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A Preliminary Investigation of the Tensile Properties of Yarns Used for Textile Conservation

BY SHIRLEY ELLIS

Hair Silk (Raw and Degummed),
Silk Crepeline Yarn & Polyester Tetex® Yarn

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A PRELIMINARY INVESTIGATION OF THE TENSILE PROPERTIES OF YARNS USED FOR TEXTILE CONSERVATION

Hair Silk (Raw and Degummed), Silk Crepeline Yarn & Polyester Tetex® Yarn

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1 INTRODUCTION

1.1 Objectives

Two types of threads often used for the stabilization of costumes and textiles are silk and polyester. Typically the thread secures the support fabric to the original, although it may also be used to reweave, or secure seams and fastenings. One of the issues which is of concern to textile conservators is the strength of the thread or yarn initially and as it ages. This investigation provides a comparison of the strength of four types of yarns used for the conservation of textiles before and after accelerated light ageing. These include: raw hair silk[1], degummed hair silk, pulled silk crepeline yarn and pulled polyester Tetex® yarn both dyed and undyed for all sample types. The effects of the dye and the gum will also be examined as well as a comparison of the fibre types. The hypothesis tested states that a difference in the tensile properties will be observed between the means of the compared pairs of yarns other than random variation.

Light ageing was selected for study as it is assumed that those textiles conserved with these yarns would be in a museum-like setting with controlled environmental conditions - either in storage or on display. Light exposure would have the greatest affect on the textiles over time.

1.2 Background

Generally, when choosing a thread for use in textile conservation it is thought to use 'like with like'. In so doing any dimensional change due to RH fluctuations will occur at roughly the same rate. This, however, is questioned as old textiles may not respond as quickly as the new thread, creating stresses within the repair.[2] The use of polyester on textiles fabricated from natural fibres is thought to be 'too strong' and may, in fact, cut the natural fibres. As well, polyester, being hydrophobic, will react differently than natural fibres to RH fluctuations.

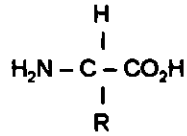
Using threads that have poor ageing behavior subjects the textile to unnecessary handling and damage caused by needle pricks. Weak threads may not support the repair over time necessitating further treatment at a later date.

1.3 Structure and Properties of Silk

Silk is a secreted fibrous protein fibre composed of sixteen amino acids. It consists of fibroin and sericin proteins held in a block copolymer formation.[3] The fibroin is extruded from two glands in the domestic silkworm *Bombyx mori* as a double filament and is cemented together by the sericin gum. The resultant filament is very fine, translucent and irregular with a smooth exterior and a triangular cross-section.

Fibroin is largely composed of the amino acids glycine (36 - 43%), alanine (29 - 35%), serine (13 - 17%) and tyrosine (10 - 13%). Because glycine and alanine are relatively simple amino acids and serine and tyrosine are hydroxylated[4], the fibroin molecular chains are tightly held together by hydrogen bonds in a closely packed ß-pleated sheet. The majority of the molecular chains in the pleated structure run in sync with each other, however where they are out of sync the chains form hydrogen bonds with those that are adjacent to it.[5] The presence of tyrosine encourages damage from light as it has a greater potential for reaction to radiant energy.[6] Fibroin is insoluble in aqueous solutions.

Basic amino acid structure:



Glycine:	R = – H
Alanine:	R = – CH_3
Serine:	R = – CH_2OH
Tyrosine:	R = – (C_6H_4) – OH

FIGURE 1. *Structure of Relevant Amino Acids of Fibroin*[7]

Sericin is largely composed of the amino acids serine (33.4%), aspartic acid (16.7%), glycine (13.5%) and threonine (9.7%). Due to the greater percentage of polar groups it is water soluble - particularly in hot, dilute alkali solutions. This also makes it more responsive to fluctuations in the RH.[8]

As the silk filaments are extruded from the silkworm the molecules are able to align themselves parallel to one another and the fibre axis forming a pleated sheet or ß-structure which is highly crystalline.[9] The crystalline region of fibroin, where the molecules are closely packed, makes up approximately 60%. This region gives silk its high strength. When wet this strength is significantly reduced by 75 - 85% of the dry strength.[10] The amorphous portion makes up the remainder. Those amino acids with the bulkier side groups such as tyrosine are found here. This region accounts for the extensibility of the pleated sheet structure.[11]

The sericin gum serves to prevent mechanical damage during processing.[12] Following manufacture it is often removed by water extraction at high temperatures, extraction by dilute alkali solutions or extraction by proteolytic enzymes.[13] Removing the gum reveals the natural lustre and softness of the yarn and reduces the tendency for water spotting.

Becker et al. found that the gum provided a protective function against light ageing, as photodegradation initially occurs on the surface. Their amino acid analysis of light aged fabrics established that high levels of tyrosine (which decreases with photodegradation) correlated with high levels of serine, indicating the presence of sericin.[14]

1.3.1 Photodegradation of Silk

Atmospheric oxygen induces oxidation of the silk polymer causing degradation which is promoted by sunlight. Photodegradation of silk causes the formation of ammonia nitrogen and the modification of the amino acids due to oxidation.[15] This results in a reduction in the tensile strength and the occurrence of yellowing. Silk is very susceptible to attack by light, especially light with shorter wavelengths (i.e. below 350 nm) but also by visible light. The reaction is oxidative due to the presence of oxygen in the atmosphere where it acts as an oxidizing agent.[16]

The absorption of light by the aromatic amino acids tryptophan, phenylalanine and tyrosine leads to damage of their side chains and cleavage of the main protein chain.[17] The light absorbed excites the molecules within the polymer resulting in the release of heat energy and the formation of free radicals. Further changes can occur to the amino acid structure or they can undergo degradative reactions.

Photodegradative reactions lead to the alteration of the crystalline regions due to chain scission exhibited by the breakage of the hydrogen bonds and reduction of molecular weight. This results in the loss in strength of the silk fibres.[19] Cross-linking also occurs with the development of covalent bonds between the molecular chains. At low levels of reaction this results in an increase in strength and toughness, whereas higher levels are associated with decreased elongation and an increase in brittleness.[20] In general, research has indicated that chain scission tends to occur in high oxygen atmospheres whereas, cross-linking tends to occur in low oxygen atmospheres. Further to this phenomenon is that areas that are more crystalline are subject to cross-linking due to the closer packing of the polymer chains and that chain scission in the amorphous areas may result in stress cracking.[21]

At low levels of UV light exposure the amorphous areas of fibroin, where tyrosine is present, are affected first.[22] When tyrosine deteriorates there is a reduction in elongation and increase in brittleness and friability, as this area is responsible for the extensibility of silk.[23] A reduction of tryptophan has been seen with an increase in yellowing.[24]

A study completed by Bresee and Goodyear from Kansas State University on the fractography of silk found that light aged silk exhibited a predominance of fractures related to surface flaws.[25] This indicates that photodegradation of silk tends to occur largely on the fibre surface. "...degradation resulting from light absorption produces numerous new surface flaws or enhances flaws already present on silk fibers so that these flaws play a more dominant role in the mechanism of fiber breakage."[26]

1.4 Structure and Properties of Polyester

Polyester is a man-made synthetic polymeric fibre produced by melt spinning. It is composed of at least 85% of an ester of a dihydric alcohol and terephthalic acid. The polyethylene terephthalate polymers are made by condensation reactions where the ethylene glycol is condensed with the terephthalic acid. The particular chemicals vary with the manufacturer.[27] The predominant forces of attraction in the polymer are van der Waals' forces. However weak hydrogen bonds also form between the carbonyl oxygen atoms and adjacent hydrogen atoms.

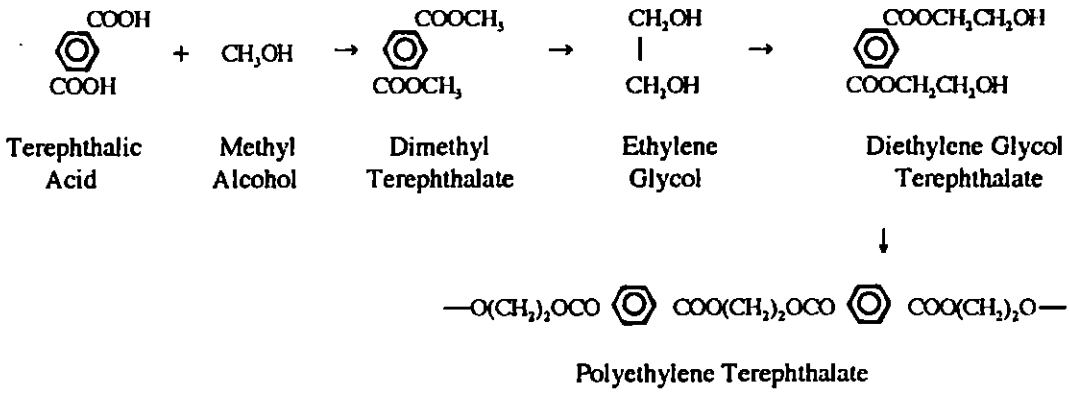


FIGURE 2. *Structure of Polyester*[28]

The resultant polyester fibres are smooth with a regular diameter and usually have a circular cross-section, although variations include trilobal and oval cross-sections. The yarns can be formed into filament or staple fibres. Polyester yarns are very crystalline and can be made into medium or high tenacity yarns depending on their method of manufacturer. They retain their strength when wet.

Polyester fibres can undergo various finishing processes. Because the fibres are thermoplastic they can be easily heat set. This is done to stabilize the fabric against any effects of a heat treatment that it may receive in subsequent handling.[29]

The Tetex® filament yarns have a circular cross-section and have undergone heat setting.

1.4.1 Photodegradation of Polyester

Polyester fibres have great resistance to many agents of deterioration. They are relatively unaffected by the sun's ultraviolet radiation due to the stability provided by the benzene rings in the polymer, however some loss of strength will occur after prolonged exposure.[30,31]

1.5 Mechanics of the Yarn

Fibres can be found as either short staple or long filament fibres. Silk is a natural filament fibre whereas, polyester can be either a staple or filament depending on its method of manufacture. Yarns of greater linear density and higher twist are stronger than those less so.[32] The polyester yarn used in this study is a filament yarn. The strength of a filament yarn is determined by the fibre strength, number of filaments, denier or tex of the filament and the yarn. When a force is exerted on filament yarns the fibre strength is maximized because the long filaments receive equal pull.[33]

The way in which the thread or yarn is wound and its denier or tex also affects the way in which it will deteriorate. A finer thread will degrade sooner than a heavier one.[34] This occurs because photochemical degradation is largely a surface phenomenon.[35]

1.6 Dyeing Theory

Dyes are organic compounds which impart colour to a textile in a dyebath. These compounds are capable of selectively absorbing certain wavelengths of visible light while reflecting others.

The portion of the organic molecule which produce the colour that we see are radical functional groups called chromophores and auxochromes. Both of these groups must be present in order for the dye to impart colour. Chromophores are unsaturated functional groups which have loosely held electrons capable of absorbing certain wavelengths in the visible spectrum. All organic compounds have the capability to absorb radiation, however, only chromophores do it in the visible light region.[36]

Auxochromes serve two functions in the dye molecule. First, they intensify the colour. Both single and double bonds are needed to obtain a strong colour. The auxochrome is able to donate electrons to the dye molecule, thus increasing the selectivity of the wavelength absorption and reflection.[37] Second, auxochromes provide the site where the dye molecule attaches to the fibre.[38] These functional groups tend to be polar. This encourages greater attractive forces between the dye molecule and the fibre, ultimately improving colourfastness. This polarity also makes the dye molecule more soluble in water increasing dye uptake.

1.6.1 Effect of Light Ageing on Dyes

The presence of dye on the fibre alters the effect of photodegradation. In 1975 a study by Leene et al. on the artificial ageing of yarns by light found that in many cases the dye will protect the textile from photodegradation. The dye exhibits fading due to its light absorbing capacity and protects the textile.[39] They did not elaborate on the type of dye or fibre that they found this to be true.

In discussing the general effects of ageing on textiles, Bresee suggests that most dyes would absorb visible light because they contain conjugated double bonds. As a result, dyed textiles would be unstable in light.[40]

1.7 Accelerated Ageing

Accelerated ageing is a way of expediating the ageing process of materials so that they can be studied and significant changes in their properties measured.[41] In so doing, one can predict a reasonable lifetime of the materials used for the conservation of artifacts. Accelerated ageing can be achieved by increasing the exposure to light, heat or humidity.

Following the ageing and analysis of materials Robert Feller of the Getty Conservation Institute suggested that materials can be classified according to their expected lifetime. Materials that remain stable at least 100 years were termed *Class A*, those stable from 20 to 100 years were termed *Class B*, while those stable under 20 years were termed *Class C*.[42]

The methods employed to age materials has been questioned recently as high exposures to ageing catalysts (light, temperature and/or humidity) may, in fact, achieve erroneous results. "The above-normal conditions of temperature and humidity usually employed in accelerated-aging tests might be such that these materials would not fall in the same relationship under "normal" conditions."[43] Therefore, the way in which a material is aged must be selected carefully.

The wavelength of light is an important factor in the mechanism of photodegradation. Short wavelengths of 100 - 280 nm, known as UV-C or far UV, cause photolytic scission of a bond. Slightly

longer wavelengths of 315 - 400 nm, known as UV-A or near UV, and visible light tend to cause photochemical reactions where the radiation leads to the excitation of the electrons in a chemical bond. This higher energy state increases the likelihood of further reactions, such as with atmospheric oxygen or the transfer of energy to neighbouring molecules.[44]

Continuous and discontinuous exposure where periods of light and dark are utilized will yield different results. When the exposure is continuous the temperature of the sample is raised and the moisture content lowered. Certain reactions may be dependent on a specific moisture content. Also, raising the temperature over a certain period of time may induce degradative reactions to occur that are independent of the light and may be solely due to the heat. [45]

The degree of photodegradation of a sample is dependent on the net exposure determined by the product of the illumination by the length of time. This is known as the reciprocity principle. For example, exposure of a sample for 1 hour at 50 lux will yield the same result of 50 hours at 1 lux. Circumstances which are induced by the light such as the sample temperature being raised and the moisture content being lowered occasionally result in its failure.[46]

Artificially aged textiles are often irradiated by xenon-arc lamps which can be fitted to eliminate ultra-violet radiation below 400 nm. These lamps have a high wattage and are intended to simulate the light produced on an intense summer day.[47] This type of light would not typically be found in a museum setting. Instead Feller, and Bilz and Grattan have found that fluorescent lights may provide a suitable alternative for the purpose of accelerated ageing.[48,49] "...the use of fluorescent tubes screened (or filtered) by UV-absorbing polycarbonate sleeves has become common within museums in Canada although there are also many other forms of lighting, ranging from filtered daylight to tungsten filament spotlights. However, UV light has been largely eliminated within Canadian museums."[50] Another advantage of these lamps is that they do not cause heating of the samples beyond 25 - 28°C because they emit very little infrared light.[51]

2 MATERIALS AND METHODS

2.1 Selection and Preparation of Yarn Samples

New silk and polyester yarn were used in this study. Two types of silk were employed, the first being a pulled weft yarn from crepeline fabric[52] with a diameter measuring ~ 34 - 39 µm. The crepeline fabric has a stiff hand suggesting that the sericin gum may be present or that it may have a gelatin finish.[53] The second being a four-ply natural hair silk[54] with a Z-twist. It measures ~ 119 - 164 µm in diameter. These yarns are coated with the natural sericin gum. Both raw and degummed yarns were used. The polyester filament yarn was pulled from the Tetex® fabric[55] in the weft direction. The brown yarn is four-ply, while the undyed yarn is a monofilament measuring ~ 50 µm in diameter.

In each yarn category natural or undyed and dyed samples were utilized. The polyester Tetex® and silk crepeline fabrics were predyed by the manufacturer. Silk crepeline is dyed with an acid dye.[56] The polyester Tetex® may be dyed with disperse dyes[57] but this information was unavailable from the distributor. The hair silk (both raw and degummed) was dyed using *Irgalan Brown BL*, a 1:2 premetallized dye.

2.1.1 Degumming

One braid of hair silk was degummed using a standard procedure prior to dyeing. A 0.5% v:v solution of Synperonic N, a nonionic detergent, was prepared using a 100:1 liquor ratio with distilled water. In order to increase the pH to approximately 10 a 10% solution of sodium carbonate (Na_2CO_3) was added to the bath. The braid was then immersed into the solution and the temperature raised to 85°C. The bath was maintained at this temperature for 30 minutes when the braid was removed and rinsed

repeatedly.

Recipe: 1.4 g braid of hair silk
200 ml distilled water
1.0 ml (0.5%) *Synperonic N*
0.6 ml Na_2CO_3

2.1.2 Dyeing

Two braids of hair silk were then dyed, one degummed and one raw. Again, a standard procedure for dyeing silk was followed to achieve a 4% depth of shade. Additives, dye and distilled water made up the dye bath utilizing a 60:1 liquor ratio.[58] The additives which included 0.5% *Albegal A*, 4% ammonium sulphate, and 5%*Glauber's Salt* (sodium sulphate) were added and mixed well until the temperature reached 50°C. At this time the loosely braided silk which had been prewetted in an equally warm bath was immersed into the dye bath. This temperature of 50°C was maintained for 5 minutes then slowly raised over a period of 30 minutes to 85°C, which was maintained for 60 minutes. After the first 30 minutes 1% acetic acid was added. Throughout the dyeing procedure the bath was stirred. Following the dyeing the braids were allowed to cool down slowly then were thoroughly rinsed, blotted and air dried.

Recipe: 1.2 g of hair silk braids
9.6 ml of 0.5% dye stock solution
0.06 ml of 10% Albegal A stock solution
0.48 ml of 10% ammonium sulphate stock solution
0.6 ml of 10% Glauber's Salt stock solution
0.12 ml of 10% acetic acid stock solution

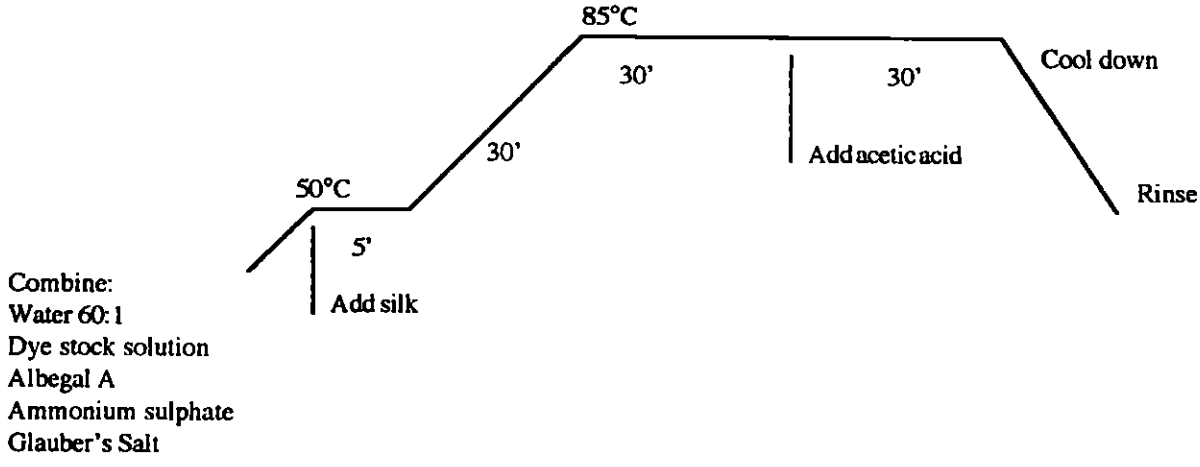


FIGURE 3. *Dye Procedure*

2.1.3 Measurement of Tex

Each type of yarn was measured to determine its linear density which is the weight in grams of a specific length of yarn. The units used to describe this are *tex* which is the weight of 1000 m of yarn or denier which is the weight of 9000 m of yarn. The linear density was determined for each category and sub-category of yarn by measuring three samples to obtain the average. For example, for degummed hair silk both dyed and undyed samples were measured.

To determine the linear density, a length of yarn was taped to a wall with a paper clip attached to the opposite end providing a light weight to extend any kinks in the yarn. Once the length was measured the yarn was cut and weighed to five decimal places.

2.1.4 Mounting of Yarns

Approximately ninety samples of yarn for each category and sub-category were cut into 45 ± 5 cm lengths and mounted onto three sheets of Coroplast®. Each end of the yarn was secured with double sided masking tape to the Coroplast® so that every yarn would receive the full light exposure.

For Each Yarn Type:	→ Undyed	→ UV light	~45 samples
		→ Filtered UV light	~45 samples
	→ Dyed	→ UV light	~45 samples
		→ Filtered UV light	~45 samples

Yarn Types Include: Raw Hair Silk, Degummed Hair Silk, Crepeline Yarn, Tetex® Yarn

2.2 Accelerated Ageing

Exposure to fluorescent light at 20,000 lux was selected as the method for accelerating photochemical degradation of the yarn samples. The mounted yarns were placed 15 cm below a bank of 16 fluorescent GE® lamps, each 34 watts of the cool white variety.

The UV radiation was measured at 60 - 120 µW/lumen (measured by an Elsec® UV Monitor type 762 which reads 300 - 400 nm). To reduce the UV light from half of the samples a Mylar® film coated with a UV filter (normally used for coating windows) was placed over the yarns. To avoid direct contact with the Mylar® film and allow for air circulation small blocks of ethafoam supported it over the yarns. The UV radiation was reduced to < 20 µW/lumen. Two fans were placed at one end of the ageing chamber to minimize the buildup of heat, where a temperature at 24 - 26° C was maintained and an RH of ~55%.

The samples were placed beneath the lamps for a total period of 58 days with 14 days off. Generally, they cycled for 5 days on and 2 off except for the final week which was extended by 3 days. Using the reciprocity principle and the CCI slide rule to determine light damage[59] the estimated equivalent length of exposure @ 50 lux would be ~80 years. These yarn samples were aged for more hours in the day than the CCI slide rule is based on so an equivalence of 180 years may be presumed, although with hesitation. The on/off cycles play a significant role in degradation so ageing behavior may not be so easily assumed.

The CCI light slide rule assumes an artifact will be displayed for 2920 hours per year (based on an 8 hour day) whereas the samples were aged according to an 8760 hour year (based on a 24 hour day), resulting in a 1:3 ratio. Therefore, ageing the samples for a total of 44 (24 hour) days assumes 60 years @ 50 lux x 3 resulting in an equivalence of 180 years.

2.3 Measurement of Physical Properties

2.3.1 Tensile Properties

Tensile testing was used to obtain load-elongation curves thus determining the breaking strength and elongation at break for each yarn. These curves were converted into stress-strain curves in order to normalize the data so that comparisons could be drawn. The breaking tenacity or stress is "the force exerted on the specimen based on the linear density of the unstrained specimen"[60] which is expressed

the original length ($\Delta L/L_o$) and is dimensionless.[7]
The yield point is the point at which the curve moves from the elastic region to the plastic region where deformation is permanent and the sample no longer returns to its original state if released. The slope of the elastic region illustrates the brittleness or stiffness of a sample. Great steepness of slope indicates high brittleness.

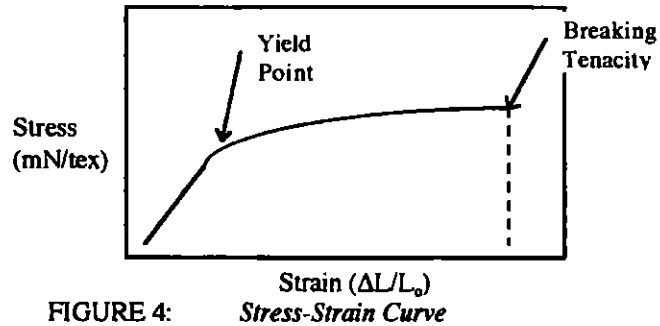


FIGURE 4: *Stress-Strain Curve*

The testing was accomplished on the *Instron TT-CM-L* which is a constant-rate-of-loading (CRL), screw driven testing machine. The clamps that were used were flat faced with a screw winding mechanism to hold the yarn in place. One end of the specimen was held in a stationary clamp (1) while the other was held in a clamp (2) that moved at varying speeds so as to exert a force at a predetermined rate. (See Figure 5).

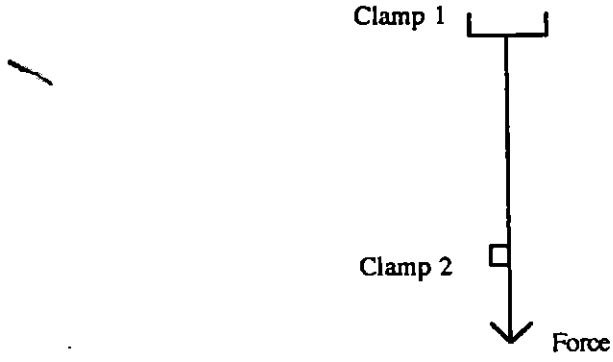


FIGURE 5: *CRL Mechanism*

Testing of each yarn type was conducted weekly. For the initial and final tests 10 ± 4 trials were done. For those weeks in between, at least 3 trials were conducted. Any samples believed to have slipped in the grips or that broke near the grip (within 3 mm) were rejected.

The standards for testing set by the *Canadian General Standards Board (CGSB)* "Breaking Strength of Yarns - Single Strand Method", No. 9.4-M91 and the *American Society for Testing Materials (ASTM)* "Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method", D 2256-95a were reviewed but not all testing parameters were able to be met. Testing was conducted in an unconditioned room where the humidity varied from 20 - 36% RH and the temperature from 23 - 26°C.

The higher humidity values occurred in the spring and affected the 'after ageing' tests and to a lesser extent, additional 'before ageing' tests. In order to try to minimize the effect of RH on the samples the mounts were transferred from the ageing site to the testing site in polyethylene bags containing an acid free card to provide a buffer. The mount was removed from the bag only immediately prior to testing and one yarn sample was cut off with scissors. The mount was then returned to the bag and resealed each time. The sample length used was 254 ± 2 mm (10 in). For the majority of the yarns the crosshead speed remained constant at 5 cm (2 in) per minute and the chart speed at 25.4 cm (10 in) per minute, giving a range of time to break from ~20 seconds to ~85 seconds. Therefore testing for each yarn sample was not conducted in the recommended 20 seconds. The additional 'before ageing' samples were recorded on a chart recorder that had a speed of 24.6 cm per minute.

2.4 Statistical Analysis

Independent pairs of samples were statistically analyzed using the *t-test for unequal variance*. A *t statistic* was generated from a statistical program in Microsoft® Excel 5.0 which was compared with a corresponding critical t-value for the 2-tailed test at a significance level of 0.05 (or 5%). The t-statistic had to exceed the critical t-value, without regard to the sign, in order for the null hypothesis to be rejected.[62]

> The null hypothesis states that no difference will be observed between the means of the compared pairs of yarns other than what can be attributed to random variation.

Within each yarn category the breaking elongation and breaking strength of the samples were analyzed before/during and before/after ageing. As well, undyed and dyed samples were compared both before and after ageing. Between types of categories raw hair silk and degummed hair silk were examined before and after ageing, both undyed and dyed. Tetex® was compared with crepeline and raw hair silk before and after ageing both undyed and dyed.

3 RESULTS AND DISCUSSION

Four types of yarns, both undyed and dyed, were exposed to a bank of fluorescent lights for 58 days in order to induce photodegradation at an accelerated rate. The temperature and humidity were kept relatively constant at 24 - 26° C and ~55% RH throughout the ageing period. The tenacity of the yarns were tested before, during and after ageing on an *Instron* tensile tester.

3.1 Analysis of Tensile Properties

The points generated from load-elongation curves for each yarn sample were converted into stress and strain data from which stress-strain curves were created. For each classification of yarn, multiple data series were plotted on one graph, for example *Undyed Hair Silk* 'Before Ageing' (see figures 6 - 29). Table 1 summarizes the means of the breaking points, both elongation and strength, as determined from the stress-strain curves.

Sample Calculation for *Undyed Hair Silk*:

Elongation	= crosshead speed x chart length/chart speed	→	Strain		= $\Delta L/L_o$
	= 0.2 x 0.4 cm				= 0.08/25.4
	= 0.08 cm				= 0.0031
Mass (g)	= 25 g →	Stress	= Force (mass x acceleration)/linear density (tex)		
			= 25g x 9.81 m/sec2/8.04 tex		
			= 30.51 mN/tex		

The time to break was not standardized at 20 seconds to break for each yarn category so generalizations regarding the tensile properties should take this into consideration, as a slower speed produces a lower breaking strength.[63] The average time to break for the crepeline yarn varied from 27 to 42 seconds, raw hair silk from 45 to 51 seconds, degummed hair silk from 35 to 45 seconds, whereas the Tetex® yarn varied from 57 to 69 seconds. (See Table 1).

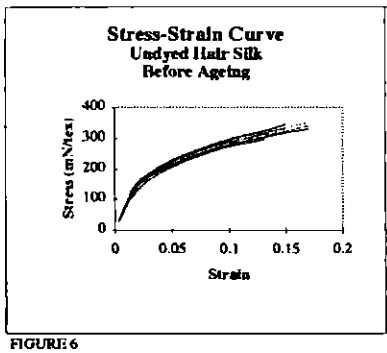
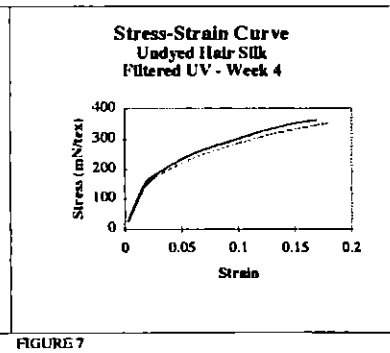


FIGURE 6



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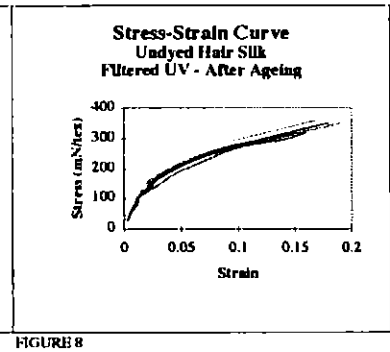

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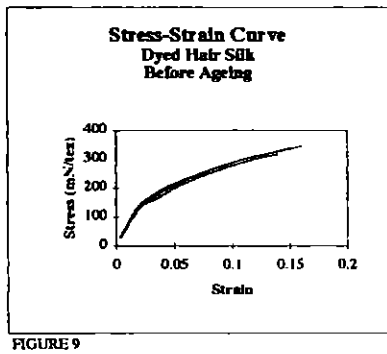

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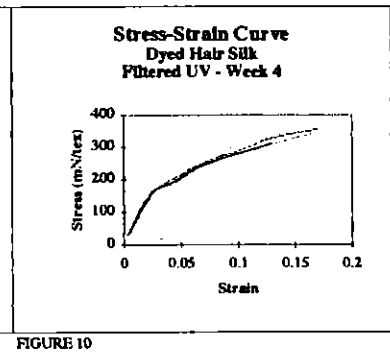
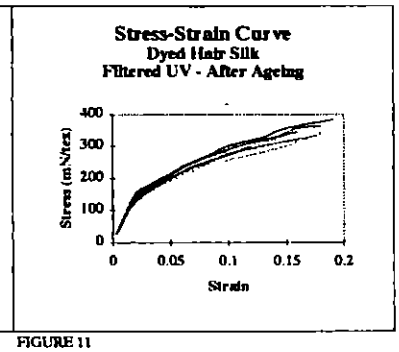


FIGURE 10



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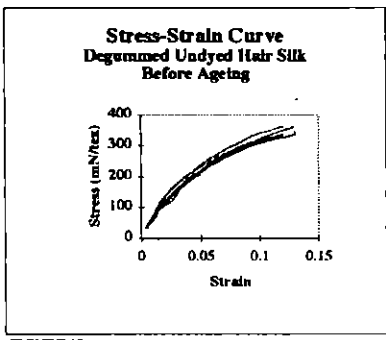

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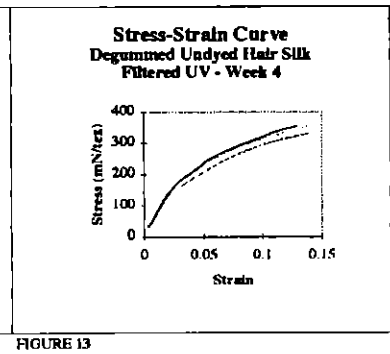

FIGURE 13

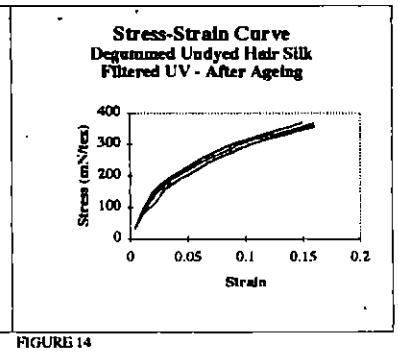

FIGURE 14

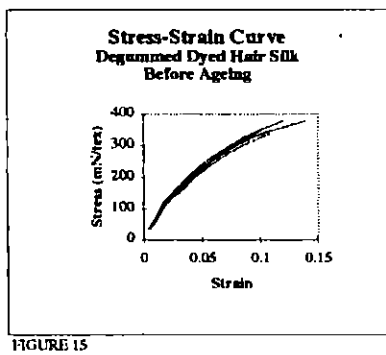

FIGURE 15

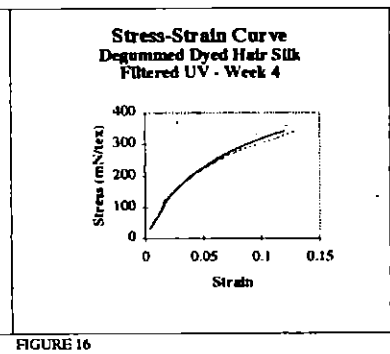

FIGURE 16

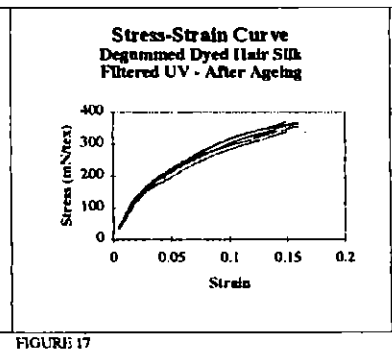

FIGURE 17

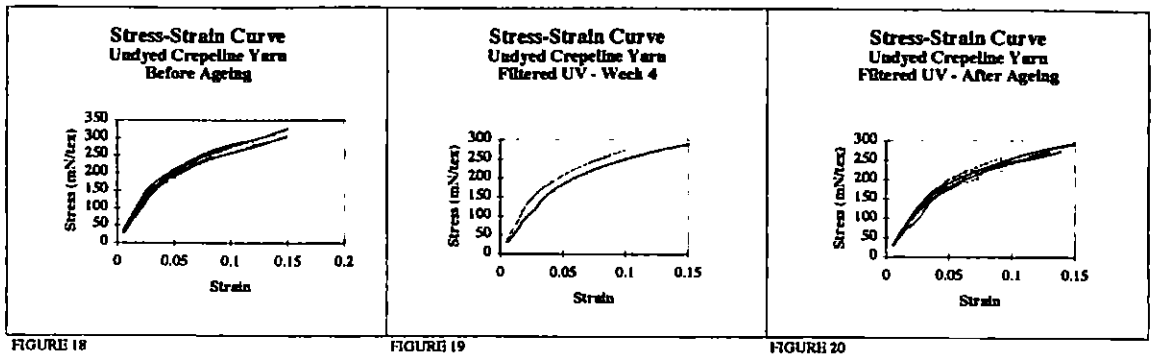

FIGURE 18 FIGURE 19 FIGURE 20

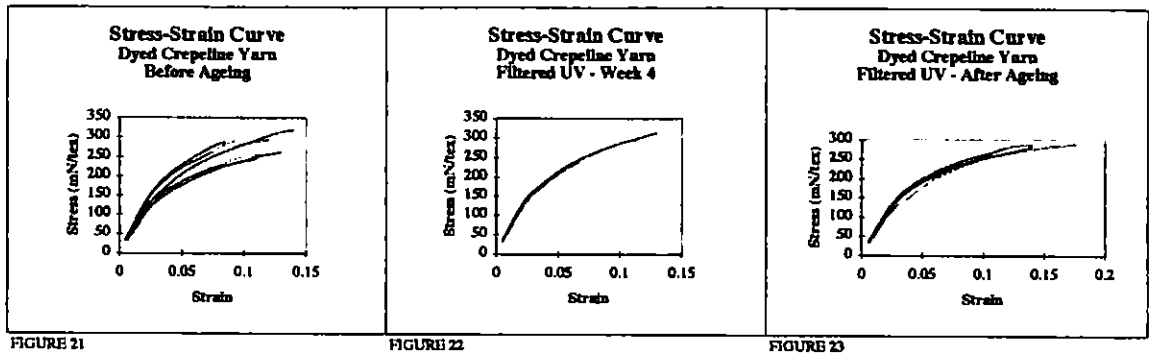

FIGURE 21 FIGURE 22 FIGURE 23

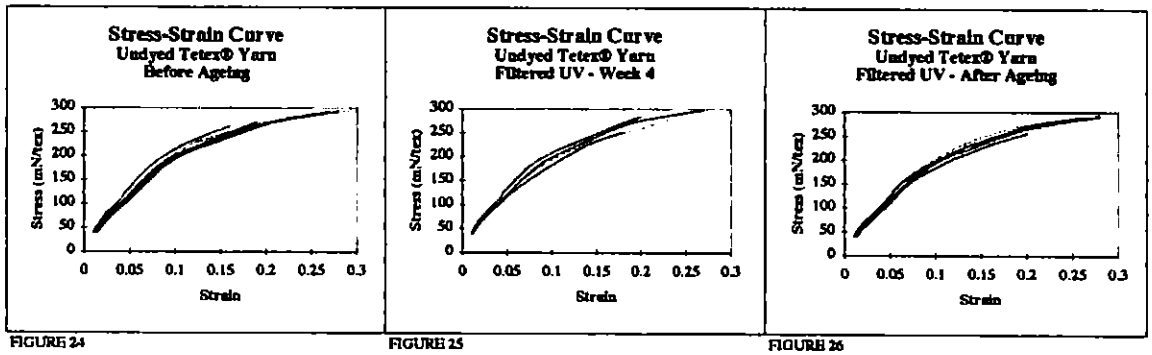

FIGURE 24 FIGURE 25 FIGURE 26

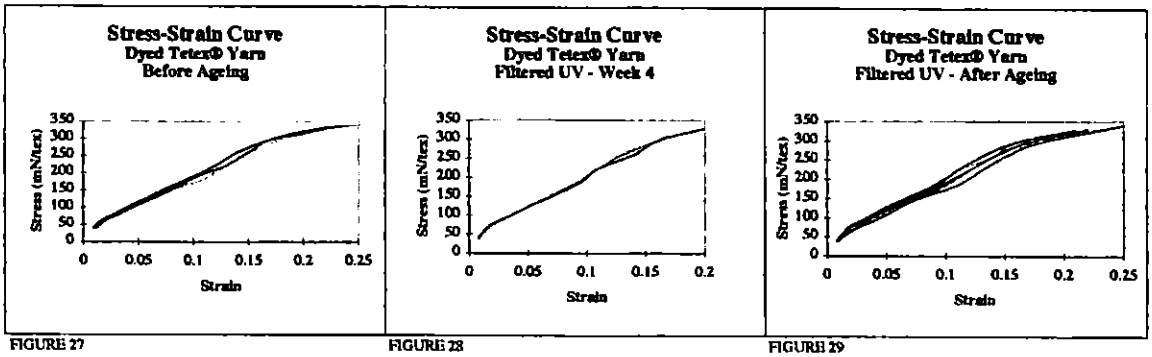

FIGURE 27 FIGURE 28 FIGURE 29

TABLE 1: *Elongation at Break and Breaking Strength of Yarn Types (Summary)*

	Before Ageing		Filtered UV Week 4		Filtered UV After Ageing	
	Temp 23.5-25°C RH 20-30%		Temp 23-25°C RH 25-29%		Temp 25-26°C RH 32-36%	
	Breaking Elongation	**Breaking Strength** (mN/tex)	**Breaking Elongation**	**Breaking Strength** (mN/tex)	**Breaking Elongation**	**Breaking Strength** (mN/tex)
	UNDYED RAW HAIR SILK					
Mean [Average Time to Break] (sec)	0.15 46	331.50	0.17 50	353.98	0.17 51	337.00
	DYED RAW HAIR SILK					
Mean [Average Time to Break] (sec)	0.15 45	334.64	0.15 46	337.46	0.17 51	337.73
	DEGUMMED UNDYED HAIR SILK					
Mean [Average Time to Break] (sec)	0.12 36	340.33	0.13 40	343.78	0.15 45	352.31
	DEGUMMED DYED HAIR SILK					
Mean [Average Time to Break] (sec)	0.12 35	355.90	0.13 38	349.28	0.15 45	355.70
	UNDYED CREPELINE YARN					
Mean [Average Time to Break] (sec)	0.14 42	308.21	0.12 35	265.54	0.12 36	260.26
	DYED CREPELINE YARN					
Mean [Average Time to Break] (sec)	0.11 33	281.80	0.09 27	266.34	0.11 33	261.95
	UNDYED TETEX® YARN					
Mean [Average Time to Break] (sec)	0.23 70	279.62	0.24 71	280.71	0.25 75	283.25
	DYED TETEX® YARN					
Mean [Average Time to Break] (sec)	0.22 66	328.89	0.19 57	323.05	0.21 64	327.32

3.1.1 Effect of Light

The most pronounced effect of the filtered UV light was seen with the *Undyed Crepeline* yarn. There was both a statistically significant decrease in the elongation at break and the tensile strength following ageing. The mean for the initial elongation at break was 0.14 which decreased to 0.12 after ageing, whereas the mean for the initial breaking strength was 308.21 mN/tex which decreased to 260.26 mN/tex. Decreases in both these properties were seen at week 4, however they were not statistically significant due to the lower sample size of the mid testing.

The *Dyed Crepeline* yarn also decreased in breaking strength from a mean of 281.80 to 261.95 mN/tex, however this was not a statistically significant difference as determined by the *t-test Assuming Unequal Variances.*

Undyed Hair Silk demonstrated a significant increase in tensile strength at week 4, increasing from 331.50 to 353.98 mN/tex. The increase dropped to 337 mN/tex after ageing which was not statistically significant. The silk may have been exhibiting signs of initial degradation when it begins to cross-link, whereby a temporary increase in strength would be expected. Again, the sample size for the mid testing was small so it is difficult to draw decisive conclusions from this increase.

Slight increases in tensile strength, although not statistically significant, were also observed for the *Dyed Hair Silk* and *Degummed Undyed Hair Silk* at week 4 and after ageing. This may have been due to the initial stages of deterioration, however the results are inconclusive.

Dyed Hair Silk, Degummed Undyed Hair Silk and *Degummed Dyed Hair Silk* all exhibited significant increases in the elongation at break after ageing. An increase was also noted with the *Undyed Hair Silk*, however it was not deemed significant. This increase may have been due to the higher humidity levels in the testing room during the final tests. Slight increases were also seen at week 4, similarly the RH was somewhat higher than most of the before ageing tests.

No significant changes were observed in the tensile properties of the polyester *Tetex®* yarn. This is in accordance with the hydrophobic nature of polyester.

The strength of a yarn is affected by the tex of the yarn. It is clear from the results of this portion of the study how this relates to the crepeline yarn. The crepeline exhibited the greatest deterioration and is the finest yarn. The tex varying from 1.57 to 1.66 compared with that of undyed hair silk being 9.09 (see Table 2). Because photodegradation is largely a surface phenomenon the finer silk thread degraded sooner than those that are heavier.

Yarn Type	Linear Density (tex)
Crepeline Yarn - undyed	1.66
Crepeline Yarn - dyed	1.57
Raw Hair Silk - undyed	9.09
Raw Hair Silk - dyed	8.99
Degummed Hair Silk - undyed	8.04
Degummed Hair Silk - dyed	7.78
Tetex® Yarn - undyed	2.54
Tetex® Yarn - dyed	2.65

TABLE 2. *Linear Density of Yarns*

3.1.2 Effect of Dye

Comparisons made between the undyed and dyed samples showed differences in the polyester and some of the silk yarns. The *Dyed Crepeline* demonstrated a significant decrease in both the breaking elongation and strength for the before ageing samples when compared with the *Undyed Crepeline*.. The mean of the breaking elongation for the Undyed Crepeline yarns was 0.14 compared with 0.11 for the *Dyed Crepeline* yarns. Likewise, the breaking strength decreased from 308.21 to 281.80 mN/tex.

Because this effect was seen only in the before ageing samples the loss of strength and elongation was related to the presence of the dye and not a photosensitizing effect caused by the dye. The yarn may have been weakened by the dyeing procedure or by the dye itself (acid dye). The crepeline fabric from which these yarn samples came had been in the Queen's artifacts laboratory for some time. Therefore, the 'before' state of these yarns is uncertain other than that they have been stored in a wooden cupboard shielded from the light. The ambient conditions of the lab are generally fairly stable. Repetition of the tensile testing for new undyed and dyed crepeline samples would shed more light on this effect.

An opposite effect on tensile strength was observed with the polyester *Tetex*® undyed and dyed yarns. Both the before and after ageing comparisons saw a significant increase in breaking strength of the dyed yarn samples. The mean of the 'before ageing' samples was 279.62 mN/tex for the undyed yarns and 328.89 mN/tex for the dyed yarns, whereas the 'after ageing' means were very similar being 283.25 and 327.32 mN/tex respectively. The elongation at break decreased significantly for the dyed 'after ageing' samples only. The difference in the tensile properties of the undyed and dyed *Tetex*® samples may be due to the variation in the ply of the yarn (the dyed yarn was 4 ply while the undyed yarn was a monofilament). Also, the type of dye used and possibly other additives such as UV absorbers are unknown.

No significant differences were observed between the undyed and dyed samples of *Raw Hair Silk* or *Degummed Hair Silk*. The dyes used on these yarns were 1:2 premetallized Irgalan dyes whereas those used by the manufacturer on the crepeline were acid dyes. This may have contributed to the difference, however it could also be due to ageing, as the hair silk may not yet have reached a similar stage of deterioration.

3.1.3 Effect of Degumming

The presence of the sericin gum on the yarns affects their tensile properties. A significant decrease was observed in the breaking elongation for the 'before ageing' and 'after ageing' of the *Degummed* yarns. Both undyed and dyed samples were compared with their corresponding degummed class, i.e. *Undyed Hair Silk/Degummed Undyed Hair Silk*. The presence of the gum makes the raw silk more responsive to the RH due to the greater percentage of polar groups found there. This would account for the higher readings for the elongation at break of the raw silk prior to degumming.

The breaking strengths increased for all categories of the degummed hair silk as above. However, only the 'after ageing' Undyed Hair Silk/Degummed Undyed Hair Silk and the 'before ageing' *Dyed Hair Silk/Degummed Dyed Hair Silk* categories were statistically significant. The increase in tenacity may be due to cross-linking which may occur during the initial stages of degradation. The protection offered by the gum would have been removed in the process of degumming.

3.1.4 Comparison of Fibre Type

Comparisons were made of the tensile properties between the silk and polyester yarns. *Undyed Tetex*® yarn compared with the *Undyed Crepeline* yarn demonstrated a significantly lower strength before ageing, their means being 279.62 and 308.21 mN/tex respectively. The opposite effect occurred after

ageing with their means being 283.25 and 260.26 mN/tex for the crepeline yarn. Compared with the *Dyed Crepeline* yarn, the *Dyed Tetex®* yarn had a significantly higher strength both before (328.89 vs 281.80 mN/tex) and after ageing (327.32 vs 261.95 mN/tex).

The *Hair Silk*, both undyed and dyed when compared with the same in *Tetex®* exhibited a significantly greater strength over that of the *Tetex®*. For example, the mean of the *Undyed Hair Silk* had a breaking strength of 331.50 mN/tex whereas the *Tetex®* mean was 279.62 mN/tex. *Tetex®* compared with all the above yarns exhibited significantly superior elongation at break.

4 CONCLUSIONS AND RECOMMENDATIONS

This study has found that a number of factors contribute to the strength and longevity of a yarn. These include the fibre strength, the tex of the yarn, the ply of the yarn, the presence of a dye and the presence of the gum, as in the case of silk. The exposure to fluorescent light radiation for 58 days with cycling incorporating 2 days off a week induced deterioration in only some of the yarn categories.

The greatest loss in tensile strength was seen in the silk crepeline yarn (particularly the undyed yarn) due to its fineness. None of the other categories exhibited losses in strength, however some showed slight increases but were not statistically significant.

The presence of a dye does have an effect on tensile strength for silk crepeline and polyester Tetex® only. The dye reduced the yarn strength of silk crepeline before the ageing began. Whereas none of the *Irgalan* dyed hair silk yarns exhibited a change in tensile strength. A study focusing on these dyes and others would help to clarify the interaction of dye and yarn. For example, crepeline which has been pre-dyed by the manufacturer could be compared with crepeline that has been in-house dyed with *Irgalan* dyes or other recommended dyes for use in textile conservation. The dyed samples of Tetex® yarns exhibited an increase in strength but a reduced elongation after ageing when compared with the undyed samples. This variation may be attributed to the difference in ply of the samples rather than the dye. Examining Tetex® yarns of the same ply would clarify the effect of the dye.

The process of degumming silk is often done by textile conservators prior to its use, especially if it will undergo dyeing as the resultant yarn becomes softer, has a higher lustre and may promote more level dyeing. The degummed hair silk showed an increase in tensile strength, possibly exhibiting the initial stages of degradation, as compared to the raw hair silk. A longer study would shed more light on this topic as the practice of degumming may not be necessary and, in fact, may accelerate degradation.

Textile conservators are often in a quandary about which yarn to choose for use on silk textile artifacts fearing that the polyester is "too strong". The results of this study have found that the polyester Tetex® yarn does not necessarily have a higher tensile strength than the silk yarn typically used in textile conservation. Even when its strength is higher, as it is with the silk crepeline, the strength of the Tetex® yarn does not exceed that of hair silk. Tetex® is hydrophobic so would not be as responsive to fluctuations in RH as silk, nor are its handling properties as favourable so this is where its use might be limited.

This preliminary study brings to light the need for further research in the area of yarns used for textile conservation. A longer period of light ageing at a low intensity would increase the confidence level so that an expected lifetime for each yarn could be better predicted. Ageing in a cycle of 8 to 10 hours of light exposure per day would more realistically simulate a museum exhibit setting.

Testing should adhere to conditions and parameters set out by the CGSB or ASTM standards - such as an RH of 65%, conditioning of the yarns to this RH prior testing, and the time to break should be ~20 seconds for all yarn types. If this is not possible, at least the same conditions should be maintained

throughout. Besides tensile testing biochemical analysis of the amino acids of the silk or the functional groups of polyester would provide additional information as to the chemical modifications occurring during ageing.

For this 8 week period of light ageing the exposure equivalency based on CCI's light slide rule is a minimum of 80 years (possibly 180 years) @ 50 lux. This life expectancy places the hair silks, both raw and degummed, and the polyester Tetex® in at least Category B (possibly Category A) as defined by Feller. The crepeline would likely fall into Category B, however the load-elongation curves for the mid weeks of testing would require further analysis illuminating that point at which degradation occurs. Increasing the rate of exposure until most or all samples demonstrated severe loss of strength would provide a greater insight on the ageing behavior of these particular yarns.

Endnotes:

[1] Refers to the yarn as it is reeled from the cocoon.
[2] Sheila Landi, The Textile Conservator's Manual (Toronto: Butterworths, 1985) 95.
[3] J.W.S. Hearle & R. Greer, Textile Progress, Fibre Structure (Manchester: The Textile Institute, 1970) 51.
[4] Howard L. Needles, "Protein Structure. Keratins and Fibroin," Protein Chemistry for Conservators (Washington: AIC, 1984) 20.
[5] Eric F. Hansen & Harry Sobel, "Effect of the Environment on the Degradation of Silk: A Review," The Textile Specialty Group Postprints, Papers Delivered at the Textile Subgroup Session, AIC 20th Annual Meeting Buffalo, NY, June 1992, Vol. 2: 15.
[6] Ibid., 16.
[7] Ibid., 26.
[8] Ibid., 16-17.
[9] Howard L. Needles, "Protein Structure. Keratins and Fibroin," Protein Chemistry for Conservators (Washington: AIC, 1984) 23.
[10] J. Gordon Cook, Handbook of Textile Fibres, Natural Fibres (Durham: Merrow Publishing Co. Ltd:, 1984) 159.
[11] Eric F. Hansen & Harry Sobel, "Effect of the Environment on the Degradation of Silk: A Review," The Textile Specialty Group Postprints, Papers Delivered at the Textile Subgroup Session, AIC 20th Annual Meeting Buffalo, NY, June 1992, Vol. 2: 16.
[12] J. Gordon Cook, Handbook of Textile Fibres, Natural Fibres (Durham: Merrow Publishing Co. Ltd., 1984) 154.
[13] Mary A. Becker, Polly Willman & Noreen C. Tuross, "The U.S. First Ladies Gowns: A Biochemical Study of Silk Preservation," JAIC 34 (1995):142-43.
[14] Ibid., 150.
[15] Eric F. Hansen & Harry Sobel, "Effect of the Environment on the Degradation of Silk: A Review," The Textile Specialty Group Postprints, Papers Delivered at the Textile Subgroup Session, AIC 20th Annual Meeting Buffalo, NY, June 1992, Vol. 2: 17.
[16] Howard L. Needles, "The Deterioration of Proteinaceous Materials. Keratins and Silk," Protein Chemistry for Conservators (Washington: AIC, 1984) 37.
[17] Ibid., 37-38.
[18] Ibid., 37.
[19] Eric F. Hansen & Harry Sobel, "Effect of the Environment on the Degradation of Silk: A Review," The Textile Specialty Group Postprints, Papers Delivered at the Textile Subgroup Session, AIC 20th Annual Meeting Buffalo, NY, June 1992, Vol. 2: 16.
[20] Randall R. Bresee & Gail Elizabeth Goodyear, "Fractography of Historic Silk Fibers," Historic Textile and Paper Materials, Conservation and Characterization (Washington: American Chemical Society, 1986) 97.
[21] Randall R. Bresee, "General Effects of Ageing on Textiles," JAIC 25 (1986):42.
[22] Mary A. Becker, Polly Willman & Noreen C. Tuross, "The U.S. First Ladies Gowns: A Biochemical Study of Silk Preservation," JAIC 34 (1995):148.
[23] Eric F. Hansen & Harry Sobel, "Effect of the Environment on the Degradation of Silk: A Review," The Textile Specialty Group Postprints, Papers Delivered at the Textile Subgroup Session, AIC 20th Annual Meeting Buffalo, NY, June 1992, Vol. 2: 20.
[24] Ibid., 17.
[25] Randall R. Bresee & Gail Elizabeth Goodyear, "Fractography of Historic Silk Fibers," Historic Textile and Paper Materials, Conservation and Characterization (Washington: American Chemical Society, 1986) 107.
[26] Ibid., 107.
[27] The Textile Institute, Identification of Textile Materials, 7th ed. (Manchester: The Textile Institute, 1985) 37.
[28] J. Gordon Cook, Handbook of Textile Fibres, Man-made Fibres (Durham: Merrow Publishing Co. Ltd., 1984) 332.
[29] Ibid.,341
[30] E.P.G. Gohl & L.D. Vilensky, Textile Science (Melbourne: Longman Cheshire Pty Ltd., 1990) 117.
[31] J. Gordon Cook, Handbook of Textile Fibres, Man-made Fibres (Durham: Merrow Publishing Co. Ltd., 1984) 358.
[32] E.P.G. Gohl & L.D. Vilensky, Textile Science (Melbourne: Longman Cheshire Pty Ltd., 1990) 95.
[33] Marjory Joseph, Introductory Textile Science 2nd ed. (Toronto: Holt, Rinehart & Winston Inc., 1972) 195.
[34] Eric F. Hansen & Harry Sobel, "Effect of the Environment on the Degradation of Silk: A Review," The Textile Specialty Group Postprints, Papers Delivered at the Textile Subgroup Session, AIC 20th Annual Meeting Buffalo, NY, June 1992, Vol. 2: 19.
[35] Robert L. Feller, Accelerated Aging, Photochemical and Thermal Aspects (Ann Arbor, Michigan: The Getty Conservation Institute, 1994) 60.
[36] E.R. Trotman, Dyeing and Chemical Technology of Textile Fibres (High Wycombe, G.B.: Charles Griffin & Co. Ltd., 1984) 256.
[37] E.P.G. Gohl & L.D. Vilensky, Textile Science (Melbourne: Longman Cheshire Pty Ltd., 1990) 125.
[38] Linda Knutson, Synthetic Dyes for Natural Fibres (Loveland, Co.: Interweave Press, 1986) 18.
[39] Jentina E. Leene; L. Demény; R.J. Elema; A.J. de Graaf & J.J. Surtel, "Artificial Ageing of Yarns in Presence as Well as in Absence of Light and Under Different Atmospheric Conditions," ICOM Committee for Conservation, 4th

Triennial Meeting, Venice, Italy, 1975: 5.
[40] Randall R. Bresee, "General Effects of Ageing on Textiles," JAIC 25 (1986):43.
[41] Robert L. Feller, Accelerated Aging. Photochemical and Thermal Aspects (Ann Arbor, Michigan: The Getty Conservation Institute, 1994) 5.
[42] Ibid., 6.
[43] Ibid., 8.
[44] Ibid., 47-48, 51.
[45] Ibid., 111-112.
[46] Robert L. Feller, Accelerated Aging. Photochemical and Thermal Aspects (Ann Arbor, Michigan: The Getty Conservation Institute, 1994) 53.
[47] Malcom Bilz & David Grattan, "The Development of an Apparatus for Studying the Effect of Light Exposure on Museum Materials," ICOM Committee for Conservation, 10th Triennial Meeting, Washington, D.C., 1993: 559.
[48] Robert L. Feller, Accelerated Aging. Photochemical and Thermal Aspects, (Ann Arbor, Michigan: The Getty Conservation Institute, 1994) 91.
[49] Malcom Bilz & David Grattan, "The Development of an Apparatus for Studying the Effect of Light Exposure on Museum Materials," ICOM Committee for Conservation, 10th Triennial Meeting, Washington, D.C., 1993: 559.
[50] Ibid., 559.
[51] Robert L. Feller, Accelerated Aging. Photochemical and Thermal Aspects (Ann Arbor, Michigan: The Getty Conservation Institute, 1994) 94.
[52] Crepeline fabric is manufactured by Paul L.G. Dulac & C^{ie} in Lyon, France.
[53] Personal communication with Season Tse of the Canadian Conservation Institute has suggested that the silk crepeline has a gelatin finish. Specifications regarding this fabric from the manufacturer were unavailable.
[54] Hair silk is manufactured by Tassinari Chatel in Lyon, France.
[55] Polyester Tetex® fabric was formerly known as Stabiltex® and is manufactured by the Swiss Silk Bolting Cloth Mfg. Co. Ltd. in Zurich, Switzerland.
[56] Personal communication with Jan Vuori of the Canadian Conservation Institute passed on this information received from the manufacturer, Paul L.G. Dulac & Cie in Lyon, France.
[57] Peter Scheibli & Gert Reinert, "Dyeing," Tomorrow's Ideas & Profits, Polyester, 50 Years of Achievement (Manchester: The Textile Institute, 1993) 152.
[58] The liquor ratio was increased from the recommended 40:1 ratio so that the yarns were more easily wetted by the dye solution.
[59] 'A Slide Rule to Determine Light Damage' available from CCI, Ottawa, Canada
[60] ASTM, "Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method1," D 2256-95a, 1995 Annual Book of ASTM Standards, Section 7 Textiles (Philadelphia, ASTM, 1995) 565.
[61] Mary Ballard, "Mechanical Properties: Preview and Review," Textile Conservation Newsletter 28 (1995):18.
[62] J.C. Miller & J.N. Miller, Statistics for Analytical Chemistry 2nd ed. (Toronto: John Wiley & Sons, 1988) 54.
[63] J.E. Booth, Principles of Textile Testing (N.Y.: Chemical Publishing Co., Inc., 1969) 366.

References:

Anon. 1995. "Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method". 1995 Annual Book of ASTM Standards. Vol. 7.1. Philadelphia: ASTM.

Anon. 1993. "Colorfastness to Light". AATCC Technical Manual. Research Triangle Park, N.C.: American Association of Textile Chemists and Colorists.

Anon. 1991. "Breaking Strength of Yarns - Single Strand Method". Textile Test Methods. Ottawa: Canadian General Standards Board.

Anon. 1987. "Linear Density of Yarn in SI Units". Textile Test Methods. Ottawa: Canadian General Standards Board.

Anon. 1987. "Precision and Accuracy of Measurements". Textile Test Methods. Ottawa: Canadian General Standards Board.

Ballard, Mary W. 1995. "Mechanical Properties: Preview and Review". Textile Conservation Newsletter 28:14-28.

Becker, Mary A.; Willman, Polly & Tuross, Noreen C. 1995. "The U.S. First Ladies Gowns: A Biochemical Study of Silk Preservation". JAIC 34.2:141-52.

Bilz, Malcom & Grattan, David. 1993. "The Development of an Apparatus for Studying the Effect of Light Exposure on Museum Materials". ICOM Committee for Conservation, 10th Triennial Meeting, Washington, D.C., 1993 II:559-565.

Booth, J.E. 1969. Principles of Textile Testing. N.Y.: Chemical Publishing Co., Inc.

Bresee, Randall R. 1986. "General Effects of Aging on Textiles". JAIC 25.1:39-48.

Bresee, Randall R. & Goodyear, Gail Elizabeth. 1986. "Fractography of Historic Silk

Fibers". Historic Textile and Paper Materials. Conservation and Characterization. eds. Howard L. Needles & S. Haig Zeronian. Washington, D.C.: American Chemical Society. 95-109.
Callister, William D. 1985. Materials Science and Engineering. An Introduction. Toronto: John Wiley & Sons, Inc.
Cook, J. Gordon. 1984. Handbook of Textile Fibres. I. Natural Fibres. 5th ed. Durham, England: Merrow Publishing Co. Ltd.
Cook, J. Gordon. 1984. Handbook of Textile Fibres. II. Man-made Fibres. 5th ed. Durham, England: Merrow Publishing Co. Ltd.
Feller, Robert L. & Johnston-Feller, Ruth. 1979. "Use of the International Standards Organization's Blue-Wool Standards for Exposure to Light. II. Instrumental Measurement of Fading". AIC Preprints of Papers Presented at the Seventh Annual Meeting, Toronto, Canada, 30-31 May and 1 June 1979 30-36.
Florian, Mary Lou. 1984. "Conservation Implications of the Structure, Reactivity, Deterioration and Modification of Proteinaceous Artifact Material". eds. C.L. Rose & D.W. Von Endt. Washington, D.C.: AIC. 67-82.
Furter, R. 1985. Strength and Elongation Testing of Single and Ply Yarns: Experience with Uster® Tensile Testing Installations. Manchester: The Textile Institute.
Griffin, Elizabeth C. 1995. "The Effects of Iron Mordants Used with Natural Dyes on Cellulosic Textiles". MAC Research Project. Kingston: Queen's University.
Gohl, E.P.G. & Vilensky, L.D.1983. Textile Science. 2nd ed. Melbourne: Longman Cheshire Pty Ltd.
Grayson, Martin. ed. 1984. Encyclopedia of Textiles, Fibers, and Nonwoven Fabrics. Toronto: John Wiley & Sons
.Halvorson, Bonnie G. & Kerr, Nancy. 1994. "Effect of Light on the Properties of Silk Fabrics Coated with Parylene-C". Studies in Conservation 39:45-56.
Hansen, Eric F. & Sobel, Harry. 1992. "The Deterioration and Preservation of Silk". The Textile Specialty Group Postprints. Papers Delivered at the Textile Subgroup Session. AIC 20th Annual Meeting, Buffalo, NY, June 1992 14-30.
Hearle, J.W.S. & Greer, R. 1970. Textile Progress. Fibre Structure. Vol. 2. No. 4 ed. P.W. Harrison. Manchester: The Textile Institute.
Hersh, S.P.; Tucker, P.A. & Becker, M.A. 1989. "Characterization of Historical and Artificially Aged Silk Fabrics". Archaeological Chemistry IV. ed. Ralph O. Allen. Washington, D.C.: American Chemical Society.
Johnson, Alan (ed.) 1989. The Theory of Coloration of Textiles. Bradford, G.B.: Society of Dyers and Colourists.Joseph,
Marjory L. 1972. Introductory Textile Science. 2nd ed. Toronto: Holt, Rinehart and Winston, Inc.
Kerr, Nancy. 1995. Edmonton: University of Alberta. Personal Communication.
Knutson, Linda. 1986. Synthetic Dyes for Natural Fibres. Loveland, Co.: Interweave Press.
Komatsu, Kei-Ichi. 1979. "Chemistry and Structure of Silk". JARQ 13.1:64-72.
Kuruppillai, R.V.; Hersh, S.P. & Tucker, P.A. 1986. "Degradation of Silk by Heat and Light". Historic Textile and Paper Materials. Conservation and Characterization. eds. Howard L. Needles & S. Haig Zeronian. Washington, D.C.: American Chemical Society. 111-127.
Landi, Sheila. 1988. "The Arguments For and Against the Use of Synthetic Fibres for Sewing in Textile Conservation". 20th Century Materials, Testing and Textile Conservation. Washington, D.C.: Harpers Ferry Regional Textile Group.
Landi, Sheila, 1985. Textile Conservator's Manual. Toronto: Butterworths.
Lyle, Dorothy Siegert. 1977. Performance of Textiles. Toronto: John Wiley & Sons.
McAngus, E.H. & Adams, W.W. 1969. Physical Textile Testing at Westpoint Pepperell. West Point, Georgia: West Point -Pepperell, Inc.
McCaffrey, Lana M. 1992. "Some Theory Behind Silk Degradation and Stabilization".

Silk. Washington, D.C.: Harpers Ferry Regional Textile Group.
Miller, J.C. & Miller, J.N. 1988. Statistics for Analytical Chemistry. 2nd ed. Chichester, West Sussex.
Needles, Howard L. 1984. "Protein Structure. Keratins and Fibroin". Protein Chemistry for Conservators. eds. C.L. Rose & D.W. Von Endt. Washington, D.C.: AIC. 18-24.
Needles, Howard L. 1984. "Technological Modifications of Proteinaceous Materials and the Effect on Stability. Wool and Silk Textiles". eds. C.L. Rose & D.W. Von Endt. Washington, D.C.: AIC. 58-60.
Rheinberg, Leslie. 1991. "Silk, The Continuous Filament Natural Fibre". Textiles 4:6-10.
Sahai, S.N. 1975. "Some Trends in Finishing of Silk". Textile Dyer & Printer 8.5:39-43.
Taylor, Marjorie A. 1990. Technology of Textile Properties. 3rd ed. London: Forbes Publications Ltd.
Textile Conservation Group, N.Y. 1993. "The Thread Survey". Insert. Textile Conservation Newsletter 24.Spring.
The Textile Institute. 1985. Identification of Textile Materials. Manchester: The Textile Institute.
Trotman, E.R. 1984. Dyeing and Chemical Technology of Textile Fibres. High Wycombe, G.B.: Charles Griffin & Co. Ltd.
Tse, Season. 1995. Ottawa: Canadian Conservation Institute. Personal Communication.
Vuori, Jan. 1995. Ottawa: Canadian Conservation Institute. Personal Communication.
Zeronian, S.H.; Alger, K.W.; Ellison, M.S. & Al-Khayatt, S.M. 1986. "Studying the Cause and Type of Fiber Damage in Textile Materials by Scanning Electron Microscopy". Historic Textile and Paper Materials. Conservation and Characterization. eds. Howard L. Needles & S. Haig Zeronian. Washington, D.C.: American Chemical Society. 77-93.