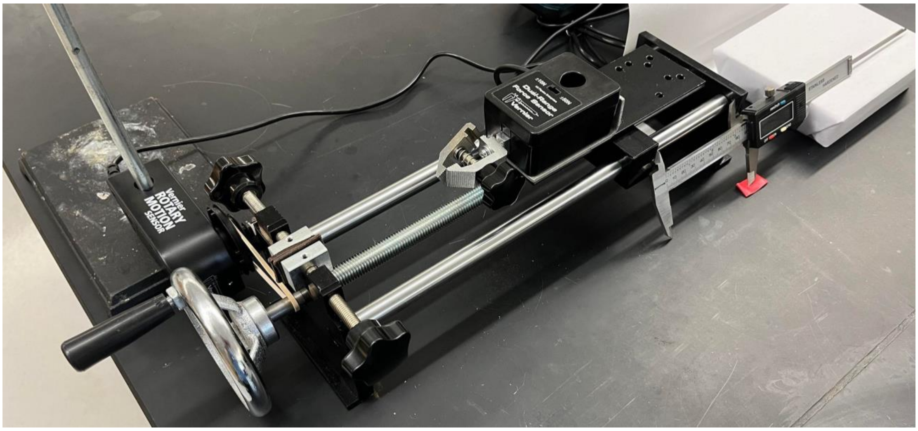
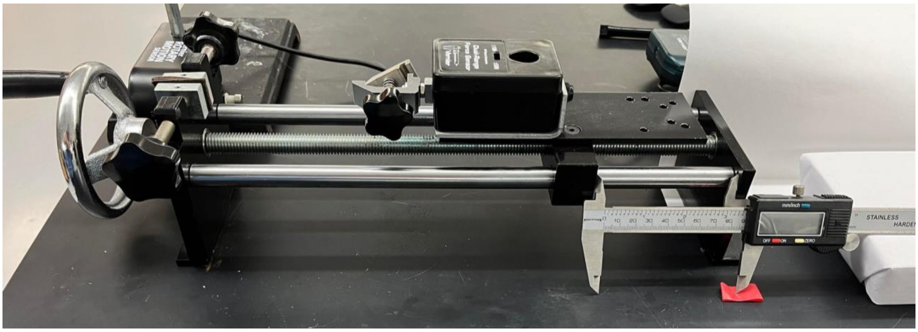


Fig. 5. (a) Typical stress-strain curves at different relative humidities and (b) yield stress as a function of strain rate (error bars represent standard deviation).

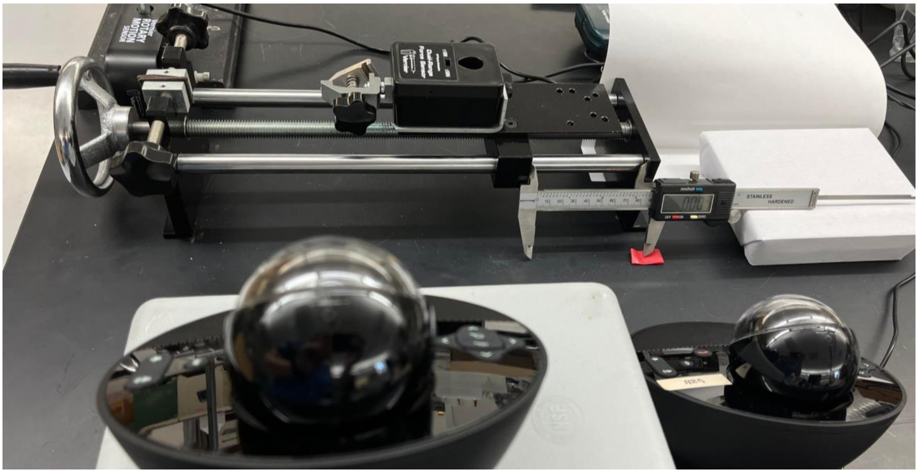
Appendix D: Structure and Mechanical Behavior of Human Hair by Y. Yu, W. Yang, B. Wang, and M.A Meyers.



Appendix E.



Appendix F.



Appendix G.

No Soak Control Data		
Hair	Stress (N/mm^2)	Strain
1	199.4853735	0.474
2	201.473739	0.478
3	178.2535363	0.471
4	158.1615222	1.15
5	184.3650861	0.348
6	183.4408085	0.525
7	180.6726914	0.753
8	219.1229537	0.55
9	212.8697364	0.474
10	216.6079127	0.55
11	181.2376914	0.386
12	196.0367993	0.52
13	185.8929735	0.529
14	175.9617051	0.532
Average	190.9701806	0.553
ST Dev	17.38301157	0.195
% dev	9.102474279	35.24

Group	Stress		Strain	
	t-value	p-value	t-value	p-value
No Soak Control		Control		
DI Water Control	2.036933343	0.003433329	2.039513446	9.30726E-15
Peroxide	2.036933343	9.94246E-06	2.051830516	6.68025E-05
Citric Acid	2.036933343	1.14381E-05	2.045229642	1.61156E-17
Sodium Chloride Pre-Trial	2.776445105	0.534173123	2.119905299	0.289432187

DI Water Control Set 1		
Hair	Stress (N/mm^2)	Strain
1	182.99	1.5739
2	180.19	1.6933
3	196.49	2.0637
4	158.01	2.1137
5	156.18	1.7582
6	223.81	1.5719
7	157.82	2.1143
8	138.37	1.8479
9	170.86	1.8275
10	189.42	0.9896
Average	175.41	1.76
ST Dev	24.58	0.34
% Deviation	14.01	19.21

DI Water Control Set 2		
Hair	Stress (N/mm^2)	Strain
1	160.47	1.7604
2	189.75	1.9084
3	178.91	2.887
4	161.24	2.0324
5	165.72	1.782
6	185.25	1.6356
7	110.28	1.8671
8	148.71	1.7055
9	170.59	1.8648
10	138.35	2.0844
Average	160.93	1.95
ST Dev	23.77	0.36
% Deviation	14.77	18.24

DI Water Control Data Combined		
Hair	Stress (N/mm^2)	Strain
1	182.99	1.5739
2	180.19	1.6933
3	196.49	2.0637
4	158.01	2.1137
5	156.18	1.7582
6	223.81	1.5719
7	157.82	2.1143
8	138.37	1.8479
9	170.86	1.8275
10	189.42	0.9896
1	160.47	1.7604
2	189.75	1.9084
3	178.91	2.887
4	161.24	2.0324
5	165.72	1.782
6	185.25	1.6356
7	110.28	1.8671
8	148.71	1.7055
9	170.59	1.8648
10	138.35	2.0844
Average	168.1705	1.85408
ST Dev	24.68113694	0.352366631
% Deviation	14.67625829	19.00493135

Appendix H: No Soak Control Comparison.

Peroxide Set 1		
Hair	Stress (N/mm^2)	Strain
1	150.99	0.72
2	148.83	0.653
3	135.11	0.695
4	146.69	0.67
5	125.34	0.535
6	178.97	0.7
7	149.03	0.963
8	146.95	0.568
9	134.8	0.512
10	207.73	0.612
Average	152.45	0.66
ST Dev	24.03	0.13
% Deviation	15.76	19.27

Peroxide Set 2		
Hair	Stress (N/mm^2)	Strain
1	146.96	1.561
2	89.67	1.814
3	171.48	1.613
4	161.21	1.679
5	162.1	1.559
6	151.41	1.561
7	188.59	1.549
8	143.1	1.304
9	167.39	1.502
10	161.11	1.603
Average	154.3	1.57
ST Dev	26.16	0.13
% Deviation	16.96	8.2

Peroxide Data Combined		
Hair	Stress (N/mm^2)	Strain
1	150.99	0.7195
2	148.83	0.6534
3	135.11	0.6949
4	146.69	0.6698
5	125.34	0.5347
6	178.97	0.6995
7	149.03	0.9628
8	146.95	0.5679
9	134.8	0.5116
10	207.73	0.6116
1	146.96	1.5612
2	89.67	1.8136
3	171.48	1.6129
4	161.21	1.6788
5	162.1	1.559
6	151.41	1.5611
7	188.59	1.5492
8	143.1	1.3037
9	167.39	1.502
10	161.11	1.603
Average	153.373	1.11851
ST Dev	24.46902749	0.484192924
% Deviation	15.95393419	43.289101

t-Test: Two-Sample Assuming Unequal Variances for Stress		
	Variable 1	*Variable 2*
Mean	190.9701807	168.1705
Variance	302.169091	609.1585208
Observations	14	20
Hypothesized Mean Difference	0	
df	32	
t Stat	3.160487977	
P(T<=t) one-tail	0.001716664	
t Critical one-tail	1.693888748	
P(T<=t) two-tail	0.003433329	
t Critical two-tail	2.036933343	

t-Test: Two-Sample Assuming Unequal Variances for Strain		
	Variable 1	*Variable 2*
Mean	0.552857143	1.85408
Variance	0.038004747	0.124162243
Observations	14	20
Hypothesized Mean Difference	0	
df	31	
t Stat	-13.77534989	
P(T<=t) one-tail	4.65363E-15	
t Critical one-tail	1.695518783	
P(T<=t) two-tail	9.30726E-15	
t Critical two-tail	2.039513446	

Appendix H: No Soak Control Comparison (Con't.).

Citric Acid Set 1		
Hair	Stress (N/mm^2)	Strain
1	180.04	1.39
2	142.86	1.792
3	119.49	1.759
4	127.24	1.703
5	152.12	1.822
6	148.85	1.704
7	122.23	1.849
8	131.85	1.694
9	151.65	1.732
10	134.61	1.56
Average	141.09	1.7
ST Dev	18.12	0.14
% Deviation	12.84	7.98

Citric Acid Set 2		
Hair	Stress (N/mm^2)	Strain
1	179.65	2.062
2	175.26	1.773
3	143.74	1.839
4	191.29	2.074
5	173.71	2.04
6	148.2	1.922
7	129.13	2.395
8	198.94	1.921
9	165.21	1.889
10	171.18	1.884
Average	167.63	1.98
ST Dev	21.68	0.18
% Deviation	12.93	8.88

Citric Acid Data Combined		
Hair	Stress (N/mm^2)	Strain
1	180.04	1.3901
2	142.86	1.7917
3	119.49	1.7591
4	127.24	1.7034
5	152.12	1.8217
6	148.85	1.7042
7	122.23	1.849
8	131.85	1.6943
9	151.65	1.7324
10	134.61	1.5597
1	179.65	2.0619
2	175.26	1.7732
3	143.74	1.8388
4	191.29	2.0741
5	173.71	2.0397
6	148.2	1.9218
7	129.13	2.3945
8	198.94	1.921
9	165.21	1.8885
10	171.18	1.8842
Average	154.3625	1.840165
ST Dev	23.7363596	0.209459601
% Deviation	15.3770246	11.38265325

t-Test: Two-Sample Assuming Unequal Variances for Stress		
	Variable 1	*Variable 2*
Mean	190.9701807	153.373
Variance	302.169091	598.7333063
Observations	14	20
Hypothesized Me	0	
df	32	
t Stat	5.238013673	
P(T<=t) one-tail	4.97123E-06	
t Critical one-tail	1.693888748	
P(T<=t) two-tail	9.94246E-06	
t Critical two-tail	2.036933343	

t-Test: Two-Sample Assuming Unequal Variances for Strain		
	Variable 1	*Variable 2*
Mean	0.552857143	1.11851
Variance	0.038004747	0.234442787
Observations	14	20
Hypothesized Mean Difference	0	
df	27	
t Stat	-4.707768016	
P(T<=t) one-tail	3.34012E-05	
t Critical one-tail	1.703288446	
P(T<=t) two-tail	6.68025E-05	
t Critical two-tail	2.051830516	

Appendix H: No Soak Control Comparison (Con't.).

t-Test: Two-Sample Assuming Unequal Variances for Stress		
	Variable 1	*Variable 2*
Mean	190.9701807	154.3625
Variance	302.169091	563.4147671
Observations	14	20
Hypothesized Me	0	
df	32	
t Stat	5.189877949	
P(T<=t) one-tail	5.71904E-06	
t Critical one-tail	1.693888748	
P(T<=t) two-tail	1.14381E-05	
t Critical two-tail	2.036933343	

t-Test: Two-Sample Assuming Unequal Variances for Stress		
	Variable 1	*Variable 2*
Mean	190.9701807	200.5
Variance	302.169091	700.7
Observations	14	4
Hypothesized Mean Difference	0	
df	4	
t Stat	-0.679388059	
P(T<=t) one-tail	0.267086561	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.534173123	
t Critical two-tail	2.776445105	

Sodium Chloride Pre-Trial		
Hair	Stress (N/mm^2)	Strain
1	195.6	0.439
2	235.8	0.469
3	198.9	0.543
4	171.7	0.511
Average	200.5	0.49
ST Dev	26.5	0.053
% Dev	13.2	10.85

t-Test: Two-Sample Assuming Unequal Variances for Strain		
	Variable 1	*Variable 2*
Mean	0.552857143	1.840165
Variance	0.038004747	0.043873324
Observations	14	20
Hypothesized Mean Difference	0	
df	29	
t Stat	-18.3745735	
P(T<=t) one-tail	8.05782E-18	
t Critical one-tail	1.699127027	
P(T<=t) two-tail	1.61156E-17	
t Critical two-tail	2.045229642	

t-Test: Two-Sample Assuming Unequal Variances for Strain		
	Variable 1	*Variable 2*
Mean	0.552857143	0.4905
Variance	0.038004747	0.002097
Observations	14	4
Hypothesized Me	0	
df	16	
t Stat	1.095693607	
P(T<=t) one-tail	0.144716093	
t Critical one-tail	1.745883676	
P(T<=t) two-tail	0.289432187	
t Critical two-tail	2.119905299	

Appendix H: No Soak Control Comparison (Con't.).

Peroxide Set 1		
Hair	Stress (N/mm^2)	Strain
1	150.99	0.7195
2	148.83	0.6534
3	135.11	0.6949
4	146.69	0.6698
5	125.34	0.5347
6	178.97	0.6995
7	149.03	0.9628
8	146.95	0.5679
9	134.8	0.5116
10	207.73	0.6116
Average	152.45	0.66
ST Dev	24.03	0.13
% Deviation	15.76	19.27

Peroxide Set 2		
Hair	Stress (N/mm^2)	Strain
1	146.96	1.5612
2	89.67	1.8136
3	171.48	1.6129
4	161.21	1.6788
5	162.1	1.559
6	151.41	1.5611
7	188.59	1.5492
8	143.1	1.3037
9	167.39	1.502
10	161.11	1.603
Average	154.3	1.57
ST Dev	26.16	0.13
% Deviation	16.96	8.2

Group	Stress		Strain	
	t-value	p-value	t-value	p-value
DI Water Control	Control			
Peroxide	2.024394164	0.064489673	2.030107928	3.59703E-06
Citric Acid	2.024394164	0.079269531	2.039513446	0.880321243
Sodium Chloride Pre-Trial	2.776445105	0.08720836	2.079613845	1.46802E-13

DI Water Control Set 1		
Hair	Stress (N/mm^2)	Strain
1	182.99	1.5739
2	180.19	1.6933
3	196.49	2.0637
4	158.01	2.1137
5	156.18	1.7582
6	223.81	1.5719
7	157.82	2.1143
8	138.37	1.8479
9	170.86	1.8275
10	189.42	0.9896
Average	175.41	1.76
ST Dev	24.58	0.34
% Deviation	14.01	19.21

DI Water Control Set 2		
Hair	Stress (N/mm^2)	Strain
1	160.47	1.7604
2	189.75	1.9084
3	178.91	2.887
4	161.24	2.0324
5	165.72	1.782
6	185.25	1.6356
7	110.28	1.8671
8	148.71	1.7055
9	170.59	1.8648
10	138.35	2.0844
Average	160.93	1.95
ST Dev	23.77	0.36
% Deviation	14.77	18.24

DI Water Control Data Combined		
Hair	Stress (N/mm^2)	Strain
1	182.99	1.5739
2	180.19	1.6933
3	196.49	2.0637
4	158.01	2.1137
5	156.18	1.7582
6	223.81	1.5719
7	157.82	2.1143
8	138.37	1.8479
9	170.86	1.8275
10	189.42	0.9896
1	160.47	1.7604
2	189.75	1.9084
3	178.91	2.887
4	161.24	2.0324
5	165.72	1.782
6	185.25	1.6356
7	110.28	1.8671
8	148.71	1.7055
9	170.59	1.8648
10	138.35	2.0844
Average	168.1705	1.85408
ST Dev	24.68113694	0.352366631
% Deviation	14.67625829	19.00493135

Appendix H: DI Water Soak Comparison.

Citric Acid Set 1		
Hair	Stress (N/mm^2)	Strain
1	180.04	1.3901
2	142.86	1.7917
3	119.49	1.7591
4	127.24	1.7034
5	152.12	1.8217
6	148.85	1.7042
7	122.23	1.849
8	131.85	1.6943
9	151.65	1.7324
10	134.61	1.5597
Average	141.09	1.7
ST Dev	18.12	0.14
% Deviation	12.84	7.98

Citric Acid Set 2		
Hair	Stress (N/mm^2)	Strain
1	179.65	2.0619
2	175.26	1.7732
3	143.74	1.8388
4	191.29	2.0741
5	173.71	2.0397
6	148.2	1.9218
7	129.13	2.3945
8	198.94	1.921
9	165.21	1.8885
10	171.18	1.8842
Average	167.63	1.98
ST Dev	21.68	0.18
% Deviation	12.93	8.88

Peroxide Data Combined		
Hair	Stress (N/mm^2)	Strain
1	150.99	0.7195
2	148.83	0.6534
3	135.11	0.6949
4	146.69	0.6698
5	125.34	0.5347
6	178.97	0.6995
7	149.03	0.9628
8	146.95	0.5679
9	134.8	0.5116
10	207.73	0.6116
1	146.96	1.5612
2	89.67	1.8136
3	171.48	1.6129
4	161.21	1.6788
5	162.1	1.559
6	151.41	1.5611
7	188.59	1.5492
8	143.1	1.3037
9	167.39	1.502
10	161.11	1.603
Average	153.373	1.11851
ST Dev	24.46902749	0.484192924
% Deviation	15.95393419	43.289101

t-Test: Two-Sample Assuming Unequal Variances for Stress		
	Variable 1	*Variable 2*
Mean	168.1705	153.373
Variance	609.1585208	598.7333063
Observations	20	20
Hypothesized Mean Difference	0	
df	38	
t Stat	1.904098124	
P(T<=t) one-tail	0.032244836	
t Critical one-tail	1.68595446	
P(T<=t) two-tail	0.064489673	
t Critical two-tail	2.024394164	

t-Test: Two-Sample Assuming Unequal Variances for Strain		
	Variable 1	*Variable 2*
Mean	1.85408	1.11851
Variance	0.124162243	0.234442787
Observations	20	20
Hypothesized Mean Difference	0	
df	35	
t Stat	5.493268383	
P(T<=t) one-tail	1.79852E-06	
t Critical one-tail	1.689572458	
P(T<=t) two-tail	3.59703E-06	
t Critical two-tail	2.030107928	

Sodium Chloride Pre-Trial		
Hair	Stress (N/mm^2)	Strain
1	195.6	0.439
2	235.8	0.469
3	198.9	0.543
4	171.7	0.511
Average	200.5	0.49
ST Dev	26.5	0.053
% Dev	13.2	10.85

Appendix H: DI Water Soak Comparison (Con't.).

Citric Acid Set 1		
Hair	Stress (N/mm^2)	Strain
1	180.04	1.3901
2	142.86	1.7917
3	119.49	1.7591
4	127.24	1.7034
5	152.12	1.8217
6	148.85	1.7042
7	122.23	1.849
8	131.85	1.6943
9	151.65	1.7324
10	134.61	1.5597
Average	141.09	1.7
ST Dev	18.12	0.14
% Deviation	12.84	7.98

Citric Acid Set 2		
Hair	Stress (N/mm^2)	Strain
1	179.65	2.0619
2	175.26	1.7732
3	143.74	1.8388
4	191.29	2.0741
5	173.71	2.0397
6	148.2	1.9218
7	129.13	2.3945
8	198.94	1.921
9	165.21	1.8885
10	171.18	1.8842
Average	167.63	1.98
ST Dev	21.68	0.18
% Deviation	12.93	8.88

Peroxide Data Combined		
Hair	Stress (N/mm^2)	Strain
1	150.99	0.7195
2	148.83	0.6534
3	135.11	0.6949
4	146.69	0.6698
5	125.34	0.5347
6	178.97	0.6995
7	149.03	0.9628
8	146.95	0.5679
9	134.8	0.5116
10	207.73	0.6116
1	146.96	1.5612
2	89.67	1.8136
3	171.48	1.6129
4	161.21	1.6788
5	162.1	1.559
6	151.41	1.5611
7	188.59	1.5492
8	143.1	1.3037
9	167.39	1.502
10	161.11	1.603
Average	153.373	1.11851
ST Dev	24.46902749	0.484192924
% Deviation	15.95393419	43.289101

t-Test: Two-Sample Assuming Unequal Variances for Stress		
	Variable 1	*Variable 2*
Mean	168.1705	153.373
Variance	609.1585208	598.7333063
Observations	20	20
Hypothesized Mean Difference	0	
df	38	
t Stat	1.904098124	
P(T<=t) one-tail	0.032244836	
t Critical one-tail	1.68595446	
P(T<=t) two-tail	0.064489673	
t Critical two-tail	2.024394164	

t-Test: Two-Sample Assuming Unequal Variances for Strain		
	Variable 1	*Variable 2*
Mean	1.85408	1.11851
Variance	0.124162243	0.234442787
Observations	20	20
Hypothesized Mean Difference	0	
df	35	
t Stat	5.493268383	
P(T<=t) one-tail	1.79852E-06	
t Critical one-tail	1.689572458	
P(T<=t) two-tail	3.59703E-06	
t Critical two-tail	2.030107928	

Sodium Chloride Pre-Trial		
Hair	Stress (N/mm^2)	Strain
1	195.6	0.439
2	235.8	0.469
3	198.9	0.543
4	171.7	0.511
Average	200.5	0.49
ST Dev	26.5	0.053
% Dev	13.2	10.85

Appendix H: DI Water Soak Comparison (Con't.).

t-Test: Two-Sample Assuming Unequal Variances for Stress		
	Variable 1	*Variable 2*
Mean	168.1705	154.3625
Variance	609.1585208	563.4147671
Observations	20	20
Hypothesized Mean Difference	0	
df	38	
t Stat	1.803332368	
P(T<=t) one-tail	0.039634766	
t Critical one-tail	1.68595446	
P(T<=t) two-tail	0.079269531	
t Critical two-tail	2.024394164	

t-Test: Two-Sample Assuming Unequal Variances for Stress		
	Variable 1	*Variable 2*
Mean	168.1705	200.5
Variance	609.1585208	700.7
Observations	20	4
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.254512566	
P(T<=t) one-tail	0.04360418	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.08720836	
t Critical two-tail	2.776445105	

Citric Acid Data Combined		
Hair	Stress (N/mm^2)	Strain
1	180.04	1.3901
2	142.86	1.7917
3	119.49	1.7591
4	127.24	1.7034
5	152.12	1.8217
6	148.85	1.7042
7	122.23	1.849
8	131.85	1.6943
9	151.65	1.7324
10	134.61	1.5597
1	179.65	2.0619
2	175.26	1.7732
3	143.74	1.8388
4	191.29	2.0741
5	173.71	2.0397
6	148.2	1.9218
7	129.13	2.3945
8	198.94	1.921
9	165.21	1.8885
10	171.18	1.8842
Average	154.3625	1.840165
ST Dev	23.7363596	0.209459601
% Deviation	15.3770246	11.38265325

t-Test: Two-Sample Assuming Unequal Variances for Strain		
	Variable 1	*Variable 2*
Mean	1.85408	0.4905
Variance	0.124162243	0.002097
Observations	20	4
Hypothesized Mean Difference	0	
df	21	
t Stat	16.61869389	
P(T<=t) one-tail	7.34011E-14	
t Critical one-tail	1.720742903	
P(T<=t) two-tail	1.46802E-13	
t Critical two-tail	2.079613845	

t-Test: Two-Sample Assuming Unequal Variances for Strain		
	Variable 1	*Variable 2*
Mean	1.85408	1.840165
Variance	0.124162243	0.043873324
Observations	20	20
Hypothesized Mean Difference	0	
df	31	
t Stat	0.151809028	
P(T<=t) one-tail	0.440160621	
t Critical one-tail	1.695518783	
P(T<=t) two-tail	0.880321243	
t Critical two-tail	2.039513446	

Appendix H: DI Water Soak Comparison (Con't.).