29 Einfluss von Rohpapier, Streichfarbenformulierung und Satinage auf die elastisch-plastischen Eigenschaften gestrichener Papiere in z-Richtung

Influence of base paper, coating formulation and calendering on the elastic-plastic properties of coated paper in the z-direction

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Zusammenfassung

In den in diesem Beitrag vorgestellten Arbeiten wurde zur Ermittlung der Verformungseigenschaften in Richtung der Blattdicke (z-Richtung) ein kommerziell erhältliches Tastschnittgerät eingesetzt. Beim so genannten MISTAN®-Verfahren wird ein Tastkörper dreimal über die Oberfläche der zu untersuchenden Papierprobe geführt. Die erste Linienmessung erfolgt ohne Last. Während der zweiten Messung ist der Tastkörper mit bis zu 100 mN belastet; die dritte Messung erfolgt wiederum ohne Last. So kann mittels dieses Verfahrens simultan die Oberflächentopographie und die gesamte, elastische und plastische Verformung der Probe in z-Richtung ermittelt werden.

Um den Einfluss von Strichzusammensetzung und Auftragsgewicht auf das Verformungsverhalten in z-Richtung zu ermitteln, wurden 16 laborgestrichene holzfreie Papiere nach einem statistischen 2^3 Versuchsplan hergestellt, wobei drei Faktoren variiert wurden:

- Pigment:	Clay/Carbonat Anteil von 100/0% bis 0/100%
- Binder:	Latex/Stärke Gehalt von 12/0% bis 8/6%
- Strichgewicht:	10 bis 18 g/m².

Die Rezepturen wurden auf ein 100 g/m² holzfreies Rohpapier aufgetragen und die Verformungswerte in z-Richtung vor und nach einer Laborsatinage ermittelt.

Während bei den unsatinierten Proben die gesamte und elastische Verformung durch alle drei Variablen – Pigment, Binder und Auftragsgewicht - signifikant beeinflusst wurde, war bei den satinierten Proben der Einfluss der Pigmentart klar dominierend, wobei die mit Clay gestrichenen Papiere die höchsten Verformungswerte aufwiesen. Die Unterschiede in der gesamten und elastischen Deformation kontze zu 70% durch die Variation in Pigment, Binder und Strichgewicht erklärt werden.

In einer zweiten Versuchserie wurden 44 Sätze von Laborblättern hergestellt, wobei Langfaserzellstofftyp, Kurzfaserzellstoffanteil und –typ, CTMP-Anteil und Füllstoffgehalt nach einem stistischen 2^5 Versuchsplan variiert wurden, um so Blätter mit stark unterschiedlichen elastisch-plastischen Eigenschaften zu erhalten. Diese Laborblätter wurden auf einer Laborstreich-maschine mit einer Standard-Strichrezeptur gestrichen und in weiterer Folge satiniert. Die Verformungseigenschaften in z-Richtung wurden sowohl für die ungestrichenen als auch die gestrichenen Papiere vor und nach Satinage bestimmt.

Wie erwartet wurde die gesamte und elastische Verformung in z-Richtung vor allem durch den Strich und durch die Satinage markant reduziert. Die gesamte und elastische Verformung der gestrichenen Muster vor und nach Satinage waren hoch korreliert mit den Verformungswerten der ungestrichenen Proben, was auf den dominierenden Einfluss des Rohpapiers auf das Verformungsverhalten gestrichener Papiere in z-Richtung hinweist.

Abstract

Few testing methods are available for the determination of the z-directional elastic-plastic properties of a paper sheet. For our work the measurement of these properties was performed using a commercially available tracing stylus type instrument. The working principle of the instrument is to perform three line measurements along the same line on the sample surface. A load of max. 100 mN is applied during the second line measurement and no load is applied during the first and third line measurement. Thus information regarding the surface structure and the elastic-plastic deformation of the paper structure is obtained simultaneously.

In order to evaluate the effect of coating composition and coat weight on deformation 16 coated papers were prepared according to an 2^3 experimental design scheme in a first series of trials with the three variables being:
- pigment: clay/carbonate content from 100/0 % to 0/100 %
- binder: latex/starch content from 12/0 % to 8/6 %
- coat weight from 10 to 18 g/m^2.

All formulations were applied on a 100 g/m^2 woodfree base paper on a laboratory coater. The total, elastic and plastic deformation was then evaluated before and after laboratory calendaring.

We found that before calendaring all three variables – pigment, binder and coat weight - influenced the total and elastic deformation, while after calendaring the pigment influence clearly dominated. The R^2 of all models was in the range of 0,7. The coating formulations with high clay content resulted in the highest total and elastic deformation with this effect being even more pronounced after calendering. Reducing the starch content in the coating resulted in higher total and elastic deformation before calendaring with this effect being far less pronounced after calendering. The models for plastic deformation showed in general rather low R^2 values in the range of 0,1.

By varying filler content, softwood pulp type, hardwood pulp content and type and CTMP content 44 sets of 70 g/m^2 handsheets with a wide range of elastic properties were prepared according to a 2^5 experimental design in a second series of trials. These handsheets where then coated in the laboratory with a standard coating formulation. Deformation behavior was again measured before and after calendering.

As expected coating and calandering significantly reduced total and elastic deformation, with the effect of coating being more pronounced. Total and elastic deformation of the coated uncalendered and coated calendered samples were highly correlated to total and elastic deformation of the uncoated base paper, showing that the base paper composition is the dominating influence on the z-directional deformation behavior of coated papers.

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1 Introduction

While significant research has been directed towards the elastic-plastic – or viscoelastic - deformation behaviour of paper in the x- and y-direction, research regarding the deformation behaviour of paper in the z-direction has been less extensive. Work has been concentrated mainly on paper grades for rotogravure printing, where – due to the hard printing nip - compressibility of paper in the z-direction has frequently been found to be an important influential factor regarding printability [1,2,3,4].

Deformation of paper in the z-direction, however, is also of importance for all other paper grades, since during paper manufacturing and finishing high compressive forces in direction of the sheet thickness are acting on the formed sheet. Typical examples, which are of special interest for coated paper grades, are blade coating and calendering. Again the viscoelastic reaction of the sheet to these compressive forces is influencing important final paper quality parameters like e.g. bulk, gloss, roughness and opacity [5]. Also in converting processes like creasing, folding or die cutting the out-of-plane compressibility is also influencing the result of this process.

In the frame of a cooperative research project for the Austrian paper industry [6,7,8] a series of trials was carried out at our institute to determine the influence of base paper composition aspects and main coating formulation components on the elastic-plastic properties of coated paper in the z-direction before and after calendaring.

The determination of the elastic-plastic properties of paper was carried out using a rather novel, commercially available tracing stylus type instrument. After a brief review of the different measurement methods applied in determination of elastic-plastic properties in the z-direction the working principle of the instrument is described.

Out of this work, the results of two series of laboratory trials are presented, which were carried out according to an experimental design plan:

a) 2^3 factorial design coating trial on a standard base paper, where pigment type, latex/starch content and coat weight where varied
b) 2^5 factorial design base paper trial, where filler content, softwood pulp type, hardwood pulp content and type and CTMP content where varied in laboratory hand sheets, which were then coated using a standard coating formulation

2 Methods to determine the elastic-plastic properties of paper in the z-direction

2.1 Review of measurement methods

In this chapter only the different measurement routines are briefly reviewed. For some theoretical background regarding the stress-strain behaviour of paper in the z-direction, refer to e.g. [9,10,11,12,13,14,15,16].

According to [7] the measurement methods for the determination of the elastic-plastic properties of paper in the z-direction can be divided in two groups:

A) Flat or compression plate methods
Here the sample to be tested is compressed between two flat surfaces, which range from a few square millimeters to a few square centimeters in area. This type of measurements can again be split into two groups – the global or integrating methods and the local methods.

In the subgroup of the global methods [e.g. 9,12,17,18,19] E-moduli or deformation or compressibility values are calculated which describe the deformation behaviour of the tested area in form of an integrative value for the whole compressed sample area. These types of tests are often performed on material testing machines, modified thickness gauges or a modified PPS-tester.

With the so called local methods [e.g. 4,15,20] data matrices for the pressure distribution or for the topography (often expressed optically as a contact area) under a given compressive force are obtained for the tested sample. Here for each compressibility value also the x.y-coordinates are available. These methods are useful, if a comparison to other localized phenomena like e.g. mottling or gloss variation is to be carried out.

Within both the global and the local methods dynamic and static methods are available, where the dynamic methods also take loading speed and dwell time of the respective compressive force into account.

B) Pointwise or stylus type methods [21,22,23,24,25]

This group includes all methods, where the deformation behaviour of paper in the z-direction is evaluated using various types of styli with a size ranging from a few micrometers to centimeters and also includes the various micro- and nanoindentation methods. The applied compressive forces are – with the exception of [23] – far lower compared to the compression plate methods. When coupled to an x,y-movable stage, local information regarding the deformation behaviour of paper in z-direction can be obtained. The results are either expressed as E-modulus or as deformation values. The so called Universal Surface Tester UST, which is the trade name of the tracing stylus type instrument we used in our investigation, also falls within this group.

None of the methods discussed above is capable of fulfilling all the requirements of an “ideal” measurement method for the deformation behaviour in z-direction which would be:

- Compressive force adjustable in the range as in industrial paper making and converting processes
- Dynamic conditions (loading and dwell time) similar to industrial processes
- Local measurement of a sample area of several square centimetres at a resolution in the micrometer scale
- Reasonable measurement time

2.2 Tracing stylus type instrument (UST Tester)

The UST (Universal Surface Tester) is a commercially available special tracing stylus instrument, which is manufactured by the German company Innowep. The determination of the local deformation behaviour of materials in the z-direction is performed according to the so-called MISTAN®-routine [25], which is schematically shown in *Figure 1*.

By measuring the surface three times along the same measurement line, information regarding the surface structure and the deformation behaviour is obtained:

Step 1: The stylus scans the surface with zero load. The result is the surface topography of the sample (see line ① in *Figure 1*).

Step 2: Along the same line the stylus scans the surface under a defined load (line ②).The delta between line ① and line ② is the total deformation (G) in µm along the line x.

Step 3: A third scan – again with zero load on the stylus - along the same line yields line ③. The delta between line ① and line ③ gives the plastic deformation value (P) in µm, the delta between line ② and line ③ the elastic deformation (E) in µm along the line x.

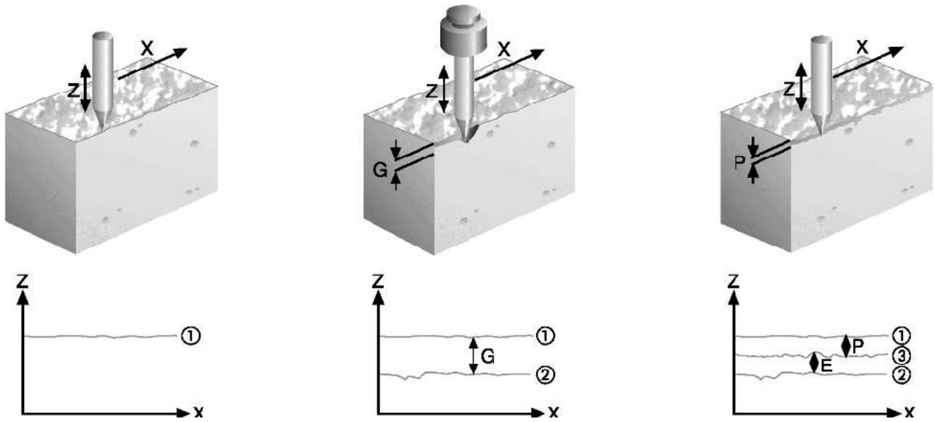


Figure 1: Schematic illustration of the working principle of the UST instrument to determine total (G); elastic (E) and plastic (P) deformation of a sample in z-direction [25]

Since the sample is mounted on an x,-y-stage the local deformation values for an area can be obtained by scanning multiple parallel lines within close distance (see *Figure 2*).

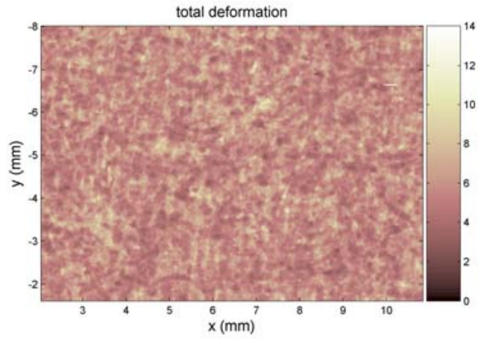


Figure 2: Total deformation map of a calandered 56 g/m² SC-paper.
(x-resolution: 1 µm; y-resolution: 25 µm; 300 µm stylus, 100 mN load,)

The technical specifications of the UST are given in *Table 1*.

Maximum sample area	25 mm x 50 mm
Max. resolution x-direction	1 µm
Max. resolution y-direction	1 µm
Max. resolution z-direction	60 nm

Table 1: Technical specification of UST

The duration of a measurement strongly depends on the selected resolution and sample area. A scan of an area of 10 mm x 10 mm at the highest resolution of 1 µm in both directions takes for instance approximately 20 hours, with the system working fully automatic.

The loads on the stylus can be adjusted between 1 mN and 100 mN and styli with different tip radii are available. Finding the optimal combination of load and stylus geometry is very important. Selecting a stylus with a small tip radius and a high load might lead to destruction of the sample due to scratching. Choosing a stylus with a larger tip radius and a low load again makes it impossible to detect details of the deformation structure. In pretrials a practical stylus-load combination for the determination of the z-directional deformation behaviour of paper was found to be a 300 - 1800 µm radius and 100 mN load at a measuring speed of 1 mm/s [7].

While the ability of the UST to obtain local deformation values for rather large areas is a definitive advantage of the instrument, the rather low compressive loads and the "static" type measurement are to be seen as a drawback.

3 Coating formulation, base paper and calendaring influence on the z-directional deformation behaviour of coated woodfree paper

3.1 Experimental

3.1.1 Experimental - Coating formulation influence (Coating trial series)

In order to evaluate the effect of pigment type, latex-starch ratio in the binder system and coat weight on the z-directional deformation behaviour, coating formulations, which were prepared according to a 2^3 factorial experimental design plan, were applied in a continuous laboratory coater on 100 g/m² woodfree paper reels. In *Table 2* the factors and factor steps are listed.

Factor	*Step 1*	*Centerpoint*	*Step 2*
Coat weight [g/m²]	*10*	*13*	*16*
Pigment Type (Carbonate/Clay) [%]	*0% Carbonate* *100% Clay*	*50% Carbonate* *50% Clay*	*100% Carbonate* *0% Clay*
Binder System (Latex/Starch) [%]	*8% Latex* *6% Starch*	*10% Latex* *3% Starch*	*12% Latex* *0% Starch*

Table 2: Factors and factor steps coating trial
(DoE, central composite 2^3+star design, face centered)

As carbonate HC90 and as clay Capim NP was used. The latex was a conventional S/B-latex with a T_g of18°C, the starch was a dextrin in the medium viscosity range. All coatings contained 0,3% of a technical CMC grade and the viscosity was adjusted with an acrylic thickener to a level of 1000 mPas (Brookfield 100 min^{-1}). Coating solids were adjusted to 63% for the 100% clay, 65% for the clay/carbonate and 67% for the 100% carbonate formulations.

The continuous laboratory reel coater was operated at a speed of 30 m/min and coat weight was adjusted by change of blade pressure and – if necessary - blade thickness. Coating was applied on one side of the paper only. The coated paper reels were cut into A4 size sheets and calendered on a laboratory calender (10 passes, 1st pass on steel, 1000 daN, 90°C).

On the uncalendered and calendered papers the total, elastic and plastic deformation in z-direction was measured on the coated side with the UST instrument described under 2.2. Only line measurements were performed (10 line measurements per sheet on 5 sheets per trial, line length 15 mm, 1µm resolution in line direction). For each measurement line the mean value for total, elastic and plastic deformation was calculated and used as an observation in the subsequent statistical analysis (resulting in 50 observations per trial point).

Besides the elastic-plastic properties PPS-roughness and gloss (Tappi 75°) were also measured.

3.1.2 Experimental - Base paper composition influence (Base paper trial)

The target of this a second series of trials was to evaluate the influence of base paper composition on the elastic-plastic properties of the base paper and of the coated and calendered paper. Therefore 44 sets of 70 g/m² laboratory handsheets with a wide range of elastic properties were prepared according to a 2^5 experimental design with varied CTMP content, filler content, hardwood pulp content and type and softwood pulp type. The factors and factor steps are listed in *Table 3* [8].

Factor	*Step 1*	*Centerpoint*	*Step 2*
CTMP content [% of fiber]	0	15	30
Filler content [%]	*5*	*12,5*	*20*
Hardwood content [% of fiber]	20	40	60
Hardwood pulp type (beaten to 25 SR)	*Bleached Eucalypt Kraft*	*Mixture Eucalypt/Birch*	*Bleached Birch Kraft*
Softwood pulp type (beaten to 20 SR)	*Bleached Sulfite*	*Mixture Sulfite / Kraft*	*Bleached Kraft*

Table 3: Factors and steps base paper trial
(DoE, central composite 2^5+star design, face centered)

All handsheets were prepared on a Rapid-Köthen type handsheet former. Softwood content was adjusted depending on hardwood and CTMP content. As a retention aid 0,03% (wet on dry total fiber amount) of a conventional PAA was added. As tolerance for the acceptance of a handsheet ±1,5 g/m² deviation for basis weight and ±1,5% deviation for filler content were defined.
On the handsheets the total, elastic and plastic deformation in z-direction was again measured with the UST instrument as described under section 3.1.1.

To coat the handsheets under constant coating conditions, the sheets were cut in half and glued to a continuous paper web using a thin packing tape (see *Figure 3*). Coating was again performed on a continuous laboratory reel coater at a constant speed of 30 m/min and a constant blade pressure of 1,2 bar. As coating color the topcoat formulation for a silk paper grade from an industrial producer of woodfree coated papers was used (solid content 68%, viscosity 900 mPas (Brookfield 100 min^{-1}). Again only one side of the handsheets was coated. The achieved coat weights ranged from16 to 21 g/m².

The coated handsheets were then calandered (6 passes, 1st pass against steel, 1000 daN, 90°C). The uncalandered and calendered samples were again measured with the UST instrument as described in section 3.1.1., but this time only 3 sheets per trial point where measured, which resulted in 30 observations for each trial point.

Figure 3: Coating of laboratory handsheets

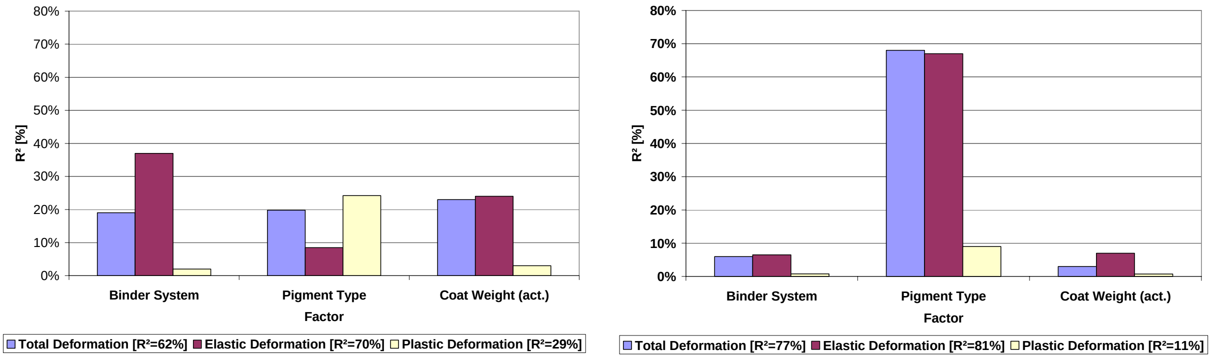
3.2 Results and Discussion

For all evaluations presented in this chapter (ANOVA, effect plots, correlations) the free statistical software package “R” was used [26].

3.2.1 Results - Coating formulation influence (Coating trial series)

Figure 4 shows the proportion of total variability – expressed as R^2 - which is explained by the factors for the total, elastic and plastic deformation values for the coated uncalendered samples on the left and for the coated calendered samples on the right.

Before calendaring the binder system, coat weight and pigment type (in this order) influence the total and elastic deformation, while after calendaring the pigment type clearly dominates with the R^2 of these models being in the range of 62% to 81%. While the effect of the binder system and of coat weight on the total and - especially for latex – the elastic deformation is quite pronounced in the uncalendered papers, this effect is hardly noticeable after calendaring. This observation is an indication for the dominating influence of the pigment type regarding coating structure after calendering.
The models for the plastic deformation behaviour all show rather low R^2 values between 11% and 29% - the later for the uncalendered papers – with the pigment type being the main effect.

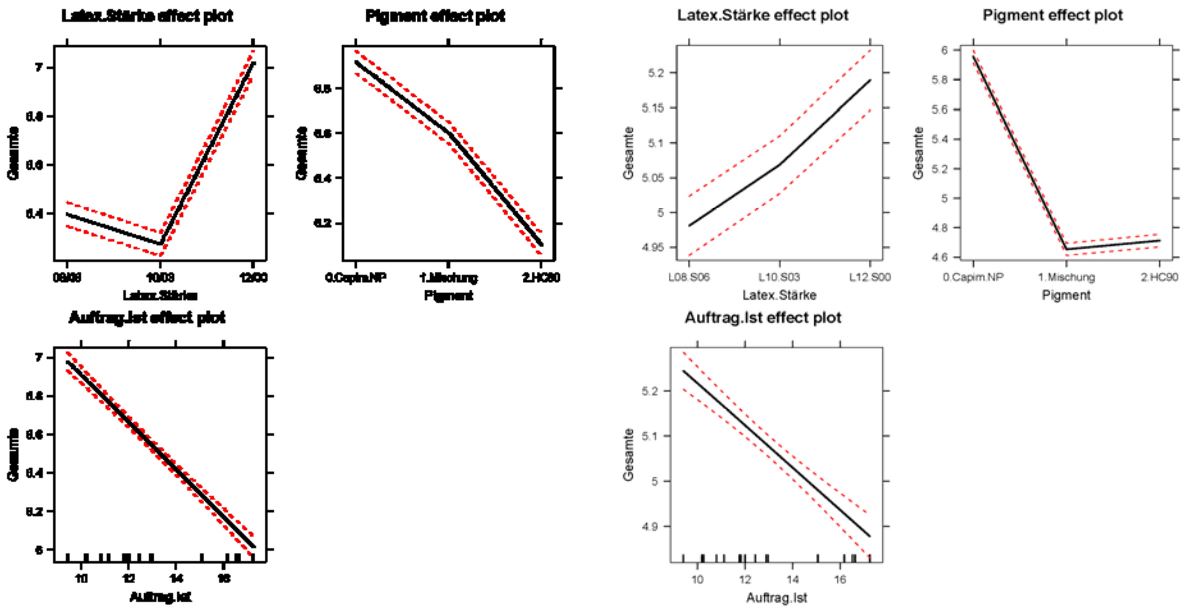


a) coated uncalendered samples

b) coated calendered samples

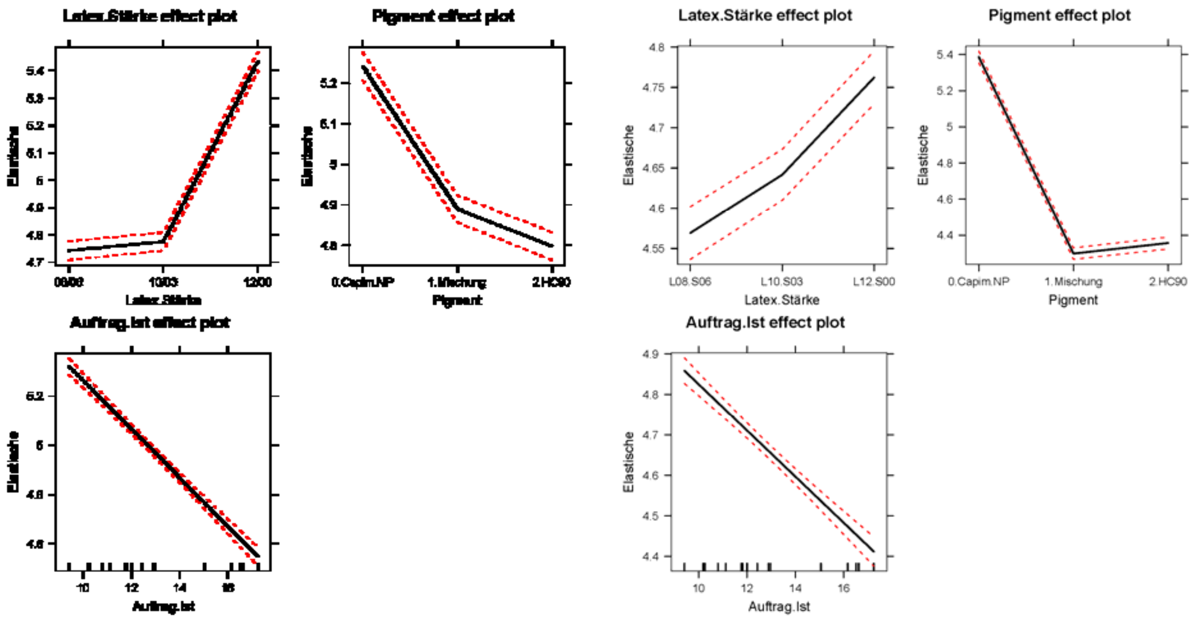
Figure 4: Proportion of total variance explained [as R^2 in %] by factors - coating trial

The effect plots for the three deformation values in *Figures 5 – 7* allow an interpretation regarding strength, direction and significance of the factors. The smaller the confidence intervals - depicted as dashed lines – the more significant is the effect of the factor.



a) coated uncalendered samples b) coated calendered samples

Figure 5: Effect plots for total deformation [y-axis in µm]



a) coated uncalendered samples b) coated calendered samples

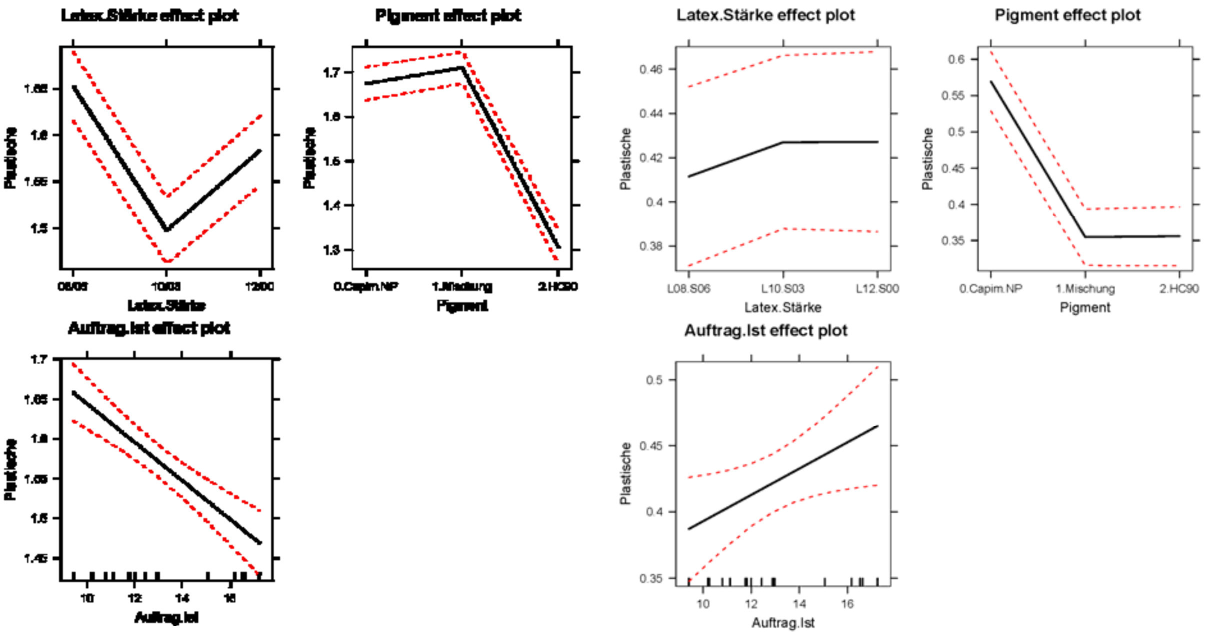
Figure 6: Effect plots for elastic deformation [y-axis in µm]

Regarding the total and elastic deformation the direction of the effect of the factors is quite clear.

A reduction of the starch amount in the binder system ("Latex.Stärke effect plot") leads to an increase in total and elastic deformation, with this effect being stronger and more significant in the uncalendered samples. The comparatively low strength and significance of the effect of the binder system in the calandered papers might also be due to the calendering temperature being above the T_g of the latex. The polymer therefore will undergo permanent deformation (viscous transformation) and therefore have a lower and less significant effect on the deformation behaviour after calendering.

The “Pigment effect plot” shows higher total, elastic and – with lower significance – plastic deformation values for the coatings containing clay, which also has been reported previously [23]. With the calendered samples only the coatings with 100% clay resulted in a higher elastic and plastic compressibility, the 50/50 mixtures clay/carbonate were on the same level as the 100 % carbonate coatings. Also the effect of pigment type is stronger and more significant in the calendered papers. An increase in coat weight (“Auftrag.Ist effect plot”) leads to an expected reduction in total and elastic deformation.

The effect plots for the plastic deformation (*Figure 7*) generally showed lower significance and also an incongruent direction of the effect of the factors.



a) coated uncalendered samples

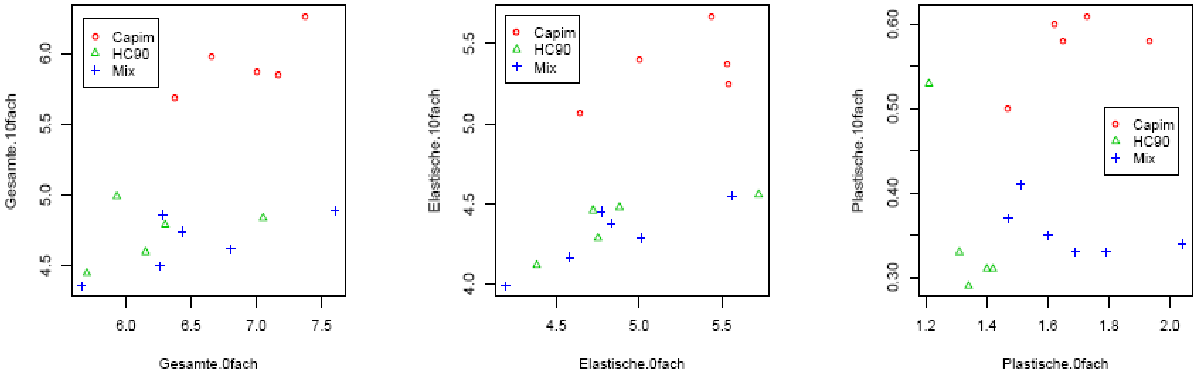
b) coated calandered samples

Figure 7: Effect plots for plastic deformation [y-axis in µm]

In *Figure 8* the deformation values before and after calendering (mean values of all 50 observations) are directly compared in form of a scatterplot, with the values of the uncalendered samples on the x-axis.

The different pigment types are identifiable via the different point markers. The papers coated with 100% clay (Capim) are clearly separated from papers coated with the 50/50 mix and with 100% carbonate (HC90). The deformation values of 100% clay coatings are not as much reduced by calendering as the other pigment types, which also is the reason for the dominating effect of the pigment type in the evaluation of the calendered samples. Whether this might have been caused to some extent by a lack of alignment of the clay particles in the coating layer due to the low coating speeds of the laboratory coater, will have to be investigated in the future.

Although the overall regression coefficient for all data points is rather low, there still is a slight trend for the total and elastic deformation values within the pigment type classes that more compressible papers before calendering also tend to be more compressible after the calendering treatment.



a) Total deformation [um] b) Elastic deformation [µm] c) Plastic deformation[µm]

Figure 8: Deformation behaviour of coated uncalendered and coated calendered samples

Legend:	Gesamte 0fach	Total deformation uncalendered
	Gesamte 10fach	Total deformation calendered (10 passes)
	Elastische 0fach	Elastic deformation uncalendered
	Elastische 10fach	Elastic deformation calendered (10 passes)
	Plastische 0fach	Plastic deformation uncalendered
	Plastische 0fach	Plastic deformation calendered (10 passes)

Looking at the absolute values of the deformation parameters it can be noticed, that in general the deformation values are – as expected - lower after calendering, with this decrease being relatively most pronounced in the plastic deformation values and barely noticeable in elastic deformation.
The fact, that the absolute plastic deformation values are low when compared to the elastic deformation values also is an indication for the already mentioned “drawbacks” of most of the stylus type instruments – the relatively low compressive force exerted on the paper surface, which is not sufficient to deform the paper permanently to a large degree. This is in line with results from calendering studies [27], where it was also found that paper shows almost purely elastic deformation behaviour at low nip pressures with permanent deformation increasing at higher nip loads

The evaluation of the influence of the factors on gloss (Tappi 75°) and PPS-roughness showed the expected results. PPS-roughness (R^2 of model 75%) was mainly influenced by pigment type (higher with clay containing coating) and coatweight, the binder system did not show any influence. Gloss (R^2 of model 79%) was influenced by all three factors to the same extent, with the highest gloss values for the clay containing, starch-free coatings and high coatweights.

3.2.2 Results - Base paper composition influence (Base paper trial)

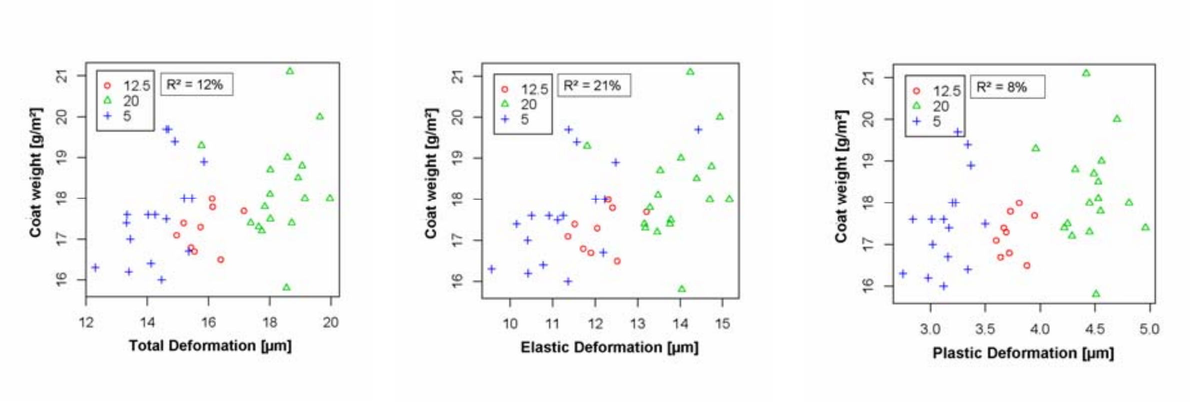
Table 4 summarizes the effect of changes in the factors on the deformation behaviour of the base paper (handsheets) before coating.

Deformation behaviour of the handsheets is clearly dominated by the filler content, with higher filler content leading to an increase in deformation. A rise in the CTMP content results in higher total and elastic deformation, the effect on permanent deformation is statistically not significant. Changes in the other factors had in general only a weak, but statistically still significant effect on the deformation values.

	Total Deformation	Elastic Deformation	Plastic Deformation
CTMP-Content ↗	+(+)	+(+)	0
Filler Content ↗	+++	+++	+++
Hardwood Content ↗	-	-	-
Hardwood type **Eucalypt → Birch**	-	-	0
Softwood type Sulfite → Kraft	-	-	-

Table 4: Effect of changes in the factors on deformation behaviour of the base paper. The algebraic signs denote the direction of the change in the deformation value if the factor is increased (changed). The number of signs denote the strength of the influence of the factor. The zero denotes that the effect of the factor is statistically not significant.

In order to evaluate the effect of base paper compressibility on applied coat weight under the chosen constant coating conditions, coat weight values are plotted against base paper in *Figure 9*. Despite rather low regression coefficients – which partly are due to “outliers” - a trend is visible, that higher coat weights were achieved on more deformable papers. This trend is more clearly noticeable for the elastic and total deformation values and can be attributed to the reaction of the base paper to the compressive forces under the blade, which already seem to have some effect even at the low coating speed of the laboratory coater (30 m/min).

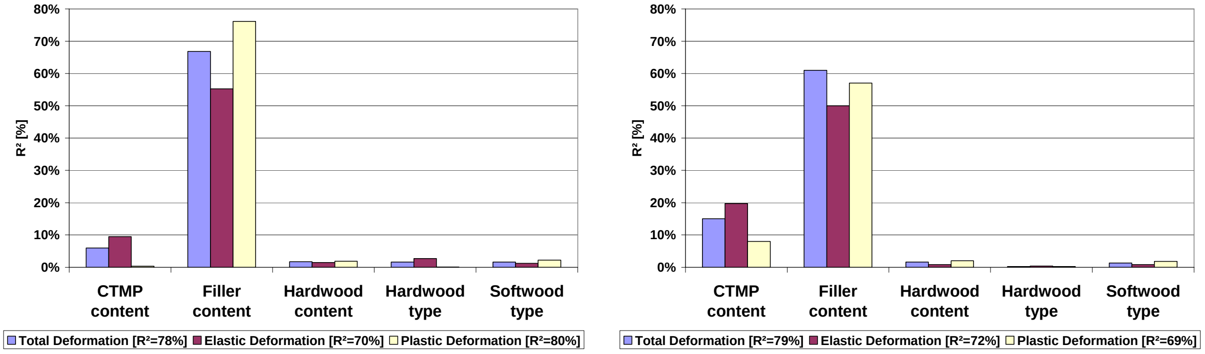


a) Total Deformation b) Elastic Deformation c) Plastic Deformation

Figure 9: Applied coat weight vs. deformation behaviour of the base paper. Point markers are coded according to base sheet filler content.

Figure 10 shows the proportion of total variability – expressed as R² - which is explained by the changes in the factors for the total, elastic and plastic deformation values for the uncoated handsheets on the left (*Figure 9 a*) and for the handsheets after coating application on the right (*Figure 9 b*). The cumulated R² values shwo that in all trials 69 – 80% of the variability in the data is explained by the changes in the factors.

While the absolute deformation values were dramatically reduced by coating, the effect of the changes in the base paper on the deformation values still remained dominant after coating. The R² values of the models before and after coating application are quite comparable, despite the fact that the applied coat weights varied from 16 to 21 g/m². As in the base paper an increase in filler content and – not as pronounced - in CTMP content results in an increase in the deformation behaviour of the coated paper. The effect of the other factors is again rather weak, as can be seen by the low proportion of explained variance for those factors.



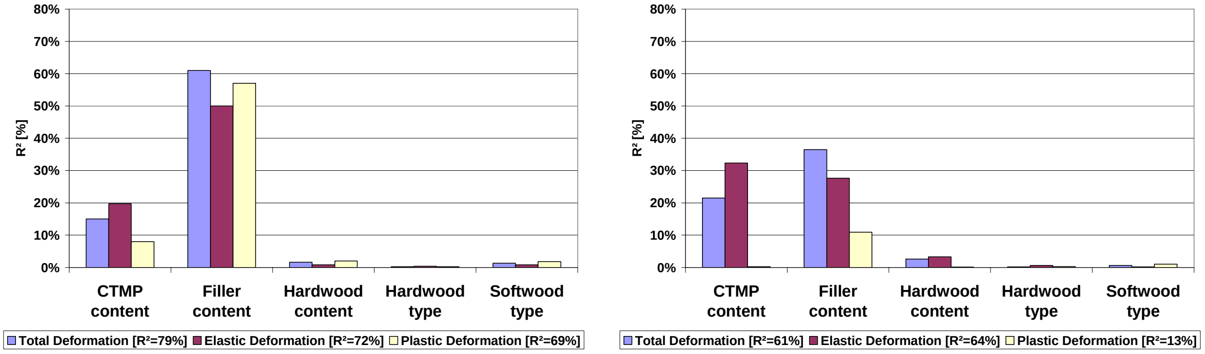
a) Handsheets (base paper) b) Handsheets after coating

Figure 10: Proportion of total variance explained [as R² in %] by factors – base paper trial

In *Figure 11a)* the proportion of total variability explained by the changes in the factors for the deformation values for coated handsheets – already shown in *Figure 10 b*) - is now compared to that for coated handsheets after calendering (*Figure 11b*). Compared to the models for the handsheets before calendering the R² values after calendering are lower, but R² values of 61 – 64% denote that still a significant share of variability in the total and elastic deformation values of the calendered handsheets can be accounted for by the changes in the base paper. The effect of the filler content is less pronounced, whereas the effect of the CTMP content on elastic and plastic deformation increases. A slight influence of the hardwood content is also noticeable.

We see this as an indication that due to the high compressive forces during calendering the filler particles are “pressed” into the fiber network structure and the reaction of the fiber network itself becomes more important after calendering, with the influence of the rather stiff CTMP fibers becoming more pronounced.

The direction of the change in elastic and total deformation of the calendered samples is again the same as for the uncoated handsheets or the coated handsheets before calendering.



a) Handsheets after coating b) Handsheets after coating + calendering

Figure 11: Proportion of total variance explained [as R² in %] by factors – base paper trial

Plastic deformation of the coated sheets after calendering can only be explained by the factors to a rather low degree ($R^2 = 13\%$), which – as already observed in the coating trials – points to the over proportionally high influence of calendering on plastic deformation. This decisive influence also becomes obvious when comparing the reduction of the deformation values by the various processes (coating / calendering / coating+calendering). While coating reduces the total and elastic deformation values by ~50% and the plastic deformation by 35%, calendering reduces total and elastic deformation by 41 and 23% respectively, but plastic deformation by 81% (*Figure 12*).

The high effect of coating on elastic and total deformation compared to calendering, which we already noticed in the coating trials, might also be attributed to the measurement method. We believe, that the compressive force applied by the stylus type instrument we use is not sufficient to compress the paper equally across the whole z-direction and therefore the effect of the paper layers closer to the stylus (in this case the coating) on the measurement is over proportionally high compared to the paper layers further away (i.e. the base paper). Therefore the effect of calendering on the measured deformation values, which is known to mainly compress the base paper and not as much the coating layer, is less pronounced.

As in the coating trial presented under 3.2.1. the plastic deformation values were again distinctly lower compared to the elastic deformation values for all measurements, which underlines that the compressive force applied by the UST device was not sufficient to deform the paper permanently.

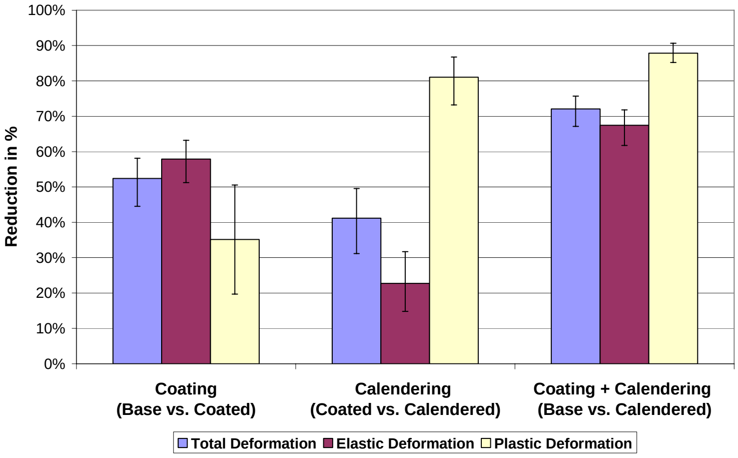


Figure 12: Reduction [%] of the deformation values by the various processes. Reduction was calculated separately for each trial point and mean value is given in graph. Error bars denote minimum and maximum values of reduction (range).

The elastic deformation values for the handsheets (base paper), handsheets after coating and the handsheets after coating + calendering are shown in form of a scatterplot matrix in *Figure 13*, with the point markers identifying the filler contents of the base paper. Some degree of clustering depending on the filler level is noticeable in the uncoated samples, which is less pronounced after coating and calendering.

There is a clear correlation of the elastic deformation values of the coated uncalendered and coated calendered handsheets to the elastic deformation values of the uncoated base paper, indicating the importance of the influence of base paper composition on the deformation behavior of coated papers in the z-direction. Total and plastic deformation showed a similar trend, with the R^2 values being slightly lower for plastic deformation.

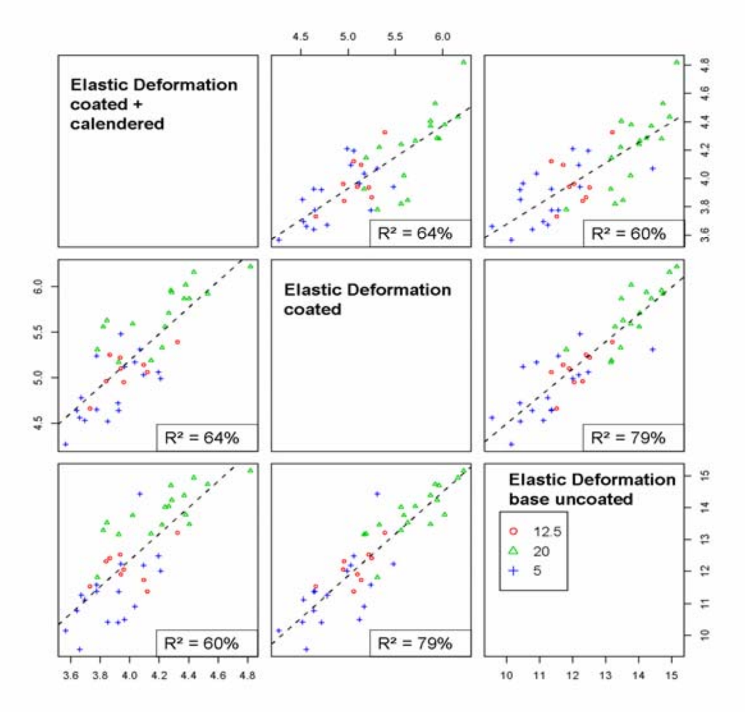


Figure 13: Scatterplot matrix of elastic deformation values [µm]

4 Conclusions

The results of the performed base paper and coating trials showed that both changes in the coating formulation as well as in base paper composition can be used to adjust the deformation behaviour of woodfree coated papers. The effect of base paper on compressibility remains highly significant even after calendering.
The observation that calendering changes the strength and significance of the effect of certain factors (e.g. binder system, CTMP content) on the deformation values underlines, that different approaches for silk or gloss papers are necessary.
While coating application primarily reduces elastic and total deformation, calendering primarily affects the plastic deformation behaviour.
The results obtained with a novel tracing stylus type instrument (UST) are plausible and the instrument therefore proved to be a useful tool for the evaluation of the deformation behaviour of uncoated and coated papers. One has to observe however, that the applied loads are not sufficient to compress the paper permanently and that the effect of the paper layers close to the stylus on the results appears to be over proportional. The capability of the instrument to provide local deformation values was not used in this study and will be in the focus of further research.

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