Nanostructure and Mechanical Properties of Hair Due to Colour Treatment

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Introduction

Colouring of hair with biological substances, in particular plant dyes such as Henna or Indigo, are widely used procedures to achieve a variation in the appearance and specific look of many people.
Strong and durable dyeing of hair, however, is a challenging task. The colouring substances have to infiltrate a material with different structures such as the cuticle and the cortex.
As hair is also a hierarchically structured material, it has additional structural features at different length scales, from atomic to the nanoscale.

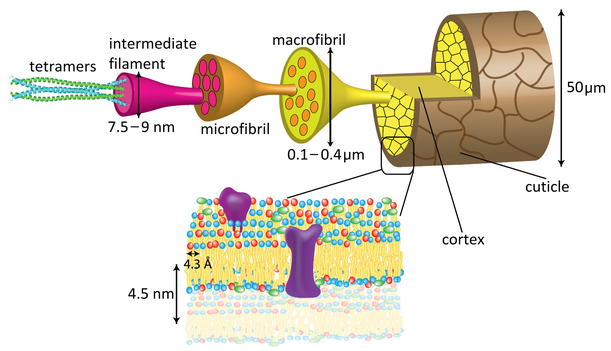


Figure 1: Hierarchical structure of hair, adapted from [1]

One important structural level is the intermediate filament formed by keratin coiled-coils with a diameter of ~7.5–9 nm.
At this size level, we investigated the effect of colouring dyes on the nanostructure by small-angle X-ray scattering (SAXS) techniques.
The structural data are correlated to mechanical data from tension tests, as well as colour data from light transmission experiments using a spectrophotometer.

Small Angle X-ray Scattering

Cu-K_α radiation with a wavelength of $\lambda = 0.1542$ nm were used in the X-ray scattering experiments. SAXS covers scattering angles $2\theta \leq 4°$. Small scattering angles correspond to larger objects in real space.

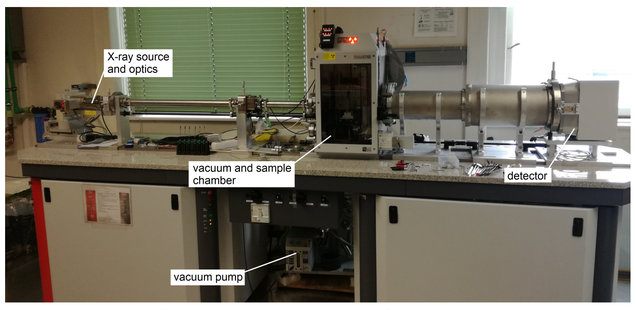


Figure 2: SAXS-system of our group

X-ray measurements were performed in our lab to investigate the nanostructure of hair treated with different types of dye containing Henna and Indigo.

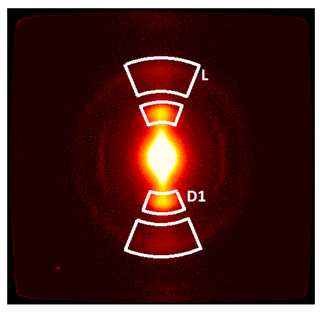


Figure 3: SAXS-diffraction pattern of a hair bundle,
D1 ... arrangement of intermediate filaments, L ... lipid layers

Mechanical Tests

A tensile testing machine was used to determine mechanical parameters of bundles of ~30 hairs with a gauge length of 10 mm.

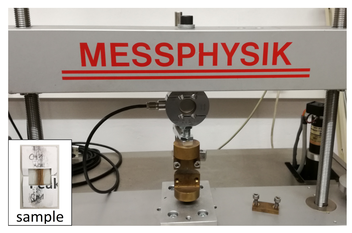


Figure 4: Tensile testing machine

Load and extension data were collected with a load cell and a linear variable differential transformer (LVDT) respectively.

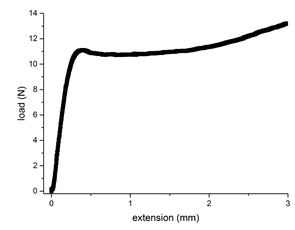


Figure 5: Collected extension vs. load plot of hair bundle

Furthermore the *area of the bundles' cross section* was determined for stress calculation using a Zeiss Axioplan microscope.

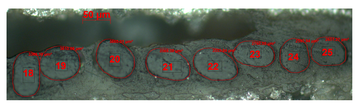


Figure 6: Microscopical view - cross section of hairs

Determination of Colours

To determine the colours of our hair samples, we used a Varian Spectrophotometer.

Figure 7: Varian Spectrophotometer

Collected spectra normalized and multiplied with CIE's colour-matching-functions (CMFs).

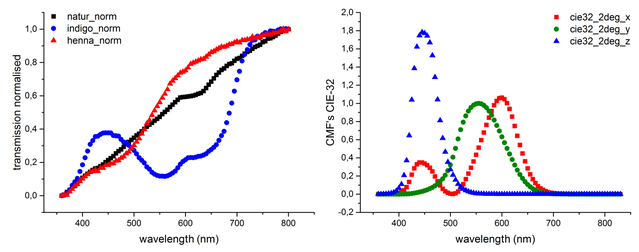


Figure 8: Normalized spectra (left), CMFs (right)

Calculations provide the *colour coordinates* [2] L*(luminosity), a*(green to red) and b*(blue to yellow) in the CIE-colourspace and *distances between colours* in this space.

L*=	75	50	80
a*=	6	18	13
b*=	36	-27	51

Figure 9: Resulting colours for the spectra in fig.8

Structural Analysis

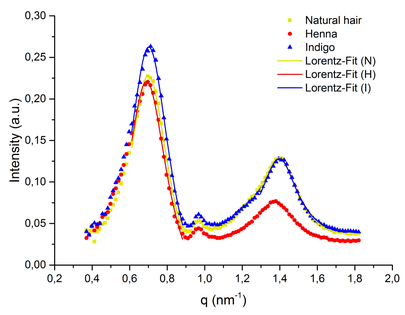


Figure 10: Integrated intensity vs. scattering vector from fig.3 and Lorentz-fits of the peaks

The 2D SAXS data from our experiments were radially integrated and background corrected to obtain intensities in dependence on the scattering vector q.
Peaks were fitted with Lorentzian functions and the maxima were used to calculate typical distances such as the filament-to-filament and the lipid layer-to-layer distance.

Mechanical Analysis

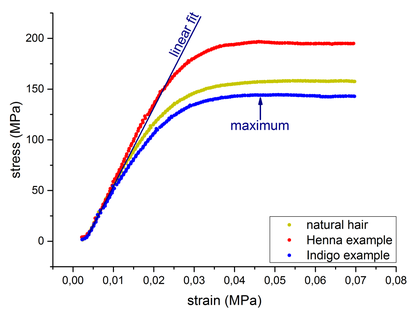


Figure 11: Stress vs. strain plots for natural hair and hair treated with Henna and Indigo

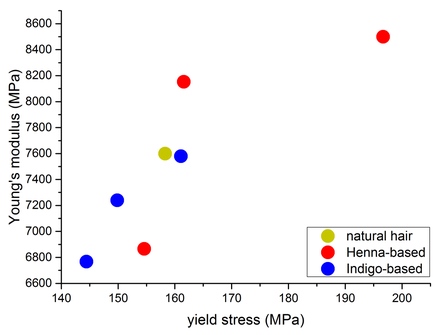
The elastic regime and the first part of the plastic regime in the stress-strain plots were evaluated. The *modulus of elasticity* (or Young's modulus) was determined using the slope of linear fits of the elastic region,

$$\sigma = E \cdot \varepsilon \qquad (1)$$

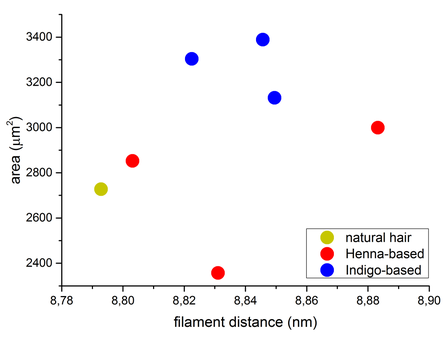
while the local maximum of the curves is the *yield stress*.

Correlation

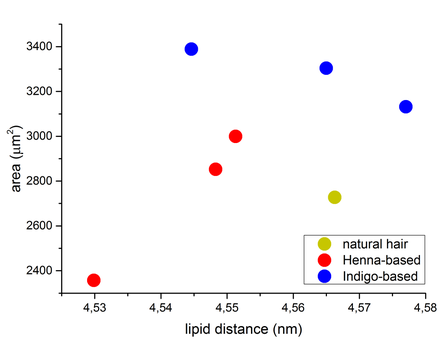
Young's modulus vs. yield stress



cross-sectional area vs. filament distance



cross-sectional area vs. lipid distance



Conclusion

Hair dyes show an effect on the properties of hair.
Indigo results in a decrease of Young's modulus and yield stress, while Henna based dyes mostly lead to a mechanical improvement.
Hair dyed with indigo based colours show an increase of the cross-sectional area, where Henna only results in minor changes to this parameter.
Both Indigo and Henna enlarge the filament distance, while Henna induces a decrease in distance between lipid layers.

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[1] Yang F., Zhang Y., Rheinstädter M.C. - https://upload.wikimedia.org/wikipedia/commons/5/55/Hierarchical_structure_of_hair_in_the_cortex_and_cuticle.png (08.03.2018)
[2] Daniel Malacara - Color Vision and Colorimetry : Theory and Applications, 2nd ed., SPIE press, 2011