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Hair Mechanical Properties Depending on Age and Origin

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***Abstract*—**Hair is a non homogenous complex material which can be associated with a polymer. It is made up 95% of Keratin.

Hair has a great social significance for human beings. In the High Middle Ages, for example, long hairs have been reserved for kings and nobles.

Most common interest in hair is focused on hair growth, hair types and hair care, but hair is also an important biomaterial which can vary depending on ethnic origin or on age, hair colour for example can be a sign of ethnic ancestry or age (dark hair for Asiatic, blond hair for Caucasian and white hair for old people in general).

In this context, different approaches have been conducted to determine the differences in mechanical properties and characterize the fracture topography at the surface of hair depending on its type and its age.

A tensile testing machine was especially designed to achieve tensile tests on hair. This device is composed of a micro-displacement system and a force sensor whose peak load is limited to 3N. The curves and the values extracted from each experiment, allow us to compare the evolution of the mechanical properties from one hair to another.

Observations with a Scanning Electron Microscope (SEM) and with an interferometer were made on different hairs. Thus, it is possible to access the cuticle state and the fracture topography for each category.

***Keywords*—**Hair, relaxation test, SEM, interferometer, mechanical properties.

I. Introduction

MANY studies have been made on the hair to improve its appearance and enhance its mechanical properties using shampoo, after-shampoos and care creams. However, no study was interested on hair as a biomaterial whose mechanical properties depend on age or ethnic origin.

The purpose of this study is to achieve this goal.

A. Hair structure

Despite the large number of studies conducted for over 40 years, hair structure is not fully known.

The hair shaft is composed of three concentric parts: the cuticle, the cortex and the medulla (Fig 1). Each element has a different structure and function which are detailed below.

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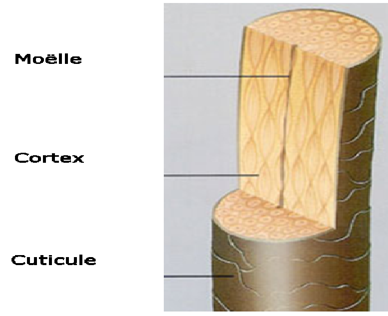


Fig. 1 Hair shaft.

- The cuticle protects the inner part of the hair against the external environment and damage caused by daily treatment (sunlight and moisture).

The cuticle has a thickness of 3 to 5µm. It represents about 10% of the hair weight. It is composed of a dozen layers of keratin cells which are in the origin flatten during ascent in the follicle. These cells, having a thickness about 0.5µm, are intertwined with each other as on a slate roof and also linked to the cortex.

- The cortex represents about 90% of the fibre weight. It is made of a complex and multi-scale fibrillary system, giving it its mechanical properties (Fig 2). It breaks down as follow:

  - The helix α is the smallest element of this structure with a diameter of 10 Ǻ;
  - The combination of two or three α helixes can provide protofibril;
  - 9 protofibrils bind to form a microfibril;
  - The macrofibril has a length of 100µm and a diameter about 3 to 6µm, combines many microfibrils by a covalent bonds with an amorphous matrix.

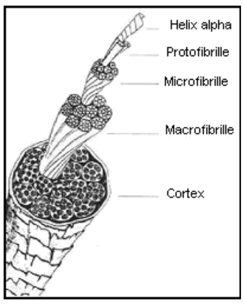


Fig. 2 Intern structure of the hair.

- The medulla: This element in the center of the hair shaft appears rarely and can in some cases totally disappear. It is more present in animals. It provides a function in regulating body temperature, but in humans its usefulness remains secondary.

B. Mechanical properties

The stress/strain curves obtained after traction tests on hair have the following form (Fig 3).

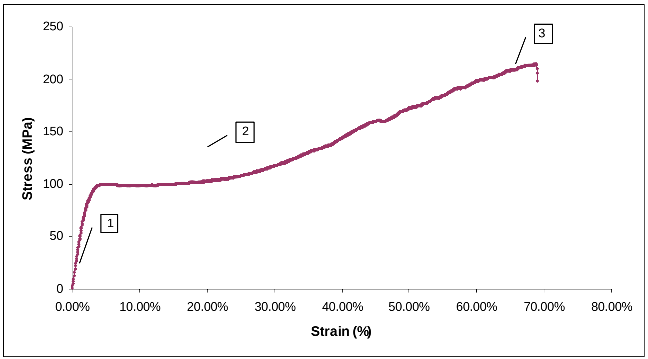


Fig. 3 Stress strain curve.

This curve can be broken up into three parts:

- A first part: the Hookean region. It can be split into two parts: a first linear rubber band, for which Young modulus is determined; and a non linear band, in which the deformation is visco elastic. In this latter, the strain is non recoverable due to a low distortion of the weakest bonds of the structure (hydrogen and the salt bonds) [3].

- A second part: the Yield region. For which the Yield stress is extracted. This region is characterised by a visco plastic deformation related to the progressive transition of keratin from the folded state (α-helical) to the extended state (β-pleated sheets) in which some hydrogen bonds are perpendicular to the axis of the fiber and stretched covalent bonds form a heavily intertwined stabilized network [4], [3].

- A third part: the post Yield region. For which the breaking stress and strain are determined. In this region, there is a transition phase that shows a gradual increase in the stress with strain. Then, a linear phase indicates a ratio relatively constant between stress and strain that led to the sudden rupture of the sample.

In the first part, the force is applied to the whole structure; Stretching requires simultaneous deformation of the microfibrils and the matrix because they are considered in parallel [1]. An extension without breaking bonds is implemented. During the transition between the Hookean and the Yield regions, the delayed mechanism of elasticity can be explained by the beginning of the process of diffusion under the action of the stress. This latter distorts the free energy barriers, of the molecular segments in the matrix [3].

In this study, instead of doing traction tests, relaxation ones were chosen. These tests were done on the elastic domain. Hair is stretched up to 2% of its original length. The curve has the following form (fig 4)

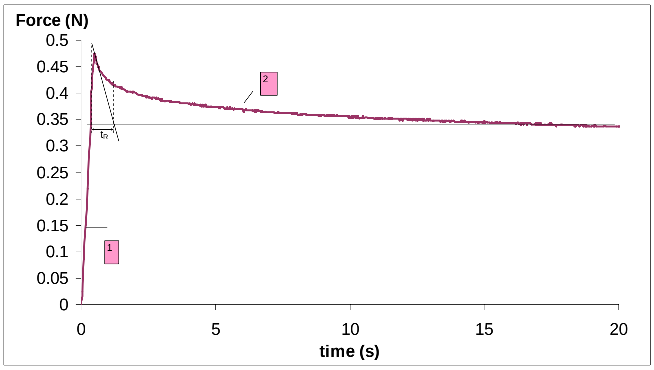


Fig. 4 Hair relaxation curve.

This curve presents two parts:

- Traction part , from which the stiffness can be determined;
- Relaxation part, from which the relaxation time can be calculated by computing the intersection of the tangent in the beginning of the relaxation curve with the tangent in his end as indicated on figure 4.

The curves and the values extracted from each experiment, allow us to compare the evolution of the mechanical properties of each type of hair.

II. Material and Methods

A. Traction and relaxation test

A tensile testing machine was especially designed for experiments on a single hair. This apparatus is composed by a high precision engine and a force sensor (Fig 5).

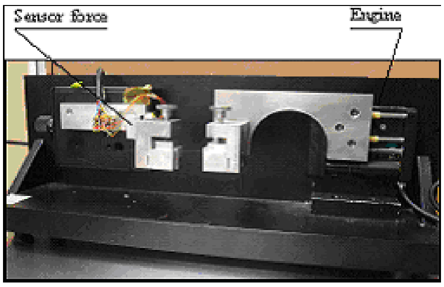


Fig. 5 Tensile test machine.

This device incorporates the functions of a conventional tensile test machine with:

- A sample holder,
- A translation module to pull on the sample;
- A force sensor to compute the applied force on the fiber.

The translation module is a Polytec Instruments stepper motor. This engine can reach a maximum speed of 1.5 mm/s over a distance of 25mm with a very high resolution lower than 1/100th.µm. The speed and the displacement are controlled by a card connected to the engine control. The force sensor which can load a maximum of 3N with a resolution of 1mN permits to calculate the force. The applied stress on the sensor is transmitted to a computer via a National Instrument capture card and an amplifier. A program, implemented on Labview, permits to control the engine movement and the data acquisition.

B. Surface characterization

Observations with a Scanning Electron Microscope (SEM) and interferometer were made on different type of hair to access the cuticle state and the fracture topography for each type.

An optical interferometer (brand device: WYKO) with high precision, was used to obtain topographic image. VSI mode was used with a PSI filter "High Magnitude" and a magnification of x 50 x 1.5.

Vertical scanning interferometer microscope

The h surface topography was studied with an interferometer microscope that combines two technologies to measure a wide range of surface heights. Phase shifting interferometry (PSI) mode is used to measure smooth surfaces, while vertical scanning interferometry (VSI) mode is used to measure the skin surface topography. This new scanning mode is based on the same principle as phase shifting interferometry: the light reflected from a reference mirror combines with the light reflected from a sample to produce interference fringes, where the best contrast of fringes occurs at the best focus.

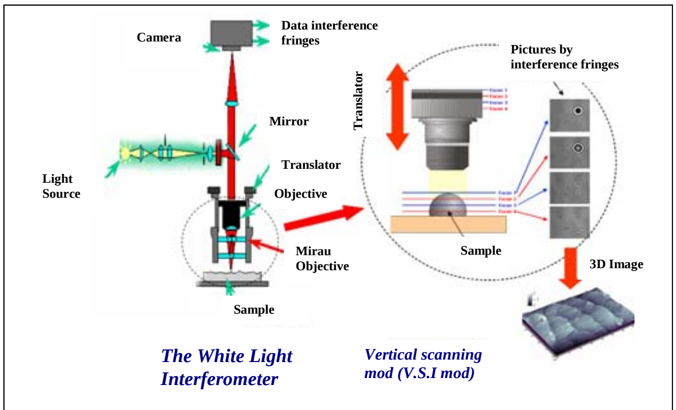


Fig. 6 Principle of interferometer [8].

During the measurement, the reference arm containing the interferometric objective moves vertically to scan the surface at varying heights.

A linearised piezoelectric transducer precisely controls the motion. Because white light has a short coherence length, interference fringes are present only over a very shallow depth for each focus position. Fringe contrast at a single sample point reaches a peak as the sample is translated through focus. The VSI technique uses an algorithm that processes fringe modulation data from the intensity signal to calculate surface heights. As seen in Figure 2, the fringe contrast increases as the sample is translated into focus, and falls as it is translated past focus. The system scans above through focus at evenly spaced intervals as the camera captures frames of interference data. As the system scans downward, an interference signal is recorded for each point on the surface. The system uses a series of advanced computer algorithms to modulate the fringe signal. Finally the vertical position corresponding to the peak of the interference signal is extracted for each point on the surface.

Resolution and range of measurements

Resolution refers to the smallest distance the interferometer surface profilers can accurately measure. It can be considered in terms of lateral or vertical resolution. The vertical resolution value of the VSI mode is about 3 nanometers with a vertical range of 2000 µm. Lateral resolution is a function of the magnification objective and the chosen detector array size. The range of lateral resolution is between 0.08 µm and 3.2 µm depending on the magnification objective. The choice of the magnification objective implies a certain sampling step and the area zone which can be scanned.

C. Hair types

The current study was carried out in Ecole Centrale de Lyon, Laboratory of Tribology and Systems Dynamics. Hairs of twenty volunteers from different regions were collected (9 from Europe, 4 from Asia and 7 from North Africa).

The age range was from 1 to 62 years, with a majority between 20 and 40 years. Between 10 and 20 hairs were cut off from each person at a distance of 1 cm from the root. The relaxation tests were done on the first 8 cm for each fibre. Mechanical properties can vary from the root to the end. [5].

All hairs were cleaned with shampoo and kept in an enclosure controlled in temperature (25°C±3) and in humidity (%45HR±3) for 24 hours before doing tests.

III. Results

A. Mechanical properties of hair depending on age

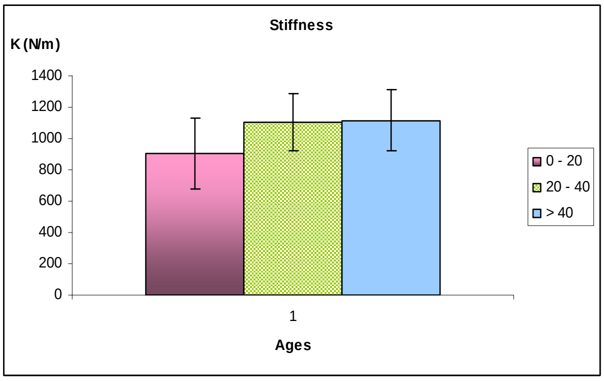


Fig. 7 Variation of stiffness depending on age.

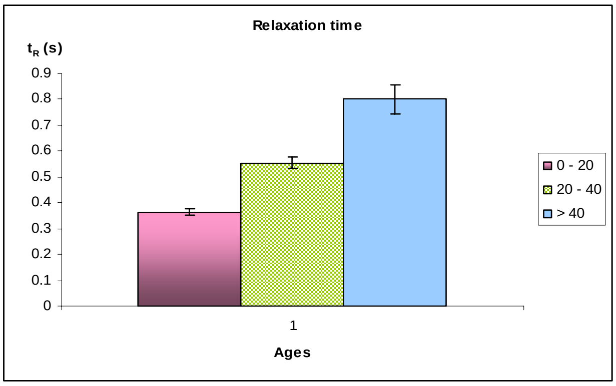


Fig. 8 Variation of relaxation time depending on age.

The statistical difference in hair stiffness between individuals with different ages was insignificant (Fig 7). However, the data showed a significant augmentation of the time relaxation with the augmentation of the age (Fig 8). The relaxation time of individuals older than 40 years was much higher than this of individuals younger than 20 years old.

B. Mechanical properties of hair depending on origin

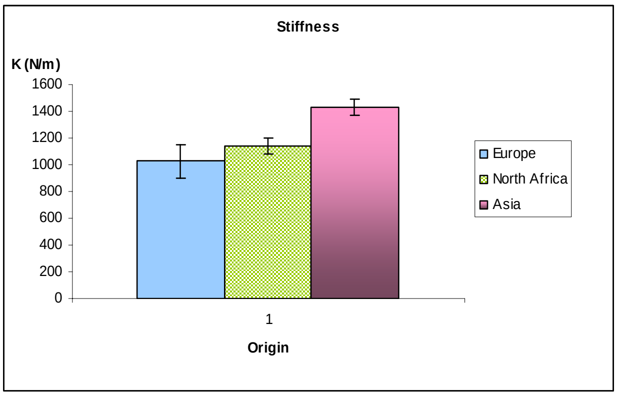


Fig. 9 Variation of stiffness depending on origin.

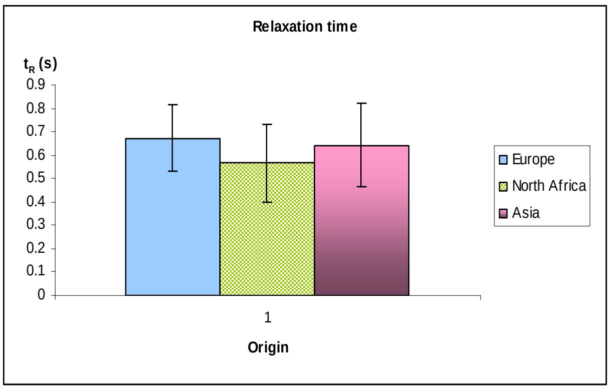


Fig. 10 Variation of relaxation time depending on origin.

The statistical difference in hair stiffness between individuals from different regions was significant (Fig 9). The stiffness of Asiatic volunteers was higher than others. However, an insignificant difference was detected for the time relaxation with the variation of the origin of individuals (Fig 10).

C. Topography

The topography measurements are generally performed on a single hair. A profil of the surface is obtained as we can see below (Fig 11) [8]:

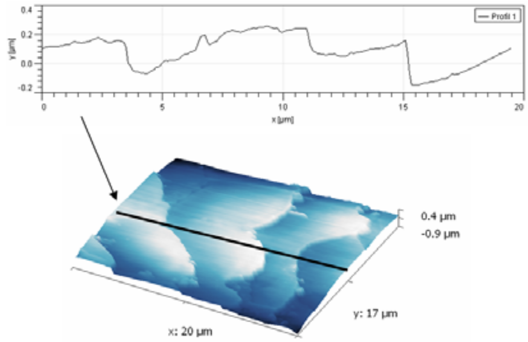


Fig. 11 Image of the cuticle and surface profile associated.

The interferometer uses a white light, reflected on the surface of the sample, allows to draw a profile of the surface on different levels: By moving the detector along the vertical axis, the focal plane occupies different heights, and makes a series of "optical sections" of the sample surface.

The most known parameter to measure the surface topography is SPA. It gives a value of the roughness of the surface. But this parameter has showed many limits. It can not alone characterise a surface [9].

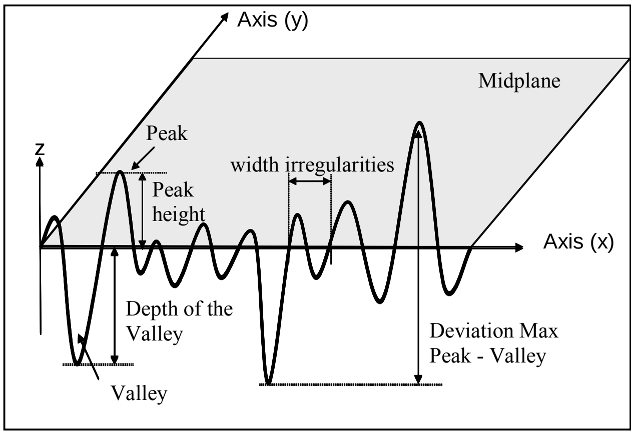


Fig. 12 Morphology of a 3D surface.

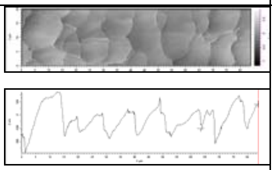
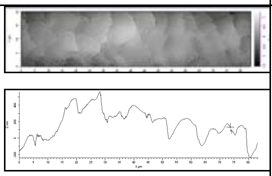
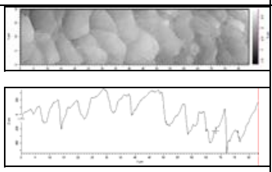
The parameters of figure 12 are used to describe the morphology of the surface relief. They describe altitude and spatial variations, defined according to 3 groups [9]:

- Extreme values of altitudes (SPt, SPp, SPv): These settings only take into account the maximum value of an altitude variation between a peak and a valley. Experiences shows that in most cases these values are not representative of the overall morphology of the surface;

- The average values of altitudes (SPtm, SPpm, SPvm): These settings present the average of each value of the same settings mentioned above. These parameters are significant, and allow the experimenter to have an initial objective approach to the surface;
- Spatially average values (SPmx, SPmy): The width of spatial irregularities of the surface can be measured on the X and Y axis of the relief. An algorithm detects in each axis the periodicity of the morphology of the relief where it intersects the baseline of the mean plane. An average value is then calculated for the X and Y axis. This parameter is a very good indicator of the average width. That's why, it is used for random surfaces.

In our study, the two last parameters were used.

TABLE I
SURFACE TOPOGRAPHY OF DIFFERENT TYPE OF HAIR

	Surface topography	SPA (nm)	bêta	SPmx (µm)	SP_{my} (µm)
Europe		206.85	16.57	4.40	3.62
North Africa		311.46	19.95	4.76	3.79
Asia		231.95	16.73	5.09	4.08

The statistical differences in surface roughness, beta and mean spatial parameters in the X and Y direction between individuals from different regions were significant (Table 1).

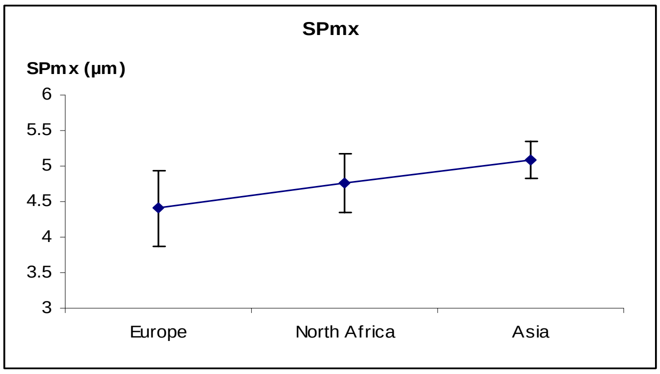


Fig. 13 Variation of mean spatial parameter in X direction depending on origin.

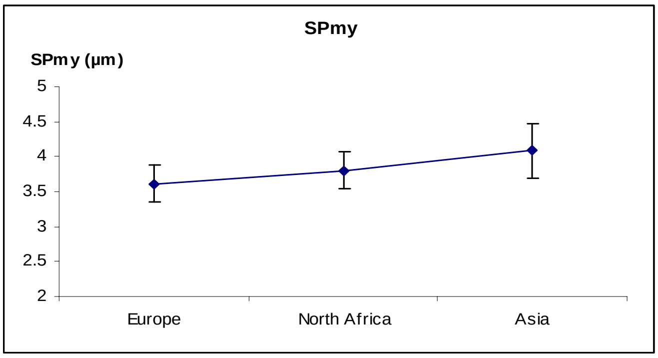


Fig. 14 Variation of mean spatial parameter in Y direction depending on origin.

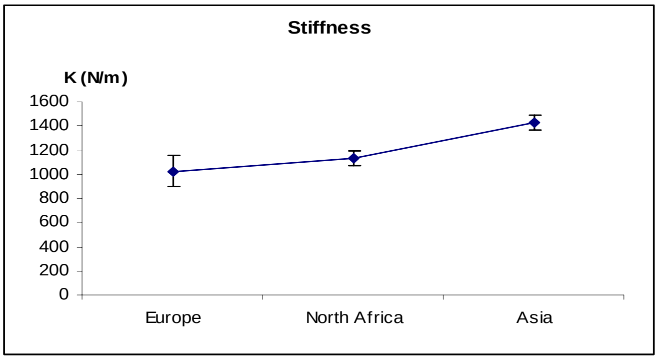
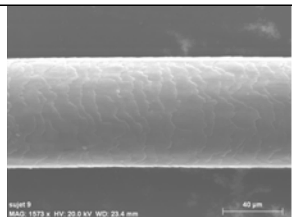
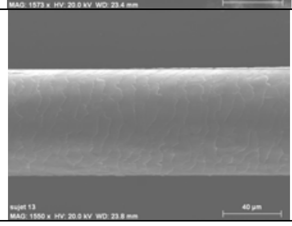


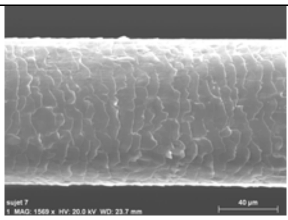
Fig. 15 Variation of Stiffness depending on origin.

The data showed a significant variation between the stiffness and the dimension of the scales. Asiatic volunteers, having large scales, have the higher stiffness (Figs 13, 14 and 15).

D. Scanning Electron Microscope

TABLE II
SURFACE TOPOGRAPHY OF DIFFERENT TYPE OF HAIR

	Surface topography	Ø (µm)	Cuticle width (µm)
Europe		72.7	9.06
North Africa		73.72	8.9

Asia		95.03	8.63

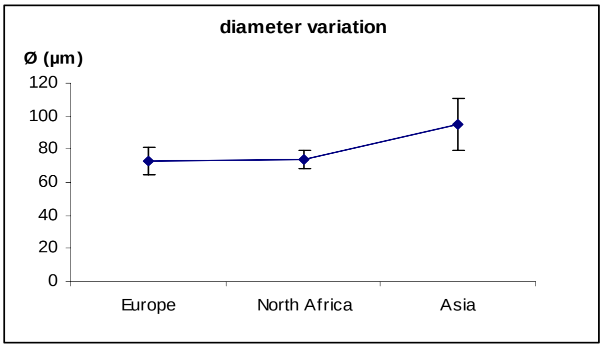


Fig. 16 Variation of diameter depending on origin

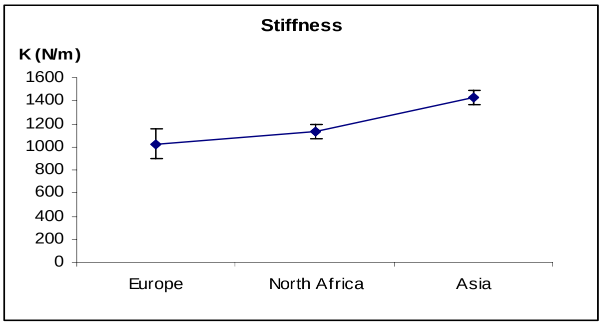


Fig. 17 Variation of stiffness depending on origin

The data showed a significant variation between the stiffness and the diameter of hairs from different volunteers (Figs 16 and 17).

IV. Discussions

Mechanical properties of hair can vary depending in many parameters, such as temperature, humidity, external environment, chemical products … these parameters was the subject of many studies to understand their influence on the behaviour of the mechanical properties of hair.

Previous studies on the mechanical behaviour of human hair were conducted using stress strain curve. Whereas, the method described in the present paper use force time curve to limit error associated with measuring the section of hair.

This method was the subject of the first part of our study, in which, influence of age and origin on stiffness and relaxation time was treated. As a result, a significant difference in the stiffness was observed, when origin is different. However, no significant difference noticed for relaxation time with the variation of the same parameter.

In the other hand, the statistical difference in hair stiffness between individuals at different ages was insignificant. However, the reverse behaviour was seen for the relaxation time with the augmentation of the volunteer age.

Based on our study, we can conclude that stiffness is related to the origin of the person, and relaxation time is related to the age.

In the second part, surface topography was studied. In this part, a significant variation was detected between the variation of the stiffness and the mean spatial parameters in X and Y directions, which allow us to conclude that stiffness depends on the dimension of the scales.

To go further, observations with a Scanning Electron Microscope (SEM) were made to access the cuticle state. No significant variation between the cuticle widths was observed. However, the data showed a significant variation between the diameter and the stiffness of hairs from different volunteers.

[4] demonstrated that there are mechanical parameters of human hair related to gross hair morphology, whereas others depend on hair microstructure. In this context, our study clearly documented that Stiffness depends on origin and scales dimension, so, it depends in the major part on the interaction between external environment and surface. While relaxation time, depends only on the internal part of the hair (cortex).

V. Conclusions

From this study, we can conclude that, to determine the influence of the parameters mentioned above on the mechanical behavior of hair, we have to use hairs from people belonging to the same age range and the same ethnic origin.

To study mechanical properties, two methods exist: traction and relaxation test. In our study, the last one was used in order to make the modelling behind.

Relaxation tests were done on the Young region, permitting to understand the behaviour of the mechanical properties of hair. Carrying out traction tests will bring more explanations about the behaviour of hair in the Yield and post Yield regions.

In the Future, different treatments will be made to try to understand causes of hair damage. The goal is to find limits of every parameter and the nature of treatment that makes deformation reversible and does not damage the hair.

Many studies were conducted to understand the behaviour of hair properties, mainly in chemical and mechanical domains. Correlating the two domains can lead to better understand the behaviour of hair with different treatments.

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