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„Advantages of the in situ diameter measurement for the tensile behavior analysis of Mangalitza pig hair and poly(ethylene terephthalate) fibers“

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List of symbols and abbreviations

PET poly(ethylene terephthalate)

IF intermediate filament

KFAP keratin filament associated protein

CMC cell-membrane complex

1. Introduction

For many industrial applications as well as for fundamental research, the accurate knowledge of material-dependent parameters is of importance. These parameters can be calculated by measuring stress-strain curves of the examined material. For some quantities, like Young's modulus, the sample's cross-section is often assumed to be constant throughout the measurement or it is calculated by measuring the sample diameter in front view. This is, however, a simplification because in most cases, the cross-section changes during the measurement and measuring the specimen's diameter at a fixed angle is not entirely suitable for samples with an elliptical cross-section. Therefore, significant errors are to be expected for elliptical samples when only the initial cross-section or the cross-section derived from the front view diameter is used to calculate the stress and deduced parameters. Measuring Poisson's ratio is often reduced to measuring the initial and final sample diameter or observing the diametric changes from one angle only. The diameter is however not guaranteed to behave the same way when looked at from different perspectives.

The present work investigates stress-strain curves of Mangalitza pig hair and poly(ethylene terephthalate) (PET) fibers as well as related parameters such as Young's modulus and Poisson's ratio. Pig hair has been chosen for its natural inhomogeneity and non-circular cross-section. The results will be compared to the technically produced and more homogeneous PET fibers. Stress (load), strain (extension) and sample diameter have been recorded using a newly-developed device which allows for an all-around detection of the sample diameter and therefore a precise calculation of the sample's cross-section and of other diameter-dependent values like Young's modulus or Poisson's ratio. The presented measuring approach enables an accurate investigation of the tensile behavior of inhomogeneous materials such as biological fibers like hair.

Another part of the present work was determining the load train compliance for the measuring device. This has been done by measuring different copper wire samples.

After introducing the theoretical background that will be needed to contextualize the present work, the above-named device will be introduced. The compliance measurement as well as the measurements with pig hair and PET fibers will be described and the corresponding results will be discussed. Besides interpreting and comparing the mechanical behavior for the pig hair and the PET fibers, the advantages of the used measuring setup compared to traditional approaches which either do not measure the sample diameter during the measurement or measure it from one angle only will be demonstrated.

2. Physical background

In the following, an overview of the straining experiment and associated parameters like Young's modulus and Poisson's ratio will be given. Afterwards, the physical and chemical properties of the materials used in this thesis, i.e. pig hair and poly(ethylene terephthalate) fibers, will be presented.

2.1. Mechanical behavior of materials

2.1.1. Stress and strain

Mechanical stress is defined as the force acting on a specific area. For a specimen under deformation, the so-called engineering stress σ consists of the occurring load F divided by the initial cross-sectional area A_0 [1]:

$$\sigma = \frac{F}{A_0}. \quad (2.1)$$

The engineering stress disregards the specimen's changes in area during loading. For this reason, one can define the true stress σ_t by dividing the load F by the actual area A [1]:

$$\sigma_t = \frac{F}{A}. \quad (2.2)$$

Strain defines the change in size of a body during deformation. The engineering longitudinal (i.e. measured along the straining axis) strain ϵ is given by

$$\epsilon = \frac{\Delta L}{L_0}, \quad (2.3)$$

where L_0 defines the initial length and $\Delta L = L - L_0$ the change in length [1]. There can also be calculated a true strain from the engineering strain. However, in the proceeding,

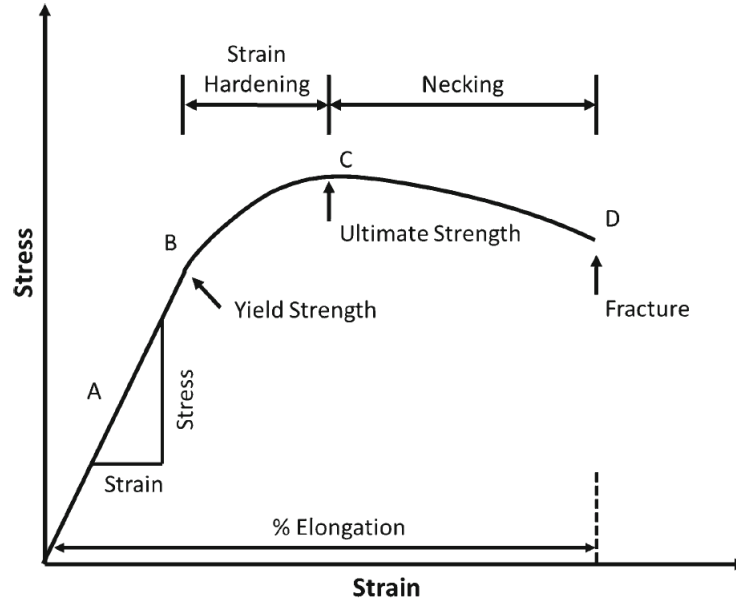


Figure 2.1.: *Typical stress-strain curve with arbitrary units [2]. The Hookean region (A), the yield point (B) and the region of plastic deformation (C) are visible.*

only the engineering strain will be used.

Strain cannot only be defined for the longitudinal change in size but also for the transverse one (see Section 2.1.3).

By straining a specimen and measuring the load required to produce the deformation, a stress-strain curve, giving the relationship between mechanical stress and strain, can be obtained. In the beginning of such a curve, the stress increases linearly with strain for most materials. This section of the stress-strain curve is called Hookean region because it satisfies Hooke's law (see Section 2.1.2).

Figure 2.1 shows a typical stress-strain curve. In the Hookean region (A), the deformation of the strained material is elastic and reversible. After the so-called yield point (B), high deformations can occur with relatively low changes in stress. This marks the beginning of plastic deformation (C) [1][2].

2.1.2. Young's modulus

For small strains, stress and strain are linearly related and the increase of the stress-strain curve can be described by Hooke's law

$$\sigma = E\epsilon, \quad (2.4)$$

with the stress σ and the strain ϵ [1]. The constant of proportionality E is called Young's modulus and is a material-dependent parameter. Young's modulus can be determined by measuring stress-strain curves and calculating the slope of the Hookean part. In many studies, the sample dimensions are measured before the straining and only the initial cross-sectional area is used for the stress (= engineering stress) calculation (compare for example [3] or [4]).

2.1.3. Poisson's ratio

When subjected to axial strain, a specimen does not only change in length but also in diameter. The relation between the specimen's deformation parallel to the direction of tension (longitudinal strain ϵ_l) and its deformation perpendicular to the direction of tension (diametric strain ϵ_d) is described by Poisson's ratio ν :

$$\nu = -\frac{\epsilon_d}{\epsilon_l} = -\frac{\Delta d}{\Delta L} \frac{L_0}{d_0}, \quad (2.5)$$

where $\Delta d = d - d_0$ is the change in diameter, $\Delta L = L - L_0$ the change in length, d_0 the initial diameter of the specimen and L_0 its initial length. [1]

In practice, Poisson's ratio can be obtained from the slope of the linear part of the diametric strain - longitudinal strain curve (compare [5]). During straining, the diameter can be kept track of using for example a laser [6] or a camera [5]. When the sample is looked at from one angle only, this does not provide full information on the diametric change and therefore Poisson's ratio if the sample is not perfectly circular in cross-section or if the diametric change is unevenly distributed.

For positive Poisson's ratios, the sample becomes thinner when strained. The diameter increases for negative values. Poisson's ratio is positive for most materials and negative values are only reported for specifically treated or synthetically produced materials in most cases [7]. Isotropic materials can only take Poisson's ratios between -1 and 0.5 [8].

Poisson's ratio is not a constant, but has been described, in case of viscoelastic materials like semicrystalline polymers, as a „time-dependent material function“ [9]. It is found to increase with time for polypropylene [10] and for polymeric solids in general [11]. Poisson's ratio is also found to be strain-dependent [12][13].

The classical definition of Poisson's ratio given above does only apply for idealized elastic materials. Therefore it is appropriate to determine Poisson's ratio from the Hookean

region of the straining process.

2.2. Chemical and physical properties of hair

In the following, the general structure of the hair fiber as well as its tensile properties will be introduced.

2.2.1. Keratin

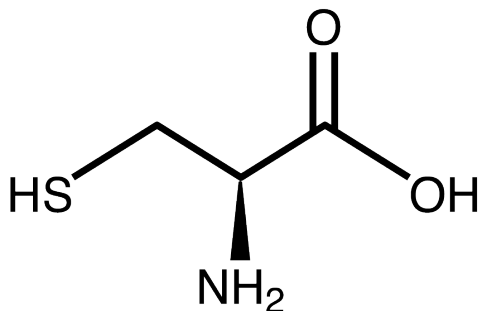
Keratins are a family of structural proteins containing a significant (high or low) amount of sulfur content [14]. After collagen, they represent the most important biopolymers found in animals [15]. Keratin is produced by specialized cells, called keratinocytes, which lie in the outer layers of the skin. Keratinized tissue consists of dead cells and is not vascularized [15]. Because of their high tensile strength, resulting in a Young's modulus of up to 10 GPa [15] (depending on the exact material), they are found in body parts subjected to high stress. In mammals, keratins are an important component of the epidermis, which protects the skin from outside influences, as well as of the skin appendages like hair, wool, horns, nails or hooves [16].

A characteristic property of keratin is its high content of the sulfur-containing amino acid cysteine [17], which forms the diamino acid cystine by linking thiol groups (-SH) with another cysteine residue and thereby produces strong covalent disulfide bonds within the polypeptide [18][16]. Cysteine therefore contributes to the mechanical stability of keratin [16] and cystine content determines softness or hardness of the keratin-containing structure. Figure 2.2 shows the chemical structure of the cysteine and cystine molecule with their respective thiol group and disulfide bond.

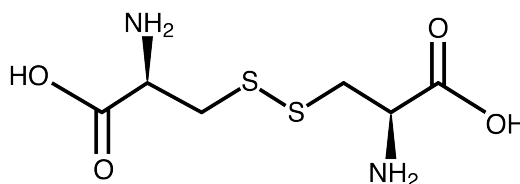
The overall mechanical stability of the keratin structure results from the disulfide bonds as well as the tight packing and mixture of structural elements like filaments and matrix (see below) [21].

Keratin can be classified as either hard or soft keratin. The soft keratin variant contains less sulfur and therefore fewer S-S cross-links than the hard one [15]. It is found in the skin, whereas the hard keratin can be found in a wide variety of animal epidermal appendages such as claws, beaks, nails and hair [22].

Furthermore, keratins can be divided into α - and β -keratins, based on their secondary



(a) Cysteine molecule [19]



(b) Cystine molecule [20]

Figure 2.2.: *Cysteine molecule with thiol group (a) and cystine molecule with disulfide bond (b)*

structure. The β -form of keratin is the major component of hard bird and reptilian tissues (feathers, beaks, scales, claws), whereas the α -form can be found in wool, hair, nails, hooves, horns and the skin of mammals [23]. When strained, the α -form can transform into the β -form (see below).

α -keratin

The α -helix is a common protein secondary structure. Its spiral shape is stabilized by hydrogen bonds between the amino and carbonyl groups of the contributing amino acids [24][25]. The α -helix structure is shown in Figure 2.3 (a). In α -keratin, two isolated α -helix chains organize themselves to a superhelix, called coiled-coil, stabilized by sulfur cross-links between the cysteine residues of the two α -chains. The coiled-coils are linked together longitudinally (head to tail) and then assemble pairwise to form a protofilament. Two protofilaments form a protofibril and two protofibrils form an intermediate filament (IF) (or microfilament) of diameter 7 nm [15] – 7.5 nm [22] (Figure 2.3 (b)) (compare e.g. [15] or [24]). The mechanical properties of an α -keratinous material are influenced by the alignment of the IFs; the more aligned the fibers are, the stronger the material becomes [15].

β -keratin

Next to α -helices, β -sheets represent another common protein secondary structure. They are made up of two linear amino acid strands, which can be parallel or antiparallel oriented with respect to each other and which link through hydrogen bonds between their carbonyl and amino groups (Figure 2.4 (a)). [26]

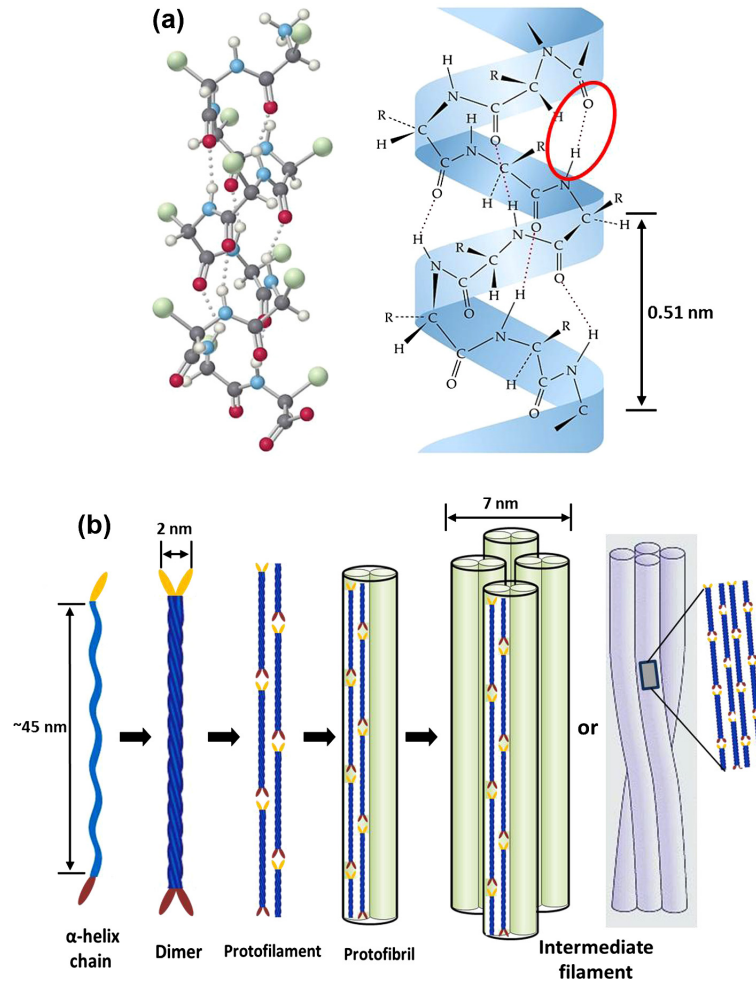


Figure 2.3.: α -helical structure of keratin (a) and the assembly of α -helix chains to IFs, taken from Wang et al. [24]

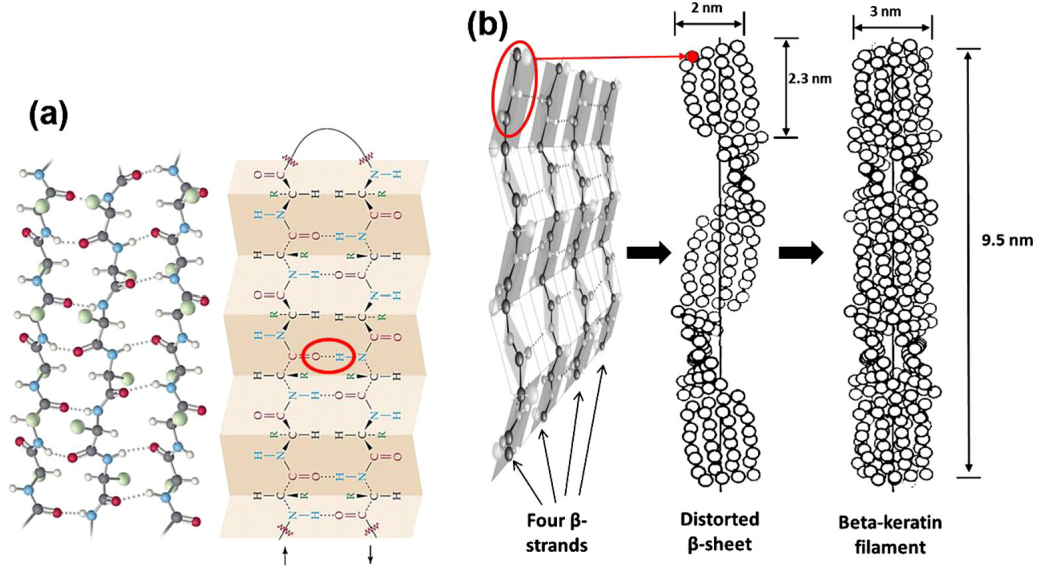


Figure 2.4.: β -sheet structure of keratin (a) and assembly to β -keratin filaments [24]

In β -keratin, two or more antiparallel keratin strands are positioned side-by-side [15] (Figure 2.4 (b)), forming a β -keratin filament. The resulting β -sheets have a diameter of 2–3 nm and show a higher stiffness than the α -helices [24].

Most keratinous materials have a composite structure: They consist of fibrous proteins (intermediate filaments in case of α -keratin, or β -keratin filaments) embedded into an amorphous matrix [24]. The matrix consists of keratin filament associated proteins (KFAPs), which are of non-helical structure and contain higher amounts of sulfur and therefore cystine than the filaments, as well as high amounts of the amino acids glycine and tyrosine [22][23]. Disulphide bonds are formed among different KFAPs but also among KFAPs and filamentous keratins [21].

The ratio of fibrous protein and matrix protein is reported to range from 0.2 – 0.45 [14] or 0.5 – 0.6 [16] in human hair, depending on ethnicity, hair structure and source. The higher the matrix amount, the lower is Young's modulus [15].

Because keratin is of biological origin, the keratin fibers are very inhomogeneous regarding their length [16].

α - to β -keratin transformation

When stretched, the α -keratin form can transform to the β -conformation. Recent analyses suggest a two-stage mechanism of the $\alpha \rightarrow \beta$ -transformation. The process starts

with the unraveling of the α -helical coiled-coils. Afterwards, transformation of the unraveled α -helices into β -sheets occurs. The transformation is a gradual one and α - and β -keratins coexist for long strain ranges [27]. A complete transition of α - to β -keratin might not be achievable in straining experiments [28].

2.2.2. Hair structure

The major component of hair is protein (α -keratin), but it also contains other compounds such as lipids, water, trace elements, and pigments [14]. Figure 2.5 shows the composite structure of a single hair.

The outermost layer, the cuticle, surrounds the hair and protects it from environmental influences [30]. The cuticle consists of overlapping, flat, and dead cells and makes up about 10 % of the hair's volume [15].

The inner part of the hair, the cortex, contains cortical cells which consist of keratinized cells and pigment. Thicker hair has a hollow core (= medulla), which is not present in fine hair, [15] and is composed of loosely packed cells [31].

Each cortical cell consists of macrofibrils and intermacrofibrillar matrix. The macrofibrils are made up of microfibrils (IFs), which are surrounded by a high sulfur intermicrofibrillar matrix. Each cortex cell contains 5 – 8 macrofibrils and each macrofibril consists of 500 – 800 microfibrils [29].

Cortical cells, as well as the cuticle cells, are separated by the cell-membrane complex (CMC), which consists of lipids and proteins [32][33]. The CMC constitutes only a small proportion of weight to the whole hair, but it has an influence on mechanical and chemical properties [34].

The hair fiber geometry is roughly cylindrical, with a diameter ranging from 10 μm (Angora rabbit, Cashmere goat) to more than 100 μm (yak, sheep, human) [29].

2.2.3. Mechanical properties of hair

Kreplak et al. [27] studied the structure of strained horse hair fibers by WAXS and found the amount of transition of the α -helices into β -keratin to be not linear with strain. In their observations, the amount of α -keratin structures began to decrease in the first few strain percentages, and β -sheets appeared above 20 – 25 % strain. Furthermore, they found the transformation to β -sheets to start in the core of the stretched keratin fiber,

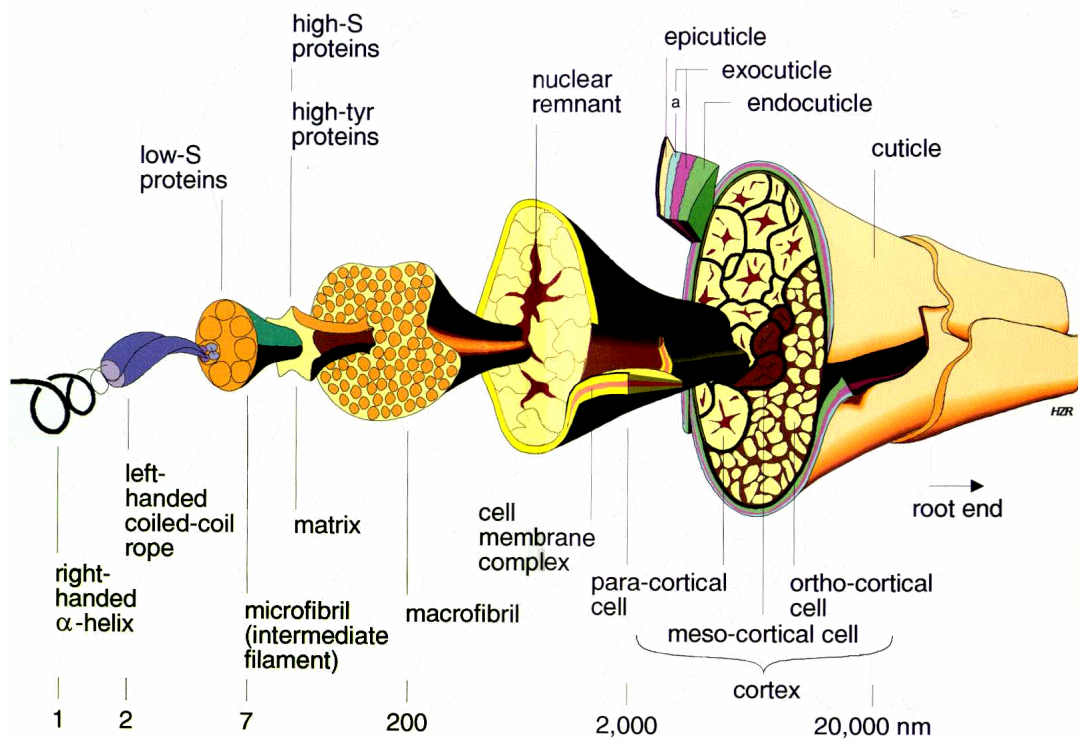


Figure 2.5.: General hair structure from the α -helix to the whole hair, taken from Popescu & Höcker [29]

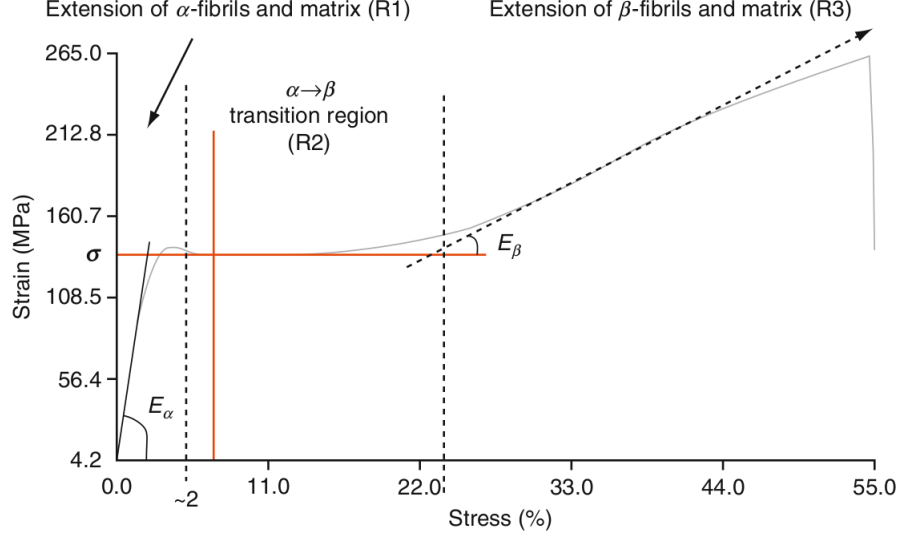


Figure 2.6.: *Typical stress-strain curve for hair, taken from Popescu & Höcker [32]*

leading to a structural gradient across the fiber's cross-section, which could be due to a radial stress gradient originating in a gradient of keratin fiber alignment. In the hair core, the fibers are more aligned (high crystalline degree) than in the periphery. These results could link the crystalline degree to the extent of $\alpha \rightarrow \beta$ -transformation. In a former study [35], the authors also showed that two mechanisms might be in competition when stretching a fiber. One is the stretching of the coiled-coils, which leads to refolding of the uncoiled α -structures into β -structures and could be prominent in well-crystallized zones. The other one is the sliding of molecules along each other, which could be more prominent in zones with a lower degree of crystallization. They did, however, study wet fibers, which might exhibit a different behavior than dry ones in this context. Rohs et al. [36] make the presumption that α -helices are difficult to stretch because of their torsional potentials, and that sliding of the α -helices against each other might be energetically more favorable. However, they did not use a composite material like hair but single peptide chains. It has been assumed [35] that pure molecular stretching of α -keratin fibers consumes more energy than breakage of the disulphide bonds and molecular sliding.

For the stress-strain curve of hair, three different regions are typically distinguished (compare for example [32] or [24]). Figure 2.6 shows a typical stress-strain curve with three regions R1–R3 ([32]).

The first region (denoted by R1) goes up until ~ 2 % strain and represents the Hookean region, where the stress increases linearly with strain [32]. This region is associated with

the elastic stretching of the α -helices [32]. There is no significant structural change within the IFs in this region [24]. Feughelman, as cited in [37], attributed the Hookean region to changes in bond angles and spacing. They did also explain the yield region as the onset of the $\alpha \rightarrow \beta$ -transformation, which starts with the unraveling of the coiled-coils [24][27]. This is the second region (R2). Some authors, like Popescu & Höcker [32], as shown in Figure 2.6, attribute this second region to the $\alpha \rightarrow \beta$ -transition and the following third region to the mechanical extension of the β -sheets. This is inconsistent with the findings of Kreplak et al. [27], who found the β -structures in horse hair fibers not to appear until approximately 20 % strain. In other publications though, the second region is supposed to represent the unraveling of the α -fibers, and the refolding into β -sheets starts in the third region at strains above 20 %. In the third region, the fiber also stiffens and finally breaks [24].

Simkova et al. [4] determined viscoelastic properties of hair for different animal species. They also found the deformation curve to be split into three parts: the elastic part in the beginning, where the change of stress is linear, a viscoplastic part, which is dependent on the strain rate, and the area of hardening shortly before fracture. They also calculated Young's modulus, which varied strongly between species or race. They found values of 1.3 ± 0.3 GPa for human hair, values between 2.3 GPa and 6.2 GPa for horse hair and 2.9 ± 1.3 for goat hair. The values have however high standard deviations. Also, they assumed the hair to be circular and only used the initial cross-sectional area.

Mohan et al. [3] studied tensile properties of hair obtained from different pig breeds. They found neck hair to be thicker than hair from the pig's back. The fracture strain was between ~ 28 and ~ 40 %, again depending on breed and hair origin. Young's modulus ranged from 3.9 to 8.1 GPa. These authors also assumed the hair's cross-section to be circular and calculated only the engineering stress, not the true one.

Hu et al. [6] found a Poisson's ratio of ~ 0.38 for human hair, using optical techniques. This result (for human hair) was also found by Lee & Kwon [5], who used a camera for the diameter measurement. There are no studies on pig hair available though.

It has to be taken into account that the mechanical properties of hair are not only dependent on the species and race, but also on the body part the hair has been taken from (compare [3]) and probably on environmental and individual factors. Therefore, it is not possible to give an exact value for parameters like Young's modulus or Poisson's ratio,

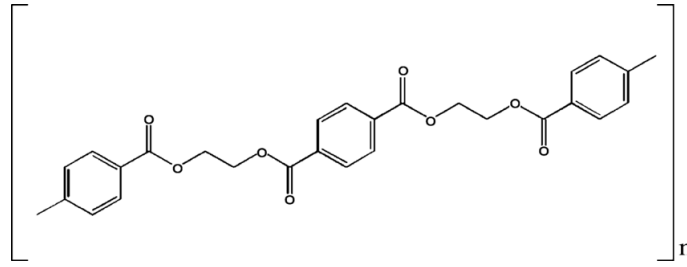


Figure 2.7.: *Repeating units of the PET polymer* [43]

which applies to every single hair.

The stress values reached during straining are dependent on the strain rate; the higher the strain rate, the higher the stress [28].

2.3. Chemical and physical properties of poly(ethylene terephthalate) (PET)

Poly(ethylene terephthalate) (PET) is industrially used for packaging (bottles for water and other beverages, packaging of food-products or pharmaceuticals) because of its high stability and good barrier properties [38][39]. In 2018, ca. 51.2 Mio tons of plastics have been produced in Europe, of which 7.7 % were PET [38].

Although it is light-weighted (the weight of an 1 L PET water bottle is ca. 25 g [40]), PET is a mechanically resistant material and is also very stretchable during processing [40].

2.3.1. PET Structure

PET belongs to the family of polyesters [39], i.e. it contains an ester group ($R1-COO-R2$) in its repeating unit [41]. It is made of repeating $C_{10}H_8O_4$ units, each unit having a length of ~ 1 nm. PET is produced by polycondensation from ethylene glycol and terephthalic acid [40] [42]. Figure 2.7 shows a cut-out from a PET molecule with some repeating units.

The length of a typical PET polymer is about 100 nm with an average number of 100 repeat units [42]. Higher polymerization levels produce higher strength fibers. The aromatic rings make the molecule relatively stiff compared to other polymers such as polyamide. [39]

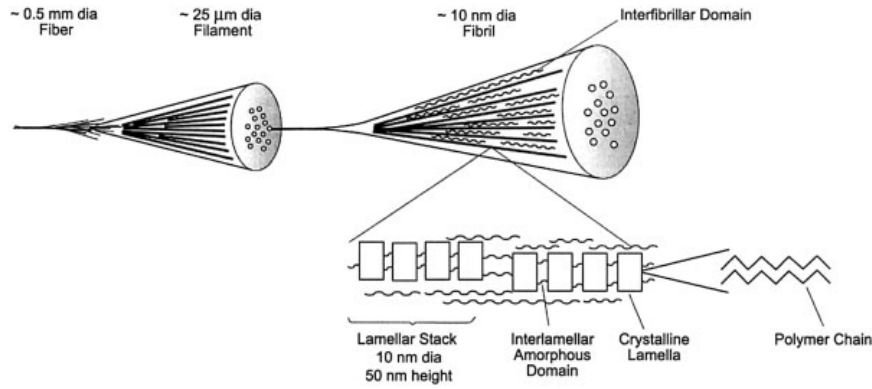


Figure 2.8.: *Model of a typical semicrystalline polymer such as PET, taken from Murthy [44]*

PET is a semi-crystalline polymer, meaning it consists of both crystalline and amorphous phases. A typical polymer fiber consists of hundreds of filaments (macrofibrils), which are aligned along the fiber axis and which consist of (micro)fibrils with diameters of $\sim 10 \mu\text{m}$ (see Figure 2.8). The filaments are approximately $25 \mu\text{m}$ in diameter [44]. The fibrils are made of stacked lamellae, which can be understood as domains of folded chains [45]. Between the fibrils, the chains lie in an amorphous phase which links the crystalline lamellae [44]. The amorphous phase can be further distinguished: The chains linking the lamellae of a fibril in axial direction are also denoted as *isotropic amorphous phase* because the polymer chains seem to be randomly distributed according to diffraction patterns. For the interfibrillar chains, the term *oriented amorphous phase* is used because the chains are preferably oriented along the fiber axis. [46][47]

The final fiber structure and therefore its tensile properties are dependent on the manufacturing process; different spinning rates or production temperatures can for example lead to different crystallinity and orientation within the sample [48][49].

2.3.2. Mechanical properties of PET

PET is reported to have a higher mechanical strength than other polymers, with a Young's modulus of 3 GPa [40] to 4.5 GPa [50] for PET film. Navarro et al. [51] investigated PET derived from waste bottles and found a Young's modulus between 11.2 and 12.9 GPa. Galeski [52] also found a Young's modulus of around 12 GPa for double-oriented PET tape. For PET fibers, values between 7.8 and 10.4 GPa [44] or

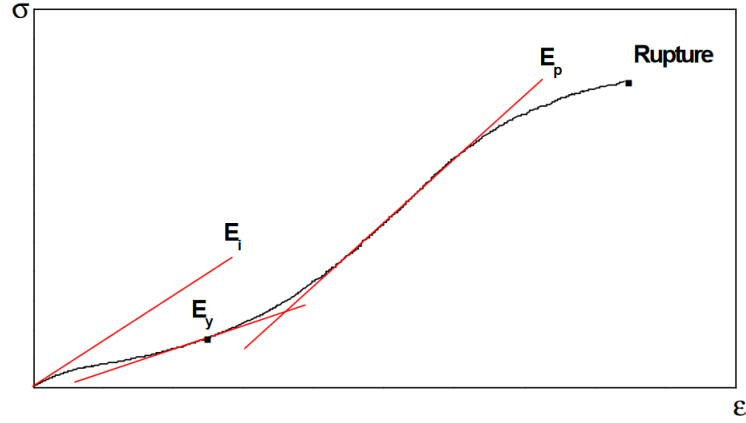


Figure 2.9.: *Typical stress-strain curve for a PET fiber, taken from Herrera [46]*

9 – 11 GPa [46] are reported for Young’s modulus. For a semi-crystalline polymer, Young’s modulus is governed by the degree of crystallinity [52].

Figure 2.9 shows a typical stress-strain curve for a PET fiber according to Herrera-Ramirez [46]. On a molecular level, the stretching of the sample starts with the uncoiling and alignment of the isotropic amorphous polymer chains [53][46] (= Hookean region). After leaving the initial linear regime, the isotropic amorphous phase continues to align until reaching an orientation similar to the oriented amorphous phase [49]. In this phase occurs significant deformation without requiring high stresses. Until the first inflection point, denoted by E_y in Figure 2.9, the structural changes inside the fiber are only in the isotropic amorphous phase [46]. At the inflection point E_y , the deformation behavior changes due to hardening of the fiber [46], which is due to a high degree of polymer chain orientation (strain-induced crystallization) [54][53]. From this point on, the oriented amorphous phase is also strained and higher stresses appear [46]. The dominant deformation mechanism here is the sliding of the polymer chains relative to each other [46]. The final stage of the deformation curve is resulting from slippage between the filaments (macrofibrils) [49] until loosening occurs and the breaking mechanism begins on the surface of the fiber [46].

Mechanical performance is strongly influenced by temperature and strain rate: Higher stresses are reached at lower temperatures and higher strain rates [54]. It is also dependent on factors such as crystalline degree (the lower the crystalline degree, the higher the elongation at break), polymer orientation or shape [40].

The strength of the polymer chains is dependent on the strength of the C-C bonds [52].

Wilson et al. [55] found a Poisson's ratio of 0.29 to 0.37 for PET sheets. The value was dependent on the sample dimensions and the load applied.

3. A new device for the precise measurement of stress-strain curves

3.1. Setup

Figure 3.1 shows the device used for the measurements in this thesis. It was built by the *Dynamics of Condensed Systems* research group of the faculty of physics at the university of Vienna for the stress-strain recording of elliptical fibers, with the main contribution to the design from Alexander Müllner. The unique feature of the device is the rotating clamping jaws which allow for the in situ measurement of the sample diameter from an arbitrary number of angles and an accurate determination of the sample's cross-section at all times. The following components are of importance:

- 1 laser
- 2 motor
- 3 clamping jaws
- 4 path recorder
- 5 load cell

The sample diameter is measured by a laser diode, which operates at a wavelength of 620 nm.

Figure 3.2 shows the measuring device with the laser removed and the upper (3u) and lower (3l) clamping jaw. The motor moves the upper clamping jaw and allows a mounted fiber to be stretched or relaxed. The load cell quantifies the appearing forces and the path recorder measures the distance the upper clamping jaw covers when moving up or down.

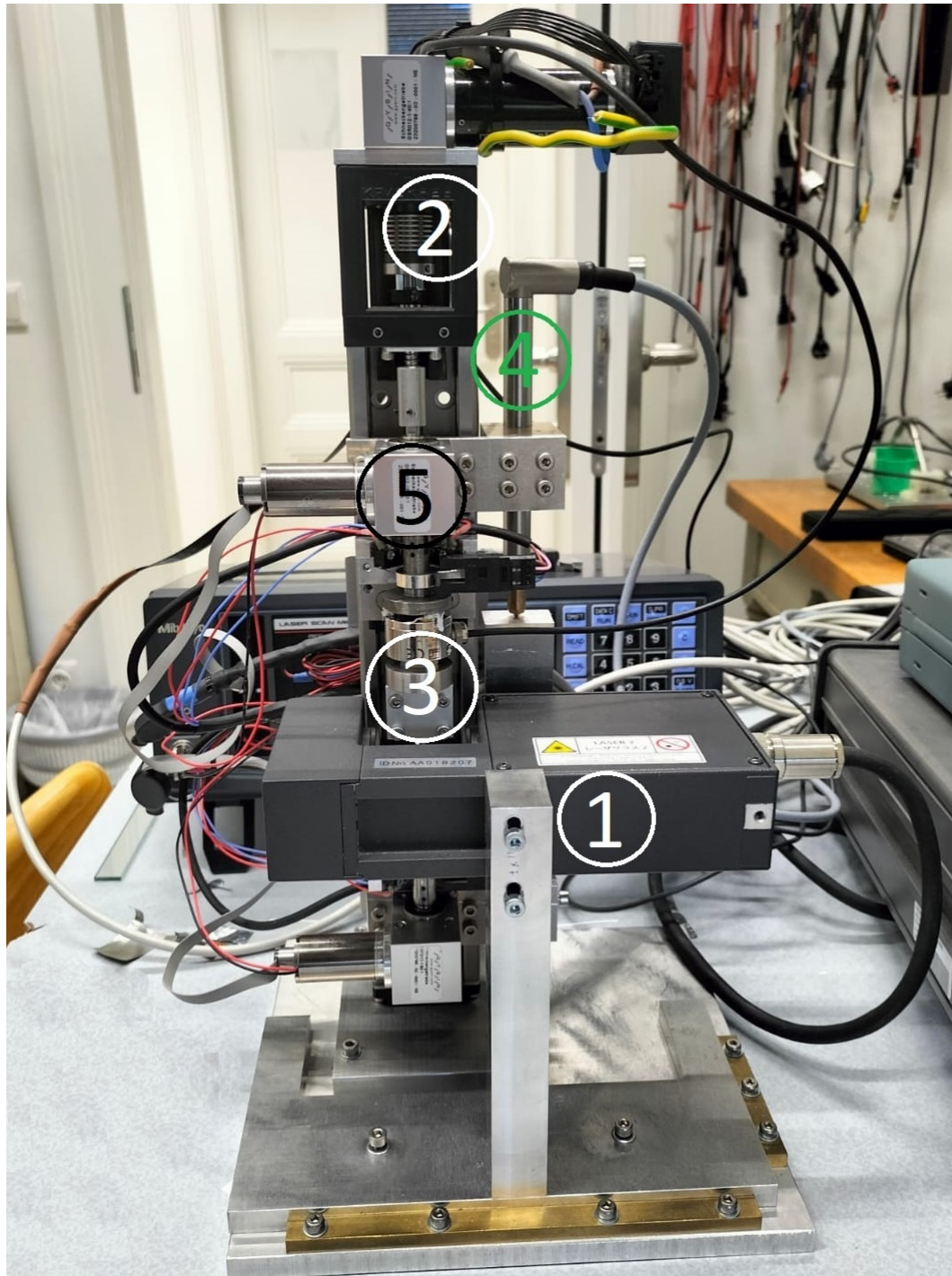


Figure 3.1.: *Measuring setup with laser (1), motor (2), clamping jaws (3), path recorder (4), load cell (5)*

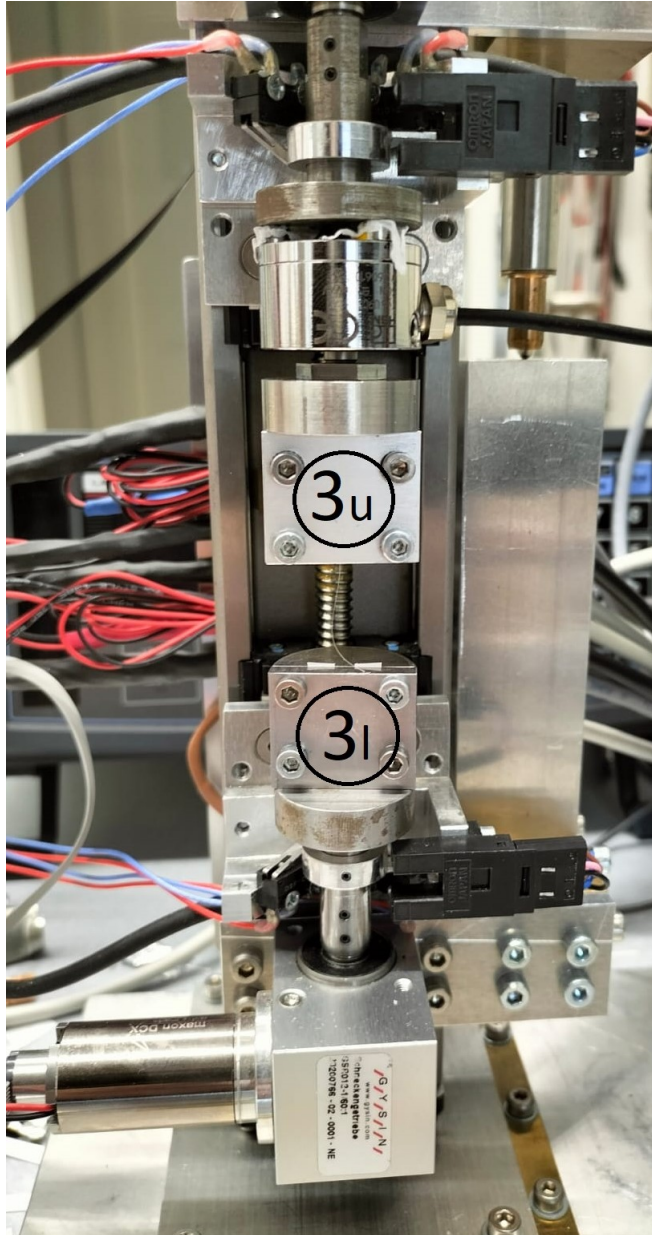


Figure 3.2.: *Measuring setup with upper (3u) and lower (3l) clamping jaw. The rotation option of the clamping jaws allows for in situ and multi-angular measurement of the sample diameter.*

During the measurement, the clamping jaws do not only move away from each other but are also able to rotate synchronously. This way, the laser can measure the sample diameter at many angles and the sample's cross-section can be known at all times.

3.2. Measuring process

At the beginning of the measurement, the upper clamping jaw dives to zero load, and the fiber's clamping length, which correlates with load zero, is calculated using the path recorder's data. The clamping length is used during the following measuring process and for the program's strain calculations.

During the measurement, the upper clamping jaw moves to a certain strain in a given number of steps. Each step allows for an arbitrary number of angles to be set at which the sample diameter will be measured. This is achieved by rotating the two clamping jaws synchronously between 0 and 180°.

Relevant output data are the clamping length and the path recorder's position (the sample extension) as well as the load and sample diameter corresponding to each position and angle.

3.3. Determination of the load train compliance

The load train compliance of a strain-measuring device is a measure for how much of the sample's deformation is caused by the measuring device itself. Because of its possible influences on the measurement data, it had to be determined for the described device. This was done according to the standard DIN 1007-4. The total compliance, which consists of the sample compliance and the load train compliance, gives information about the measured extension in dependence on the applied load. It is determined by calculating the inverse slope of the linear part of the load-displacement curve. The total compliance of each specimen is assigned to the corresponding L_0/A_0 ratio of the specimen with its clamping length L_0 and its initial cross-sectional area A_0 . A linear regression yields the y-axis intercept, which gives the desired load train compliance (Figure 3.3).

The part of the measured extension which originates from the deformation of the load

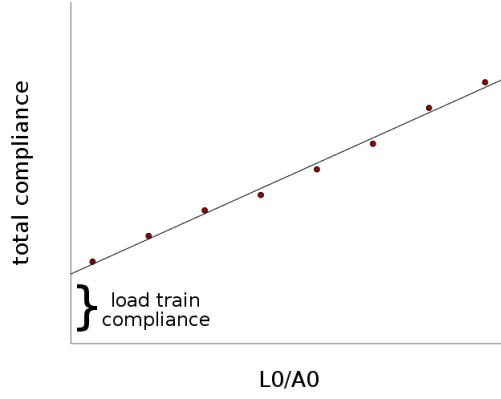


Figure 3.3.: *Determination of the load train compliance. The constant of regression of the total compliance against the L_0/A_0 -ratio gives the requested value.*

train can be calculated for any measurement by multiplying the load train compliance C_L with the measured load. It can then be subtracted from the total measured extension to calculate the strain correction:

$$strain_{corrected} * L_0 = extension - load * C_L \quad (3.6)$$

4. Material and measurements

4.1. Material

The measuring device was used on copper wire for the compliance measurements and afterwards tested on pig hair as a biological material and PET fibers as a synthetical material.

4.1.1. Copper wire

For the determination of the load train compliance, copper wire of three different diameters ($50\text{ }\mu\text{m}$, $150\text{ }\mu\text{m}$, and $220\text{ }\mu\text{m}$) has been used. In the following, the three wire types will be denoted by Cu-50, Cu-150, and Cu-220 respectively.

The samples were prepared with lengths between ~ 10 and ~ 35 mm in steps of 5 mm. Some lengths were used twice and thus appear twice in the results, because the first measurement did not seem reliable on first sight and was repeated but turned out to be utilizable after a second evaluation. 10 samples of the Cu-50 wire, 6 of the Cu-150 wire and 8 of the Cu-220 wire have been measured and kept for evaluation in the end.

4.1.2. Mangalitza pig hair

Mangalitza pig hair has been used to demonstrate the device's advantages with inhomogeneous biological fibers with non-circular cross section. The hair stemmed from an approximately five year old blonde breeding sow.

Seven single pig hairs, labeled sample 1–7, have been prepared with clamping lengths of approximately 20 mm.

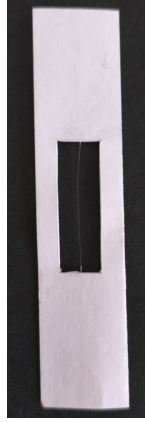


Figure 4.1.: *PET fiber in a paper frame. The frame has been cut-off after mounting the sample to the clamping jaws.*

4.1.3. PET fibers

As a technically produced material, PET fibers are very homogeneous and have a circular cross section. A 100 μm diameter PET fiber (monofilament) of the company GoodFellow has been used for the measurements. Six single fibers, labeled sample 1–6, were prepared with clamping lengths of ~ 20 mm.

4.2. Sample and measurement preparation

The to-be-measured wires, hairs and fibers were glued to a paper frame as shown in Figure 4.1. After mounting the frame to the clamping jaws of the measuring device described in section 3.1, the lateral paper ridges were cut off.

In order to prepare the measurement, the sample fiber was then tightened but not stretched by moving the clamping jaws manually. In order to run the measuring device on constant heat, it was switched on half an hour before mounting the first sample.

4.3. Measuring parameters and performing

All measurements were performed at room temperature. The upper clamping jaw was set to move with a speed of 0.05 mm/s for all measurements (velocity the clamping jaws move away from each other with). The time between two angle measurements was approximately 1.2 s. The settling time between two strain steps before the angle measurements started was set to 0.2 s.

Load, extension and diameter have been measured from different angles for each straining step. The first measurement, which was the Cu-50 wire with the smallest clamping length, has been performed with 6 angle steps, with angles equally distributed between 0 and 180°. For all other measurements with copper, pig hair and PET, a higher angle resolution was chosen, for which reason the diameter measurements were carried out at 13 angles (the first at 0° and the last at 180° are redundant), which were equally distributed between 0 and 180° in steps of 15°.

In the following, the angle steps will be labeled as angle steps 0–12, accentuating the redundant angle with 0.

Measured samples have been left out of the subsequent analyses when showing high irregularities in one of the measured quantities which could be explained by external factors (wrong parameters set, sample slipped out of the clamping jaws etc.).

4.3.1. Measurements with copper wire (load train compliance)

Multiple linear sections of the stress-strain curves were produced by consecutive loading and unloading of the specimen. Starting at a strain of 0.3 % (the strain piloted by the measuring device; the exact strain has been calculated from the recorded extension later), the specimen was unloaded until the strain had decreased by 0.1 % and then loaded again until a decrease of strain by 0.2 %. This was repeated until a strain of 0.6 % was reached. In Figure 4.2, the strain progress is displayed as a function of measuring steps using for one of the Cu-50 specimens.

4.3.2. Measurements with Mangalitza pig hair

The pig hair samples have been measured until fracture in strain steps of 0.25 %. There has no reloading and unloading been done because the results should be comparable to the PET fibers' which showed pronounced hysteresis during unloading and reloading.

4.3.3. Measurements with PET fiber

Like the pig hair, the samples were measured until fracture. The measurement has been tried with iterative unloading and reloading, but the load showed hysteresis in

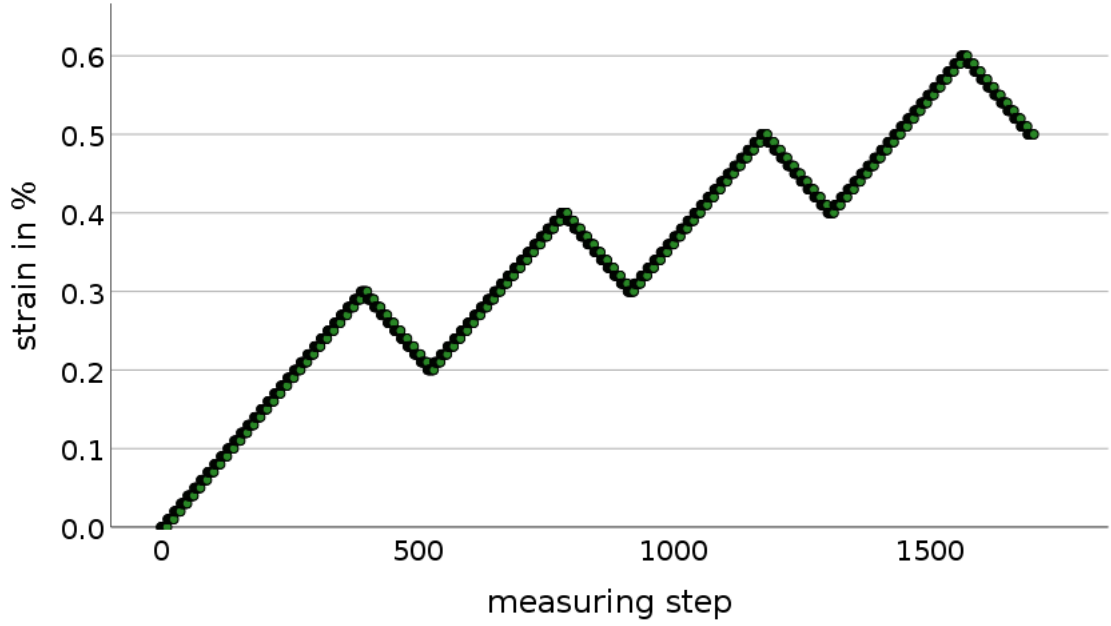


Figure 4.2.: *Progress of the strain measurement of the copper wires using the example of one of the Cu-50 wire specimens*

Table 4.1.: *Straining steps for the six PET fiber samples*

sample	configuration 1		configuration 2	
	strain range [%]	straining step [%]	strain range [%]	straining step [%]
3, 4	0 – 6	0.10	6 – fracture	0.25
1	0 – 15	0.15	15 – fracture	0.15
2, 5, 6	0 – 15	0.15	15 – fracture	0.25

this case, making it difficult to find linear parts for the calculation of Young’s modulus or Poisson’s ratio. For this reason, the strain was set to increase monotonously. The measurements have been tried with different settings for the strain steps. Amongst other reasons, this was because the measurements took a very long time to finish and the device couldn’t be left unattended, so the aim was to reduce the measuring time to under two hours if possible. Table 4.1 shows the straining step settings for the six samples. The steps were chosen to be smaller in the beginning to get detailed data for the determination of Young’s modulus and Poisson’s ratio (configuration 1) and larger in the end (configuration 2).

Table 4.2.: *Input and output parameters for the tensile test. Mean values were obtained by averaging over all angles.*

recorded parameters	calculated parameters
clamping length [mm] = L_0	
extension [mm]	mean extension strain = $\frac{\text{mean extension}}{L_0}$, mean strain
diameter [mm]	cross-sectional area [mm ²] and area type
load [N]	mean load [N]

4.4. Data recording and evaluation

Table 4.2 displays the relevant parameters recorded during the measurement as well as the data gained by first processing of these parameters. For the load and the extension, mean values have been calculated for each straining step by averaging over all angles when looking at the sample as a whole and not at its behavior observed from different angles. The mean strain was obtained by dividing the mean extension by the clamping length.

Thanks to Alexander Müllner, who provided a self-written Python script for the main data evaluation, the angle-averaged means of the extension, strain, and load could be calculated in a fast manner. In addition, the script output the cross-sectional area and the shape of the cross-section (which could be circular or elliptical). For samples with a circular cross-section, the cross-section was calculated with the mean diameter and the common circular area equation. The area calculation of the non-circular cross-sections, as included in the script, can be taken from Appendix A.

True and engineering stresses and the engineering strain have been calculated according to section 2.1.1. Young’s modulus and Poisson’s ratio were obtained by performing a linear regression on the linear part of the corresponding stress-strain or diametric strain - longitudinal strain curves (compare Sections 2.1.2 and 2.1.3).

Statistical analyses, further calculations, linear regressions, and graphics were performed and created respectively with IBM SPSS Statistics ver. 27.

For testing differences of two related samples, Wilcoxon signed-rank test has been used. All statistical tests were performed at a significance level of $\alpha = 0.05$.

In most cases, median and interquartile range are given instead of mean and standard deviation when comparing different samples. This is because the sample sizes are small and not normally distributed in respect of the calculated quantities. Adequacy of calculating the means of extension and load over all angles, as done by the above-mentioned evaluation program, has been checked and verified separately for all specimens.

4.5. Optical measurements of the pig hair and PET fibers

Some pig hair and PET fiber samples have been studied under the optical microscope for visual presentation.

The fibers have been embedded into a resin for top-view measurement of the diameter and exposure of the cross-section.

5. Error estimation

In most cases, the statistical error (e.g. obtained from linear regression) was expected to be higher than the absolute one. For this reason, the statistical errors are presented in the following for all quantities derived from linear regression. Because the mean values of the extension and load have been calculated in many cases and each material is expected to behave differently, the absolute errors of the extension and the load as well as the diameter error have been estimated separately for each material. The exact values can be found in Appendix B.

6. Results

6.1. Determination of the load train compliance from copper wire force-displacement curves

Figure 6.1 shows the mean load - mean displacement curve for the Cu-50 sample with the highest clamping length (~ 35 mm). The first linear region of increase, marked with an X, has been ignored for the analyses. This way, it was assured that the copper wire was straightened properly and that any kinks were removed from the wire for the to-be-evaluated parts of the curve. Also, it can be seen that the first part of the curve differs in slope from the unloading-reloading loops. Two linear regression lines are shown for the unloading (orange) and the following reloading (black) of the sample. The unloading line shows a slightly higher slope than the reloading one. The inverse of the slope (= total compliance) was calculated for each section of unloading and reloading respectively.

Figure 6.2 shows the average total compliance for each sample and all three wire types. Linear regression yields the load train compliance. The slope for the reloading case is slightly higher than for the unloading case.

In Table 6.1, the regression data are shown for the unloading and the reloading case. Both yield the same intercept and therefore the same load train compliance. The slope of the reloading data is higher than the slope for the unloading data though.

There are different opinions on whether the reloading or unloading curves should be

Table 6.1.: *Linear regression data of the total compliance against the L_0/A_0 ratio for all three wire types together and for both unloading and reloading data*

	(intercept $\pm$ std. error) [mm/N]	(slope $\pm$ std. error) [mm ² /N]	R ²
unloading	0.004 ± 0.001	$1.0\text{E-}5 \pm 1\text{E-}6$	0.997
reloading	0.004 ± 0.001	$1.1\text{E-}5 \pm 1\text{E-}6$	0.996

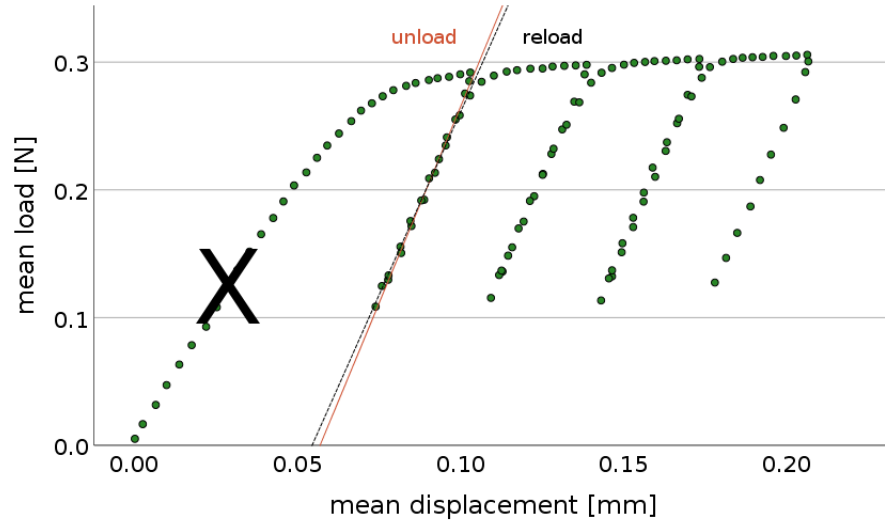


Figure 6.1.: Load-displacement curve of the Cu-50 wire with clamping length ~ 35 mm. The first increase, marked with an X, was ignored for further analyses. A regression line for the first unloading section (orange) can be seen together with the regression line of the following reloading (black).

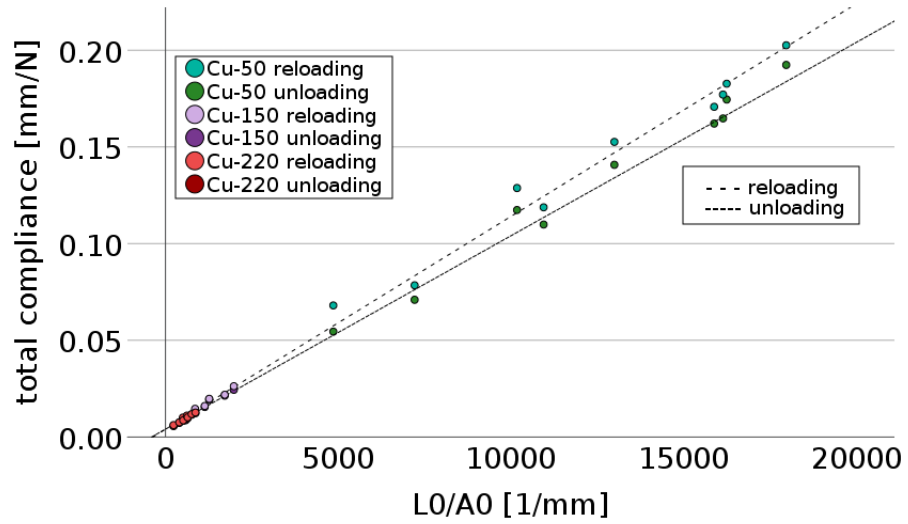


Figure 6.2.: Total compliance in dependence of the L_0/A_0 ratio and corresponding regression lines for all three wire types and both unloading and reloading. The intercept with the y-axis gives the load train compliance.

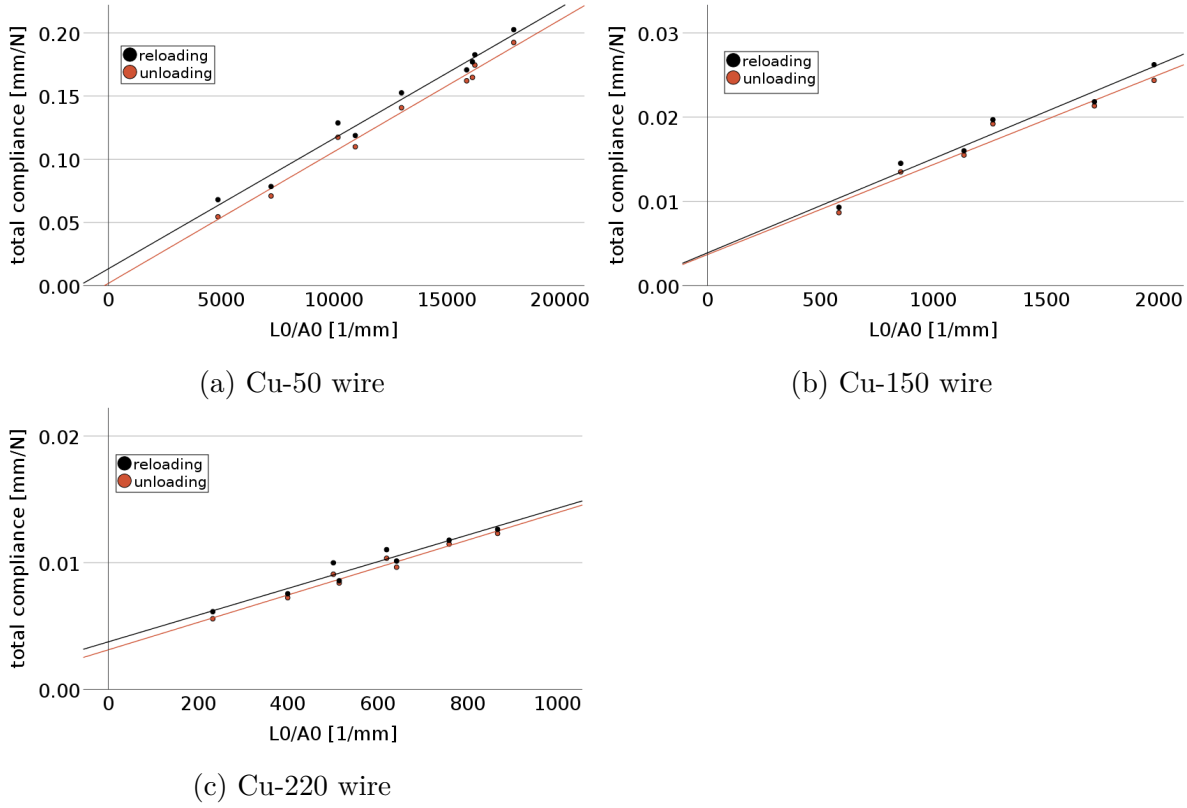


Figure 6.3.: *Total compliance in dependence of the L_0/A_0 ratio for each of the three wire types*

chosen for determining strain behavior, but since both approaches lead to the same result of 0.004 mm/N, no decision needs to be made at this point.

Hence, the load train compliance for any subsequent analyses will be

$$C_L = (0.004 \pm 0.001) \text{ mm/N}. \quad (6.7)$$

6.1.1. Investigating the three wire types separately

In the preceding, all three copper wire types were handled as one. Figure 6.3 shows the total compliance - L_0/A_0 data pairs together with the corresponding regression lines for each of the three wire types.

Table 6.2 displays the linear regression values for the unloading and reloading data for all

Table 6.2.: *Linear regression data of the total compliance against the L_0/A_0 ratio for all three wire types and for both unloading and reloading data. The intercept with the y-axis gives the load train compliance. For the Cu-50 and Cu-150 wire, the intercept values are not significant.*

unloading			
	(intercept $\pm$ std. error) [mm/N]	(slope $\pm$ std. error) [mm ² /N]	R ²
Cu-50	0.002 $\pm$ 0.006	1.0E-5 $\pm$ 1E-6	0.986
Cu-150	0.004 $\pm$ 0.002	1.1E-5 $\pm$ 1E-6	0.958
Cu-220	0.003 $\pm$ 0.001	1.1E-5 $\pm$ 1E-6	0.972
reloading			
	(intercept $\pm$ std. error) [mm/N]	(slope $\pm$ std. error) [mm ² /N]	R ²
Cu-50	0.013 $\pm$ 0.008	1.0E-5 $\pm$ 1E-6	0.979
Cu-150	0.004 $\pm$ 0.002	1.1E-5 $\pm$ 1E-6	0.960
Cu-220	0.004 $\pm$ 0.001	1.1E-5 $\pm$ 1E-6	0.934

three wire types. For the Cu-150 wire, the load train compliance is 0.004 mm/N for both reloading and unloading. The compliance for the Cu-220 wire is 0.004 mm/N for the unloading data and 0.003 mm/N for the reloading. For the Cu-50 wire, the compliances are smaller (0.002 mm/N for the unloading, 0.013 mm/N for the reloading). All things considered, (0.004 $\pm$ 0.001) mm/N seems to be a good approximation of the load train compliance.

6.2. Measurements with Mangalitza pig hair

6.2.1. Optical measurements

Figure 6.4 shows a single Mangalitza pig hair fiber under the light microscope. in Figure 6.5, a zoomed-in fragment of another fiber is shown. The inhomogeneous surface, which consists of flat cuticle cells, can be seen.

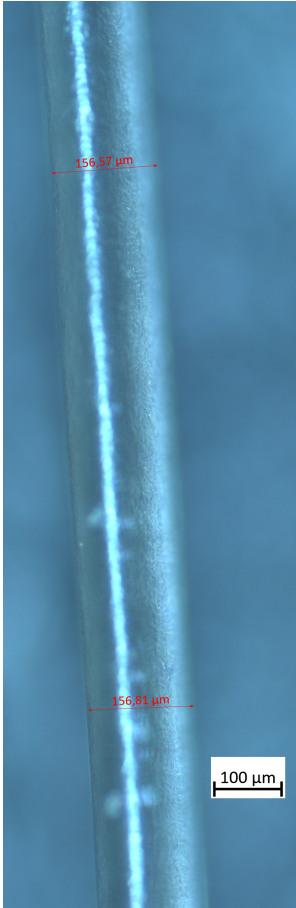


Figure 6.4.: *A Mangalitza pig hair fiber in longitudinal view under the light microscope*

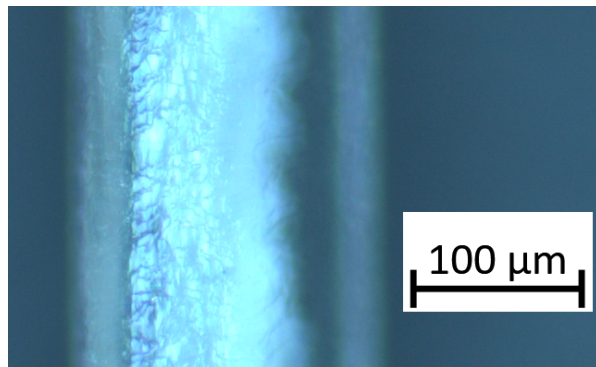


Figure 6.5.: *Mangalitza pig hair surface with inhomogeneous structure*

Cross-sections of four pig hairs are displayed in Figure 6.6. The hairs' cross-sections are of elliptical shape or even slightly triangular (Figure 6.6 (b)). None of the hairs exhibited a hollow core at the positions photographed. Straight-line discolorations originate from the grinding of the sample, but apart from that, the surface of the cross-section also looks rough and uneven in each case.

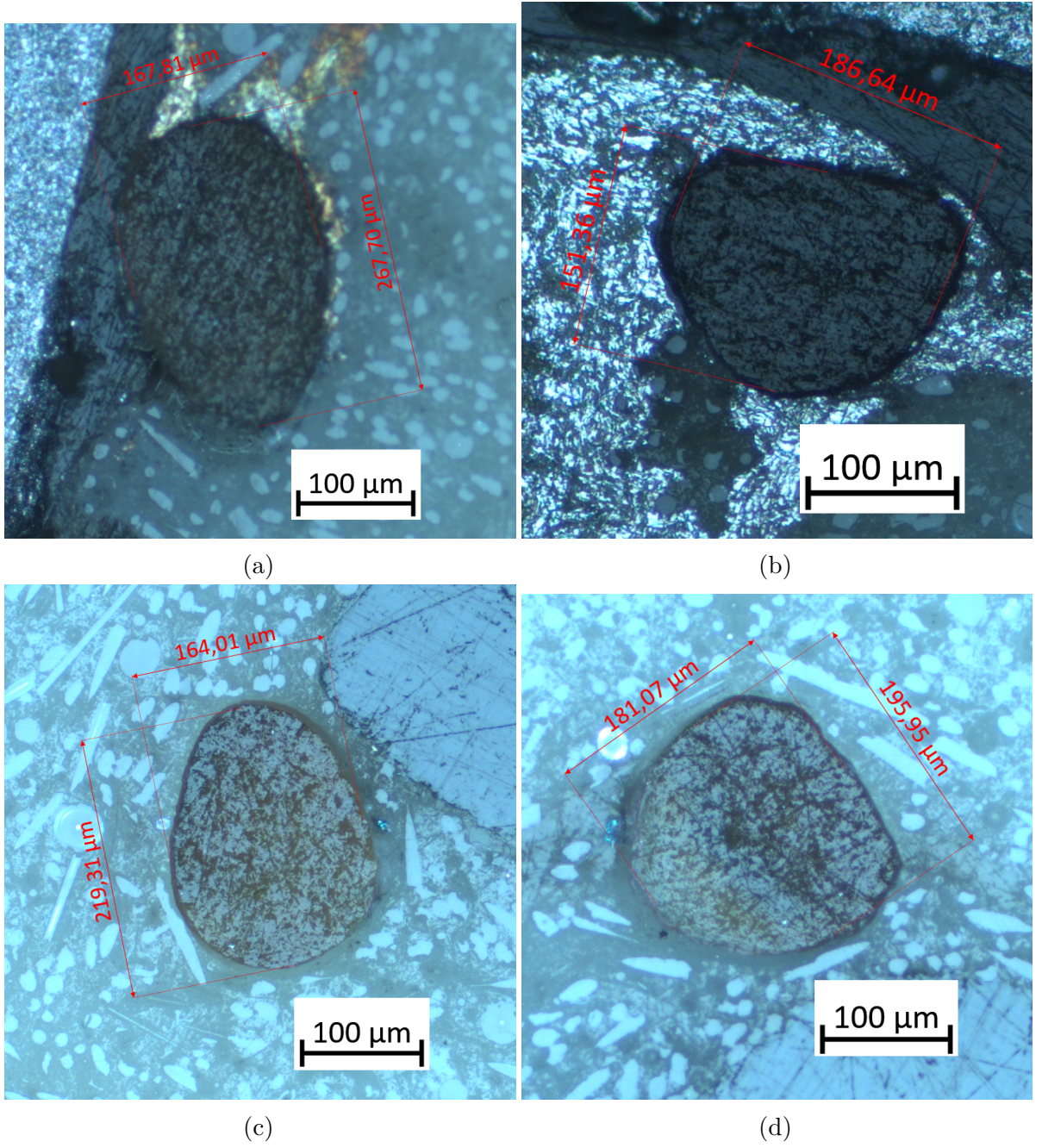


Figure 6.6.: *Cross-sections of some pig hairs embedded into resin*

6.2.2. Sample description

Clamping lengths and initial cross-sections of the seven pig hair samples used for the straining experiment are displayed in Table 6.3 together with the corresponding area types. The cross-sectional areas took values around 0.02 mm^2 , except for sample 5,

Table 6.3.: *Clamping lengths, initial cross-sectional areas and area types of the seven pig hair samples*

sample ID	clamping length [mm]	initial cross-sectional area [mm ²]	area type
1	19.36 $\pm$ 0.01	0.0203 $\pm$ 0.0003	elliptical
2	20.36 $\pm$ 0.01	0.0181 $\pm$ 0.0002	elliptical
3	20.12 $\pm$ 0.01	0.0168 $\pm$ 0.0002	elliptical
4	20.14 $\pm$ 0.01	0.0170 $\pm$ 0.0002	elliptical
5	20.36 $\pm$ 0.01	0.0410 $\pm$ 0.0005	elliptical
6	20.39 $\pm$ 0.01	0.0208 $\pm$ 0.0003	elliptical
7	20.94 $\pm$ 0.01	0.0198 $\pm$ 0.0002	elliptical

which was about twice this size. All the cross-sections were of elliptical shape.

6.2.3. Compliance correction

The compliance-corrected strain has been calculated according to Eq. 3.6, Section 3.3. For the pig hair, the difference between the corrected and non-corrected compliance is very small; the median of differences ranges from 0.0004 (samples 2 and 3) to 0.001 (sample 6), which is in the range of the absolute uncertainty of the strain measurement.

6.2.4. Stress-strain curves with true and engineering stress

Figure 6.7 shows the true and engineering stress-strain curves for the seven pig hair samples. In the Hookean region in the beginning (up to ~ 2 % strain), true and engineering stress are close to each other for all the samples. At fracture, the true stress is always higher than the engineering one.

The engineering stress roughly shows three regions for all the samples: one with a very high slope in the beginning (Hookean region), a second one with a significantly lower slope between ~ 5 and 25 % strain and a final region, again with a higher slope.

In some cases, the stress curves show a small local maximum after the region of high slope (elastic region) in the beginning (yield point).

For all the samples, there is a point at which the true stress diverges from the engineering stress more or less abruptly. The divergence takes place after the Hookean region and after the occasional yield point. After the divergence of true and engineering strain, the true stress increases in slope and then increases again at a later point. This can be seen very distinctly for samples 1, 4 and 5, which look like there are four different

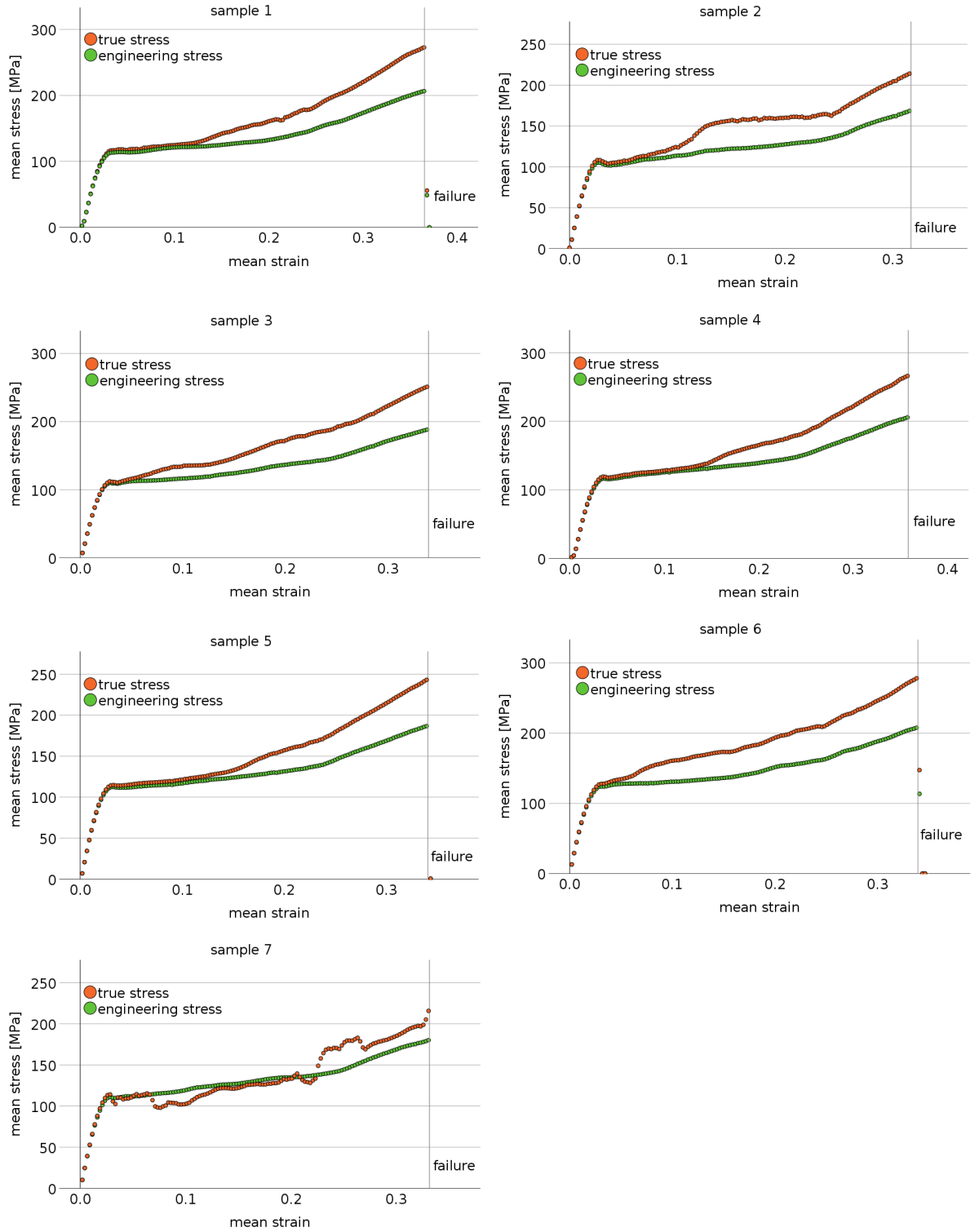


Figure 6.7.: Stress-strain curves for all seven pig hair samples. The true stress is displayed in orange, the engineering stress in green. The true stress is significantly higher than the engineering stress in all seven samples.

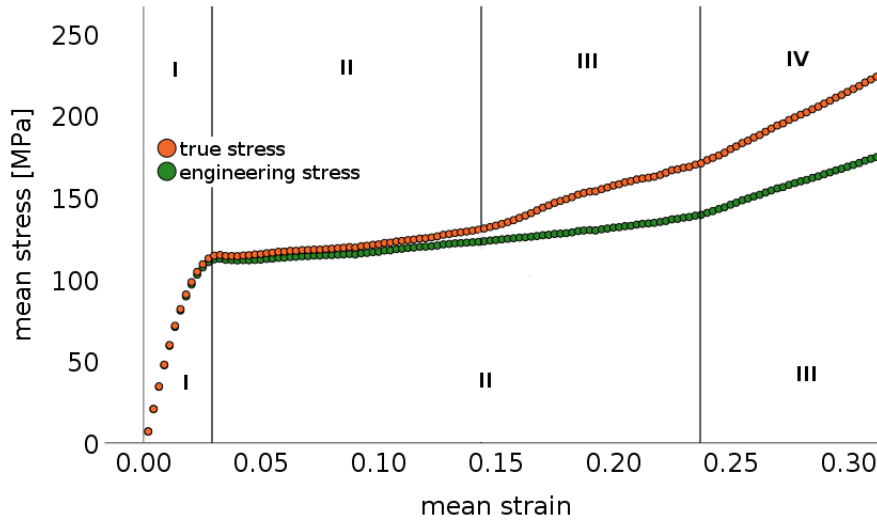


Figure 6.8.: Possible scheme for dividing sample 5's engineering stress into three regions and the true stress into four regions

linear regions: one in the beginning, a second one where the true stress follows the engineering stress until the point of divergence at $\sim 10 - 15$ % strain, a third one between ~ 15 and 25 % strain, and a fourth one which begins at ~ 25 % strain.

Figure 6.8 shows a possible division of the true and engineering stress curve of sample 5 into different regions. Sample 5 has been picked as an exemplification; but it should be kept in mind that not all samples show this simple scheme.

The true stress curve of sample 7 looks very irregular, which is probably because of pollution of the sample and not due to the sample's properties (see Section 7.2.1). For this reason, this sample will be left out of any further analyses which include the irregular part after 1.5 % strain.

Figure 6.9 shows the evolution of the difference between true and engineering stress for the pig hair samples 1–6. The fracture stress (tensile strength) is about 60 MPa higher when the true stress is chosen instead of the engineering one.

Table 6.4 shows the fracture strains and stresses for the six evaluable pig hair samples. For sample 7, no values are displayed because the last values are not clearly reliable. The hairs could be strained to between ~ 32 and ~ 36 % before failure. The true fracture stresses range from 210 to 280 MPa, the engineering stresses from 170 to 210 MPa.

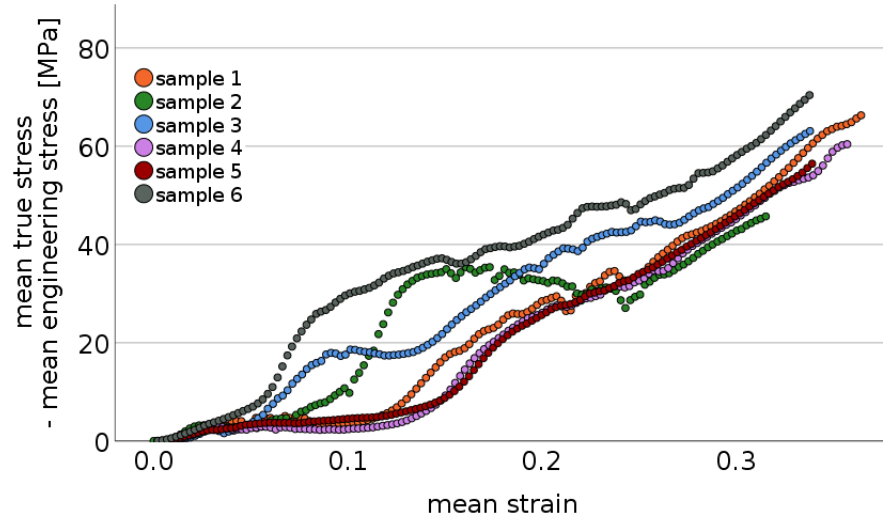


Figure 6.9.: *Development of the difference between the mean true stress and the mean engineering stress for pig hair samples 1–6*

Table 6.4.: *Fracture strain and corresponding true and engineering stress (tensile strength) for the pig hair samples 1–6*

sample ID	mean fracture strain	mean fracture stress [MPa]	
		true stress	engineering stress
1	0.364 ± 0.004	270 ± 20	210 ± 10
2	0.316 ± 0.004	210 ± 10	170 ± 10
3	0.339 ± 0.004	250 ± 20	190 ± 10
4	0.358 ± 0.004	270 ± 20	210 ± 10
5	0.337 ± 0.004	240 ± 10	190 ± 10
6	0.338 ± 0.004	280 ± 12	210 ± 10

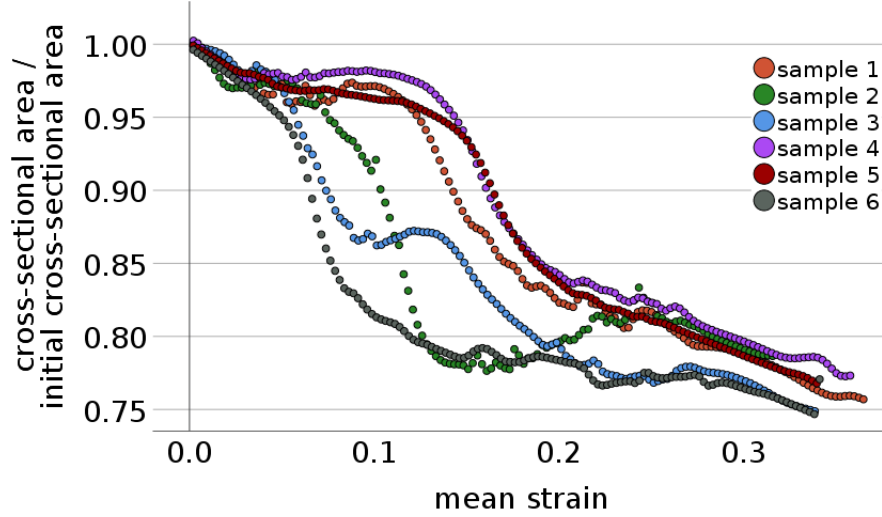


Figure 6.10.: *Cross-sectional area divided by the initial cross-sectional area during the strain measurement for the pig hair samples 1–6*

6.2.5. Development of the cross-section

Figure 6.10 shows the development of the cross-sectional areas, standardized to their respective initial cross-sectional area for the pig hair samples 1–6. The area remained elliptical throughout the measurement for all samples.

One can see that in the beginning, there is a short linear region (below ~ 2 % strain). After a region of slowed-down decrease or constant cross-section, the cross-sectional area decreases rapidly before slowing down and reaching an almost linear decrease in the end again. The point of highest decrease is located at ~ 15 % strain for samples 1, 4 and 5 and around 10 % strain for samples 2, 3 and 6. Samples 2 and 3 show an increase in the cross-sectional area at ~ 25 % strain and ~ 12 % strain respectively.

Table 6.5 shows the initial cross-sections and the final cross-sections at fracture as well as the ratio of initial and final cross-section for the pig hair samples 1–6. At fracture, the cross-sectional areas are roughly 75 % of the initial cross-sectional area.

6.2.6. Development of the sample diameter

As a visual representation of the evolution of the cross-sectional shape, the measured diameter is shown in dependence of the angle step at strains of ~ 7.5 %, ~ 15 %, ~ 22.5 %, and ~ 30 %, and for the pig hair samples 1–6 in Figure 6.11 (a)–(f).

For samples 1, 2, 5, and 6, one can see that the shape of the distribution does not change

Table 6.5.: *Initial cross-sectional area, cross-sectional area at fracture and ratio of initial and final cross-sectional area for the pig hair samples 1–6*

sample ID	initial cross-sectional area [mm ²]	cross-sectional area [mm ²] at fracture	initial cross-section / cross-section at fracture
1	0.0203 ± 0.0005	0.0153 ± 0.0004	~ 0.75
2	0.0181 ± 0.0004	0.0142 ± 0.0003	~ 0.78
3	0.0168 ± 0.0004	0.0126 ± 0.0003	~ 0.75
4	0.0170 ± 0.0004	0.0131 ± 0.0003	~ 0.77
5	0.0410 ± 0.0009	0.0315 ± 0.0007	~ 0.77
6	0.0208 ± 0.0005	0.0156 ± 0.0004	~ 0.75

Table 6.6.: *initial and final diameter ranges for the seven pig hair samples*

sample ID	initial diameter range [mm]	final diameter range (before fracture) [mm]
1	0.120 ± 0.002 – 0.202 ± 0.003	0.107 ± 0.002 – 0.179 ± 0.002
2	0.190 ± 0.002 – 0.269 ± 0.002	0.167 ± 0.002 – 0.236 ± 0.003
3	0.118 ± 0.002 – 0.179 ± 0.002	0.103 ± 0.002 – 0.153 ± 0.002
4	0.121 ± 0.002 – 0.176 ± 0.002	0.108 ± 0.002 – 0.138 ± 0.002
5	0.125 ± 0.002 – 0.177 ± 0.003	0.114 ± 0.002 – 0.157 ± 0.003
6	0.131 ± 0.002 – 0.194 ± 0.002	0.116 ± 0.002 – 0.171 ± 0.002
7	0.120 ± 0.002 – 0.202 ± 0.003	(0.131 ± 0.002 – 0.176 ± 0.002) ¹

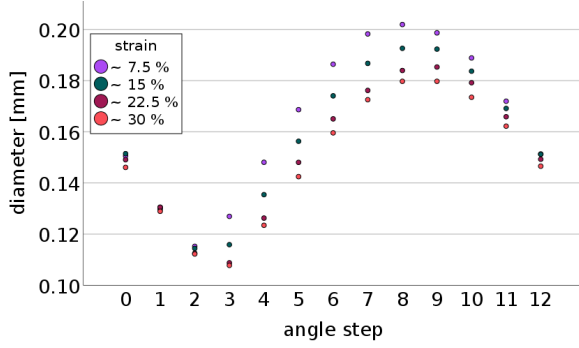
much during the measurement. It can be seen, however, that the diameter does not always change by the same amount for all angles. For example, between angle steps 2 and 6 for sample 1, the difference between initial and final diameter is smaller than for the other angle steps. For samples 3 and 4, the diameters are more irregularly distributed. This can be better seen in Figure 6.12.

Table 6.6 shows the highest and smallest diameter recorded in the beginning and before fracture for the seven pig hair samples. The initial diameters range from 0.120 mm to 0.269 mm. The final diameters lie between 0.103 mm and 0.236 mm.

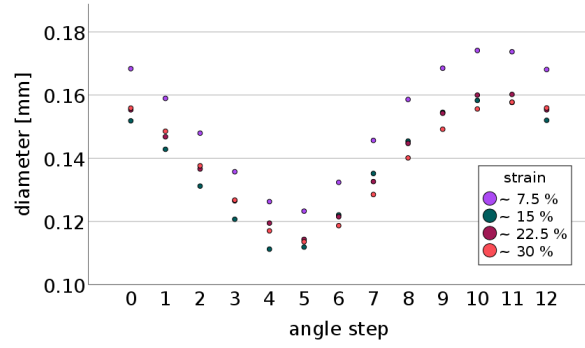
In Figure 6.12 ((a)–(f)), the sample diameter recorded for each angle during the measurement of the pig hair samples 1–6 is shown.

Each of the six samples shows some angles at which the diameter increases. The amount of increase is very prominent for samples 2, 3 and 4, but the increase or decrease of curves takes place at different strains for these three samples. There are also many cases where the diameter temporarily increases by a small amount only.

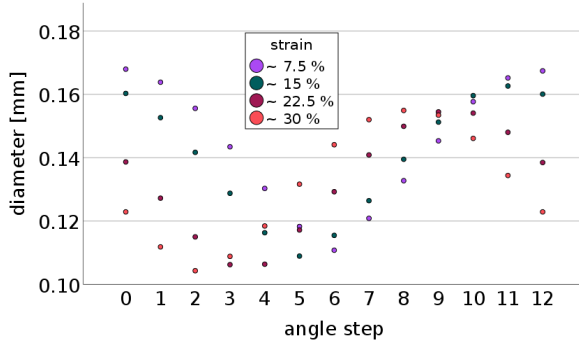
¹the diameter values of sample 7 are very irregular for higher strains.



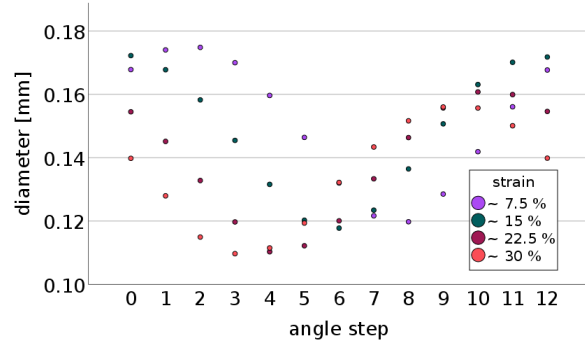
(a) sample 1



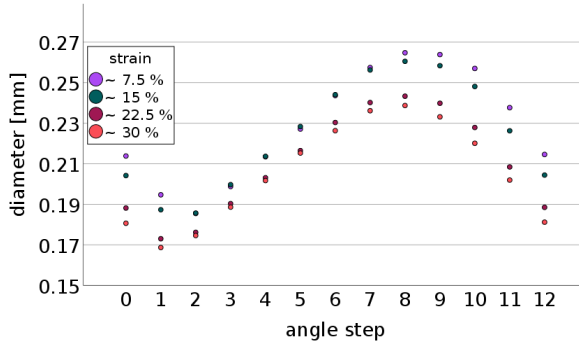
(b) sample 2



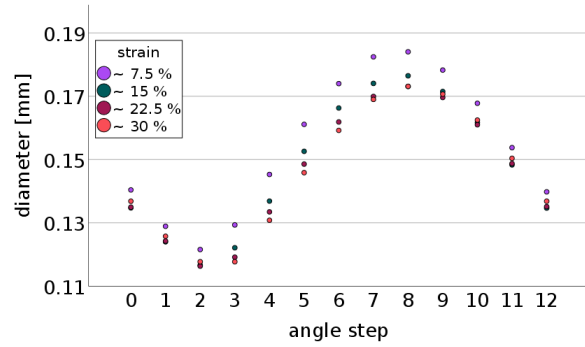
(c) sample 3



(d) sample 4



(e) sample 5



(f) sample 6

Figure 6.11.: Sample diameter in dependence on the angle step for different strains and for the pig hair samples 1–6

In general, it is difficult to see common characteristics of the diameter behavior between all the samples. Roughly, samples 1, 2, 5, and 6 look similar to each other.

For samples 2, 5, and 6, a collective bending of the curves takes place, where most of the curves decrease pronounced and have an inflection point. For sample 2, this can be seen at ~ 12 % strain. Sample 5 shows this behavior at ~ 15 % strain and sample 6 at ~ 7 %. For the monotonically decreasing curves of sample 1, this behavior can also be seen at ~ 15 % strain.

For samples 3 and 4, the order of diameters is inverted in the end compared to the beginning. For the other samples, the order of diameters roughly stays the same even though there are many cases where some of the diameter curves cross each other.

In Figure 6.13, again the development of the diameters is shown for the pig hair samples 1–6 and for each angle step, but with standardized diameters (in relation to the initial diameter). Even though some diameters increase during the measurement, the relative diameter curves show a similar shape for samples 1, 2, 5, and 6 in each case.

One can see that the relative change in diameter is not the same for all angles of a sample. For samples 5 and 6, the diameters measured from different angles are close to each other in the end. Especially in samples 3 and 4, the diameters diverge strongly.

6.2.7. Young's modulus

The elastic region of hair is reported to be below 2 % strain [32]. To make the samples comparative, the linear region was chosen to be below 1.5 % strain for the calculations of Young's modulus for all of the pig hair samples. In this region, all the samples showed linear stress-strain behavior. However, Young's modulus was highly dependent on the choice of points belonging to the linear region (see Section 7.2).

Table 6.7 shows Young's modulus for all seven pig hair samples and calculated for the true and engineering stress. The values for the true stress are always higher than or equal to the values for the engineering stress, even though the difference between the true and engineering stress is not significant ($Z = -1.789$, $p = 0.063$ ²).

²Related-samples sign test; the result is not significant on a significance level of $\alpha = 0.05$, but because $p < 0.1$ it can be said there is a clear trend of the true stress Young's moduli being statistically higher than the engineering ones.

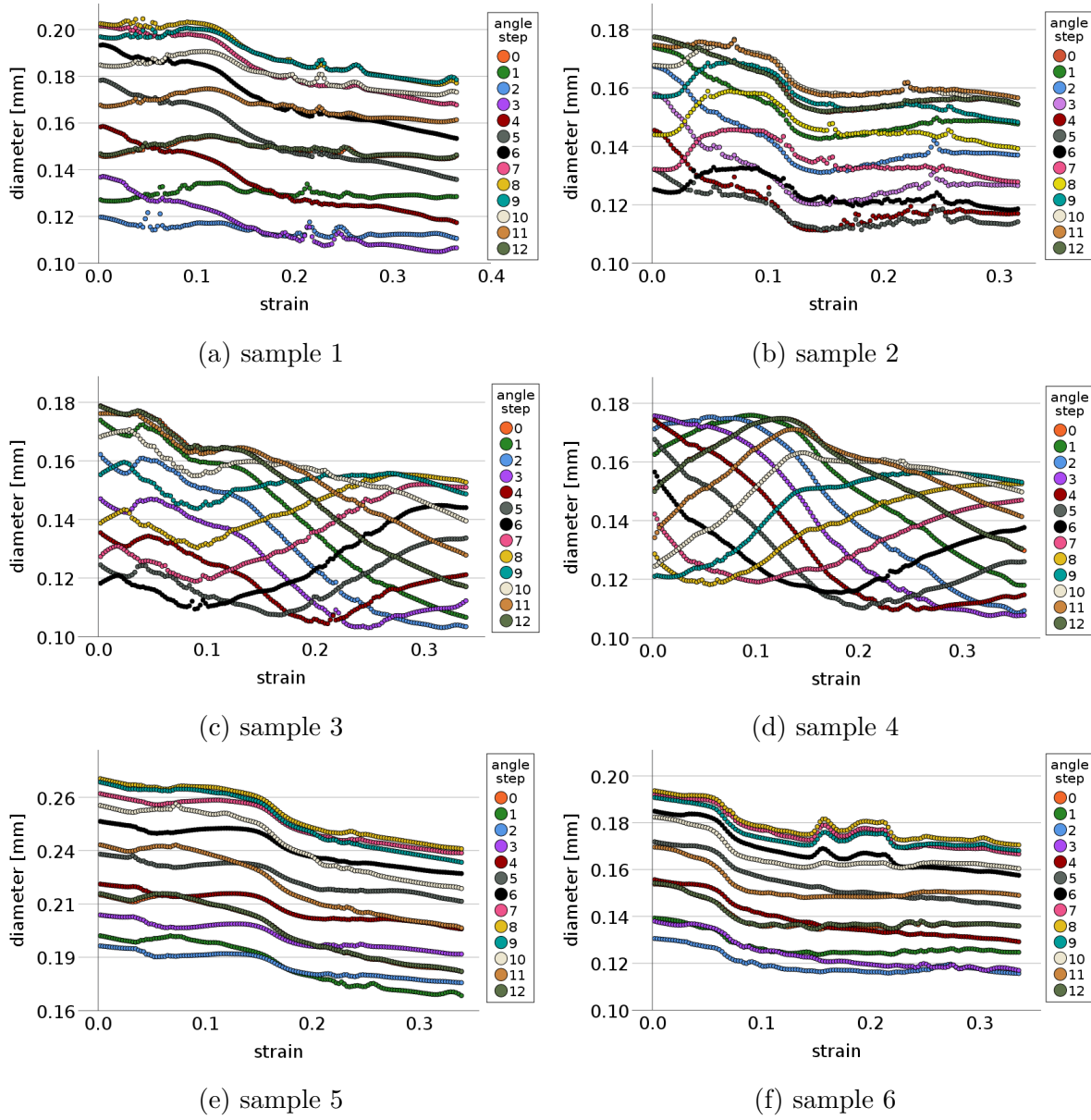


Figure 6.12.: Development of the sample diameter, measured from different angles, for the pig hair samples 1–6

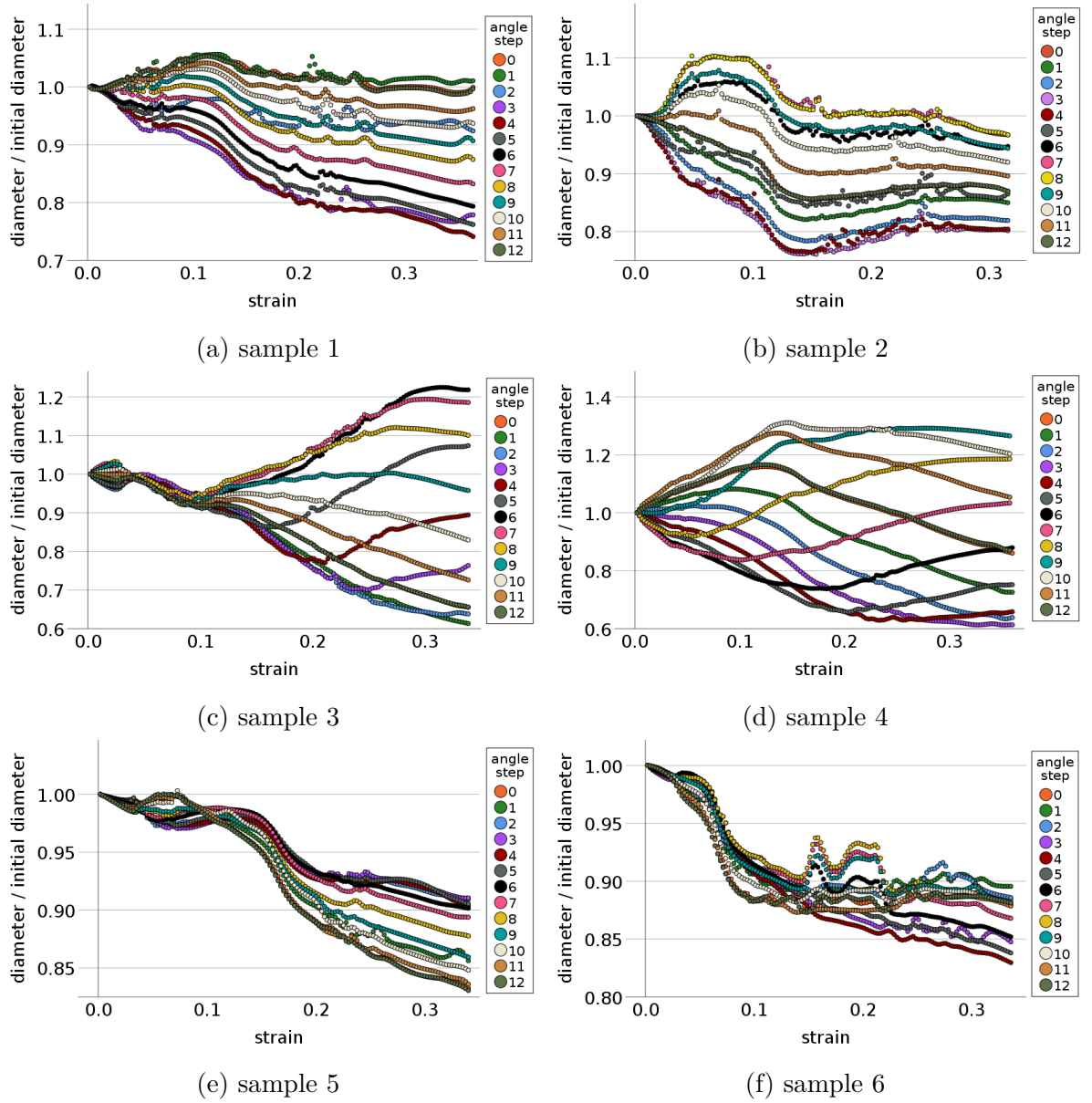


Figure 6.13.: *Development of the sample diameter, measured from different angles and standardized to the respective initial diameter, for the pig hair samples 1–6*

Table 6.7.: Young's moduli of the seven pig hair samples, calculated from the true stress and the engineering stress

sample ID	Young's modulus calculated from true stress [GPa]	Young's modulus calculated from eng. stress [GPa]
1	5.5 ± 0.3	5.5 ± 0.3
2	5.6 ± 0.2	5.5 ± 0.2
3	5.7 ± 0.2	5.6 ± 0.2
4	5.6 ± 0.2	5.6 ± 0.2
5	5.7 ± 0.2	5.6 ± 0.2
6	6.1 ± 0.2	6.0 ± 0.2
7	5.8 ± 0.2	5.7 ± 0.2

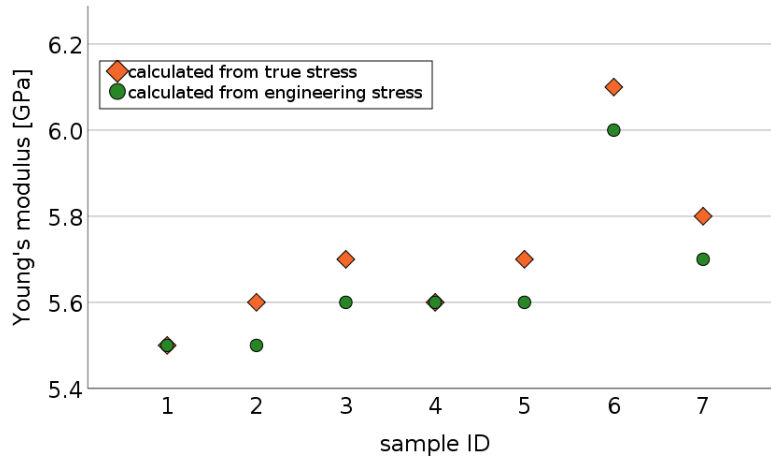


Figure 6.14.: Young's modulus calculated from the true and from the engineering stress in comparison

For the Young's moduli calculated from the true stress, one obtains a median E_{pig}^{true} of

$$E_{pig}^{true} = 5.7 \text{ GPa} (IQR = 0.2 \text{ GPa}). \quad (6.8)$$

The median $E_{pig}^{eng.}$ of the Young's moduli calculated from the engineering stress is

$$E_{pig}^{eng.} = 5.6 \text{ GPa} (IQR = 0.2 \text{ GPa}). \quad (6.9)$$

Figure 6.14 shows the results of Table 6.7 graphically.

In Figure 6.15 ((a)–(g)), the true and engineering stress-strain curves are shown for strains below 1.5 % for all seven pig hair samples. The difference between true and engineering stress is very small but visible.

Table 6.8.: *Young's moduli of the pig hair sample 5, obtained by treating all 13 angles seperately and assuming a circular cross-section*

angle step	Young's modulus [GPa]
0	6.6 ± 0.3
1	7.9 ± 0.3
2	8.2 ± 0.3
3	7.1 ± 0.3
4	6.2 ± 0.3
5	5.4 ± 0.3
6	4.8 ± 0.2
7	4.3 ± 0.2
8	4.1 ± 0.2
9	4.1 ± 0.2
10	4.5 ± 0.2
11	5.2 ± 0.2
12	6.4 ± 0.3

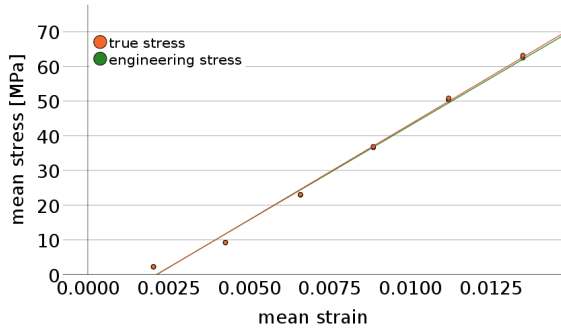
To demonstrate the advantage of recording the sample diameter from different angles, in Figure 6.16 the linear part (below 1.5 % strain) of the stress-strain curves obtained from sample 5 by treating all angles separately and calculating the cross-sectional area with the circular equation are shown. One can see that measuring Young's modulus from one angle only would lead to a different result than measuring it from another angle.

In Table 6.8, Young's modulus has been calculated for each of the angles shown in Figure 6.16. The results range from 4.1 GPa to the doubled value 8.2 GPa (when using the cross-sectional area calculated from twelve different angles, one obtains a Young's modulus of ~ 5.7 GPa).

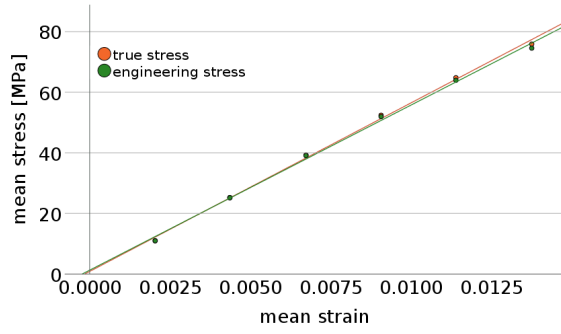
6.2.8. Poisson's ratio

For the determination of Poisson's ratio, again the longitudinal strain region below 1.5 % has been used for all samples.

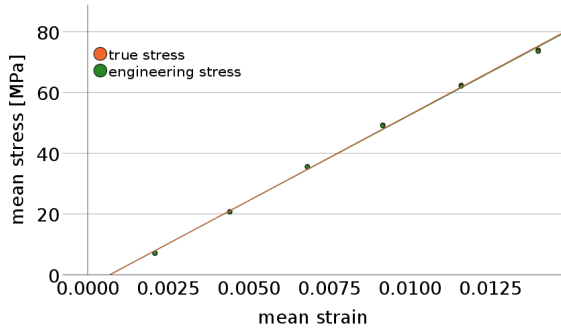
In Figure 6.17, the linear parts of the negative diameter change - strain curves are shown for all of the seven pig hair samples. The linear region has been defined as the region below 1.5 % strain again. One can see that the slope, which gives Poisson's ratio, shows considerable scatter of the data for all the samples.



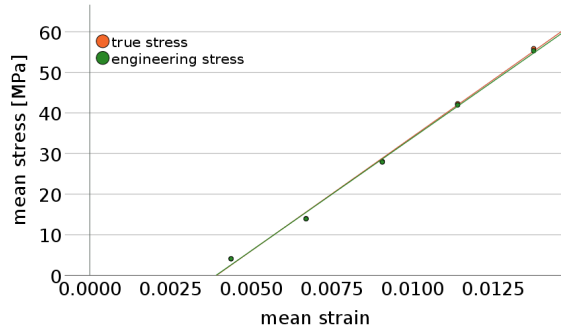
(a) sample 1



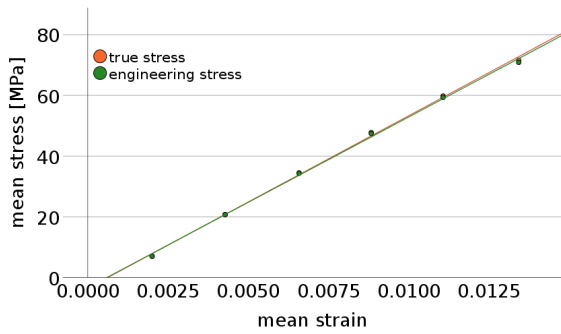
(b) sample 2



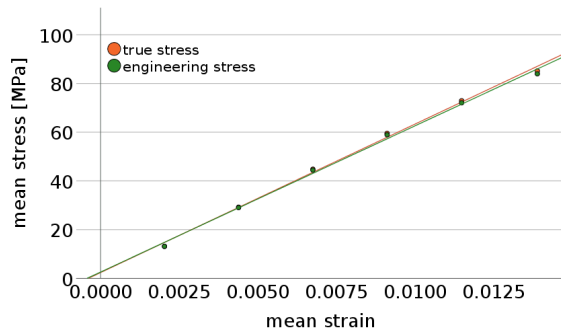
(c) sample 3



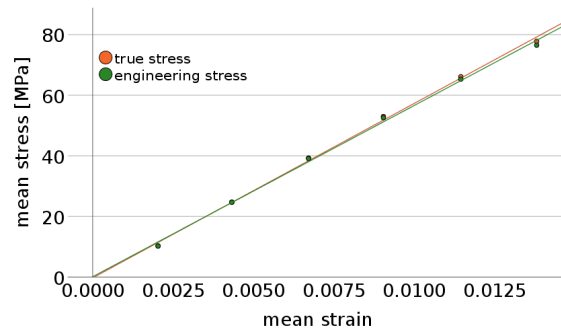
(d) sample 4



(e) sample 5



(f) sample 6



(g) sample 7

Figure 6.15.: *Hookean region of the engineering stress-strain curves of all seven pig hair samples with the corresponding regression lines. The true stress is displayed in orange, the engineering stress in green.*

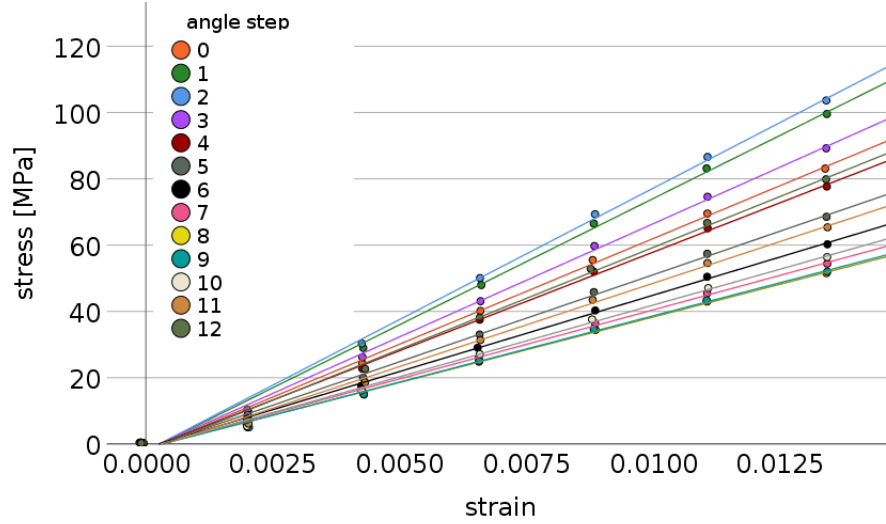


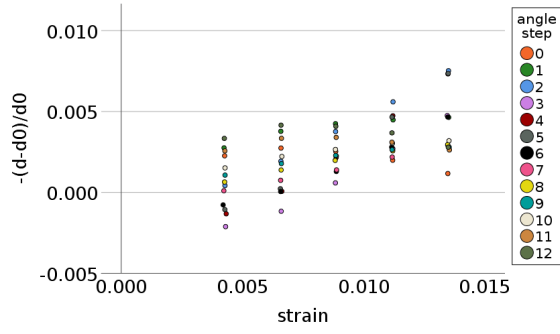
Figure 6.16.: *Linear part of the stress-strain curves obtained by treating each of the 13 angles separately and calculating the cross-sectional area with the common area equation for circular cross-sections. The results show that measuring the diameter from one angle only and treating the sample as circular can lead to variable results for Young's modulus for the same specimen.*

In Figure 6.18, the distribution of Poisson's ratio, obtained by taking the slope of the linear part of the diametric strain - longitudinal strain curve for each angle, is shown as a boxplot for all seven pig hair samples. The median is between 0 and 0.5 for samples 1, 2, 4, 5, and 6. Samples 5 and 6 show Poisson's ratios which are close to each other. For samples 3 and 4, the values have a very high range of ~ 4 and ~ 8 respectively and also very high interquartile ranges.

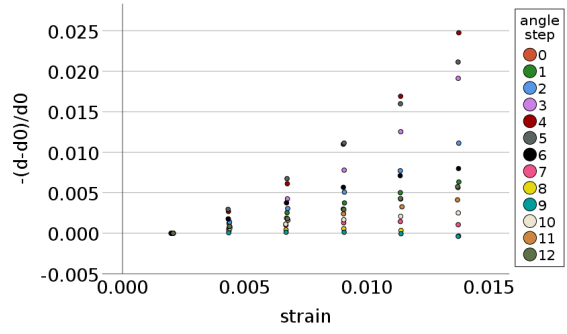
Table 6.9 shows the median values of Poisson's ratio for all seven samples.

Figure 6.19 shows the negative change in diameter $((d-d_0)/d_0)$ against the change in length (strain) for all seven samples. To compare the samples, the angle-averaged diameter has been used for each sample.

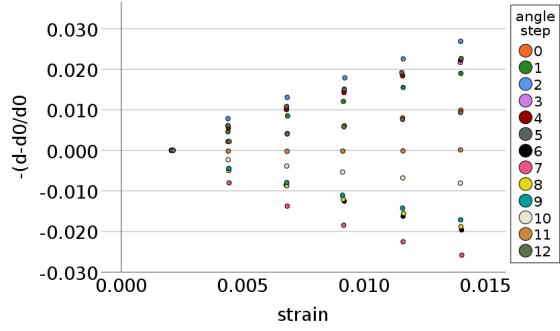
Table 6.10 shows Poisson's ratio calculated from the linear part displayed in Figure 6.19 for all seven pig hair samples. The values range from 0.15 (sample 3) to 0.78 (sample 2).



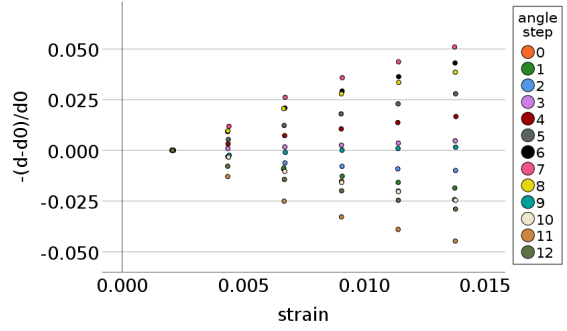
(a) sample 1



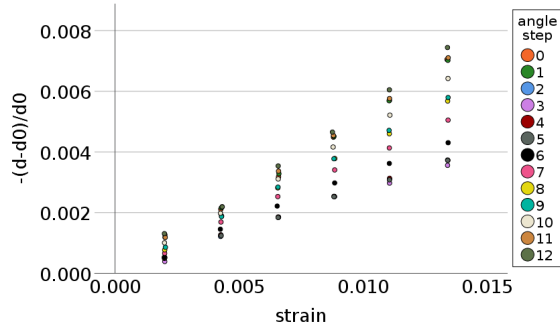
(b) sample 2



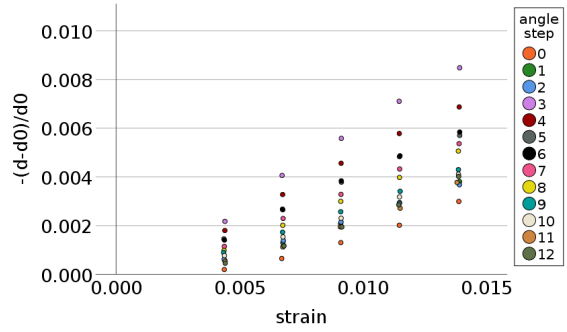
(c) sample 3



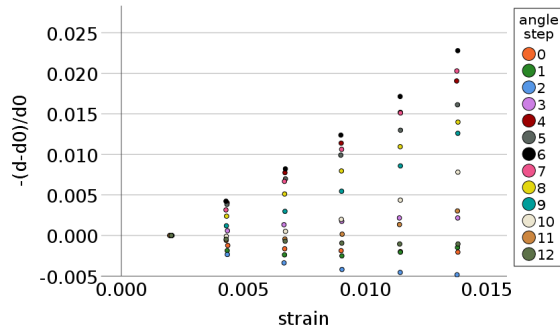
(d) sample 4



(e) sample 5



(f) sample 6



(g) sample 7

Figure 6.17.: *Linear region of the diametric strain - longitudinal strain curves for each angle of the seven pig hair samples*

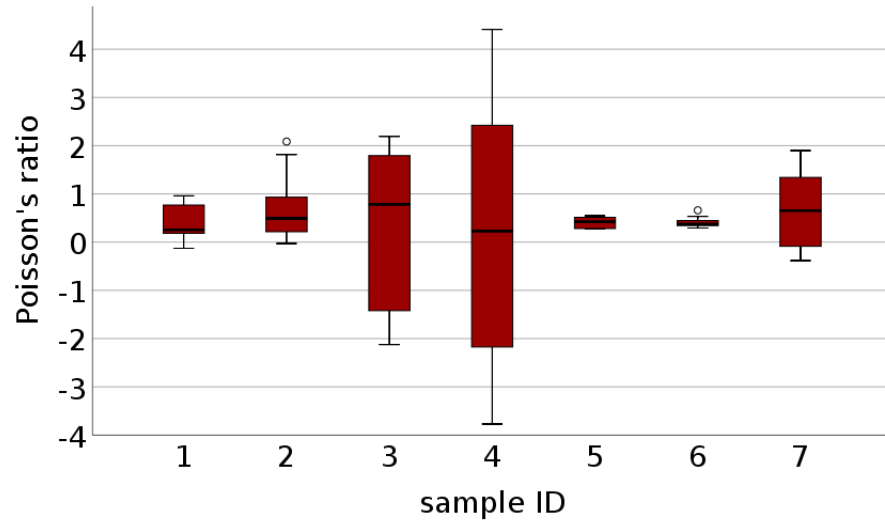


Figure 6.18.: *Boxplot for Poisson's ratio, obtained for each of the seven pig hair samples from the linear part of the diametric strain - longitudinal strain curve for each angle. The interquartile range is shown in red.*

Table 6.9.: *Median of Poisson's ratio obtained for each angle and from the linear part of the diametric strain - longitudinal strain curve for the seven pig hair samples*

sample ID	median of Poisson's ratio (IQR)
1	0.3 (0.7)
2	0.5 (1.2)
3	0.8 (3.4)
4	0.2 (5.1)
5	0.4 (0.3)
6	0.4 (0.1)
7	0.7 (1.6)

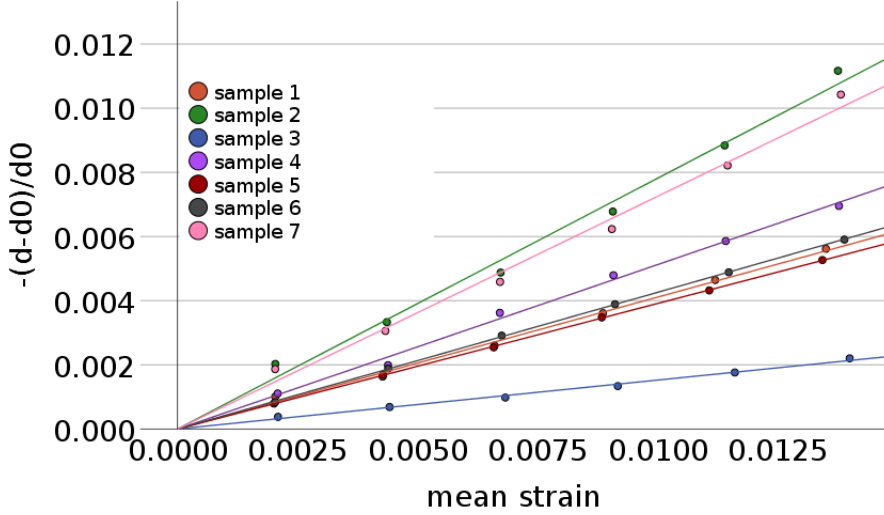


Figure 6.19.: *Determination of Poisson's ratio. The linear region where the diameter decreases with a constant rate is shown and used for the calculation.*

The median Poisson's ratio ν_{pig}^{lin} of all seven pig hair samples is

$$\nu_{pig}^{lin} = 0.43 \text{ (IQR} = 0.34\text{)}. \quad (6.10)$$

For each of the samples, Poisson's ratio has also been calculated by using the initial and final diameter values (as observed before the first measurement step and shortly before fracture; $\nu(\epsilon_d, \epsilon_l) = -\frac{d(\epsilon_d) - d_0}{L(\epsilon_l) - L_0} \frac{L_0}{d_0}$). This way, one obtains values which are very close to each other (between 0.34 [sample 4] and 0.40 [sample 3]) (see Table 6.10). The median value $\nu_{pig}^{fin-init}$ is

$$\nu_{pig}^{fin-init} = 0.36 \text{ (IQR} = 0.02\text{)}. \quad (6.11)$$

In Figure 6.10, the development of Poisson's ratio is shown for the pig hair samples 1–6. As before, the average diameter has been taken in each case, assuming the sample to be circular. Poisson's ratio has been calculated using the first diameter value and for each strain the diameter present at that strain. After 20 % strain, the values remain roughly constant.

Figure 6.21 shows for the pig hair samples 1–6 the negative change in diameter $-(d-d_0)/d_0$ against the strain (black curve) and the slope of the curve (for each strain step calculated from the slope triangle between the diameter change and strain values of the preceding

³There is no reliable final value for sample 7.

Table 6.10.: *Poisson's ratio of the seven pig hair samples calculated by linear regression and by using the initial and final diameter values*

sample ID	Poisson's ratio	
	calculated from linear part	calculated from initial and final values
1	0.41 ± 0.02	0.36 ± 0.02
2	0.78 ± 0.04	0.36 ± 0.02
3	0.15 ± 0.01	0.40 ± 0.02
4	0.52 ± 0.02	0.34 ± 0.02
5	0.39 ± 0.01	0.36 ± 0.02
6	0.43 ± 0.01	0.36 ± 0.02
7	0.73 ± 0.04	$\sqrt[3]{}$

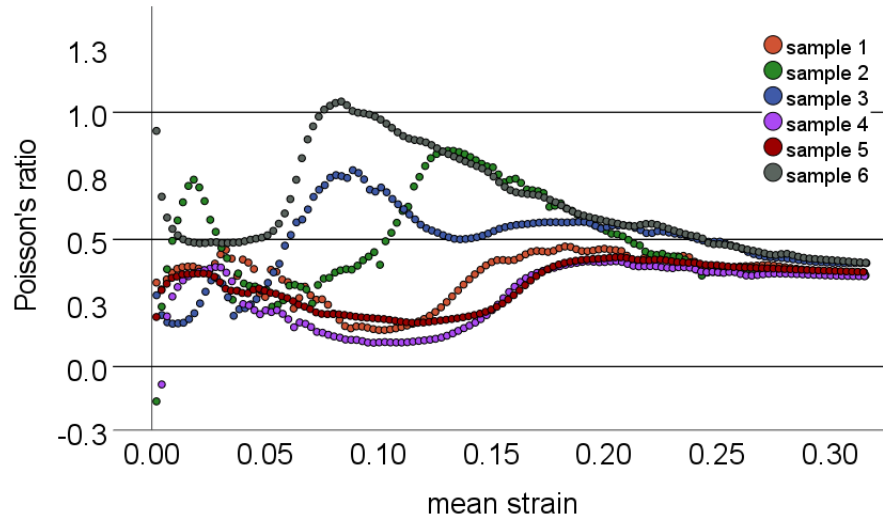


Figure 6.20.: *Development of Poisson's ratio obtained by using the first diameter and for each strain the diameter present at that strain during the straining process for the pig hair samples 1–6. To compare the six samples, the mean diameter has been used for each of them.*

and the subsequent strain step), which gives Poisson's ratio. The majority of values lies between 0 and 1 for each of the samples, but the values exhibit a high scatter and there are many values above 0.5. Some values are also below 0.

The curves of Poisson's ratio show a maximum between 10 and 15 % strain, except for sample 6 (maximum at ~ 5 % strain), where the change in diameter is maximal. Sample 3 also has a second maximum at ~ 5 % strain.

6.2.9. Development of the load

Figure 6.22 shows the measured load at all angles and for strains of ~ 7.5 %, ~ 15 %, ~ 22.5 %, and ~ 30 % for the pig hair samples 1–6. The load decreases with time (angle step) for all the samples and for all of the four strains. The load curves do not show any obvious peculiarities such as sharp changes or deviations from a monotonic behavior.

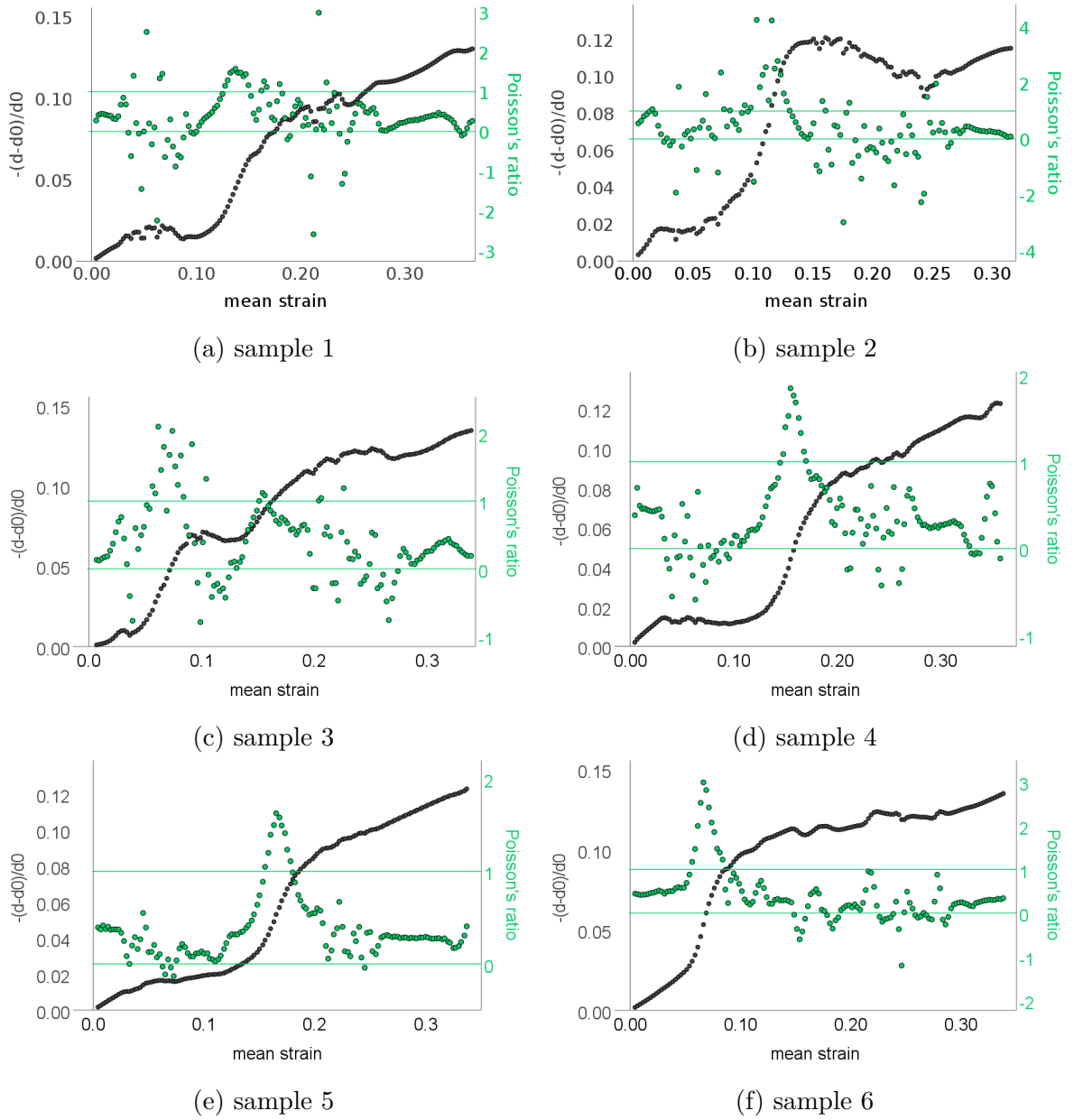


Figure 6.21.: *Diametric strain - longitudinal strain curves (black symbols, left scale) for the pig hair samples 1–6, together with the first derivative (Poisson's ratio) (green symbols, right scale)*

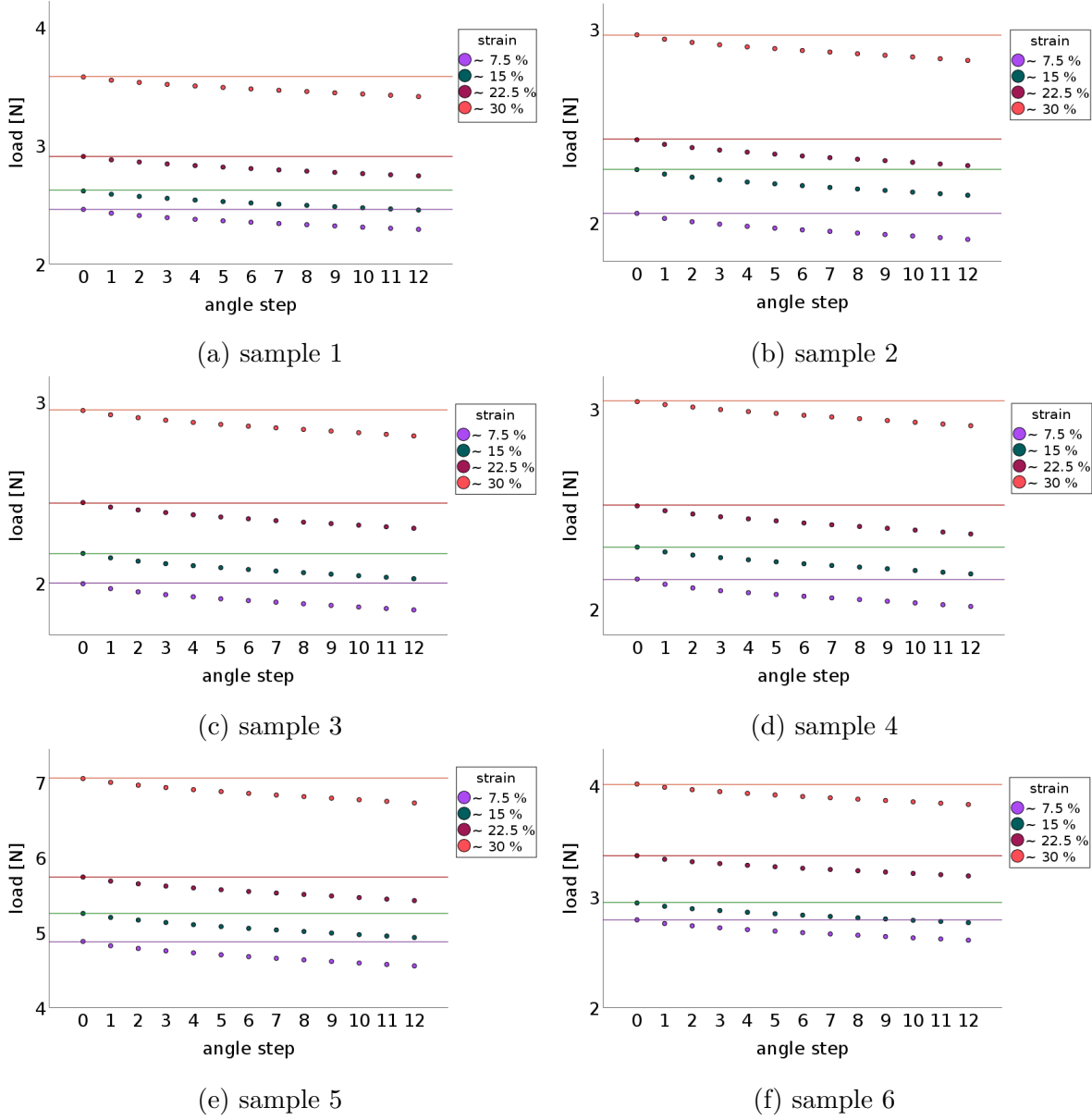


Figure 6.22.: Load as measured from different angle steps for the pig hair samples 1–6 for four different strains each

6.3. Measurements with PET fibers

6.4. Optical measurements

A single PET fiber as seen under the light microscope is displayed in Figure 6.23. The fiber's surface can be seen to be smooth and homogeneous. The diameter is about $100\text{ }\mu\text{m}$, as stated by the manufacturer.

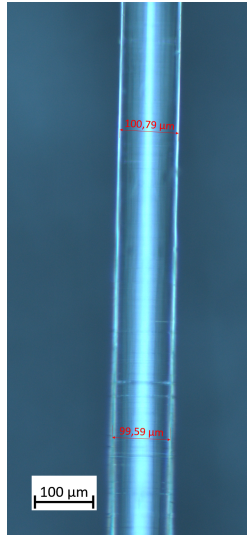


Figure 6.23.: *Longitudinal view of a PET fiber under the light microscope*

Figure 6.24 shows the cross-section of three different PET fibers embedded to resin. The cross-sectional area is circular but the diameter is about 50 % higher than expected. This might be due to the embedding process which includes heating and grinding and therefore maybe expansion of the fiber. There might also have been a reaction with the PET and the resin used. The diameter measured from side-view (Figure 6.23) could be verified to be very close to $100\text{ }\mu\text{m}$ for several fibers however.

The surface of the cross-section is scratched from grinding but very homogeneous apart from that.

6.4.1. Sample description

Clamping lengths and initial cross-sectional areas for the six PET fiber samples used for straining are displayed in Table 6.11. The cross-section is of circular shape for all the samples. The initial cross-sectional areas are about $0.08 - 0.09\text{ mm}^2$.

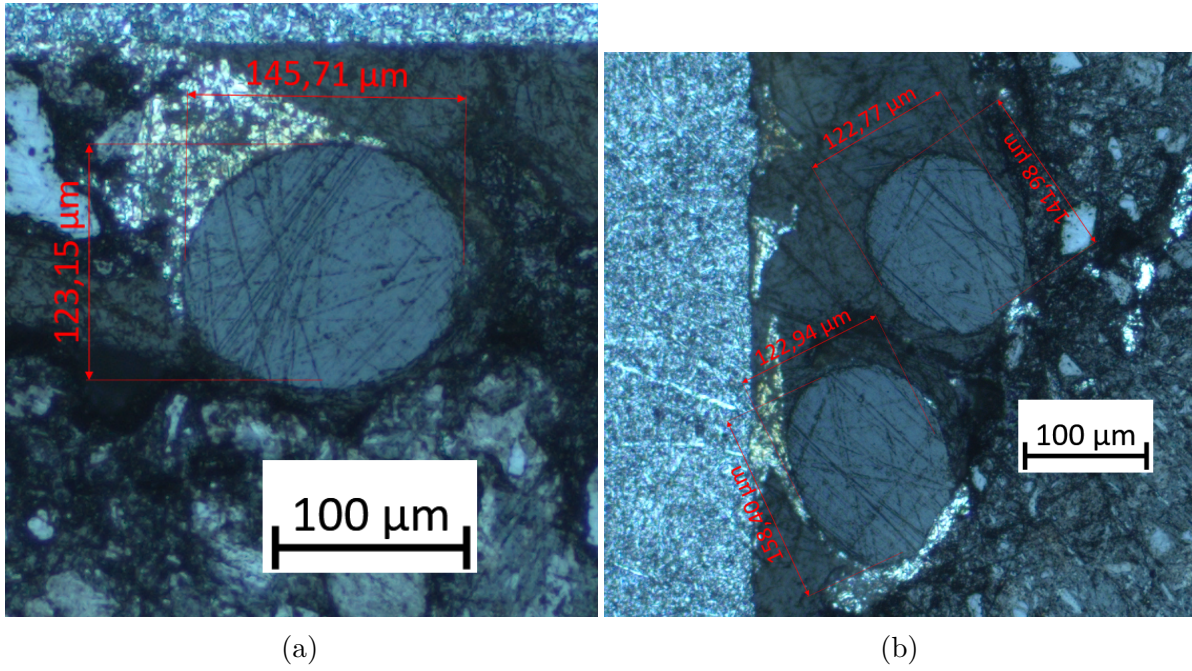


Figure 6.24.: Cross-sections of some PET fibers embedded into resin. The sample dimensions have probably been altered during the embedding process.

Table 6.11.: Clamping lengths, initial cross-sectional areas and area types for the six PET fiber samples

sample ID	clamping length [mm]	initial cross-sectional area [mm ²]	area type
1	19.39 ± 0.01	0.0086 ± 0.0004	circular
2	19.48 ± 0.01	0.0089 ± 0.0004	circular
3	19.55 ± 0.01	0.0079 ± 0.0004	circular
4	19.94 ± 0.01	0.0092 ± 0.0004	circular
5	19.89 ± 0.01	0.0093 ± 0.0004	circular
6	20.55 ± 0.01	0.0084 ± 0.0004	circular

6.4.2. Compliance-correction

The compliance correction of the strain has been calculated according to Eq. 3.6. The difference between the compliance-corrected strain and the non-corrected strain is small. The medians of differences between corrected and non-corrected strain range from 0.0003 (samples 3 and 4) to 0.0007 (sample 2) and are thereby of the order of the uncertainty of the strain measurement.

6.4.3. Stress-strain curves

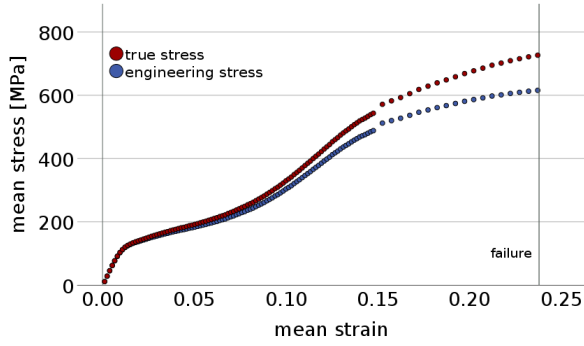
Figure 6.25 ((a)–(f)) shows the stress-strain curves for the six PET samples. The true stress is shown in red, the engineering stress in blue. The true stress is always higher than the engineering stress. True and engineering stresses diverge at strains of $\sim 5\%$. For all samples, the shape of the true and engineering stress curves are similar to each other. Between the different samples, no striking differences are visible. The curves all show a small leap at the point where the strain step is increased. The true stress curve of sample 5 looks irregular around 15% strain. Sample 6 shows a small piece of the true stress curve that is higher than the rest of the curve. Possible causes will be discussed in section 7.3.1.

The engineering as well as the true stress-strain curves increase linearly until about 2% strain. Afterwards, the curves flatten and then increase again between $\sim 5\%$ and $\sim 10\%$ strain. The curves flatten again at $\sim 15\%$ strain.

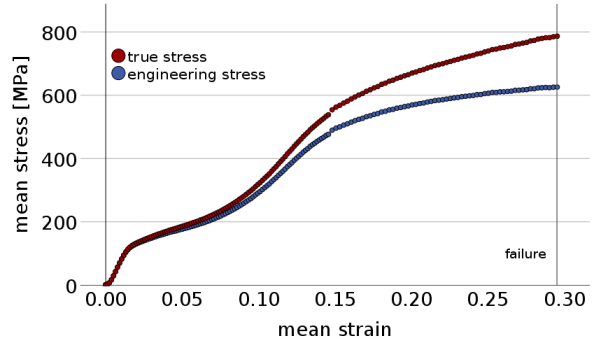
There are four approximate regions seen in the true and engineering stress-strain curves, shown in Figure 6.26, using the example of the PET fiber sample 2.

Figure 6.27 shows the development of the difference between the true and engineering stress for the six PET samples. The fracture stress (tensile strength) for the true stress is about $100 - 150$ MPa higher than the one for the engineering stress.

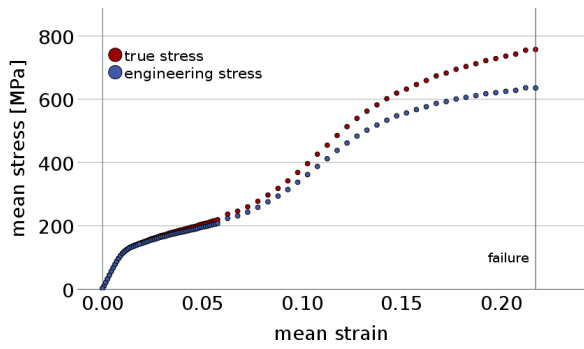
Table 6.12 shows the fracture strains and true and engineering stresses for the six PET samples. The samples could be stretched until ~ 22 to $\sim 30\%$ before failure. The true fracture stresses range from 710 to 790 MPa, the engineering fracture stresses from 590 to 640 MPa.



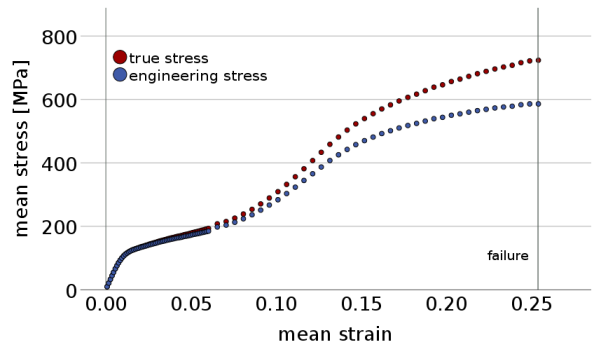
(a) sample 1



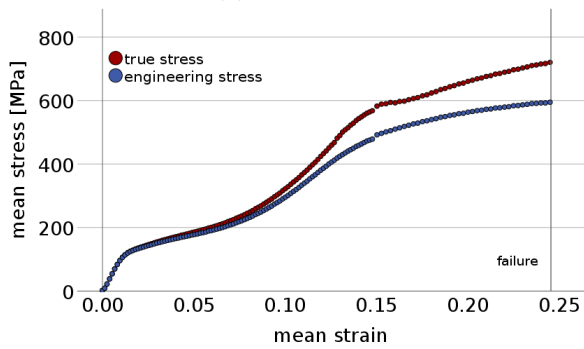
(b) sample 2



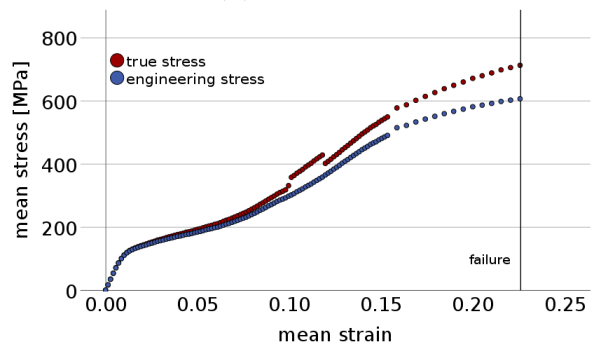
(c) sample 3



(d) sample 4



(e) sample 5



(f) sample 6

Figure 6.25.: Stress-strain curves for the six PET fiber samples. The true stress is displayed in red, the engineering stress in blue.

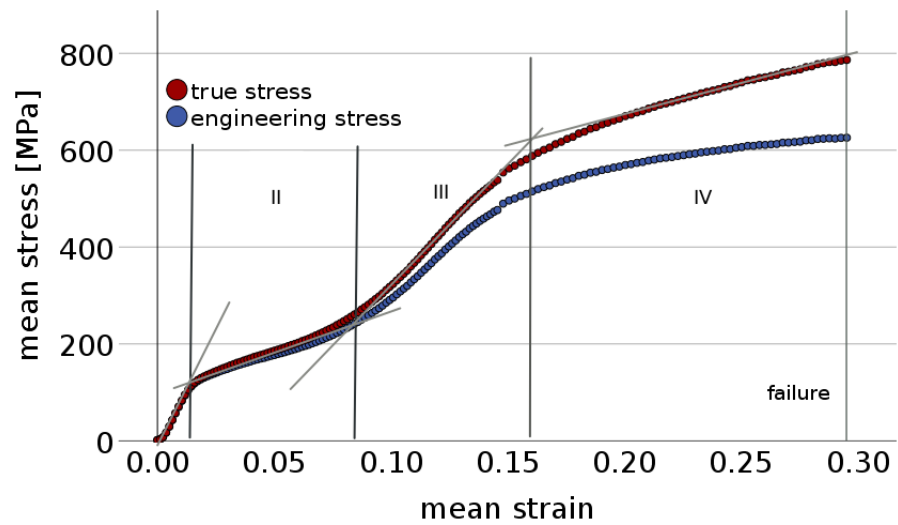


Figure 6.26.: Possible division of the PET fiber 2's stress-strain curve into four regions. The scheme is shown for the true stress but applies for the engineering stress, too.

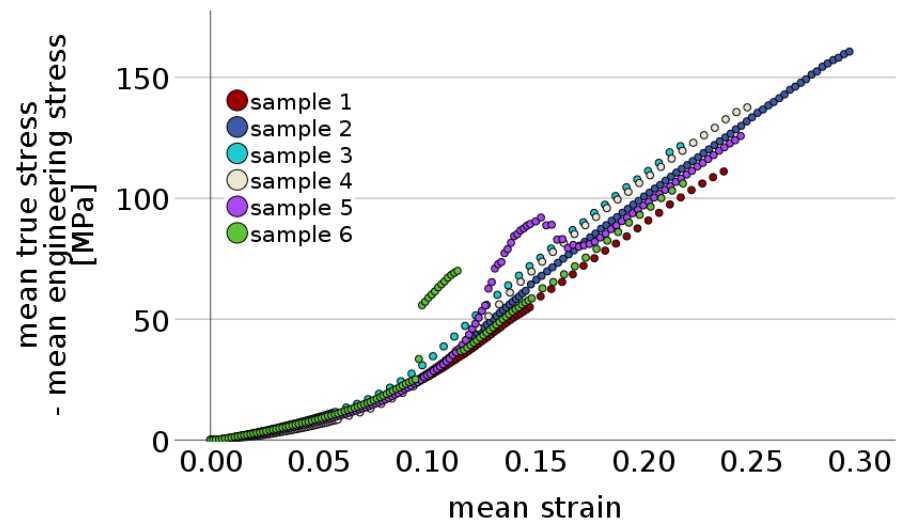


Figure 6.27.: Development of the difference between true and engineering stress for the six PET fiber samples

Table 6.12.: *Fracture strain and corresponding true and engineering stress for the six PET samples*

sample ID	mean fracture strain	mean fracture stress [MPa]	
		true stress	engineering stress
1	0.237 ± 0.003	730 ± 40	620 ± 40
2	0.295 ± 0.003	790 ± 50	630 ± 40
3	0.217 ± 0.003	760 ± 40	640 ± 40
4	0.248 ± 0.003	720 ± 40	590 ± 40
5	0.245 ± 0.003	720 ± 40	590 ± 40
6	0.218 ± 0.003	710 ± 40	610 ± 40

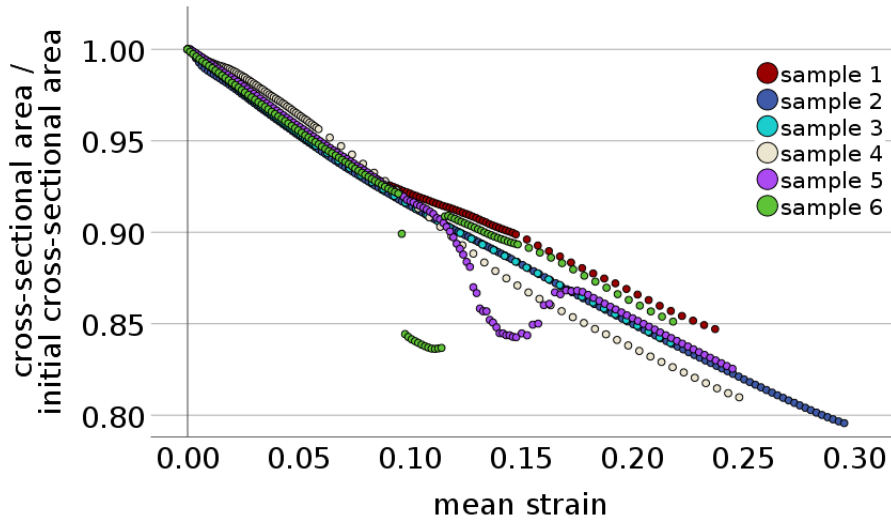


Figure 6.28.: *Development of the sample cross-sectional area, standardized to the initial cross-sectional area, for the six PET samples*

6.4.4. Development of the cross-section

Figure 6.28 shows the development of the standardized cross-sectional area during the measurement for the six PET samples. The decrease in cross-section is roughly linear for all six samples. The irregularities of samples 5 and 6 at ~ 10 and ~ 15 % strain respectively have been observed before in the stress-strain curves. Until ~ 10 % strain, the six samples follow a common line. Afterwards, all the samples slightly decrease in slope by different amounts but remain linearly decreasing.

In Table 6.13, the initial and final cross-sections are shown together with the ratio of both quantities. At fracture, the cross-sectional areas are between 80 and 85 % of the initial cross-section.

Table 6.13.: *Initial cross-sectional areas, final cross-sectional areas and ratio of both for the six PET fiber samples*

sample ID	initial cross-sectional area [mm ²]	cross-sectional area at fracture [mm ²]	initial cross-section / cross-section at fracture
1	0.0086 ± 0.0002	0.0073 ± 0.0002	~ 0.85
2	0.0089 ± 0.0002	0.0071 ± 0.0002	~ 0.80
3	0.0079 ± 0.0002	0.0066 ± 0.0002	~ 0.84
4	0.0092 ± 0.0002	0.0075 ± 0.0002	~ 0.82
5	0.0093 ± 0.0002	0.0076 ± 0.0002	~ 0.82
6	0.0084 ± 0.0002	0.0071 ± 0.0002	~ 0.85

Table 6.14.: *Ranges of the initial diameter and the diameter before fracture for the six PET fiber samples*

sample ID	initial diameter range [mm]	final diameter range [mm]
1	0.104 ± 0.002 – 0.106 ± 0.002	0.096 ± 0.001 – 0.099 ± 0.001
2	0.105 ± 0.002 – 0.109 ± 0.002	0.094 ± 0.001 – 0.095 ± 0.001
3	0.100 ± 0.002 – 0.100 ± 0.002	0.092 ± 0.001 – 0.092 ± 0.001
4	0.107 ± 0.002 – 0.112 ± 0.002	0.098 ± 0.001 – 0.098 ± 0.001
5	0.108 ± 0.002 – 0.108 ± 0.002	0.098 ± 0.001 – 0.099 ± 0.001
6	0.103 ± 0.002 – 0.103 ± 0.002	0.095 ± 0.001 – 0.096 ± 0.001

6.4.5. Development of the sample diameter

Figure 6.29 shows the diameter against the angle step at strains of about 5 %, 10 %, 15 %, and 20 % for the six PET samples. Apart from some exceptional cases, the shape of the curves remains the same for each sample. The diameter changes evenly for all angles and the distances between two points of different strains are approximately constant. Samples 5 and 6 show the already mentioned irregularities. For this reason, angle step 2 at ~ 15 % strain is not shown for sample 5, as well as angle step 8 at ~ 10 % strain is not shown for sample 6 because these values are far out of the range of the other data points. The irregularities for some angle steps can be better seen in Figure 6.30.

Table 6.14 shows the initial and final (before fracture) diameter range for each of the six PET samples. The diameters range from 0.100 mm to 0.112 mm in the beginning and from 0.092 mm to 0.099 mm before fracture.

Figure 6.30 shows the diameter evolution of the PET fiber samples 1–6 for all angles. For samples 5 and 6, the complete data are shown on the left ((e), (g)), and a zoomed-in view, which leaves out the runaway values, is shown on the right ((f), (h)).

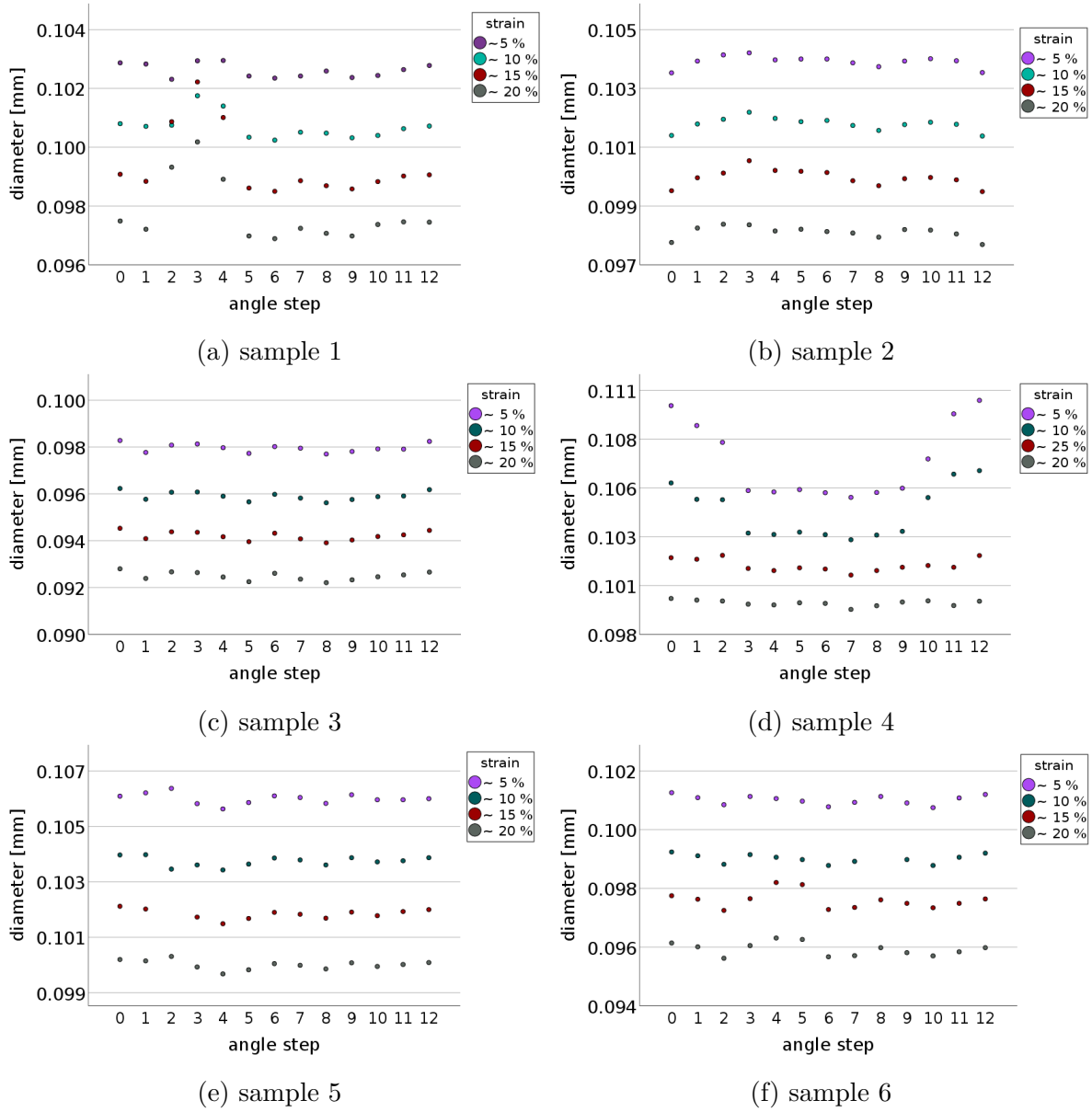


Figure 6.29.: Sample diameter in dependence of the angle step for different strains and for the six PET samples

Sample 1 shows an increase of diameter at some angles between ~ 5 and ~ 10 %. Apart from some runaway cases, the samples all show the same linear decrease in diameter. The slope of the curves seems to be a bit flatter in the end than in the beginning. This can be seen very pronouncedly for sample 6. For sample 1, some of the diameters increase slightly or remain constant between about 10 and 15 % strain. Half of the diameters for sample 4 are divergent until about 15 % strain.

Figure 6.31 shows the relative diameter behavior (standardized to the initial diameter) of the six PET samples and for all angles. Some relative diameters are above one in the beginning because d_0 has been found by extrapolating the diameter to zero and leaving out the first few data points for some cases. It has been assumed here that the first few strain steps of samples 1 and 2 (see 6.30 (a) and (b)) are higher in diameter because of incomplete tightening of the fiber in the beginning.

The diameters decrease to $\sim 90 - \sim 94$ % before fracture. In general, the curves show the same behavior as the unstandardized curves. For nearly all samples and angles, the diameter decreases by the same amount and with the same linear shape.

6.4.6. Young's modulus

Because all the samples' stress-strain curves show linear behavior under strains of 0.7 %, the calculations of Young's modulus are performed for strains between 0 and 0.7 % to make the samples comparable.

Table 6.15 shows Young's modulus, calculated from the true and engineering stress, for the six PET samples. The values of the true stress are higher than or equal to the engineering stress values. The difference between the two is not statistically significant ($Z = -1.789$, $p = 0.063$ ⁴), but since $p < 0.1$, there is a trend of the true stress moduli to be higher. For sample 2, Young's modulus is about 3 GPa lower than for the other samples. For the true stress, the median for Young's modulus (E_{PET}^{true}) is

$$E_{PET}^{true} = 12.0 \text{ GPa} (IQR = 1.9 \text{ GPa}). \quad (6.12)$$

For the engineering stress, one obtains a Young's modulus ($E_{PET}^{eng.}$) of

⁴Related-samples sign test.

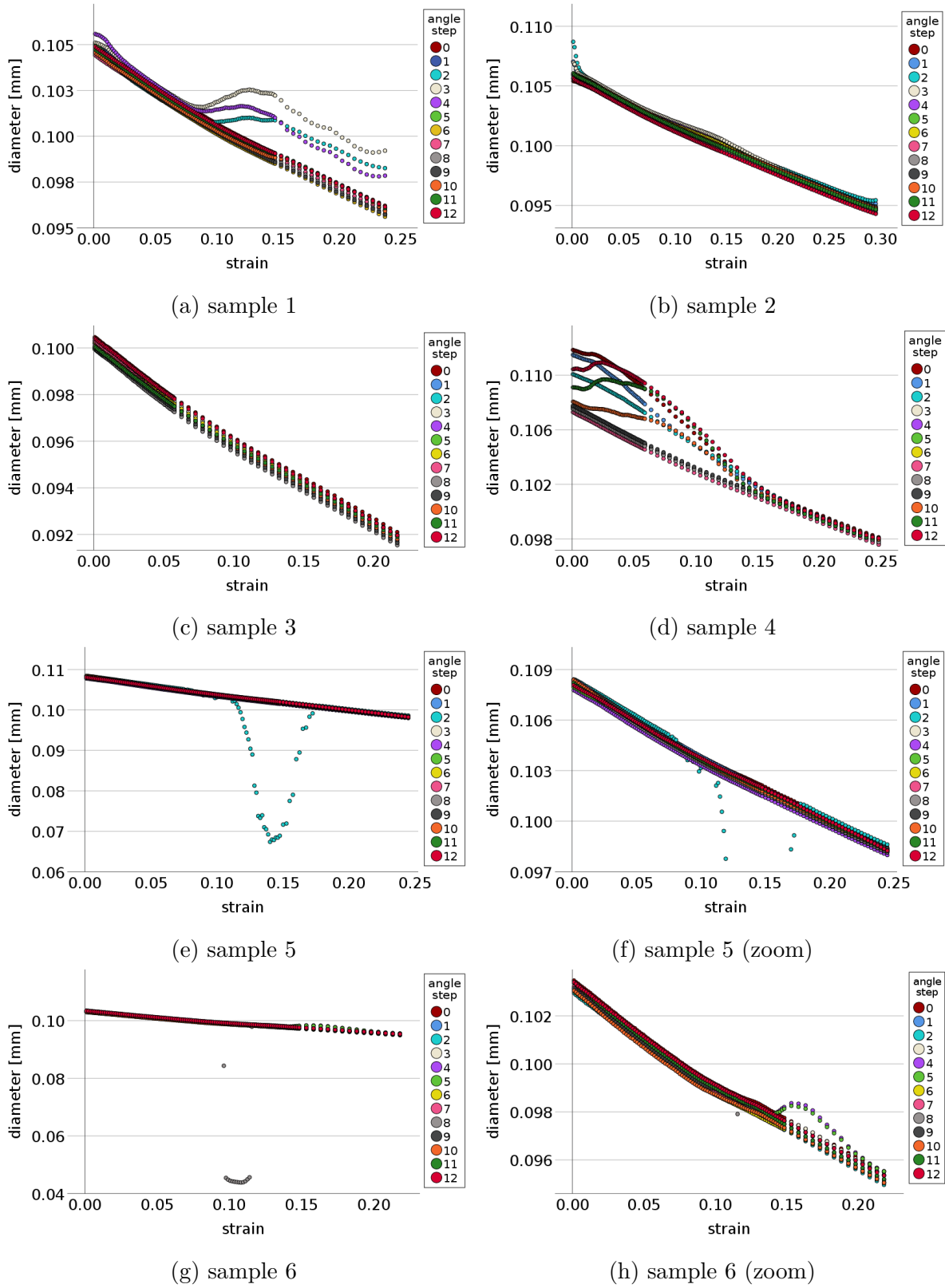


Figure 6.30.: Development of the sample diameter during the straining for all six PET samples and all the angles

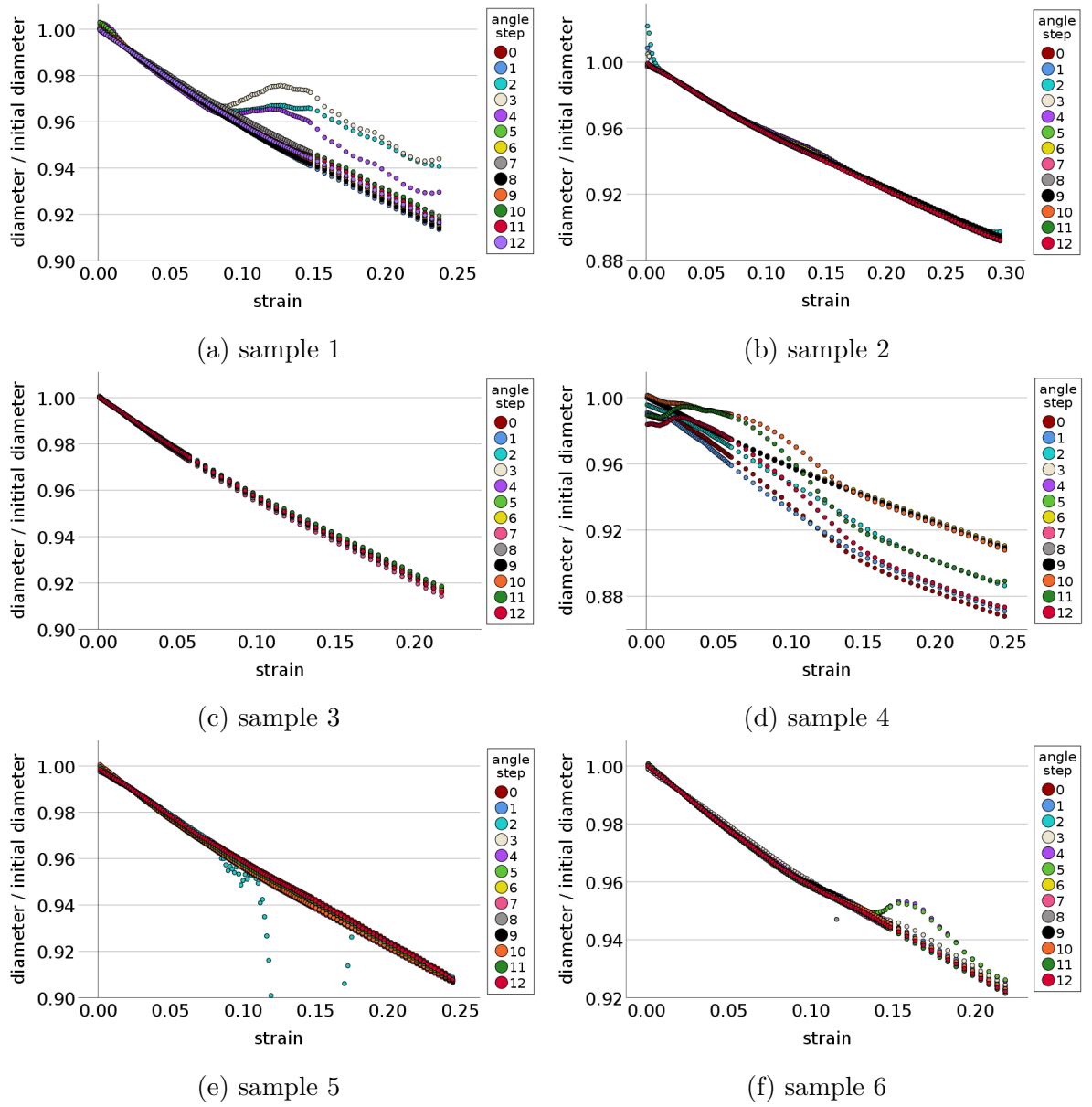


Figure 6.31.: *Development of the standardized sample diameter during the straining for all six PET samples and all the angles*

Table 6.15.: *Young's modulus, calculated from the true and engineering stress, for the six PET fiber samples*

sample ID	Young's modulus [GPa]	
	calculated from true stress	calculated from engineering stress
1	12.0 ± 0.2	11.9 ± 0.2
2	9.0 ± 0.6	8.9 ± 0.6
3	12.5 ± 0.2	12.4 ± 0.2
4	11.9 ± 0.2	11.8 ± 0.2
5	11.2 ± 0.1	11.1 ± 0.1
6	12.7 ± 0.3	12.7 ± 0.3

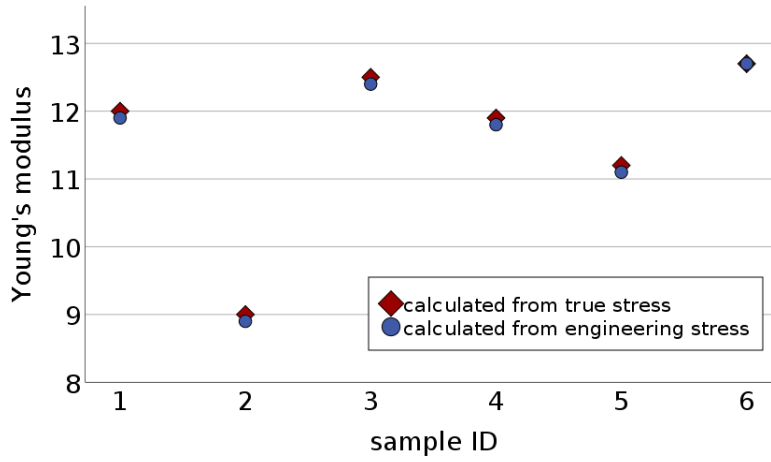


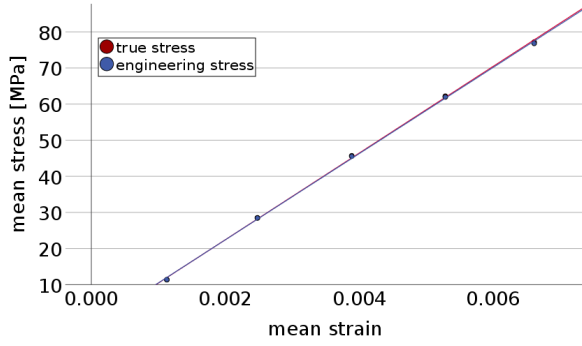
Figure 6.32.: *True and engineering Young's modulus for the six PET fiber samples in comparison*

$$E_{PET}^{eng.} = 11.9 \text{ GPa} (IQR = 2.0 \text{ GPa}). \quad (6.13)$$

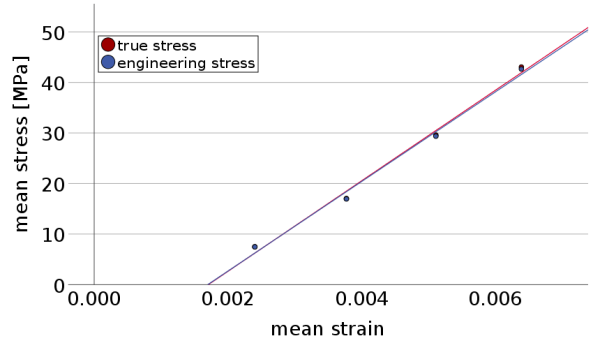
Figure 6.32 shows the results for Young's modulus graphically.

In Figure 6.33 ((a)–(f)), the true and engineering stress-strain curves are shown for strains below 0.7 % for all PET fiber samples. The differences between the curves are very small.

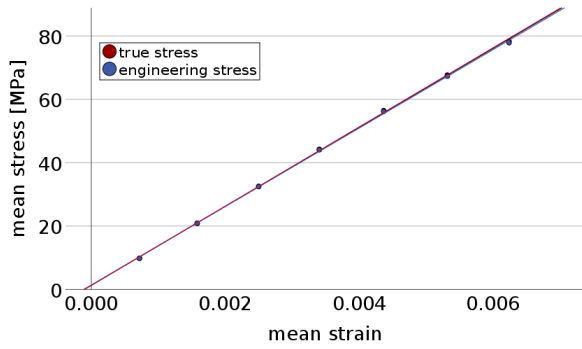
Sample 2 has been randomly chosen for calculating Young's modulus for all angles, using the recorded diameter for the calculation of the corresponding cross-sectional area. The differences between the different angles are small and the obtained values for Young's modulus are close to each other (Figure 6.34 and Table 6.16). The median of the



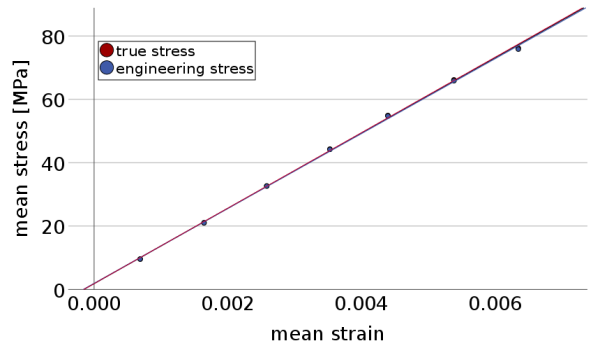
(a) sample 1



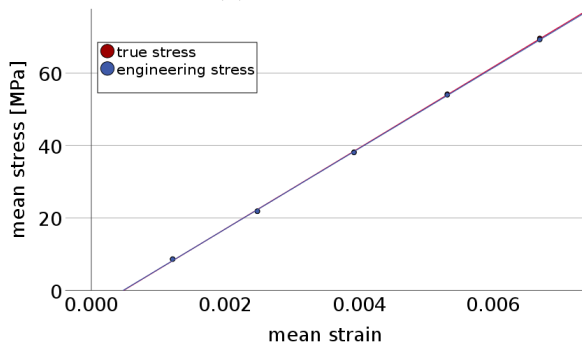
(b) sample 2



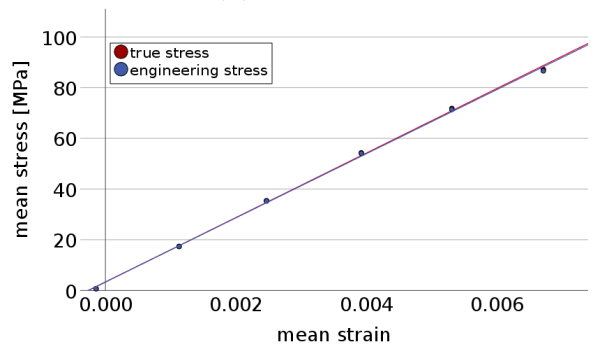
(c) sample 3



(d) sample 4



(e) sample 5



(f) sample 6

Figure 6.33.: *Linear part of the stress-strain curves for all six PET fiber samples. The true stress is displayed in red, the engineering stress in blue.*

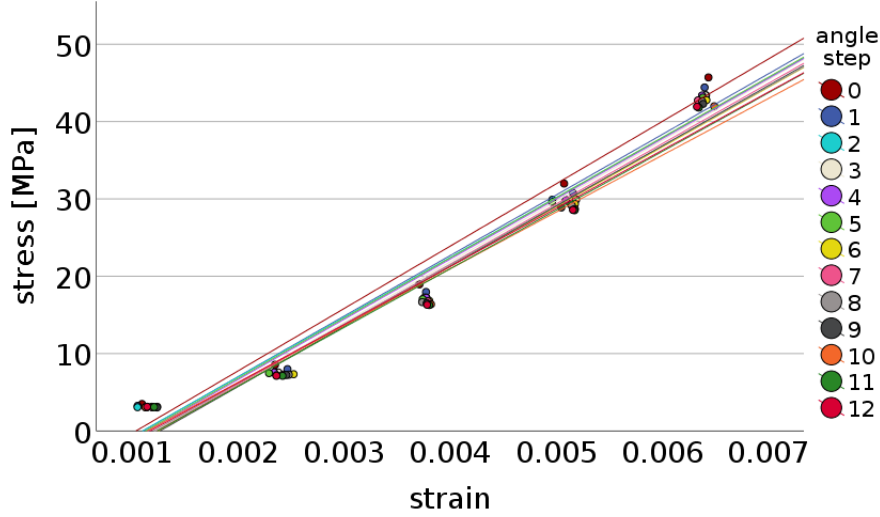


Figure 6.34.: *Linear part of the stress-strain curves for the PET fiber sample 2. The true stress has been calculated using the corresponding diameter for each strain and angle step.*

values shown in Table 6.16 is 9.0 GPa (IQR = 0.3 GPa). When using the cross-section calculated from diameters measured at twelve angles, one obtains a Young's modulus of (9.0 ± 0.6) GPa (see Table 6.15).

6.4.7. Poisson's ratio

As for Young's modulus, the strain regions below 0.7 % have been used for the determination of Poisson's ratio. For sample 2, the first few values were not taken into account because their high diameter values were probably due to the fiber not being stretched entirely in the beginning (see Section 7.3.1).

In Figure 6.35, the negative change in diameter against the strain for all PET samples and angle steps are shown. Except for sample 4, the slopes of the curves are very similar within all the samples.

In Table 6.17, the median values for Poisson's ratio, obtained by calculating the slopes for the data shown in Figure 6.35, are displayed.

The median value for Poisson's ratio ν_{PET} of the data displayed in Table 6.17 is

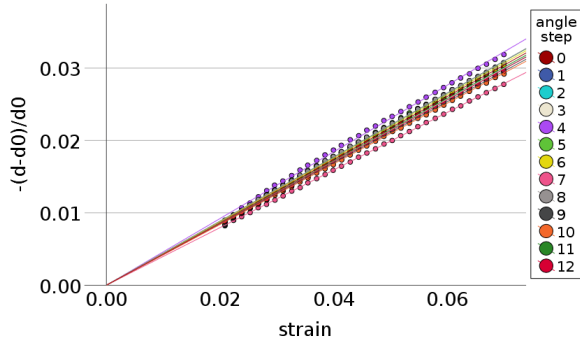
$$\nu_{PET} = 0.44 \text{ (IQR = 0.02)}. \quad (6.14)$$

angle step	Young's modulus [GPa]
0	9.1 ± 0.4
1	9.3 ± 0.6
2	9.0 ± 0.6
3	8.9 ± 0.7
4	8.9 ± 0.7
5	8.8 ± 0.6
6	9.1 ± 0.6
7	9.1 ± 0.7
8	9.0 ± 0.6
9	9.0 ± 0.6
10	8.5 ± 0.7
11	8.8 ± 0.8
12	8.8 ± 0.8

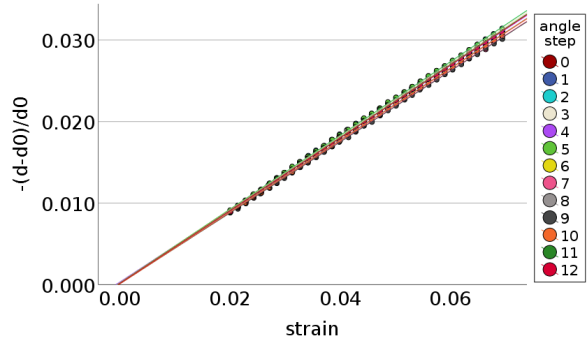
Table 6.16.: *Young's modulus obtained for the different angles of the PET fiber sample 2*

Table 6.17.: *Median of Poisson's ratio for each of the six PET fiber samples*

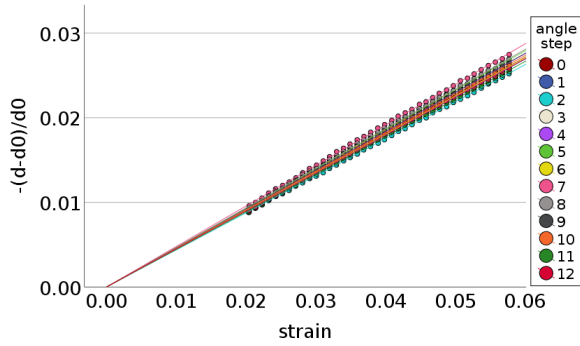
sample ID	median of Poisson's ratio (IQR)
1	0.43 (0.02)
2	0.45 (0.01)
3	0.45 (0.02)
4	0.43 (0.05)
5	0.44 (0.03)
6	0.44 (0.02)



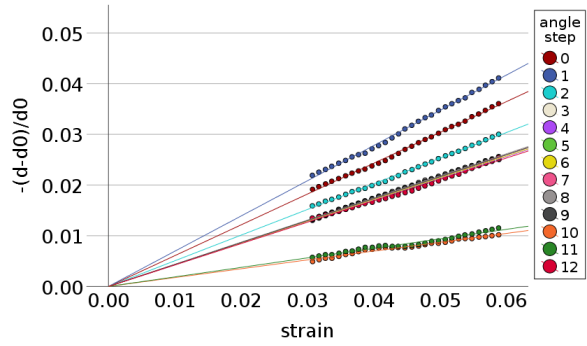
(a) sample 1



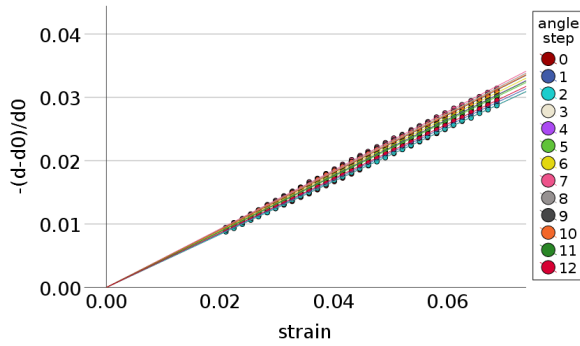
(b) sample 2



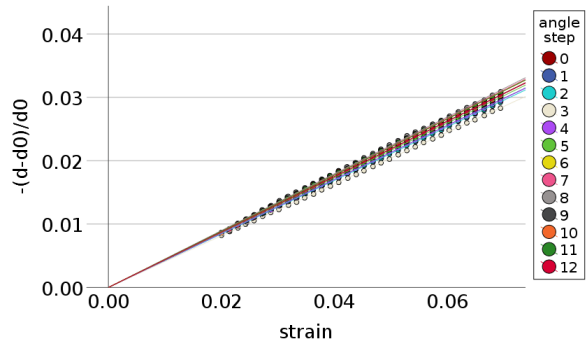
(c) sample 3



(d) sample 4



(e) sample 5



(f) sample 6

Figure 6.35.: *Linear part of the diametric strain - longitudinal strain curves for each angle of the six PET fiber samples*

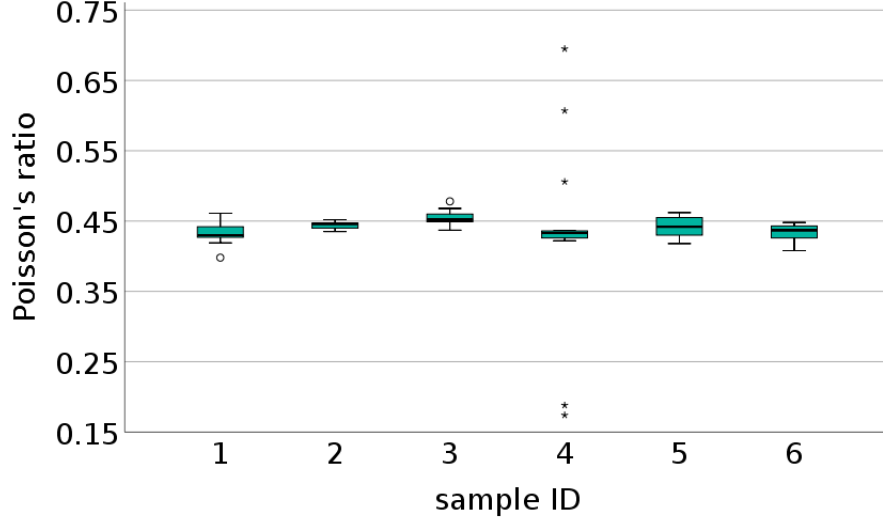


Figure 6.36.: *Boxplot for Poisson's ratio, obtained from the different angles for each of the six PET fiber samples. The interquartile range is shown in green.*

In Figure 6.36, the distribution of Poisson's ratio is shown as a box plot for the six PET samples. The values are very close to each other and the interquartile ranges (green boxes) are small, i.e. there is no significant difference between the single samples. Apart from the runaway values for sample 4, all the values lie approximately between 0.4 and 0.48.

Figure 6.37 shows the negative change in diameter $-(d - d_0)/d_0$ against the strain for the six PET samples. For the diameter, the mean diameter has been used. The six straight lines all have a similar slope.

Table 6.18 shows Poisson's ratio calculated from the linear data shown in Figure 6.18. The median ν_{lin}^{PET} is

$$\nu_{PET}^{lin} = 0.44 \text{ (} IQR = 0.02 \text{)}. \quad (6.15)$$

In the right column of Table 6.18, Poisson's ratio has been calculated using the initial sample diameter and the diameter before fracture. Using the initial and final values, one gets lower values for Poisson's ratio $\nu_{PET}^{fin-init}$ for all of the samples:

$$\nu_{PET}^{fin-init} = 0.37 \text{ (} IQR = 0.05 \text{)}. \quad (6.16)$$

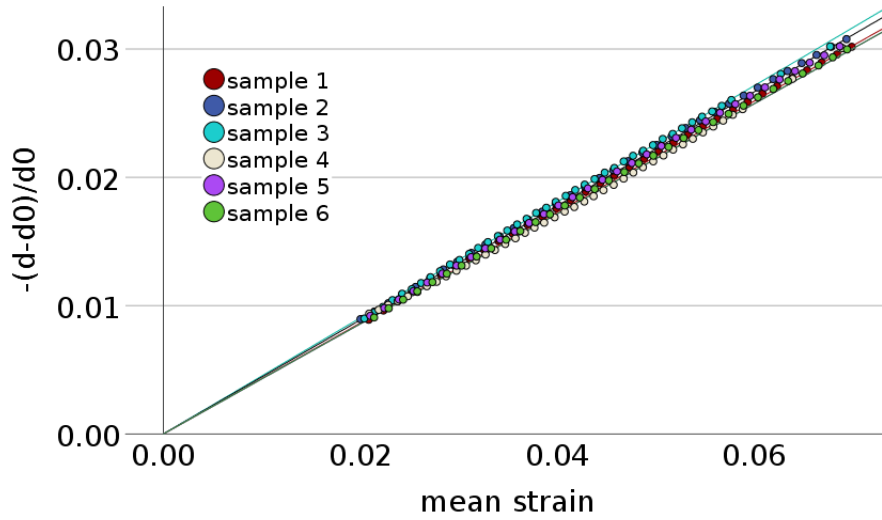


Figure 6.37.: *Linear part of the diametric strain - longitudinal strain curve for the six PET samples. The displayed diameter is the mean diameter for all angles.*

Table 6.18.: *Poisson's ratio for the six PET fiber samples, calculated from the mean diameter of all angles. The left column shows the values obtained by linear regression of the linear part of the diametric strain - longitudinal strain curve, the right column shows the values obtained by using the initial and final diameters.*

sample ID	Poisson's ratio	
	calculated from linear part	calculated from initial and final values
1	0.43 ± 0.01	0.33 ± 0.01
2	0.44 ± 0.01	0.36 ± 0.02
3	0.45 ± 0.01	0.38 ± 0.02
4	0.43 ± 0.01	0.42 ± 0.02
5	0.44 ± 0.01	0.38 ± 0.02
6	0.43 ± 0.01	0.35 ± 0.02

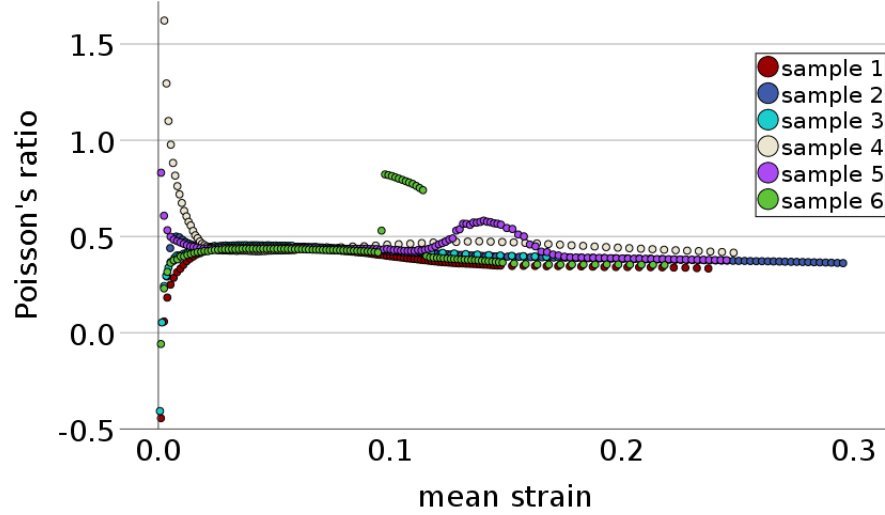


Figure 6.38.: *Development of Poisson's ratio obtained by using the first diameter and for each strain the diameter present at that strain during the straining process for the PET fiber samples 1–6. To compare the six samples, the mean diameter has been used for each of them.*

Figure 6.38 shows Poisson's ratio for the six PET fiber samples, calculated for each strain by using the mean diameter at that particular strain and the initial diameter. After ~ 2.5 % strain, Poisson's ratio obtained like this is relatively constant and similar for all of the samples until ~ 10 % strain, where Poisson's ratio goes down slightly and becomes slightly divergent between the different samples.

Figure 6.39 shows the negative change in diameter against the strain for the six PET samples as well as the corresponding first derivative (Poisson's ratio). Poisson's ratio is between 0.2 and 0.5 during the whole measurement for all the samples, except for the already mentioned irregularities of sample 5 and 6.

6.4.8. Development of the load

Figure 6.40 shows the load at strains of ~ 5 %, ~ 10 %, ~ 15 %, and ~ 20 % for each angle step and for each of the six PET samples. The load decreases with time (angle step); this effect is more pronounced in the higher strains.

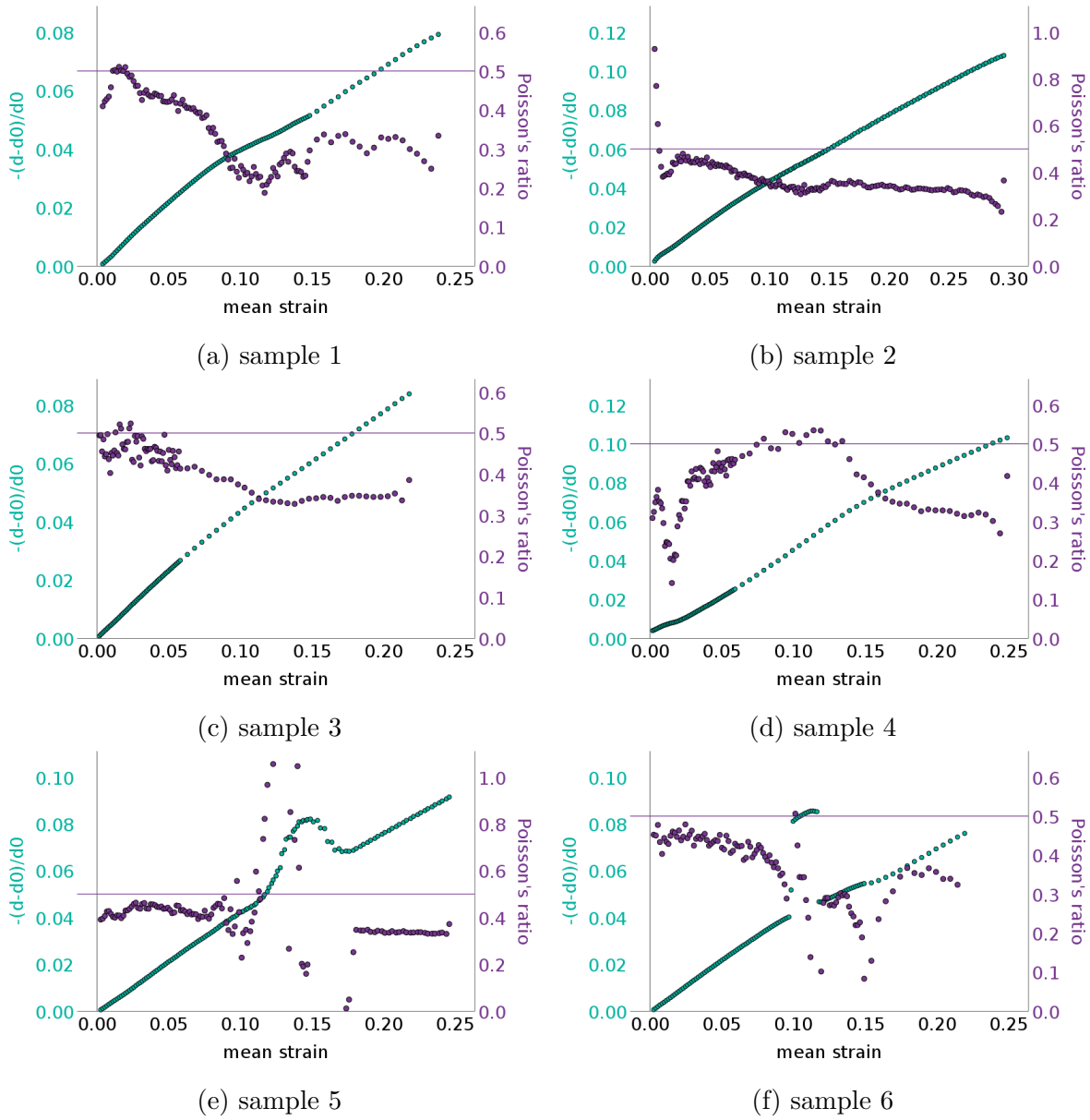


Figure 6.39.: Diametric strain - longitudinal strain curves (green symbols, left scale) for the six PET fiber samples, together with the first derivative (Poisson's ratio) (purple symbols, right scale)

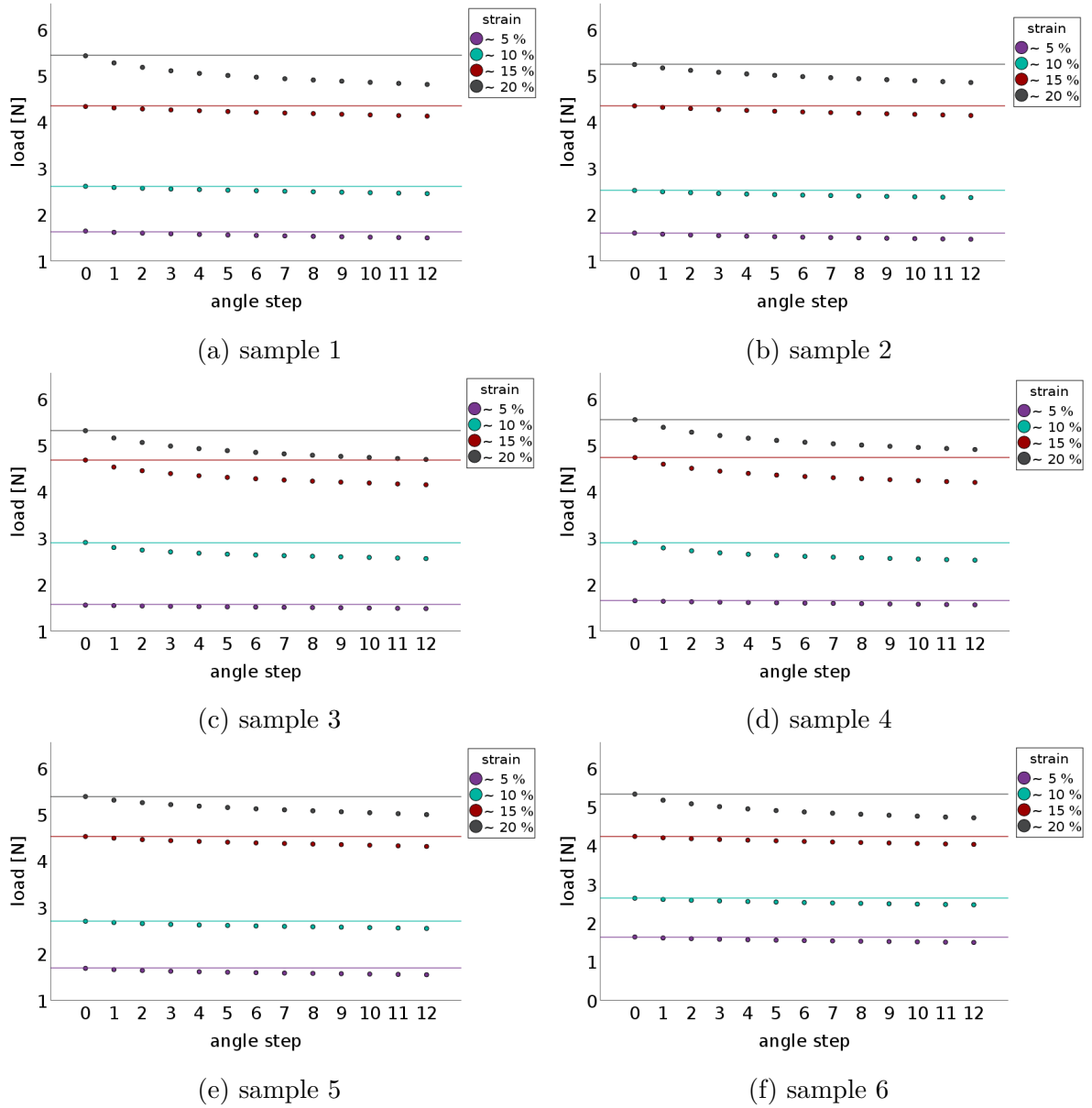


Figure 6.40.: *Development of the load with angle step (= time) for four different strains and for each of the six PET fiber samples*

7. Discussion

In the following, the obtained data for the compliance measurement with copper wire and the measurements with pig hair and PET fibers will be discussed in terms of possible sources of data inaccuracy, errors, and interferences with the findings of other studies. The mechanical behavior observed for the pig hair and PET fibers will be compared. Finally, the general data accuracy and the applied method will be reviewed.

7.1. Compliance measurements with copper wire

Looking at Table 6.2, it obviously makes a difference whether the unloading or reloading data are used, except for the Cu-150 wire, where both regression equations are equal within the means of accuracy. It also makes a difference which copper wire type is used. The values for wires with higher diameters (Cu-150, Cu-220) are probably more reliable because the L_0/A_0 ratios are located at smaller values. For the Cu-220 sample, the highest L_0/A_0 ratio is about 900 mm^{-1} , which is closer to zero than the ratio of approximately 19000 mm^{-1} for the Cu-50 wire. On the other hand, higher values are more stable concerning arbitrary errors.

Because the mean values of the load and the extension have been used, and because these quantities have relatively high standard deviations (compare B.2), it would probably be more accurate to calculate the compliance for just one angle or for each angle separately and not use mean values.

The DIN 1007–4 standard only uses the initial cross-sectional area for the determination of the load train compliance. With the possibility of knowing the actual area, one might be able to adapt the method of determining the load train compliance in a more accurate way which includes the change in the cross-section.

7.2. Measurements with Mangalitza pig hair

7.2.1. Review of the measured data and possible error sources

Stress-strain curves

The true stress-strain curve of the pig hair sample 7 looks irregular (Figure 6.7). The load shows a smooth course, as the curve of the engineering stress shows, therefore any irregularities should originate in the diameter measurements. Looking at the diameter, there are no single runaway values which deform the curve, but the diameters are all irregular. A possible cause of this might be contamination of the hair's surface or a natural inhomogeneity or damage of the hair at the position where the diameter has been recorded. Because the other six samples look different, the behavior of sample 7 was classified as defective and not as intrinsic. Therefore, sample 7 was excluded from most analyses.

In general, because the true stress is calculated from the cross-sectional area and therefore from the sample diameter, any irregularities (deviations from the remaining curve progression) in the sample diameter echo in the true stress-strain curves.

Development of the sample diameter

There is at least one angle for each sample which shows an increase in sample diameter. For some cases, the increase is of small magnitude and limited to a small strain range, for example for sample 6 (compare Figure 6.12) at $\sim 15\%$ strain. In other cases (samples 3 and 4), the diameter increases significantly for a longer strain scope and doesn't decrease again.

Besides random error effects or errors from the measuring devices, irregularities could stem from pollution of the sample, either residues of dirt that weren't cleaned away properly, or dust particles, or from damages inside the specimen. However, dust particles might be more expected to produce non-smooth or sudden irregularities rather than smooth ones. Also, the constriction site could have moved during the straining.

As another possible error source, construction works that were carried out at the floor below the measuring room could have contributed to any runaway diameter values by moving the laser or the measuring device slightly.

As a biological material, hair is highly inhomogeneous and non-isotropic. Runaway values of the diameter might be due to ripping of the cuticle or macrofilaments. They

could also stem from non-straight mounting of the fiber. Also, the keratin in the hair fibers is sensitive to humidity [32] and swelling might appear. The humidity of the air has not been taken track of during the measurements.

The strong increase in diameter seen in samples 3 and 4 and in the beginning of sample 2 might have been caused by irregular constriction of the hair fiber which could be due to the general inhomogeneity of the hair.

In general, it is difficult to distinguish between an increase in diameter because of actual extending of a hair fiber's component and potential error sources. This is because the curves all show a very individual course. The irregularities of the diameter do not seem to be completely random though. There are for example small increases in diameter seen between 20 and 30 % strain for samples 1 and 2.

Inaccuracies in the diameter also have an impact on derived quantities, such as the true stress, Young's modulus, and Poisson's ratio.

Young's modulus

The amount of data points considered to belong to the Hookean region of the stress-strain curves has been crucial for the exact value of Young's modulus. Figure 7.1 shows (for the pig hair sample 1) the regression lines for several amounts of data points which can all be considered to be linear by eye measure. The more points are included, the smaller Young's modulus becomes. The values range from 5.0 to 6.0 GPa. Therefore, the Young's moduli determined in the present work are not expected to be accurate to a few GPa. They do, however, give an idea of the approximate range of Young's modulus.

Poisson's ratio

The determination of Poisson's ratio is probably very inaccurate for the pig hair. There are values far below -1 and above 0.5 reached and, especially for samples 3 and 4 (compare Figure 6.18), the range of values is very high for each of the samples. It is unlikely for any material to exhibit such extreme values for Poisson's ratio and values below 0 or above 0.5 in general [8] [7]. As the determination of Poisson's ratio is based on diameter measurements, the same error sources as for the sample diameter can be expected.

The evaluation of the part below 0.7 % of the diametric strain - longitudinal strain curves is probably more accurate than the evaluations that involve the whole straining process because the change in diameter is linear for all samples here. However, this part is also very variable between samples and angles.

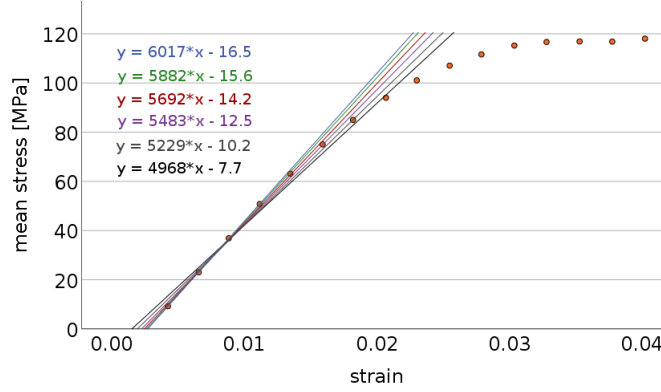


Figure 7.1.: *Calculation of Young's modulus for the pig hair sample 1. Both constants of linear regression decrease with inclusion of more data points. Young's modulus is given by the slope.*

For zero longitudinal strain, the diametric strain should be zero. This was not the case for the present data because the first few data points have not been used for all of the samples because they showed negative extensions and were expected to have a high probability of being erroneous (the fiber might have been compressed or not entirely straightened in the beginning). The value for d_0 can be found by performing a linear regression on the diameter against the strain. This did, however, not make a difference for the pig hair (within the scope of measuring accuracy). In Figure 6.17, however, it can be seen that, for all of the samples, the curves do not go through the origin. The intercept is small on an absolute scale but relatively large compared to the maximum (or minimum) of the presented data.

Looking at the range of values (6.18), sample 1, 2, 5 and 6 are probably more reliable on Poisson's ratio than samples 3, 4 or 7. These are also the samples for which the diameter shows an, in sum, monotonously decreasing behavior.

In general, the concept of Poisson's ratio is based on linear elasticity and constant material properties. If the inner structure changes or non-linear effects play a role, one does not obtain a single and precise value for Poisson's ratio.

7.2.2. Interpretation and discussion of the obtained findings

Stress-strain behavior

For the engineering stress-strain curves, the tripartite build-up (regions I–III, compare Figure 6.8) described by Popescu & Höcker [32] could be found. The first – linear – region I is associated with the stretching of the α -helices [32]. In the following region II, the coiled-coils should start to unravel. In region III, the refolding of the unraveled α -fibers into β -sheets should take place [24], [27]. Regions I, II, and III, which are found in all of the pig hair samples, are synonymous with the regions R1, R2 and R3 described by Popescu & Höcker [32], Figure 2.6.

The true stress could be interpreted to show four regions (at least for some samples) (compare Figure 6.8). These regions are not clearly distinguishable, but there seem to be more than the classical three regions of α -helix stretching, the unraveling of the coiled-coils and the refolding into β -sheets. Looking at Figure 6.8, the two regions I as well as region IV of the true stress and region III of the engineering case are identical, whereas region II of the engineering stress splits into regions II and III of the true stress curve. As described in section 2.2.3, there is no clear consensus on the different regions of the stress-strain curves of hair; while some authors already see the $\alpha \rightarrow \beta$ -transition in the second region and the mechanical extension of the β -sheets in the third, in other publications one finds the second region being due to the unraveling of the coiled-coils and the third region stemming from β -sheet folding. The extra region seen in the true stress curves might be due to taking into account both approaches, which could give the following assignment of the different regions: region I: stretching of the α -fibers (identical to the engineering stress case), region II: unraveling of the coiled-coils, region III: formation of β -sheets, region IV: stretching of the β -structures. However, this is not entirely in line with the findings of Kreplak et al. [27], according to which the β -structures should appear above 20 % strain only. Also, for sample 4, as displayed in Figure 6.8, the border between regions II and III can be assigned to the maximum decrease of cross-sectional area at roughly 15 % strain (compare Figure 6.10), which appears at even lower strains for samples 1, 2 and 6. This makes it more unlikely for the β -sheets to appear in this region already. There might just be a change in the structures that are energetically the most favorable to stretch (see below).

Hearle [37] pointed out that IFs cannot be treated as ideal α -keratin molecules and that the $\alpha \rightarrow \beta$ -transition might not operate over the full length of the IF. Also, as the considerations of Kreplak et al. [35] and Rohs et al. [36] show, α -helices might

also slide against each other instead of transforming into β -sheets. For this reason, it is probably not adequate to generalize what could happen in a specific region to the whole sample. The transformation of the α -helices into β -sheets might be more prominent in well-crystallized zones [35], which could explain the different shapes of the true stress-strain curves for the inhomogeneous and non-isotropic pig hair.

Because errors or material failure in the diameter measurement also influence the true stress, it is difficult to make a statement on the character of the true stress-strain curves. There are, however, more than the "classical" three regions seen.

Fracture stress and strain

Fracture strains were between 32 % and 36 % for pig hair. This is consistent with the findings of Mohan et al. [3] who found fracture strains of 28 % to 40 %, depending on the pig breed.

Development of the cross-sectional area

All the cross-sectional areas show a region of high negative slope (Figures 6.12, 6.13) (roughly around 10 % for samples 1, 2 and 6 and at around 15 % for samples 1, 4, and 5). This is approximately where true and engineering stress diverge (compare Figure 6.7). Because all the samples share this strong decline in diameter, it makes sense to assume a major structural change inside the strained fiber in this region where small strains suddenly induce large cross-sectional changes. According to Kreplak et al. [27], the strain might be too low to exhibit any β -structures, especially for samples 1, 2, and 6, and the uncoiling of the coiled-coils should be completed with the Hookean region. There might be any transition from the set of structures subjected to the strain to another set which is energetically more favorable to stretch or a transition from structures sliding against each other to actual stretching.

It should be taken into account that the hair does not consist of keratin only but also of other components like the cuticle or the matrix (see 2.2.2). Therefore, the development of the sample dimensions and as a result the development of the true stress could also be explained by other hair constituents.

Development of the sample diameter

Figures 6.12 and 6.13 show that, despite many error sources for the diameter, the change

in diameter is not homogeneous for the pig hair. It looks different for each sample, which might be because of the individuality of each hair fiber. Also, as Hu et al. [6] explain, the properties of hair vary in dependence on the distance to the hair root.

Figures 6.12 and 6.13 also show that the diameter does not change in the same direction and by the same amount for all angle steps. When measuring biological fibers like hair, it might therefore be informative to consider more than one angle.

From Figure 6.11 one can see that, at least for samples 1, 2, 5, and 6, the shape of the fiber remains the same during straining. In some cases, however, for example for sample 1, it is visible that not all the diameters measured from different angles decrease by the same amount, but there seems to be one-sided contraction of the fiber. This might also explain a small amount of some of the diameter irregularities. The cause for this is probably the inhomogeneous hair structure, or the effect might be due to non-straight mounting of the fiber.

Young's modulus

For the pig hair, Young's modulus was 5.7 GPa (IQR = 0.2 GPa) for the true stress and 5.6 GPa (IQR = 0.2 GPa) for the engineering stress. It does make a small difference whether the true stress or the engineering stress is used, but this difference is not statistically significant. Also, treating the sample's cross-section as circular (compare Table 6.8) yields very diverse values for Young's modulus. In the example presented in Table 6.8, the highest value for Young's modulus (8.2 GPa) was two times the lowest one (4.1 GPa) and the modulus obtained with the real cross-sectional area was 5.7 GPa for this sample. These findings suggest that, for inhomogeneous fibers like pig hair, calculating the true modulus by keeping track of the sample diameter is highly dependent on the angle from which the diameter is measured, and using a simple circular equation yields ambiguous results. Therefore, using the engineering stress (with the actual initial cross-sectional area) might be more accurate than calculating the true stress from one angle only.

Literature values for Young's modulus of pig hair are between 3.9 GPa and 8.1 GPa [3]. The values obtained in the present work are in the same range. The values are higher than for human hair (~ 1.3 GPa [4]). However, it is difficult to compare results from other studies to the results found in this thesis because the hair samples were not taken from the same breed, individual or position on the body, which are all factors that can influence the hair's mechanical properties [3]. Young's modulus is probably influenced by many factors as well, such as the diameter measurements and its possible errors, and

it is generally difficult to give an exact value for Young's modulus for a biological and inhomogeneous material.

Poisson's ratio

As Figure 6.19 and the left-hand side of Table 6.10 show, Poisson's ratio calculated from the linear part of the diametric strain - longitudinal strain curve is different for each of the samples. The median value of 0.43 (IQR = 0.34) is close to the literature value of 0.38 [6] [5] for human hair, but the single values range from 0.15 ± 0.01 to 0.78 ± 0.04 , which is a wide range considering that all the samples are of the same material. Because pig hair is non-isotropic, it might not be impossible for it to reach Poisson's ratios above 0.5, but it seems rather unlikely that the values are as widely spread as displayed in Table 6.10. Here, it might show that it is not reasonable to use a mean diameter for each sample because the fiber is not of circular cross-section and the straining is not homogeneously distributed along the sample surface, as the diameter developments for each angle step show, and also the overall shape of the cross-sectional area seems to change during the straining process (compare Figure 6.11). It is probably not reasonable to calculate any mean diameter values for the pig hair.

In contrast to the values of Poisson's ratio which have been obtained for the elastic region, the values obtained from taking the initial diameter and the diameter before fracture are consistent (Table 6.10) and the single values as well as the median value of 0.36 (IQR = 0.02) are in line with [6] and [5], who found a Poisson's ratio of 0.38. However, the data in Table 6.10 can only give an approximation for Poisson's ratio because the diameter is only a mean diameter for all angles. Using the initial values and the values at an arbitrary higher strain (Figure 6.20) disregards the non-linear decline in diameter and cross-sectional area. However, the curves for samples 1, 4, and 5 are located between 0 and 0.5 all the time and the other samples reach higher values but do not fall below 0. Because of this, the results seem to be more realistic than the ones obtained from the slope of the elastic regions.

Figure 6.20 and the right-hand side of Table 6.10 also show that the sample dimensions in the beginning and the dimensions before fracture are related in the same way for all the samples.

Calculating Poisson's ratio separately for each angle step does also lead to very variable results for each sample, as Figure 6.18 and Table 6.9 show.

Looking at Figure 6.18, only samples 5 and 6 show ranges of Poisson's ratio which look

realistic. Both have Poisson's ratios located around 0.4. There is, however, no cogent reason to prefer the results for these two samples to those of the other samples. From Figure 6.13, one can see that for samples 5 and 6, the changes in diameter measured from different angle steps are more similar to each other than for the other samples, which is probably the reason of the Poisson's ratios being closer to each other for these two samples. There is no evidence that the diametric behavior measured for samples 5 and 6 is more reliable than the measurements for the other samples, though. Figure 6.18 and Table 6.9 show that the diameter variabilities make it difficult to give an accurate approximation of Poisson's ratio, even when each angle is treated separately. The found medians point to a value around 0.4, though.

The variability of Poisson's ratio can be ascribed to the variability in the diameter changes. Possible error sources have already been discussed in section 7.2.1. It is supposed that the diametric measurement is inaccurate due to either errors in the measuring process or to the hair's inhomogeneity, which could imply ripping and uneven stretching of its single components. Also, unloading and subsequent reloading would possibly have lead to more consistent results because this way it could have been made sure that the fiber is tightened appropriately before the measurement. Furthermore, iterative unloading and reloading would have yielded multiple representations of the elastic region for each sample, by which runaway measurements could be told apart. However, as Figure 6.21 shows, the extreme Poisson's ratios (far above 0.5 and below 0) are not only limited to the initial elastic region of the hair samples but appear throughout the whole straining process.

The findings show that Poisson's ratio is a highly strain-dependent parameter for pig hair.

Again, these findings are only an approximation because they are based upon the mean diameter values for all angles.

For Poisson's ratio and Young's modulus, it could also be taken into account that the structure of the hair varies from root to shaft [6] and that the diameter measurement has not been carried out in a specific distance to the hair root.

Development of the load

The decrease of load with increasing angle step can probably be explained by relaxation

of the sample, as the angle step coincides with the amount of time the sample is left in the same position.

7.3. Measurements with PET fibers

7.3.1. Review of the measured data and possible error sources

Stress-strain curves

All the samples show a small leap for both the true and the engineering stress at strains where the strain step has been increased (see Figure 6.25). As the strain rate remains constant, this is probably due to the relaxation behavior or any strain-hardening properties of the fiber because of the increased amount of straining between two measurement points.

For samples 5 and 6, the deviations of the true stress curves from a smooth course at ~ 12 – 17 % and ~ 10 – 12 % strain respectively can be explained by the development of the corresponding sample diameters.

Development of the sample diameter

Looking at Figure 6.30, one can see that for sample 5, the recorded diameter of angle step 2 decreases (smoothly) to ~ 60 % between about 12 and 17 %. Because the diameter decreases, temporary contamination of the sample is probably not the cause. The sample might not have been mounted straightly or there might have been a fissure in the sample that disappeared by further stretching or movement of the defective area (the laser which measured the diameter remained at a fixed position during the whole measurement). Also, there might be any kind of systematic error. The same applies to sample 6, where, for angle step 8, the diameter decreases almost instantaneously to about 45 % between about 10 and 12 % strain.

For sample 1 and angle steps 2, 3 and 4, the diameter is constant between ~ 10 and 15 % strain, or does even increase, before decreasing again. A contamination of the sample by a dust particle would probably have caused an instantaneous increase in diameter. Because the transition is smooth, it is more likely that the higher diameter is due to changes inside the sample, maybe rupture and protruding of a fiber part or change in the inner porosity by crazing. The same could be the case for sample 6 (at about 15 % strain). For samples 1 and 6, the slope of the cross-sectional development curve (Figure 6.28) flattens slightly between 10 and 15 % strain. This is probably because of the increase of some diameters in this strain region.

Some diameters for sample 4 are significantly higher in the beginning than the others, but transition to the curve of the other diameters at ~ 12 % strain. In the beginning, the sample could have been not straightened entirely, but this would not explain why

these diameters remain higher than the others until about 15 % strain. There might have been a contaminant on the sample from the beginning on, which then slowly shifted during the measurement (the laser was at a fixed position).

The initial diameters of sample 2 are scattered but align at a very early stage of the straining. Therefore, the higher diameters are probably due to the sample not being straightened entirely or having a dent in the beginning.

These diameter irregularities affect all derived quantities such as the cross-section, the true stress, Young's modulus, and Poisson's ratio.

7.3.2. Interpretation and discussion of the obtained findings

Stress-strain curves

From the stress-strain curves of the PET fiber (Figure 6.25), one can see that the shape of the true and engineering stress curve is almost identical. The true stress curves reach higher values. Using the true stress instead of the engineering stress therefore does only scale the curve along the stress-axis but does not change its shape. This is because the change in diameter and in cross-sectional area is linear. Therefore, characteristic points of the stress-strain curve only change in stress but not in strain when using the true stress instead of the engineering one.

The stress-strain curves coincide with the findings of [46], [49], and [56], who found similar-shaped deformation curves for PET fiber.

Comparing with [46] and [49], one could find the following division of the stress-strain curves, illustrated for sample 2:

Firstly, there is the Hookean region, assigned to the uncoiling of the isotropic amorphous phase, which assigns to region I of the possible division scheme shown in Figure 6.26.

The first inflection point, which is supposed to mark the transition from straining of the isotropic amorphous phase only and adding the oriented amorphous phase to the straining, is located in region II. It is not entirely clear, whether by „inflection point“ [46] and [49] mean the classical definition of the point at which the direction of curvature changes, which would be at ~ 5 % strain for the curves shown in Figure 6.25, or the point at which the curves' left bend is maximum, which would assign to the border between regions II and III. In Figure 2.9, the point E_y to which the shown line is tangent, looks more like denoting the latter one. The term *inflection point* is used in many publications, but rarely defined graphically. In region III, however, slippage between the filaments should occur. The flattening of the curve in the end (region IV) might be due

to progressive loosening of the polymer chains before the fiber breaks. This region is much more prominent than seen in other publications and is nearly linear in the end before fracture of the fiber.

It is remarkable that there are no striking points in the curves of cross-sectional and diametric change which reflect the characteristic points and regions of the stress-strain curves.

Cross-sectional area and diameter

The change in cross-sectional area as well as the change in diameter is linear for all samples and angles, apart from the deviations already discussed in 7.3.1. The diameter therefore changes evenly in all radial directions and its rate of change remains constant until fracture. One could expect to find the structural rearrangements inside the fiber reflected on the diametric and therefore cross-sectional change, but this is not the case. For samples 1 and 6, the diameter-strain curves (Figure 6.30) show a slight bending followed by a decrease in slope at strains of about 10 %, which could roughly coincide with the second inflection point in the corresponding stress-strain curves, but this observation is very subtle and not visible for the other samples. Figure 6.31 shows that the decline in diameter is homogeneous in most cases and the shape of the diameter distribution between the different angle steps stays approximately constant, indicating that the overall-shape of the fiber surface remains constant throughout the straining process (except for being thinned).

Young's modulus

For the true stress, the median of Young's modulus is 12.0 GPa (IQR = 1.9 GPa) for the PET fibers. For the engineering stress, the median is 11.9 GPa (IQR = 2.0 GPa). The difference between true and engineering stress is therefore probably neglectable for Young's modulus. For sample 2, Young's modulus is only (9.0 ± 0.6) GPa, which is lower than the values obtained for the other samples. There is no significant difference in diameter or cross-sectional area for this sample that could explain the lower modulus. There might have been a structural deviation of the piece of fiber sample 2 has been cut-out from due to the manufacturing process, or there could have been a systematic error during the measurement. When calculating Young's modulus separately for each angle step (Figure 6.34 and Table 6.16), one obtains, for sample 2, Young's moduli that range from (8.5 ± 0.7) GPa to (9.3 ± 0.6) GPa. The difference is rather small compared to the measuring accuracy, but existent. It would have been more reasonable to chose

another sample than the irregular sample 2 for this evaluation. Nevertheless, the results show that, even for the round PET fiber, it does make a (small) difference from which direction the fiber diameter is measured from if only one angle is chosen for the area calculation. It therefore seems to be more accurate to keep track of the diameter from more than one angle. However, if the cross-sectional area has been determined from many angles in the beginning and the engineering stress is used, the result should nearly be as accurate as the one obtained for the true stress.

The values found for Young's modulus are close to the literature values of 7.8 GPa to 10.4 GPa [44] or 9 – 11 GPa [46] respectively, but are slightly higher. They are more in the range of values found by Navarro et al. [51] (11.2 – 12.9 GPa) for PET derived from waste bottles.

Because the exact properties of the fiber are dependent on the manufacturing process and the crystalline degree, the results from different works are expected to vary slightly. The approximate guess for the PET fiber used in this thesis is 12 GPa and is in line with other findings for PET fiber, though.

Poisson's ratio

Poisson's ratio for strains below 0.7 %, which is the elastic region for the PET fiber, is 0.44 (IQR = 0.02) for using the mean diameter for each sample. Taking the very first value and the last value before fracture, one obtains a Poisson's ratio of 0.37 (IQR = 0.05). A possible cause could be the stiffening of the polymer chains at very high strains, which might lead to a lower Poisson's ratio in these extreme conditions. Thus, it does make a difference, whether the Hookean strain region or the whole straining process is included, even though the change in diameter is linear for each sample. Figure 6.38, however, shows that Poisson's ratio is relatively constant when calculated from the initial diameter and the diameter at an arbitrary strain. Therefore, straining the fiber by small amounts and taking the initial and final diameter yields approximately the same result as straining the sample to fracture and taking the initial and final values.

Looking at the slope of the diametric strain - longitudinal strain curves for all the samples (Figure 6.39), one finds that the values tend toward 0.3 to 0.4 in the end, which is roughly the values found using the initial and final diameter (right-hand side of Table 6.18). In general, the ratio of diametric strain and longitudinal strain changes during the measurement, but the values are more consistent than the ones for pig hair. Figure 6.39 also shows that Poisson's ratio is a function of strain for the PET fibers.

In contrary to the pig hair, the values are bounded by 0.5 and some value above 0 in each case. Because the PET fiber is circular, Figures 6.38 and 6.39, in which the mean diameter has been used, should give a more accurate representation of Poisson's ratio than the figures' pig hair counterparts.

Using the mean diameter for comparing different samples yields similar results to treating each angle separately for the PET fibers because the fibers' cross-sections are circular and the diameter increases by roughly the same amount for all angles.

Because of the PET fiber's circular cross-section, there are no striking differences expected when only measuring one diameter instead of twelve. The median values obtained by calculating Poisson's ratio for each sample and angle (Table 6.17) and the values obtained by using the mean diameter of the sample (left-hand side of Table 6.18) are very similar and all lie around 0.44. Also, the values obtained for different angles are alike (compare Figures 6.35 and 6.36). There is only one sample (sample 4) for which significantly different slopes are obtained for the diameter change in strain regions below 0.7 %. This is because sample 4 shows very diverse diameters in the beginning (compare section 7.3.1).

Summarizing, the PET fiber is relatively robust in terms of the used method for calculating Poisson's ratio. The values found are between 0.37 and 0.44 and are therefore higher than the values found for PET sheets [55]. There is no significant gain of information when measuring the diameter from more than one angle, but it is probably more accurate to use the Hookean region for the calculations, for which in situ measurement of the diameter (from at least one angle) is required.

The time-dependency of Poisson's ratio should yield slightly different results for the different angle steps because a higher angle is corresponding to a longer relaxation time of the fiber. When taking a very close look at Figure 6.35, there does not seem to be a reappearing order of the curves belonging to the different angle steps, although for samples 3, 5 and 6 it does look like the lower angle steps belong to the lower curves and the higher angle steps to the higher ones. Certainly, a possible time-dependency cannot be told apart from natural variations in diameter, and Figure 6.29 also shows no distinct increase or decrease in diameter with increasing angle step.

Behavior of the load

The effect of load decrease with the angle step is more prominent for higher strains. This might indicate that the relaxation time either becomes shorter with increasing strain

or that the effect of relaxation is just more pronounced. For possible examinations of the time-dependent Poisson's ratio, this might be of relevance because the relaxation behavior does obviously change throughout the straining process.

7.4. Mangalitza pig hair and PET fibers in comparison

7.4.1. Similarities and differences in mechanical behavior

Using Mangalitza pig hair and PET fibers, an inhomogeneous and non-isotropic material could be compared to a homogeneous one.

The pig hair's cross-sectional area was elliptical, as expected, and the PET fibers were of circular cross-section. The compliance correction was in the same order for both materials and of the order of the strain uncertainty. The PET fibers' surface could be found to look very homogeneous (Figure 6.23), whereas the pig hairs were more craggy (Figure 6.4). In transversal view, the pig hairs could also be found to look more rough and uneven (Figure 6.6) than the PET fibers (Figure 6.24).

Straining behavior

For both materials – the pig hair and PET fibers – there were clear differences between the true and engineering stress. The true stress was higher than the engineering stress in all cases, as expected, because the cross-sectional area decreases with straining. For the pig hair, the true stress curves also were of different shape than the engineering stress curves, whereas for the PET fibers the true stress curves were scaled along the stress-axis but kept the shape of the engineering stress curves. This is because the change in cross-sectional area is linear for the PET fibers, but not for the pig hair. For the latter, the true stress curves also were more individual compared to one another. For the PET fibers, the difference between true and engineering stress evolve linearly and all the curves show the same course.

The pig hair could be strained until higher strains (about 32 – 36 %) than the PET fibers (about 22 – 30 %) before fracture. The PET fibers reached final stresses that were about three times higher than the ones reached for the pig hair: The true stress before fracture was $\sim 710 - 790$ MPa for the PET fibers and $\sim 210 - 280$ MPa for pig hair. The difference between true and engineering stress was higher for the PET fibers. The total

decline in cross-sectional area was higher for the pig hair, where the final cross-section was about 75 % of the initial cross-section. For the PET fiber, the cross-sectional area at fracture was between 80 and 85 %.

The cross-sectional area decreases linearly for the PET fibers. The change in the pig hairs' cross-sections was not linear but showed different regions of higher or lower rates of decrease. For the PET fibers, the diameter decrease was linear and did not differ significantly between angles, suggesting homogeneous thinning of the fiber and structural rearrangements that are of the same extent for all angles. The diametric change of the pig hair was highly dependent on the angle it was measured at. Considering all things, the PET samples' behavior was homogeneous throughout all the samples. There were no major differences in stress, cross-sectional area or diameter decrease between the different samples or between the angles of a single sample. All the changes inside the PET fiber seem to be homogeneous and linearly-dependent on the strain. For the pig hair, the change in diameter and therefore cross-section was very diverse and there were also measured increases in diameter in some cases. As a synthetically produced material, the PET fiber should be more or less isotropic on the plane perpendicular to the fiber axis and its structure should remain constant along the fiber axis, whereas the pig hair is expected to be more inhomogeneous in both directions. It is therefore more difficult to compare two hair fibers than to compare two of the PET fibers, which all stemmed from the same reel and were therefore fabricated under the same conditions. As a biological material, pig hair is expected to behave more individually because each hair has its own composition and growing history. Furthermore, the pig hair's structure probably also changes along the fiber axis and the pig hairs might stem from different body parts. This suggests that the changes inside the hair fiber are not homogeneously distributed. Other than for PET, there is also a major molecular transformation taking place during straining a hair fiber, which is the α - to β -keratin transition.

Derived quantities

Young's modulus of the PET fibers was about twice the modulus of the pig hair fibers, suggesting that the PET fibers show higher resistance to deformation than the pig hair. For both materials, the modulus calculated from the true stress was higher than the one calculated from the engineering stress, but the differences were not statistically significant.

Poisson's ratio of the pig hair was difficult to determine. The results show a ten-

dency to lie around 0.4, though, which is very close to the values found for the PET fiber. However, comparing the exact values for both might be insignificant regarding the low reliability of the values of the pig hair.

For both, the pig hair and the PET fiber, Poisson's ratio was highly strain-dependent, which has not been expected for the PET fiber because of its linear and homogeneous diameter decline. For the pig hair, this is the expected behavior based on the major structural changes inside the sample during straining and the fiber inhomogeneity.

For both the pig hair and the PET fibers, the load was found to decrease with time (= angle step). For the PET fibers, the effect was more pronounced for higher strains.

7.4.2. Review on the multi-angle measuring approach

For investigating the shape of the stress-strain curves, calculating the true stress for the PET fibers does not provide new information due to the (almost) linear decline in cross-sectional area. For the pig hair, however, it is informative to study the true stress curves and the change in cross-sectional area because the fibers exhibit some behavior that cannot be seen from the engineering stress only.

For Young's modulus, it is, within the measurement accuracy, not necessary to calculate the true modulus for both pig hair and PET fiber because the obtained results are almost equal. For the pig hair, however, very diverse results are found when measuring the diameter from only one angle and calculating the corresponding area pretending a circular cross-section. The results obtained this way might be several GPa above or below the modulus found by using the true stress, and therefore diameters measured from different angles, or the engineering stress, which also uses an initial area calculated from multiple angles. For the PET fiber, this was also found but the effect was significantly smaller and can probably be disregarded within the measuring accuracy.

Poisson's ratio is probably the most reasonably calculated from the elastic part of the straining curves. For the pig hair, it could be shown that measuring the change in diameter between two arbitrary points of the straining process would yield non-distinct results because this method disregards the non-linear change in diameter. The PET fiber seems to be more stable in terms of the determination method of Poisson's ratio. Comparing Poisson's ratio of different specimens by using the mean diameter is probably not reasonable for the pig hair because the hair fibers are non-circular and the diameter

does not change homogeneously, but it works for the PET fiber.

Summarizing, it can be stated that measuring the diameter from more than one angle is not of exceeding importance for studying homogeneous materials like PET fiber, which have a circular cross-section and show a linear decrease in both diameter and cross-sectional area. However, any new kind of fiber has to be studied in terms of its diameter changing behavior first, which makes the multiple-angle measurement important again. For inhomogeneous biological fibers like pig hair with non-circular cross-section, it is more accurate and also informative to measure the diametric change from multiple different angles.

7.5. Review on the data accuracy and perspectives for future research

For the pig hair, it would have been informative to record more stress-strain curves to get a more comprehensive idea of the true stress curve's shape. Also, comparison with other hair types would be reasonable. Because the diametric change curves of the pig hair were of high variability, collection of more data could give a better insight into the hair's straining nature and therefore also into Young's modulus or Poisson's ratio. Also, it would be informative to see whether the diameter measurements presented in the current work were erroneous for the pig hair. The $\alpha \rightarrow \beta$ -transition is still not fully understood and getting an idea of the change in cross-sectional area during straining could help to investigate this topic further.

The hypothetical additional region in the pig hair's true stress-strain curve might deserve further investigation, as well as the possible bend inside the PET fibers' diametric change curves (Figure 6.30), which might be seen for samples 1 and 6 at about 10 % strain.

For the determination of Young's modulus and Poisson's ratio, it would probably have been more accurate to record a higher amount of data points in the critical strain ranges (below 1.5 % for pig hair and below 0.07 % for the PET fiber). Also, one could determine Young's modulus and Poisson's ratio from unloading-reloading loops instead of using the very first part of the curve. This way, it could have been ensured that the fiber is tightened properly and that any kinks are removed. Because the PET fiber showed pronounced hysteresis when unloaded and reloaded, this has not been done in this thesis to keep both the PET fibers and the pig hair comparable to each other.

With the tool for measuring the diameter in situ and from multiple angles, cross-sectional area or diameter dependent quantities like the true stress or Young's modulus and Poisson's ratio can be further investigated. The setup also allows for volume calculations which could give further insight into a sample's nature. Also, fibers that are not circular in cross-section can be studied more accurately without simplifying the cross-section to a circular one.

8. Summary and conclusion

In the present work, an experimental setup designed for recording stress-strain curves of fibers and in situ diameter measurement from different angles has been tested on pig hair and PET fiber samples. Also, the load train compliance of the measuring device has been determined. The multiple angle diameter measurement allowed for precise calculation of the fibers' cross-sectional areas during the straining process and therefore for the determination of the true stress as well as true Young's modulus and also Poisson's ratio.

The pig hair samples were found to exhibit an additional region in their true stress-strain curves which could be related to the $\alpha \rightarrow \beta$ -transition taking place during the straining of keratinous materials. The cross-sectional area of the hair fibers was found to be elliptical throughout the measurements. The change in cross-sectional area was non-linear for all the samples and showed a region of high negative slope that could also be related to the $\alpha \rightarrow \beta$ -transitions or other structural changes inside the hair fiber. The diameter measurements were very disperse for the pig hair and might have been falsified by any arbitrary errors. Poisson's ratio could not be determined reliably for this reason but it was found that Poisson's ratio is highly strain-dependent and dependent on the method used for its determination (using the slope of the elastic region vs. using the initial diameter and a second diameter at an arbitrary higher strain). Young's modulus was not significantly dependent on using the true or the engineering stress curves for the pig hair, but it was highly dependent on the angle if only one angle was used for the area calculation. Because the hair is of elliptical cross-section, measuring the diameter from one angle only and calculating the area from the circular equation leads to very different results. Therefore, measuring the diameter from multiple angles is advantageous for studying inhomogeneous materials like hair.

For the PET fiber, the cross-sectional and diametric change was almost linear. For this reason, the true and engineering stress-strain curves were of the same shape and Young's modulus and Poisson's ratio were not found to be overly dependent on the amount of

angles used for the diameter measurement. Also, Poisson's ratio could probably be determined with a higher accuracy for the PET fibers than for the pig hair because of the more homogeneous diametric change behavior.

Because the PET fibers are synthetically produced and all stemmed from the same reel, they have been expected to show a more consistent behavior than the pig hair in terms of their diameter change and all derived quantities.

Even though the determination of the material-specific parameters might be in need of improvement by means of measuring a higher amount of specimen and maybe performing unloading-reloading loops, the recording of the fibers' diameter from different angles gave an insight on the straining behavior of the samples' dimensions which is more detailed than many results found in current research. For further research, the results presented in the present work should be confirmed and strengthened by collecting higher amounts of data.

It could be shown that it is advantageous and future-proof to be able to measure the sample diameter from multiple angles and in situ during straining. Apart from the more accurate determination of any diameter and cross-sectional area dependent quantities, which can also be applied to a wide range of inhomogeneous and non-round materials, new phenomena that include the sample volume for instance could be studied using the presented measuring device.

A. Determination of the cross-sectional area for non-circular fibers

For each straining step, the cross-sectional area is calculated with the diameters recorded from different angles. This is done with the following code fragment (written by Alexander Müllner, modified for visual clarity):

```
def funct(x,a,b,c):  
    return abs(2.0 * (b ** 2.0) * cos(x + c) / (b * sqrt(1.0 - 1.0 /  
    (1.0 + b ** 2.0 / ((a ** 2.0) * tan(x + c) ** 2.0)))))
```

with constants a , b , and c to be fitted and the angle x .

For each straining step, the set of angles x is fitted to this function with the corresponding set of sample diameters as the dependent variable.

The diameters are then calculated from the resulting function and are compared to the original diameters with a coefficient of determination regression score function.

If the coefficient of determination is greater than 0.9, an elliptical cross-section is assumed and the cross-sectional area A_{ell} is calculated by $A_{ell} = a * b * \pi$.

Else, the cross-section is output as circular and the corresponding area A_{circ} is calculated with the $A_{circ} = \pi * d^2$, where d is the mean diameter recorded for the respective straining step.

B. Error estimation for the measurements of the copper wire, pig hair and PET fiber samples

B.1. Estimating the minimum error for each measured quantity

The following section discusses the error estimation done for the described measurements. Arbitrary errors were taken into account but systematic errors remain unknown. Since it was the main aim of this thesis to compare the pig hair and PET samples and to test the measuring device, any systematic errors that falsify the result by the same amount and in the same direction for every sample were not considered to be crucial for the analyses and assumed to be taken care of by rounding the random error.

The following shall give an overview of the assumed absolute errors for the basic quantities diameter, extension and load. Also, it is meant to provide a more detailed insight into the character of the single measurement accuracies.

The diameter error was assumed to be the same for all the samples, therefore only the load and extension error will be looked-at separately for the different materials.

B.1.1. Diameter error

Looking at the diameter's change with the angle, disregarding any systematic errors, the diameter measurement could be assumed to be accurate in the third significant digit for all measurements because the diameters measured at angle step 0 and angle step 12 are identical in most cases and for all materials, samples, and strains. This estimation includes random errors, but it excludes any systematic errors which could not be determined for any of the materials because there was no reference sample with

exactly known diameter. The diameter of the PET fiber was approximately known, as it should be about 0.1 mm according to the manufacturer, but there should be variation expected. For this reason, the diameter error was assumed to be in the third significant digit, giving an absolute error of $1\text{ }\mu\text{m}$ or $\sim 1\%$ for the raw diameter for all materials and samples. Any errors of derived quantities were analyzed by error propagation. Because the resolution of the laser showed at least a reliable shape of the diameter distribution (see Figures 6.29, 6.11), where the values at angle steps 0 and 12 are identical, it seemed to come with a loss of information to cut the diameter accuracy down to only two significant digits.

B.1.2. Extension error

To estimate the error of the extension, the extension distribution within the different angles has been looked at for different strains and for each material separately. The fluctuation in the extension for a certain strain was assumed to reflect the order of the minimum arbitrary error of the measurement. Because the extension was averaged over all angles most of the times, for each material the standard deviation of the extension was taken as an error measure and rounded up. Any errors of derived quantities were calculated by error propagation. As for the diameter, no systematic errors have been determined.

B.1.3. Load error

The load could be shown to decrease with time, i.e. with increasing angle step for all the materials. Because the calculations of the mean load and therefore stress involved averaging over all angles, this should be taken into account. Because the resolution of the load measurement was high enough to show the decrease of the load with increasing angle step, which should be due to relaxation of the sample, an accuracy of the measurement of at least two significant digits was expected for the load measurement and for all materials and samples. Therefore, as a minimum error, the rounded-up standard deviation of the load has been taken for each material. Any arbitrary errors were assumed to be covered by rounding up the standard deviation. No systematic errors could be determined for the load. Any errors of derived quantities were analyzed by error propagation.

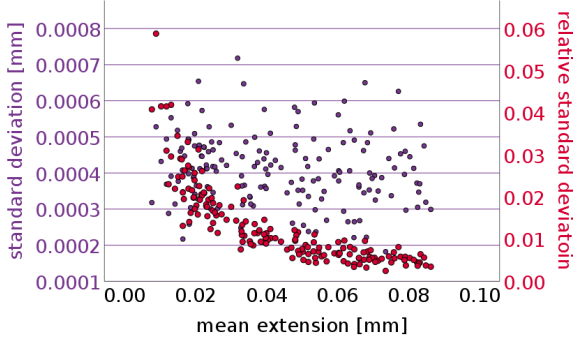


Figure B.1.: *Standard deviation and relative standard deviation for the mean extension of the Cu-50 wire with clamping length ~ 10 mm*

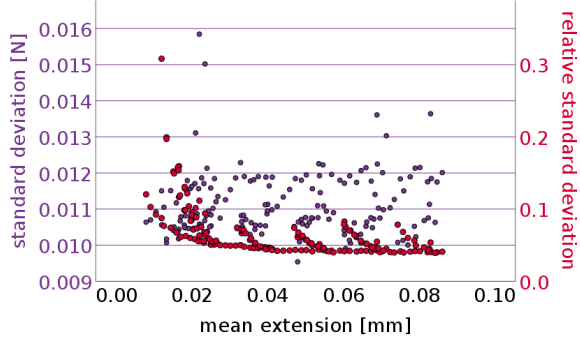


Figure B.2.: *Standard deviation and relative standard deviation for the mean load of the Cu-50 wire with clamping length ~ 10 mm*

B.2. Extension and load error estimation for copper wire

The compliance has been determined using average (averaged over all angles) values of the load and extension. However, the standard deviation of the mean load and mean extension is high. Figure B.1 shows the standard deviation and relative standard deviation for the mean extension for the Cu-50 sample with the shortest clamping length (~ 10 mm). The relative standard deviation is approximately between 5 and 1 % with a tendency for smaller values for higher extensions (strains). For that reason, an error 0.5 % has been assumed for the extension.

Figure B.2 shows, for the shortest Cu-50 sample, the standard deviation and the relative standard deviation of the load during the measurement. If not in the unloading/reloading loop, the relative standard deviation is about 5 %. It goes up to nearly 10 % during unloading and reloading.

It might be more accurate to not use mean values for the compliance determination but to calculate the compliance for each angle separately.

B.3. Extension and load error estimation for pig hair

Extension error

The extension values are randomly distributed around a mean value for most samples

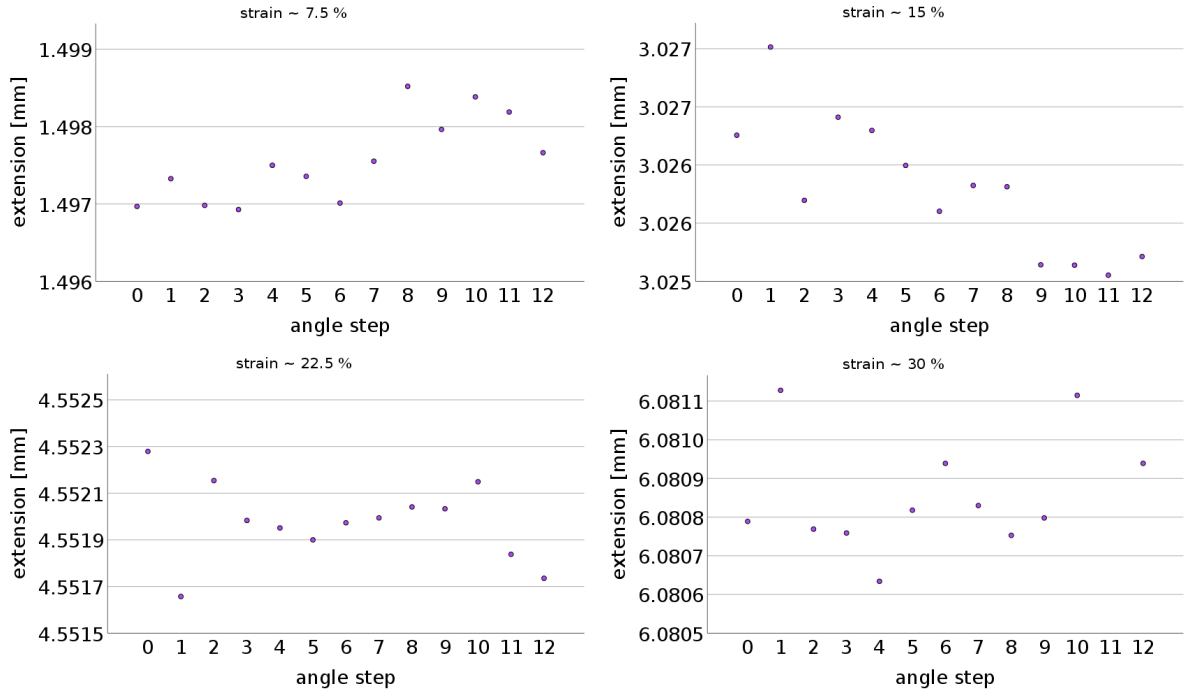


Figure B.3.: *Extension measured from different angles for the pig hair sample 5 for four different strains*

and strains and there is no outstanding relation to the angle (= time) for a certain strain. Therefore, the corresponding standard deviation should give a rough idea of the dimension of error. Figure B.3 shows, as an example, the distribution of the extension for strains of $\sim 7.5\%$, $\sim 15\%$, $\sim 22.5\%$ and $\sim 30\%$.

Figure B.4 shows the absolute and relative standard deviation from the mean extension for each straining step for the pig hair sample 5. From both figures, B.3 and B.4, one can see that the range of the extension values and therefore the standard deviation decreases with increasing strain. Because it did not seem reasonable to use an error below 1 %, because there are still unknown systematic errors, an error of 1 % has been assumed for the extension measurements for the pig hair, even though the standard deviation of the extension is lower.

Load error

The absolute and relative standard deviations of the load are shown for the pig hair sample 5 in Figure B.5 in dependence of the mean strain. Rounding up, an error of 3 % has been assumed for the load measurements of the pig hair samples .

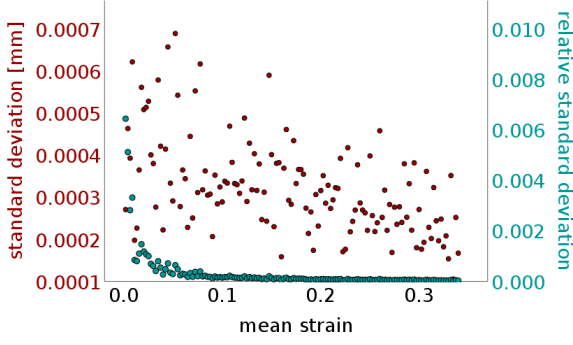


Figure B.4.: *Development of standard deviation and relative standard deviation of the extension for the pig hair sample 5 during straining*

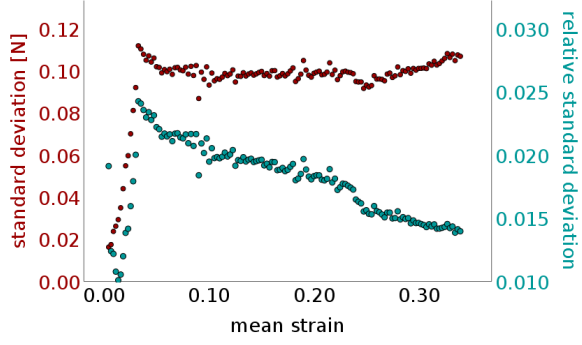


Figure B.5.: *Development of standard deviation and relative standard deviation of the load for the pig hair sample 5 for each straining step*

B.4. Extension and load error estimation for PET

Extension error

Figure B.6 shows the angle-dependent distribution of the extension of the PET sample 3. For higher strains, the extension was decreasing for higher angles. For most strains, however, the extension seemed to be randomly distributed around a mean value, giving no dependence on the angle step, for which reason the standard deviation has been taken as an error measure.

Figure B.7 shows the absolute and relative standard deviation of the extension for each strain for sample 2. Most of the absolute errors lie beneath 0.0005 mm, most of the relative ones are below 0.1 %. Rounding up, a relative error of 0.001 or 1 % has been assumed for the extension.

Load error

Figure B.8 shows, exemplary for sample 3, the absolute and relative standard deviation for the mean load for each strain. The standard deviation rises by a significant amount when the strain steps become larger. The minimum error was assumed to be 0.2 N or 5 % for the load measurement, regarding the deviations in load. Because the 5 % are already rounded-up, this was taken to be the final error for the raw (mean) load and any arbitrary errors were assumed to be covered.

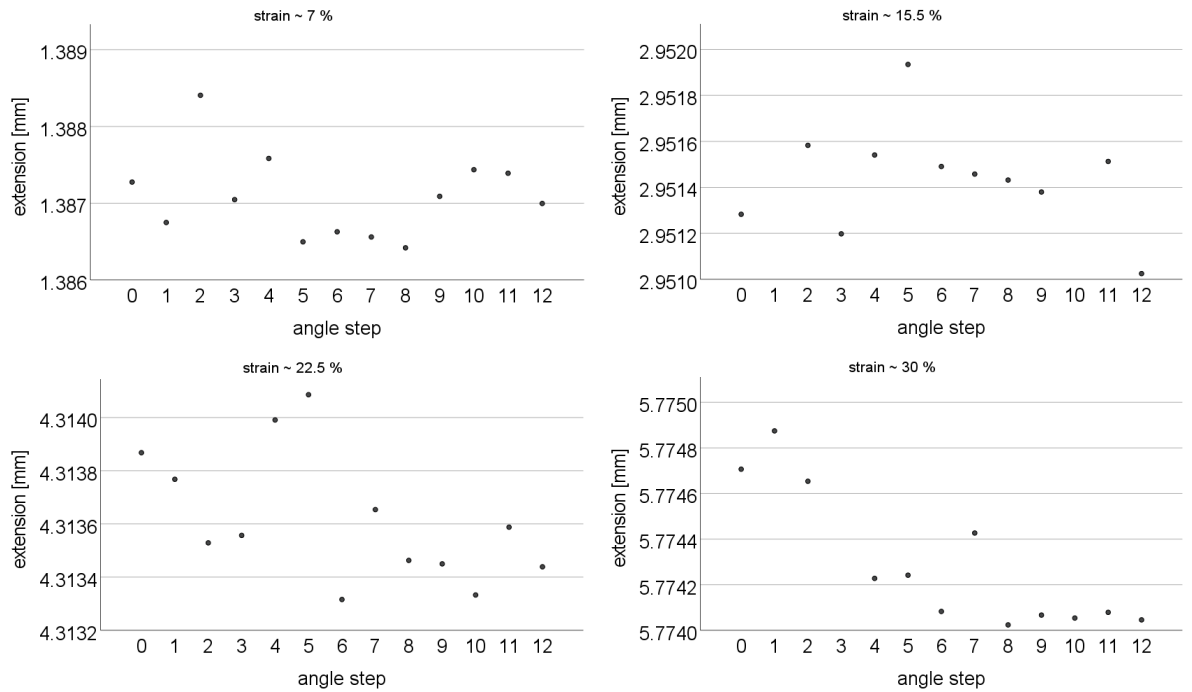


Figure B.6.: *Extension measured from different angles for the PET fiber sample 3 for four different strains*

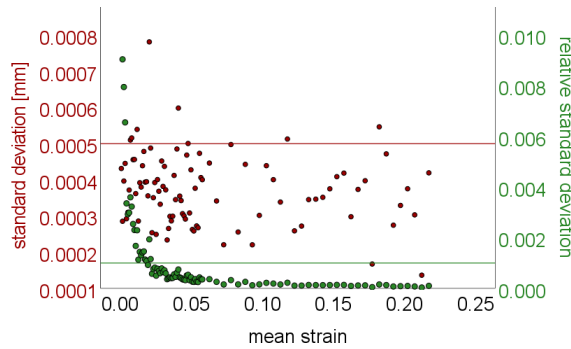


Figure B.7.: *Standard deviation and relative standard deviation for the mean extension of the PET fiber sample 3*

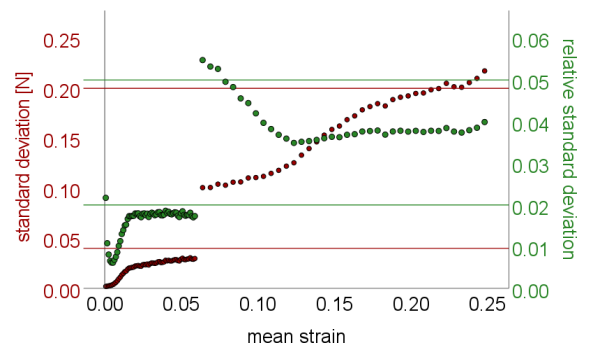


Figure B.8.: *Standard deviation and relative standard deviation for the mean load of the PET fiber sample 3*

C. Summary of the present thesis (abstract)

Abstract

Determining material specific parameters and the straining behavior of fibers is of importance for both scientific and industrial purposes. In many cases however, the diameter of a strained sample is not kept track of during the measurement or measured from one angle only, leading to the need of making simplified assumptions on the sample's shape. This can be especially problematic for fibers of non-circular cross-section.

The present work investigates the longitudinal and lateral straining behavior of Mangalitza pig hair and poly(ethylene terephthalate) (PET) fiber samples stretched by a newly-built device that allows for the in situ and multi-angular measurement of the sample diameter. Seven pig hair samples and six PET fibers have been strained until failure. From the sample diameters recorded at different angles, it was possible to determine the cross-sectional area for each straining step. This allowed for the calculation of the true stress for both the circular PET fibers and the elliptical pig hair samples.

This way, for the pig hair, an additional region to the classical concept of hair straining was found for the true stress-strain curves. This region is possibly assigned to some phase of the α - to β -keratin transition taking place in keratin-containing strained materials.

It could be shown that the observed straining behavior of all the samples as well as derived quantities were highly dependent on the angle it was looked at, especially for the pig hair. Because of the circular cross-section of the PET fibers, measuring the diameter from more than one angle is probably not of high importance for basic physical properties like Young's modulus or Poisson's ratio. For the pig hair however, it is informative and more accurate because of the hair's inhomogeneity.

Being able to study the cross-sectional change of strained fibers with a non-circular cross-section raises many points of application for future research. Also, even for circular fibers like PET fibers, the presented measuring approach provides the possibility of studying material-dependent parameters in a more accurate way.

Zusammenfassung

Die Bestimmung materialspezifischer Parameter und des Spannungs-Dehnungs-Verhaltens von Fasern ist sowohl für die wissenschaftliche Forschung als auch für industrielle Anwendungen relevant. Viele entsprechende Untersuchungen beruhen jedoch auf vereinfachenden Annahmen bezüglich der Querdimension der Faser, da die Änderung des Durchmessers während der Messung nicht oder aus nur einer Richtung verfolgt wird. Vor allem für Fasern mit nicht-kreisförmigem Querschnitt sind deshalb Ungenauigkeiten in den untersuchten Größen zu erwarten.

In der vorliegenden Arbeit wird das laterale und longitudinale Dehnungsverhalten von Mangalitzaschweinehaaren und Polyethylenterephthalatfasern (PET-Fasern) untersucht. Hierfür wurde ein neues Gerät verwendet, das die Messung des Durchmessers in situ und aus beliebig vielen Winkeln ermöglicht.

Insgesamt sieben Schweinehaare und sechs PET-Fasern wurden bis zum Bruch gedehnt. Mit den aus verschiedenen Winkeln aufgenommenen Durchmessern konnte für jeden Dehnungsschritt die entsprechende Querschnittsfläche der Probe bestimmt werden, wodurch die wahre während der Dehnung auftretende Spannung sowohl für die PET-Fasern als auch für die elliptischen Schweinehaare ermittelt werden konnte.

Hierdurch konnte ein möglicher weiterer Abschnitt im klassischen Modell der Spannungs-Dehnung-Kurve von Haaren aufgezeigt werden, der mit dem $\alpha \rightarrow \beta$ -Übergang im gedehnten Keratin in Zusammenhang stehen könnte.

Es zeigte sich für alle Proben eine Abhängigkeit zwischen beobachtetem Dehnungsverhalten sowie abgeleiteten Größen und dem Winkel, aus dem der Probendurchmesser gemessen wurde. Am stärksten betroffen waren hier die Messungen mit Schweinehaaren. Da die PET-Fasern einen kreisförmigen Querschnitt haben, ist die Bestimmung des Durchmessers aus mehreren Winkeln für grundlegende Materialparameter wie den Elastizitätsmodul oder die Poissonzahl von geringer Signifikanz. Bei Untersuchung von inhomogenen Materialien wie Schweinehaaren ergibt sich jedoch ein deutlicher Informationsgewinn und ein höherer Grad an Genauigkeit.

Die Möglichkeit, die Änderung des Durchmessers von gedehnten Fasern in situ zu untersuchen eröffnet viele Angriffspunkte für die zukünftige Erforschung von Spannungs-Dehnungs-Kurven inhomogener Materialien. Zudem erlaubt der vorgestellte Ansatz die genauere Untersuchung von materialspezifischen Parametern.

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