An analytical approach to assess the interrelation of surface properties and softness of tissue paper

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ABSTRACT: The tissue industry constantly strives for improving the overall quality of tissue paper, as customers pay more attention to special quality features when it comes to a purchase decision between different products. As producers need to optimize their processes and furnish mixtures to keep production costs low, accurate and fast methods are crucial for characterization of important tissue properties. Here, we present a method for the characterization of the tissue surface regarding roughness and describe its relation to the tissue surface softness properties, based on a sample set of dry-creped bath tissue (DCT) with different amounts of softwood (SW), hardwood (HW), and nonwood pulp (NWP).

The surface of tissue is complex and consists of several overlying structural features; thus, the optical non-contact measurement principle of focus variation was used to provide robust and reliable topographical surface information. Based on the obtained 3D data, areal surface analysis was performed to determine the surface roughness of the tissue samples, which is described by the developed interfacial areal ratio (Sdr) and the power spectral density (PSD). To determine the surface softness properties (TS7) of the tissue, a widely-used tissue softness analyzer (TSA) in the industry was employed. The surface softness (TS7) and the stiffness (D) parameters of this instrument were considered for surface and structural characterization. The results of the surface roughness (Sdr and PSD) and surface softness TS7 measurements show a good linear correlation, with higher surface roughness implying a higher TS7. The presented evaluation of these aspects of tissue softness allows an objective, fast, and accurate assessment of the relevant properties in addition to standard panel tests and is also applicable to other hygiene products.

Application: Readers may use this information to understand the complexity of tissue surfaces and the need for appropriate characterization, as well as for understanding the interrelation of surface roughness, softness, and bulk properties.

The hygiene paper market is a constantly growing segment within the global paper industry, with comparably higher annual growth rates. In particular, the strong demand in the away-from-home segment combined with rising health and hygiene awareness are the main drivers for this growth. Apart from facial tissue, napkins, and kitchen towels, the toilet tissue segment is, in particular, one of the most important within the hygiene paper market [1].

On one hand, the quality of toilet tissue depends on machine technology. Although the through-air-drying (TAD) concept is used for producing high-quality premium tissue, the conventional dry-creped tissue (DCT) technology is the most widely used in the world, as the production costs are lower compared to advanced technologies like TAD [2]. The production process of DCT comprises mechanical dewatering of the paper web, followed by contact drying on a Yankee cylinder. After drying, the paper web is scraped of the coated Yankee surface using a crepe blade. During this creping process, the tissue network and surface is significantly affected, and properties such as bulk and softness are increased, while tissue strength is reduced [3]. Due to the partial mechanical disruption of the fiber network and the cohesion between Yankee and paper web, fibers get pulled out from the fiber network towards the surface layer [3]. The amount and characteristics of these fibers contribute to the overall tissue softness.

Aside from the machine technology, the fiber source has a major influence on final tissue properties. DeAssis et al. [4] performed a comprehensive study regarding the performance of several wood and nonwood pulps during refining and their effects on uncreped tissue handsheet properties.

Toilet tissue must meet certain characteristics when it comes to the purchase decision of customers. According to Wang et al. [5], properties such as water absorbency, caliper, basis weight, and softness are correlated with the shelf price of toilet tissue; hence, tissue manufacturers focus on the optimization of these properties. Besides the water absorbency, which is mainly affected by fiber and structural properties, tissue softness is a key parameter that defines the sensually perceived quality and the so-called handfeel of the tissue product [2]. Usually, tissue softness is assessed by

human panel tests that consider different locations and application setups for the end users. Softness panel tests are mandatory in product development, because the softness is a subjective property. Nevertheless, in quality optimization, panel tests are not always available; hence, it is also common to use a combination of measurement systems that measure softness indicating parameters. The perceptual softness depends on various tissue properties. Hollmark's [6] approach to distinguishing between "bulk" and "surface" related softness has been widely accepted in previous work. Bulk properties related to softness are discussed extensively by Hollmark and Ampulski [7], with physical properties like flexural stiffness, thickness, and compressibility identified as the main influential parameters regarding this property. Surface softness, on the other hand, is attributed to surface roughness, including friction and the stiffness of the protruding fibers, respectively [6,8].

In this work, we use a tissue softness analyzer (TSA) to measure softness; when we use the term "softness" in the discussion, it refers to these measurements (if not specifically discussed otherwise). Specifically, we use a TSA from Emtec (Leipzig, Germany) to determine the influence of bulk and surface softness separately. In softness measurement using the TSA, three basic parameters are usually determined: surface softness (TS7), surface structure (TS750), and bulk stiffness (D). The TSA is used extensively in the tissue industry for quality control at production facilities, and furthermore, it is a referenced device in the relevant literature. It must be mentioned that the TSA measures only a portion of the properties that contribute to tissue softness and should not replace standard measurement procedures. However, Wang et al. [9] investigated the relationship between human perception (panel tests) and TSA-based assessment for several bath tissues, obtaining high correlations between the panel softness score and the surface softness parameter TS7. Several further studies were carried out to evaluate the influence of fiber type and different fiber compositions on tissue softness properties as characterized with the TSA; however, these measurements were often based on tissue handsheets [4,10-13].

The surface softness value TS7 represents the surface roughness and single fiber flexibility within one parameter; however, proper characterization of the tissue surface parameters with the TS7 value has rarely been discussed in previous work. To assess the relationship between tissue surface roughness and TS7, a method to adequately characterize the tissue surface is indispensable.

Reitbauer et al. [14] introduced the optical method of focus variation microscopy using infinite focus measurement (IFM) for the enhanced characterization of complex surfaces like tissue. The measurement procedure, along with several filtering steps and the determination of areal roughness parameters that were also used in this work, were presented. Although IFM provides a high-resolution topographical dataset of the tissue surface that is well-suited for further evaluation, it is still rarely used in the tissue industry. Based on the characterization of three tissue grades as regards their structural and surface roughness properties, two independent areal surface parameters were developed for roughness characterization [14]. The first one is the developed interfacial area ratio (Sdr), which determines the areal ratio between the "real" and projected surface area and describes the deviation of the surface from a perfectly smooth surface. The second parameter is based on the power spectral density (PSD) of the tissue surface and provides a measure of the surface roughness [15]. Both parameters are suitable for adequately characterizing the surface roughness of different tissue samples, because the underlying structures, like crepe or patterns, only have a minor influence on the results [14]. The fact that tissue consists of several overlapping features excludes common line and height-based roughness parameters like root-means-square based height (Sq) and arithmetic mean-based surface height (Sa). They are not able to properly differentiate between roughness features and the underlying structure.

The aim of this work is to determine tissue surface roughness in a novel way and to discuss its interrelation to TS7 properties for DCT samples of varying fiber composition. The areal surface analysis was carried out using the IFM method, and tissue roughness was characterized using the areal surface parameters Sdr and PSD, as described in [14]. The TS7 and D properties were determined using the TSA device.

MATERIALS AND METHODS

Materials

In this work, DCT samples produced on a pilot tissue machine from a blend of kraft softwood (SW), hardwood (HW), and nonwood pulp (NWP) fibers were used. The tested sheet properties may differ from commercially produced sheets due to differences in the white water system for the pilot machine used. The respective fiber furnish compositions are presented in **Table I**. This set of samples is the basis for evaluation of the correlation of surface

Name	NWP Content, %	SW Content, %	HW Content, %
S 0/5/5	0	50	50
S 0/7/3	0	70	30
S 2/3/5	20	30	50
S 2/5/3	20	50	30
S 3/4/3	30	40	30
S 5/3/2	50	30	20

I. Overview of fiber furnish composition of the dry-creped bath tissue (DCT) samples. The amount of softwood (SW), hardwood (HW), and nonwood pulp (NWP) is given in weight-percent for each sample.

Sample	Caliper		Basis Weight	
	Mean, µm	SD, µm	Mean, g/m²	SD, g/m²
S 0/5/5 n1	117	0	17.27	0.15
S 0/5/5 n2	118	1	17.20	0.2
S 0/7/3 n1	108	0	17.19	0.26
S 0/7/3 n2	103	1	17.09	0.11
S 2/3/5 n1	107	1	17.63	0.11
S 2/3/5 n2	109	0	17.70	0.11
S 2/5/3 n1	104	1	17.08	0.11
S 2/5/3 n2	106	1	16.92	0.07
S 3/4/3 n1	107	1	16.79	0.16
S 3/4/3 n2	110	1	16.51	0.29
S 5/3/2 n1	109	0	16.66	0.44
S 5/3/2 n2	105	1	16.77	0.28

II. Mean caliper and basis weight data of the tissue samples with the corresponding standard deviation (SD).

roughness and softness. Further data on pulp properties and production parameters were not disclosed to us. For each fiber composition, two samples were taken from separate production rolls (n1 and n2) to be analyzed. The measurements were carried out under standard climate conditions (23°C, 50% relative humidity [RH]). All surface-relevant properties were determined on the Yankee side of the tissue samples. Caliper and basis weight of the tissue samples were measured according to EN ISO 12625-3 "Tissue paper and tissue products—Part 3: Determination of thickness, bulking thickness and apparent bulk density and bulk" and EN ISO 12624-6 "Determination of grammage." These properties are listed in **Table II**.

Tissue softness analyzer

As one of several available non-panel methods, the TSA from Emtec was used to evaluate TS7 and D, representing the displacement under an external force. As mentioned earlier, the TSA can represent only part of the surface and bulk properties that contribute to the perceived softness of human panel tests; however, correlations are evident and discussed elsewhere [9]. For surface softness measurements, a fan with six blades moves downwards on the single-ply tissue sample and rotates on the surface. Vibrations occur due to the contact between the blades and the tissue surface. The generated sound spectrum is captured with a microphone at the bottom of the device and further evaluated by the TSA software. The TS7 is defined as the peak at approximately 7000 Hz within the sound frequency spectrum and is expressed in decibels (dB). The parameter is mainly related to micro-roughness, the amount of protruding fibers on the tissue surface, and their single-fiber properties. A high TS7 value indicates, in general, a low surface softness and vice versa. By the definition of Emtec, a deviation of 1 dB in the TS7 parameter can also be perceived by the human skin. The D parameter is expressed in mm/N and is defined as the ratio of displacement to the vertical force that is applied on the tissue sample in a range within 100 mN and 600 mN. The higher the parameter D, the more flexible the tissue sample is, and therefore, the lower the stiffness is. Ten single-ply sheets were evaluated to replicate tissue sample property testing.

Parameter	Value
Magnification	20x
Vertical resolution	800 nm
Lateral dataset size	3.5 mm x 3.5 mm
Lateral pixel size	795.3 nm

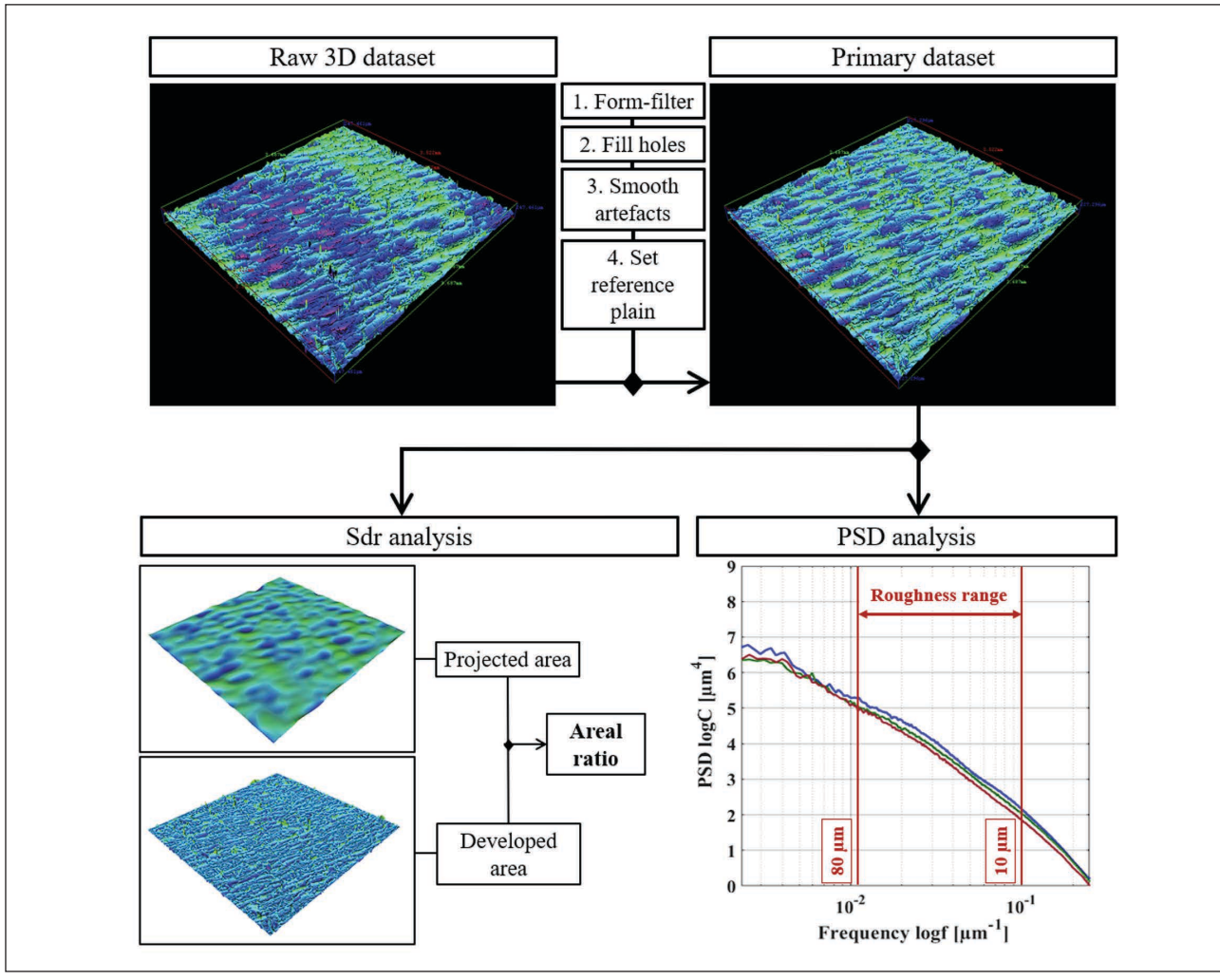
III. Measurement parameters for topographical surface roughness analysis with focus variation.

Focus variation measurement and areal surface analysis

Tissue surface topography was characterized with focus variation measurements using an infinite focus measurement device, the IFM Model G3 from Bruker-Alicona (Graz, Austria). Detailed information on the method and data processing procedures are presented in Reitbauer et al. [14]. A 3D height map of the tissue surface is generated by lateral repetition of the detection of the best focus position in the vertical direction. Based on this focus point, the height distance between the tissue surface and the optical sensor of the IFM device is determined [16]. For roughness characterization, a magnification of 20x is suitable, as single fibers are determinable and a certain periodicity of structures is given. Three different areas of all samples were analyzed on the Yankee side. The applied measurement parameters are listed in **Table III**.

Data processing and areal analysis

The raw 3D data were processed and evaluated using the MeasureSuite 5.3.5 software from Bruker-Alicona. The procedure is schematically shown in **Fig. 1**. As the measured raw data include artefacts due to optical interferences and holes and irregularities in the tissue network, these have to be removed by smoothing the artefacts and filling missing data points resulting from holes by interpolation between the nearest adjacent data points. Of course, these optimization steps have an influence on the resulting surface properties. However, the influence is minor, as identical optimization routines were applied for all samples. A large-scale (form) filter is applied to the dataset to eliminate



1. Schematic overview of the data processing procedure and the subsequent evaluation of tissue surface roughness (Sdr = interfacial areal ratio; PSD = power spectral density).

in-plane deviations that occur from small planar variances of the sample. Following these steps, all subsequent calculations are based on the resulting so called "primary" dataset, which was used for further surface analysis. Due to the lack of accuracy of height-based parameters for complex surfaces like Sq or Sa, we defined two parameters that will be briefly introduced in the following sections. Detailed information regarding the preparation of the dataset and determination of the roughness parameters is also given in Reitbauer et al. [14].

Developed surface area ratio

A suitable and robust parameter to describe the surface roughness of complex surfaces like tissue is the developed surface area ratio (Sdr), as defined by ISO 25178 "Geometrical product specifications (GPS)—Surface texture: Areal—Part 700: Calibration, adjustment and verification of areal topography measuring instruments." According to Eq. 1, this parameter is defined as the ratio of the excess of the developed (true) area to the projected area in percent. For a totally flat and smooth surface, the value is zero, because the developed area equals the projected one. With increasing complexity (e.g., roughness) of the surface, the developed area increases while the projected area remains nearly the same; thus, the higher the value of the Sdr, the higher the surface roughness. The Sdr value was evaluated for each of the three measured areas and subsequently used to calculate a mean Sdr-figure for each sample.

$$\mathrm{Sdr} = \frac{A_{\mathrm{developed}} - A_{\mathrm{projected}}}{A_{\mathrm{projected}}} * 100 \qquad [\%] \qquad (1)$$

Power spectral density

The second roughness parameter is based on power spectral density (PSD) evaluation of the tissue surface. With the PSD, all apparent spatial frequencies on the surface are determined through Fourier transformation of the autocorrelation function signal [17]. The result of a PSD analysis is usually shown in a diagram where the logarithmic power spectral density (logC) on the y-axis is plotted over the

logarithmic spatial frequency spectrum (logf) on the x-axis. The spatial frequency spectrum logf (μm^{-1}) is limited by the maximum lateral size of the measurement as upper limit and by the pixel size (see values in Table III) as the lower limit. The power spectral density logC (μm^4) is depicted as a so-called pseudo 1D PSD curve, where periodic spatial features of the surface are visible as peaks at a certain frequency, as shown in Fig. 1. To determine the surface roughness of a tissue sample using PSD analysis, the height of the PSD curve within a certain frequency range is of importance, where the roughness increases with a higher level of the PSD curve. In our work, we defined the frequency range where roughness is evaluated within 10 µm to 80 µm; hence, all variations inside this range are assigned to roughness features. To simplify the comparison of roughness between the different samples, the PSD curves within the mentioned frequency range were numerically integrated and expressed as single figures. As in the Sdr evaluation, three areas per sample were analyzed to calculate the average PSD results.

Tensile properties and statistics

To describe the relationship between surface and structural properties of the tissue sample, tensile tests according to EN ISO 12625-4 were carried out. At least ten measurements in the machine direction (MD) and cross-machine direction (CD) were performed, and the results were averaged as the geometrical mean tensile strength (GMT) according to Eq. 2:

$$GMT = \sqrt{MD * CD} \qquad [N\,m^{-1}] \tag{2}$$

For the evaluation of the results, basic statistics were applied. Except for the GMT parameter, all parameters were averaged using an arithmetical mean, with standard deviation used to determine the variability. To assess the relationship between two variables, the coefficient of determination (R^2) was used, assuming a linear correlation. To test the significance of the null hypothesis, the significance level (p-value) was defined as $p \leq 0.05$. All correlations with a p-value below 0.05 are considered as statistically significant.

RESULTS AND DISCUSSION

Surface roughness measurements

As already mentioned, two methods are applied for the evaluation of the tissue surface roughness. The results of both Sdr and PSD evaluation are listed in **Table IV**, and the values for the PSD analysis are numerically integrated (see Materials and Methods section). The higher the value of PSD and Sdr, the higher the surface roughness is. The roughness results in Table IV are sorted from low to high amount of NWP in the fiber composition. The highest surface roughness is evident for the S 0/5/5 samples with 0% NWP, 50% SW, and 50% HW content. By shifting the SW/HW ratio to 70/30, the surface roughness is significantly reduced. With the addition of 20% NWP to the fiber furnish, a certain increase in the surface roughness of the samples S 2/3/5 and S 2/5/3 compared to S 0/7/3 can be obtained, whereas compared to S 0/5/5, a slight decrease in surface roughness is evident. Based on sole interpretation of these results, the given NWP seems to be an intermediate between SW and HW properties, with generally higher stiffness than SW. With a further increase of the NWP content from up to 30% and 50%, the surface roughness decreases. This especially the case for samples with 50% NWP (S 5/3/2), which show a significantly lower surface roughness compared to all other samples.

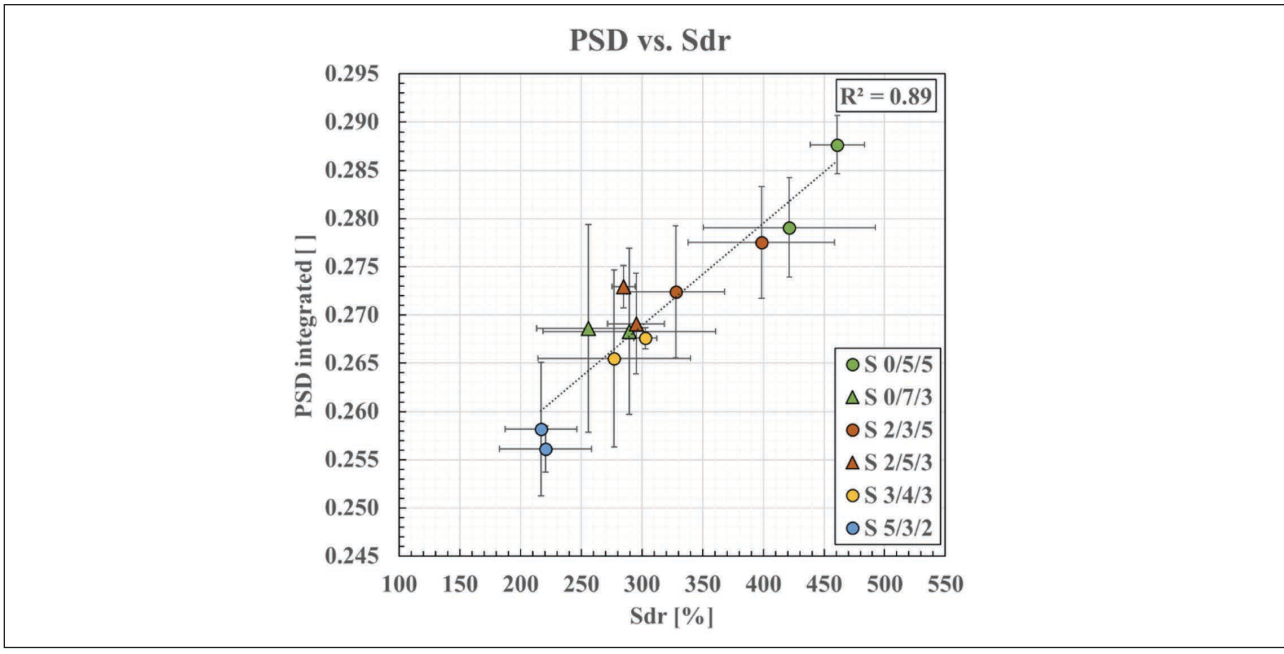
Sample	Sdr		PSD Integrated	
	Mean, %	SD, %	Mean, -	SD, -
S 0/5/5 n1	460.9	22.4	0.288	0.003
S 0/5/5 n2	421.5	71.0	0.279	0.005
S 0/7/3 n1	289.6	71.0	0.268	0.009
S 0/7/3 n2	256.0	42.6	0.269	0.011
S 2/3/5 n1	327.8	40.2	0.272	0.007
S 2/3/5 n2	398.6	60.3	0.278	0.006
S 2/5/3 n1	284.9	9.7	0.273	0.002
S 2/5/3 n2	295.2	23.2	0.269	0.005
S 3/4/3 n1	277.3	62.9	0.266	0.009
S 3/4/3 n2	302.7	9.5	0.268	0.001
S 5/3/2 n1	220.7	37.7	0.256	0.002
S 5/3/2 n2	217.0	29.3	0.258	0.007

IV. Integrated and averaged (three per sample) surface roughness values resulting from power spectral density (PSD) and developed surface area ratio (Sdr) analysis with the respective standard deviation (SD). Numerical integration for PSD analysis was performed between the spatial frequency range of 10 µm to 80 µm.

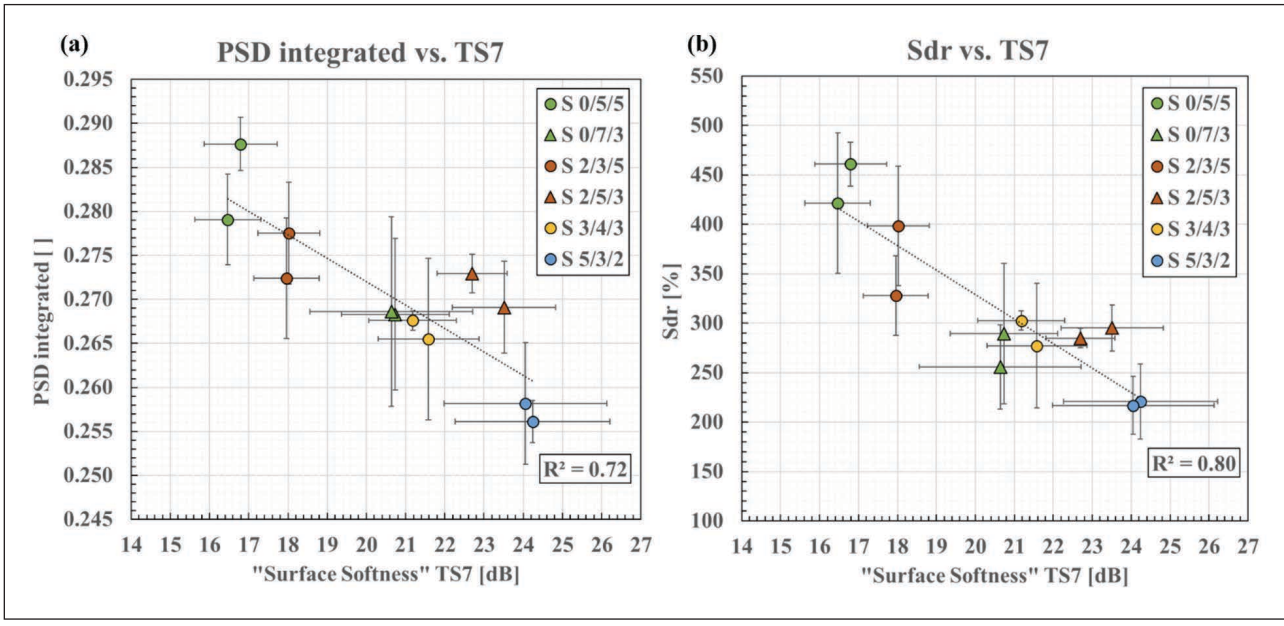
In **Fig. 2**, the linear correlation between the integrated PSD data and the developed Sdr is shown. Despite the different evaluation principles for surface roughness, both methods correlate well ($R^2 = 0.89$).

Surface roughness and softness

The linear relationship between TS7 and surface roughness parameters is shown in **Fig. 3**. The lower the measured TS7 value, the higher the surface softness is by the Emtec definition. In Fig. 3a, the integrated PSD is shown, and in Fig. 3b, the Sdr is plotted over the TS7. The linear regression models show quite good correlation between surface roughness and TS7, with the correlation to the Sdr

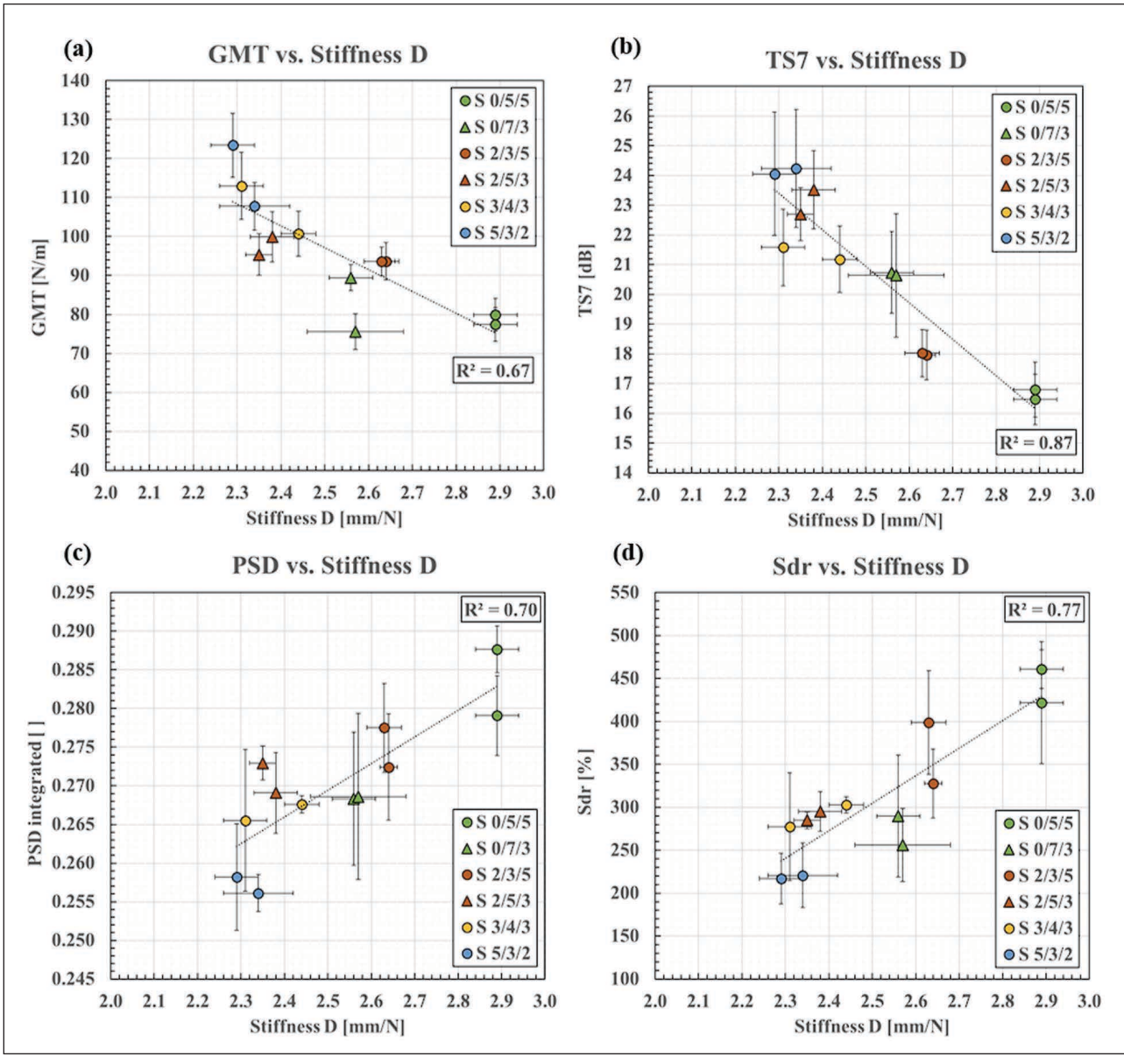


2. Linear correlation of the surface roughness parameters PSD (integrated between 10 and 80 µm) and Sdr (R^2= 0.89 and a p-value = $4.7*10^{-6} \leq 0.05$)



3. (a) Linear correlation between surface roughness (integrated PSD) and surface softness (TS7), with R^2 = 0.72 and p-value = $4.8*10^{-4} \leq 0.05$. (b) Linear correlation between Sdr and TS7, with R^2 = 0.80 and p-value = $9.38*10^{-5} \leq 0.05$.

parameter having a higher coefficient of determination (R^2 = 0.80). Differences in fiber composition provide significant effects on measured surface softness, which is indicated by the TS7 range between 16 dB and 25 dB. In Fig. 3b, S 0/5/5 shows the highest TS7 and the highest surface roughness, while the opposite is true for S 5/3/2. Also, sample S 2/3/5 with 20% NWP and 50% HW shows a high TS7 and simultaneously high roughness. Other samples like S 2/5/3 and S 3/4/3 cannot be distinguished based on Sdr. Their TS7 value is, on the other hand, different, where S 3/4/3 has a higher softness than S 2/5/3 at a comparable roughness level. Obviously, despite the different furnish mixtures of these samples, the number of protruding fibers, and hence the effects on roughness, is minor. This may indicate that the single fiber stiffness of the protruding fibers that is also considered in TS7 measurement is affecting TSA softness as well. For example, when comparing S 3/4/3 and S 2/5/3, the increase in softness of S 3/4/3 could be explained with a higher amount of stiff fibers in the furnish mixture. This observation, however, is dis-



4. (a) Linear regression plot between the mean geometrical tensile strength (GMT) and the stiffness (D) measured with the tissue softness analyzer (TSA) device (R^2 = 0.67, p-value = $1*10^{-3} \leq 0.05$). (b) Linear correlation between surface softness (TS7) and stiffness (D), both measured with the TSA (R^2 = 0.87, p-value = $8.97*10^{-6} \leq 0.05$). (c) Surface roughness (PSD integrated) measured with the infinite focus measurement (IFM) device vs. D (R^2 = 0.70, p-value = $8.4*10^{-4} \leq 0.05$). (d) Second surface parameter (Sdr) vs. D (R^2 = 0.77, p-value = $1.7*10^{-4} \leq 0.05$).

cussed in the following section, which covers stiffness and strength properties in detail. The high linear correlation coefficients show that the applied method of focus variation (IFM), including subsequent areal analysis and the TS7 value from the TSA measurement, are in principle suitable for an extensive evaluation of the tissue surface.

Stiffness and strength properties

To get a holistic view on softness, we compare the already discussed surface properties with bulk properties like GMT and D. Another structural property of interest would be the basis weight; however, differences between the given tissue samples are minor (Table II). In **Fig. 4**, linear relationships between several bulk/surface properties and D are plotted. A higher D value indicates more flexibility and thus a lower stiffness. This D parameter has already been considered as an indicator for bulk softness in another study [4]. To show the relation between stiffness and tensile strength, the results of both measurements are presented in Fig. 4a. With higher stiffness (lower D), the tensile strength increases; however, the overall correlation is relatively weak (R^2 = 0.67). A possible explanation could be the use of different measurement devices for both parameters, since the principle of D is based on the resistance

to displacement, while the tensile properties are evaluated by elongation tests. In general, with a higher amount of NWP, both stiffness and GMT increase. This fact is evident when comparing S 0/5/5 with S 2/5/3 and S 2/3/5 with S 5/3/2 where the SW content is held constant and the HW is substituted with NWP. In Fig. 4b, TS7 is plotted vs. D with a high overall correlation of the linear regression (R^2 = 0.87). Thus, the measured surface softness TS7 is highly related to network-based properties like stiffness. It has to be mentioned that the single-fiber stiffness (affecting the TS7 parameter) and bulk stiffness are not necessarily directly related, as bulk stiffness depends not only on the single fiber stiffness, but also on the network and strength properties. The highest surface softness (lowest TS7) is reached with the highest D value (lowest stiffness) at the bottom right (S 0/5/5) of the plot and vice versa. According to the shown plots (Figs. 4c and 4d), the Sdr analysis demonstrates a slightly higher overall linear correlation (R^2 = 0.77) compared to the PSD analysis (R^2 = 0.70).

In Figs 4b and 4d, several samples (S 0/7/3, S 2/5/3, and S 3/4/3) are not distinguishable based on their surface roughness, while D and TS7 vary. As discussed earlier, a possible explanation could be the different effects of single fiber stiffness on surface properties (TS7) on the one hand and bulk properties (stiffness D and GMT) on the other hand. A variation in single fiber stiffness does not necessarily imply a shift in surface roughness, but should lead to changes in terms of surface softness.

CONCLUSION AND OUTLOOK

Robust and accurate surface roughness data is provided by the IFM and represented by the Sdr and PSD parameters, respectively. Although the Sdr and PSD values are based on different analysis concepts, both roughness parameters show a high linear correlation (R^2 = 0.89) and represent the surface roughness properly. The measured surface softness parameter TS7 shows a high linear correlation (R^2 > 0.70) to the measured surface roughness parameters, demonstrating the relevance of roughness features for surface softness. Combining surface roughness and single fiber stiffness should allow an optimization of fiber furnishes regarding surface softness. Additional insight into the tissue surface, in combination with perceivable and measurable properties like surface softness, provides the basis for further improvement of tissue quality.

In addition to the surface properties, the bulk properties of the tissue samples were also evaluated. The stiffness D measured with the TSA is an indicator for bulk softness and correlates well with surface softness TS7 and surface roughness parameters (Sdr and PSD), with R^2 > 0.70. In summary, the combined application of fast and objective methods like IFM and TSA allow a novel approach for the characterization of tissue surfaces and structure properties that contributes to the perceived tissue softness. **TJ**

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ABOUT THE AUTHORS

As a field of research, tissue in general is interesting, but especially the tissue surface, with its complex features and the corresponding effects on tissue properties. In previous research, we have used the optical non-contact method of focus variation for areal surface characterization of different tissue types. The current work should show the applicability of the so-derived surface roughness by correlating it to relevant tissue properties.

When characterizing tissue surfaces, the major issue is the different overlaying structures and features like protruding fibers, crepe, and texture. For proper characterization, several steps are necessary to isolate the different features and to retrieve the desired surface roughness information.

We discovered that there are no standard roughness parameters applicable to complex surfaces, and proper characterization needs suitable roughness indicators. Although somewhat expected, the most interesting finding in this study is the proven high correlation between the areal surface roughness and surface softness parameters.

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With the given method, mills are able to characterize the surface properties with respect to process and raw material optimization to support research and development tasks. Our next step would be to extend this approach to other tissue types, such as TAD.

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