Experiments Investigating the Local Paper Structure

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Abstract

The accurate characterization of paper structure may provide critical information for ideal selection of raw materials and papermaking processes as well as for predicting the behavior and the quality of final paper products. In this study, local paper structure and the relationship among the structural parameters, thickness, grammage, apparent density and surface roughness of various handsheet and commercial paper samples were evaluated by using recently developed methods. A new concept of surface roughness was also introduced.

The results demonstrate that there is significant overestimation in the measured thickness when using the conventional caliper method that originates from the surface roughness and poor paper formation. A novel non-contact thickness tester, referred to as the twin laser profilometer (TLP), provided results that were not subject to these artifacts and thus provided the local intrinsic thickness and consequently the local intrinsic apparent density.

1. Introduction

Uniformity of paper structure has substantial influence on the various end use properties such as mechanical (1), optical (2), and printability (3,4). The physical parameters, mass, thickness, and density are most often used to characterize a material as in this case for the paper. The variations of these parameters within the structures of fibrous webs are considered as an important origin of the non uniformity observed in the variation of paper properties. In practice, since paper has a much smaller dimension in thickness, or Z- direction as compared to in-plane dimensions, it has often been considered and even modeled as a two-dimensional material (5). As such, the local mass variation within x-y plane of the sheet, i.e. paper formation, has been given substantial attention from many investigator (6-9). Most end use paper properties are directly or indirectly affected by the paper formation and important relationship have been developed (10,11). Although paper formation is often considered as a primary source of non uniformity of paper properties, the underlying material property that influences the mechanical, optical and absorptive properties of paper is apparent density, which is obtained by reducing the paper grammage by the thickness (12-14). However, the lack of reliability in the measurement of thickness, especially at spatial resolution under 100 μm^2, has limited the number of reported investigation of the local variation of paper thickness and apparent density (15,16).

In order to evaluate local structure of paper more accurately, a non-contacting method, referred to as the twin laser profilometer (TLP) instrument was developed (17). The spatially localized (local) thickness of paper obtained from the TLP instrument may be represented as a two-dimensional data array or map. This data can be used to reduce the local distribution of mass, or formation, to obtain the local density distribution in X-Y plane of a paper sample. Formation was measured by using a recently developed measurement method, based on a storage phosphor imaging system (18). Surface profiles were also obtained from the opposing sensors and were used to determine surface topography and roughness of both surfaces.

In this study, the systematic methods for the evaluation of local paper structure were introduced. The fundamental relationship between the three structural parameters, grammage, thickness and apparent density was examined using various handsheet samples. A novel concept for roughness measurement also was introduced.

2. Material and Methods

2.1 Sample preparation

Laboratory paper samples were formed by using a British handsheet mold according to TAPPI Method T205 sp-95. The standard research pulps available from the National Institute of Standards & Technology (NIST) were used for this work. All handsheet samples for this work were made of 60 % softwood and 40 % hardwood. In order to change the formation of the handsheet samples, three different settling times were applied during the forming step. These were 0, 60, and 120 seconds, with formation quality decreasing with time.

2.2 Measurements of Mass Distribution

The local grammage distribution (formation) maps of the samples were obtained using a storage phosphor β-radiographic imaging system. The paper sample was exposed to β ray emission of a ^{14}C radiation source that was backed by the storage phosphor screen that stores the latent image of transmitted radiation. The screen was then scanned at 100 μm pixel size using a PhosphorImager-SI™ (Molecular Dynamics, Sunnyvale, CA) scanning instrument. The image that was obtained was calibrated to convert instrument units to actual grammage images, based on a Mylar reference wedge. This system has a linear response to β ray exposure and has good sensitivity, i.e. ~ 0.1 g/m^2 (18,19).

2.3 Measurements of Local Thickness Distribution

The local thickness was measured by using the twin laser profilometer (TLP) instrument as shown in figure 1.

The sample, which was marked with three pinholes for registration with the respective grammage map, was held by the metal frame between two opposing laser sensors. Each sensor provided the surface profile of its side with a resolution of at least ~1 μm. The combination of the two surface profiles gave an accurate distance between the two surface profiles that when combined resulted in the local thickness distribution map of the sample.

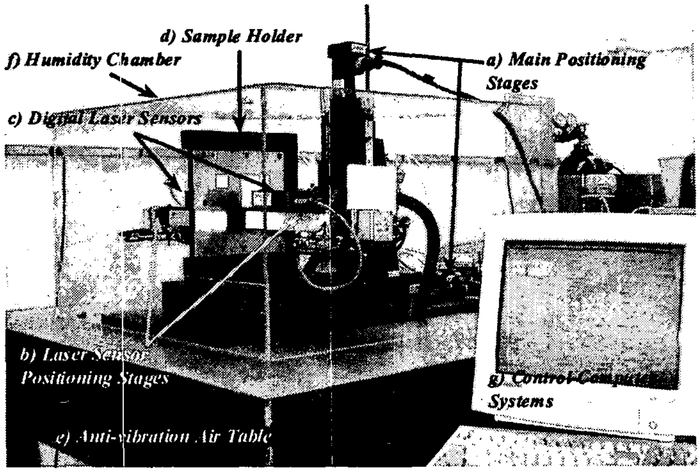


Figure 1. System configuration of a twin laser profilometer (TLP) instrument.

The TLP is composed of a) main and b) sensor positioning stage systems, c) digital laser sensors, d) sample holder, e) anti-vibration air table, f) humidity chamber, and g) control computer system. The entire system is maintained at TAPPI Standard conditioning.

3. Results and Discussion

3.1 The relationship between grammage and thickness

Many investigator found that for a paper, a linear relationship existed between mean grammage, $\bar{W}$, and mean thickness, $\bar{Z}$, and that there was no significant difference in the apparent density. This was especially true for laboratory paper samples (20-22). Thus, the basic relationship is given by

$$\bar{Z} = \alpha\bar{W} + \beta \quad (1)$$

where, α, β : empirical constant.

And the mean apparent density, $\bar{\rho}$, of the paper is given by

$$\bar{\rho} = \left(\frac{\bar{W}}{\bar{Z}}\right) = \left(\frac{\bar{W}}{\alpha\bar{W} + \beta}\right) \cong \frac{1}{\alpha}(if\, \beta \cong 0) \quad (2)$$

Therefore, the mean apparent density theoretically becomes constant and is sometimes referred to as an intrinsic density (23), for $\beta \to 0$ (intrinsic thickness).

Since the constants α and β may be significantly changed by the type of furnish and its properties, the papermaking processes, and the thickness measurement methods, it is very complicated to accurately determine the relationship between thickness and grammage and the resultant the apparent density. The indirect method based on the standard caliper thickness measurement has been widely used for obtaining the intrinsic thickness and the intrinsic density or an apparent density, which tolerate the thickness overestimation of the standard caliper method.

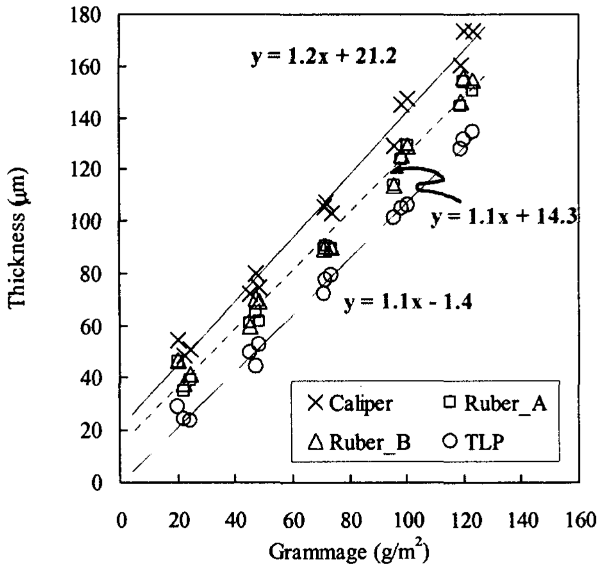


Figure.2. Average thickness measured by four different methods as a function of the sample grammage. The 30×30 mm area of each handsheet sample was tested 10 times with the conventional methods and was scanned with 100μm interval by the TLP instrument.

Figure 2. shows the average measured thickness using four different methods. These include three conventional methods: TAPPI standard caliper, and two modified rubber platens methods, and the TLP method all of which are plotted as a function of grammage. A linear relationship between grammage and thickness is evident for all methods.

The conventional methods provided higher values of thickness compared to the TLP instrument. The difference was incremental for all samples tested. For the empirical relationship between thickness and grammage cf. Eq.1, the difference existed mainly among the y-intercept, β, while there is little difference between the slope, α values. Since all samples were prepared with same furnish and process and while there are significant difference in the formation, the constant α shows no variation between measuring methods. However, the β values differed widely, especially for the TAPPI standard caliper method which had the highest β constant, >20μm. This would lead to overestimation of thickness value (24) and resultant lower apparent density, making the TAPPI standard caliper method suspect for an inaccurate determination of the paper density. The β constant of the TLP instrument was very close to zero, i.e.-1μm that is within the error limits of the method. These findings support the premise that thickness values measured using the TLP instrument may be considered as the intrinsic thickness, and consequently can be used for calculation the intrinsic density.

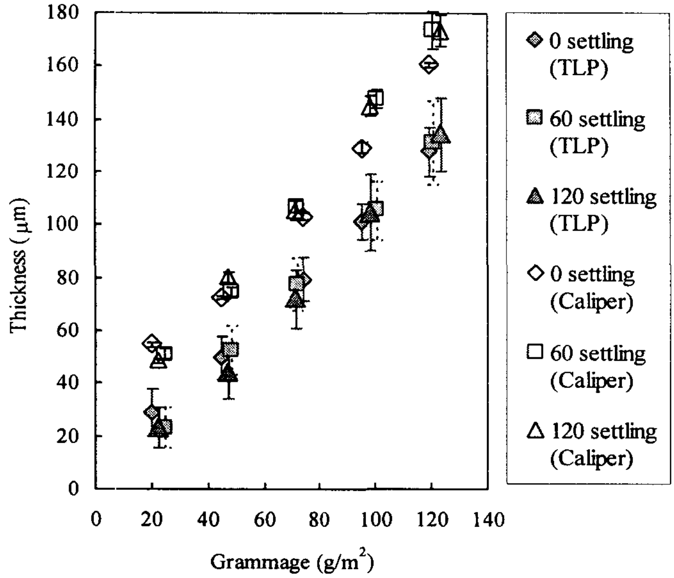
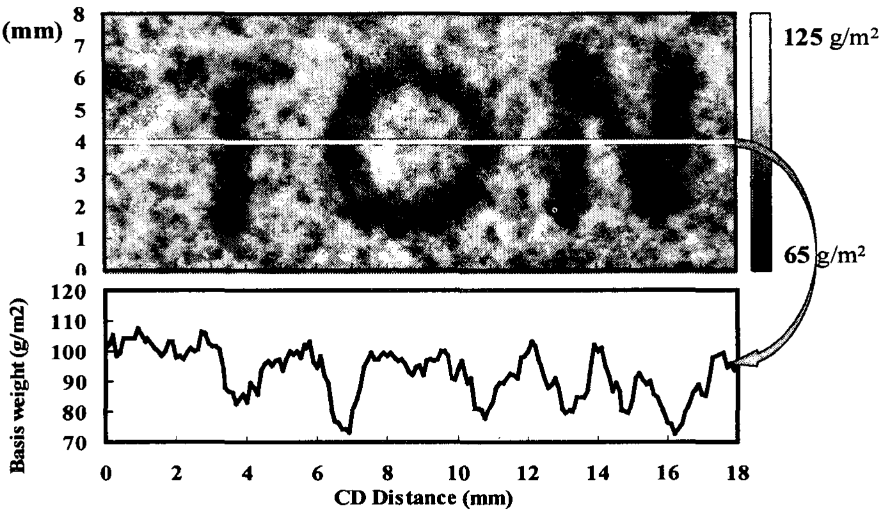


Figure3. The relationship between average thickness and average grammage depending on the settling time. The 30 × 30 mm square area of each handsheet sample was scanned with 100 μm interval using the TLP instrument

Figure 3 shows the thickness measured as a function of the grammage and the settling time, the paper formation. In case of caliper method, the poor formation resulted in higher thickness, especially for the higher grammage sample, which originated from the bigger overestimation for the poor formation sample. However, since the TLP instrument can effectively avoid overestimation of the thickness by robust measurement of the surface including both low spots and peaks on the surface, the thickness measured by the TLP instrument was not affected by the sample formation. And this result provided the overall linear relationship between the grammage and the thickness which was not significantly influenced by the formation of sample.

3.2 Evaluation of the local structure of a commercial paper sample with a watermark

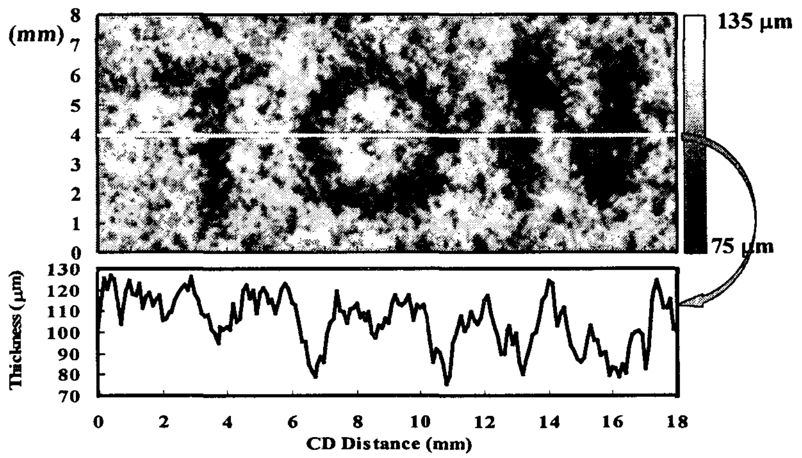
In order to examine the relationship between local grammage and local thickness in a paper sample, the local paper structure of a commercial paper which had an induced low grammage area, such as water mark, was tested. Figure 4. shows the local basis weight map of the watermarked sample area. The '**TON**' is a lower grammage region in the paper sample.



Mean : 93.6 g/m², STDEV : 8.1, COV(%) : 8.7

Figure 4. Local basis weight map and line profile of a watermarked sample. Each local value has 100 μm × 100 μm pixel sizes.

The lower grammage region of the sample resulted in a lower local thickness as shown in figure 5. The same pattern of text was also easily observed in the local thickness map. The center line profile of both maps was similar which indicates a strong relationship between local thickness and local grammage.

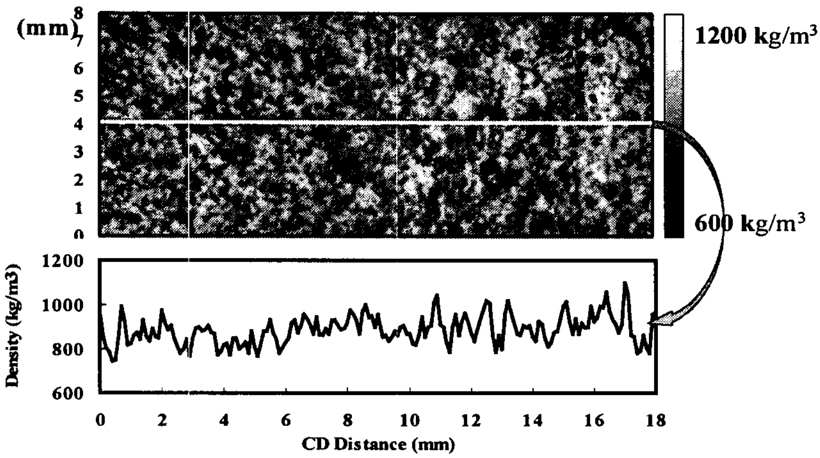


Mean : 105.2μm, STDEV :13.5, COV(%) : 12.8

Figure5. Local Thickness map and line profile of a watermarked sample.

The sample was scanned with 50 μm X and Y interval and each local value was represented as an average value of four local values and has 100 μm × 100 μm pixel sizes.

The linear relationship between local thickness and local grammage resulted in less variation in the local density of the sample and the disappearance of the text, as shown in Fig. 6.



Mean : 892.5 kg/m³ , STDEV :46.3 , COV(%) : 5.2

Figure 6. Local density map and line profile of a watermarked sample.
Each local value has 200 μm ×200 μm pixel size.

3.3 Measurement of the surface roughness with the TLP instrument

3.3.1 <u>A New concept of Surface Roughness Measurement</u>

Traditional methods for measuring surface roughness have usually tested only one side of the specimen. In as such, the analysis relies on the assumption that the opposite side is ideally flat in the plane of reference. The roughness is therefore the variation in the distance from the reference plane to the sample surface, i.e., variation in the profile. Although, from a practical perspective, the one sided roughness testing can simulate the real end use situations, such as offset printing or pigmented coating, in which the opposite side surface is supported by a smooth roll, severe waviness (out of plane deformation) or lumpiness of a paper specimen could contribute to excessively misleading results for roughness measurement. This is especially important when considering non-contacting printing paper, such as ink jet printing paper.

In this work, the surface roughness of both sides was evaluated simultaneously. The reference plane for calculating each side surface profile was determined as the imaginary center position between the two outer surfaces. After the imaginary center position was obtained at each point, a moving average filter was applied in order to smooth local variation and to obtain an appropriate centerline surface. Since the size of filter kernel (zone size) determines the smoothing range, the contribution of each wavelength (floc size in bulk paper structure) on the roughness can easily be identified and analyzed. The schematic diagram of this roughness is shown in Fig. 7.

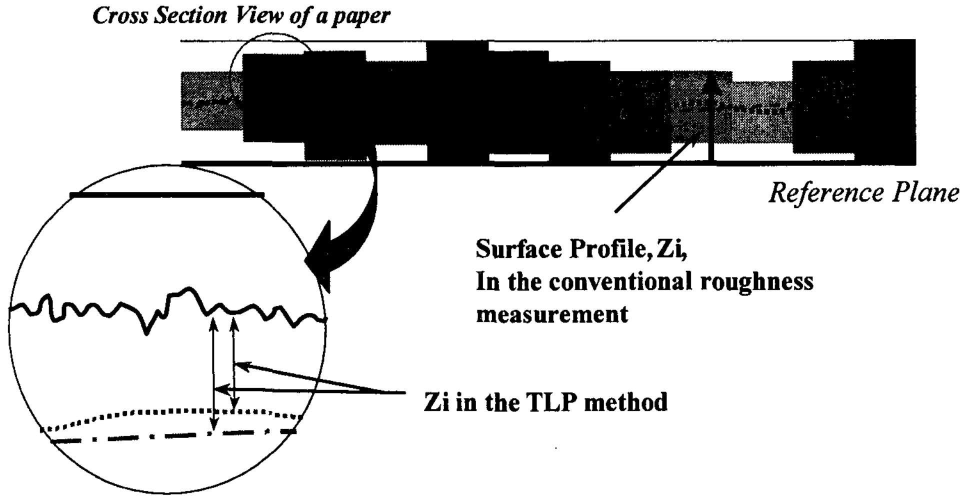
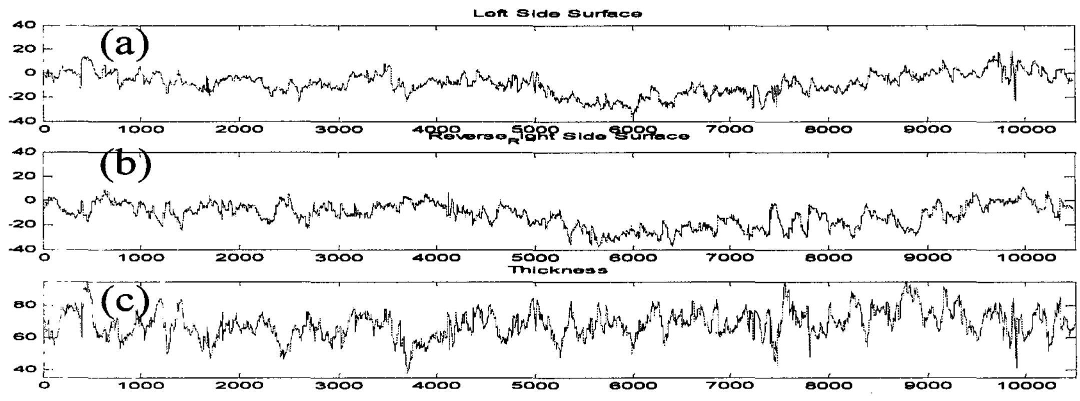


Figure 7. The schematic diagram of roughness measurement by the conventional method and the TLP instrument method. Zi is the distance from reference plane to surface. The variation of Zi is the surface roughness.

3.3.2 Surface roughness of commercial paper samples

The surface roughness measurement by the TLP instrument was demonstrated in Fig. 8. Figure 8. (a) and (b) show the original surface height variation profile of both surfaces. The thickness profile of the sample was obtained by calculating the difference at each point between those two surface height variation profiles, c.f. Fig. 8.(c). Figure 8. (d) indicates the centerline between both surfaces. Figure 8.(e) illustrates the out of plane deformation, which was calculated by using moving average filtering with different filtering window sizes, 100 *μm, 500 μm, and 1000 μm* filter size selected based on the scale of the variation. Finally, each roughness profile is obtained by subtracting the filtered out of plane deformation profile from the original surface height profile.



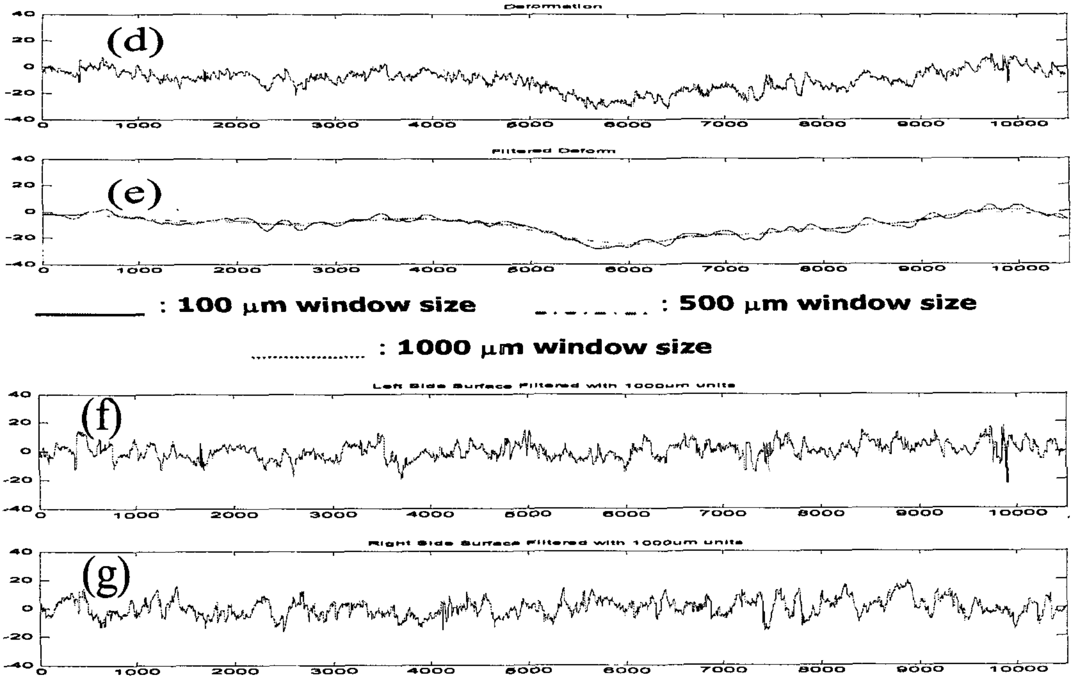


Figure 8. The surface roughness of SC (Super Calendered) grade paper before calendering. (unit : micrometer) The line profiles of 10.5 mm (5 μm interval) were obtained from both surfaces.
(a) surface height variation of top side surface, (b) surface height variation of bottom side, (c) local thickness variation, (d) the center line between both surface, (e) out of plane deformation which was obtained by using moving average filtering with three different window sizes, (f) surface roughness of top side filtered with 1000μm window size, (g) surface roughness of top side filtered with 1000μm window size.

4. Conclusions

Systematic methods for evaluating the fundamental parameters of paper structure, i.e. grammage, thickness, apparent density and surface roughness were presented. The TLP instrument was shown to be unaffected by the thickness overestimation seen with the standard caliper method and therefore directly provided values for the intrinsic thickness and resultant intrinsic local density. Specifically, combining of the local thickness map obtained using the twin laser profilometer (TLP) instrument with the local grammage map by a storage phosphor β-radiography provided the local apparent density map with 200 μm pixel size (spatial resolution). These unique characteristics of the TLP instrument made it possible to study on the local structural properties accurately.

The fundamental relationships between the structural parameters such as grammage, thickness, and apparent density were investigated using bleached hardwood and softwood handsheet samples. The mean thickness of the handsheet samples showed a very strong linear relationship with the mean grammage of the handsheet samples. The relationship was not affected by the sample formation, when the TLP instrument was used for thickness measurement. The evaluation of local structural parameters of a watermarked paper demonstrated that there is a linear relationship between local grammage and local thickness, which resulted in less variation in local density.

A novel concept for roughness measurement was introduced and demonstrated with a uncalendered paper sample. This method reduced the influences of the bulk structure on the roughness measurement and could be used for the study on the printability for the non-contacting printing.

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