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Long and short term measurements of printed uncoated fine paper using a high speed inkjet testing setup

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Ein Gelehrter in seinem Laboratorium ist nicht nur ein Techniker; er steht auch vor den Naturgesetzen wie ein Kind vor der Märchenwelt.

Marie Curie

To my parents, my grandmothers and Gertrude Schweinzer

Acknowledgments

Without the support of my family and my friends, I would have never reached this level. Therefore, at the beginning I am expressing gratefulness to them.

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Abstract

Within this thesis, the curl behaviour of uncoated wood free fine paper by using a high speed inkjet testing system was investigated. The high-speed inkjet testing device uses print on demand systems and industrial print heads. The printing and the investigation of the curl- behaviour was done with papersheets and full tone printing using different ink amounts and different ink types (latex- pigment- ink and dye- ink). The papers investigated were four industrial produced model papers produced at fourdrinier paper machines; a natural fine paper with no internal sizing, a pigmented paper which has a surface coating with anorganic pigments at the size press, a calendered unsized paper which is smoothed at the surface by thermal compression and a AKD mass- sized fine paper. The evaluation of the curl after the print was done with a laser surface analysis. The result of the measurement was evaluated with a MatLab routine using quadratic curl equations to fit the three curl types (MD, CD and diagonal curl) which results in curl height as a function of this 3 curl types. These investigations were done on short- and long- term curl.

The results show that the short- term- curl is a structural curl, caused by the paper properties such as fiber orientation anisotropy, fillers- and fines two sidedness and similar paper properties. The curl direction of the printed sheet depends on the paper side and not on the printing side. The short term curl flips side when the printing side is changed. This short- term- curl of paper can be minimized by reducing the swelling/ shrinkage of the paper sheet. As a consequence the short- term curl of all model paper has the best behaviour if latex- pigment- ink with primer is printed and the worst behaviour if dye ink is printed. Regarding the paper grades, the best behaviour was observed with the AKD sized paper and the worst with the unsized paper.

The long- term curl is not dependent on the paper side, but on the printing side. Its height and behaviour depends on the paper used, as well as the time it needs to develop. Long- term curl needs initial wetting followed by reconditioning at a relative humidity at ~50% to develop. Just drying with a hot plate from one side triggers a short- term- curl, but does not lead to a long- term- curl. Storage at 0% RH freezes the short- term curl. The reconditioning at 50% RH releases the long- term curl, which in case of printed papers (pigment- and dye ink) is always positive. Just primer printing or printing with free air-drying without conductive drying on a hot plate leads to a negative long- term- curl. It is unclear why the long- term- curl is negative for free- air- drying and for printing with only primer and the mechanism are not fully understood.

Kurzfassung

Um das Curl- Verhalten von holzfreien Papieren im Highspeed- Inkjetdruck zu untersuchen wurden vier industriell hergestellte Papiere mittels eines High- Speed- Inkjet Testdruckers vollflächig bedruckt. Es wurden sowohl Farbstofftinten als auch Pigmenttinten verwendet, um den Einfluss dieser auf den Curl feststellen zu können. Der Druck erfolgte vollflächig mit unterschiedlichen Variationen der Flächendeckung. Im Anschluss an den Druck wurden die Proben auf einer heißen Platte konduktiv von der Gegenseite getrocknet. Die verwendeten Papiere sind Langsiebmaschinen- Papiere, die aus der Mittelbahn der Papiermaschine entnommen wurde. Es handelt sich um ein holzfreies Naturpapier ohne Massenleimung, aber mit Oberflächenleimung, ein pigmentiertes ungeleimtes Papier, dem in der Leimpresse ~ 4,5 g/m^2 Pigment aufgetragen wurden, ein ungeleimtes kalandriertes Papier und ein AKD massegeleimtes Papier. Nach dem Druck wurde mittels eines Laser-Sensors die Oberfläche des gedruckten Substrates vermessen und unter zu Hilfenahme eines MatLab Programmes ein 3- Dimensionaler Fit hinsichtlich der Curl Parameter in Maschinenrichtung, Querrichtung und Diagonalrichtung durchgeführt. Das Ergebnis dieser Analyse ist eine Aufschlüsselung der Curl- Höhen auf die drei Curl- Parameter.

Die Beobachtung des Kurzzeit- Curls hat ergeben, dass dieser auf Papiereigenschaften wie Faserorientierungsanisotropie-, Füllstoff- und Feinstoff- zweiseitigkeit oder ähnliches zurückgeführt werden kann. Dieser strukturelle Curl ist abhängig von der Papierseite, die bedruckt wird und ändert seine Richtung, wenn die anderes Seite bedruckt wird. Das Trocknen ohne vorher erfolgter Befeuchtung des Papiers führt, wenn man nur den Kurzzeit- Curl betrachtet, zum selben Effekt wie das Bedrucken des Papiers. Die Reihenfolge der Papiere hinsichtlich ihrer Curl Eigenschaften ergibt, dass das AKD geleimte Papier die besten Eigenschaften (schlechtester Curl) und das ungeleimte Papier die schlechtesten Eigenschaften besitzt.

Ein Langzeit- Curl wurde ebenfalls gemessen und untersucht. Dieser ist NICHT von der Papierseite, sondern von der Befeuchtungs- oder Druckseite abhängig. Wenn mit Tinte bedruckt wird, gleich ob Farbstofftinte oder Pigmenttinte, entwickelt sich dieser Langzeit- Curl immer zur bedruckten Seite. Die Lagerung von bedruckten Proben unter Ausschluss der Luftfeuchtigkeit konserviert den Kurzzeit- Curl. Wird die Probe der Luftfeuchtigkeit wieder ausgesetzt, entwickelt sich der Langezeit- Curl. Das Bedrucken von Papierproben mit anschließender Lufttrocknung (ohne konduktiver Trockung auf einer heißen Platte) und das Drucken von ausschließlich Primer (mit konduktiver Trockung auf der Platte) ergibt einen negativen Langzeit- Curl. Die Mechanismen, die zu dieser Entwicklung des Langzeit- Curl führen sind nicht völlig klar.

Contents

1 Introduction

This thesis was generated within the Christian Doppler Laboratory for Fiber Swelling and Paper Performance, which is a cooperative project of several industrial partners and the KTH Stockholm, the Montanuniversität Leoben and the Graz University of Technology.

The thesis deals with the measurement of curl properties of uncoated wood free fine paper in high-speed inkjet printing, which is the most rapid growing printing technology. One of its advantages over conventional printing technologies like offset or rotogravure printing is that it is a digital printing process. This means, there is no printing plate, cylinder, or rubber blanket, which must be changed in order to change the printed image. Also, there is no direct contact to the substrate which can damage it or lead to printing failures. The printer does not have to stop in order to change the print job. Furthermore the minimum number of printed samples can be as low as one and can be scaled up to several thousands. Inkjet printing for really high volumes is currently still more expensive than conventional print technologies like heatset web-offset or rotogravure.

The major part consists of a practical and experimental investigation on the curl behaviour of uncoated fine paper in high-speed inkjet printing.
The practical work of the thesis was done at Océ Printing Systems Poing, Germany and the analysis of the experiments was performed at the Institute of Paper, Pulp and Fiber Technology at TU Graz. The task was to develop a method to characterize qualitatively and quantitatively the curl behaviour by using the Ink-Paper-Testing-System (IPTS) and a Laser-Sensor. The IPTS is a laboratory high-speed inkjet printer for cut sheets located at Océ Printing Systems, Poing.
It uses industrial high-speed printing heads for high-speed roll printing. Both ink systems (dye and pigment inks) can be used. The analyses of the printed and curled samples were done with a mathematical curl fit developed in MATLAB based on existing curl-equations developed by Tetsu Uesaka, Pulp and Paper Research Institute of Canada.[1]

2 Fundamentals on curl and printing

2.1 Two-sidedness of paper related to industrial production

The relevant effects during the sheet forming process can be divided into three major hydrodynamic process. These three parts are drainage, oriented shear and turbulence. Drainage is needed to remove the water and forms a flow pattern perpendicular to the direction of the porous media and the forming fabric. Oriented shear is induced through a velocity gradient during forming by the jet to wire ratio or wire shaking. In sheet forming turbulences are defined as a randomized fluctuation of flow velocity[2]. **Figure 1** shows this**.** Illustration of the three hydrodynamic processes during sheet forming .

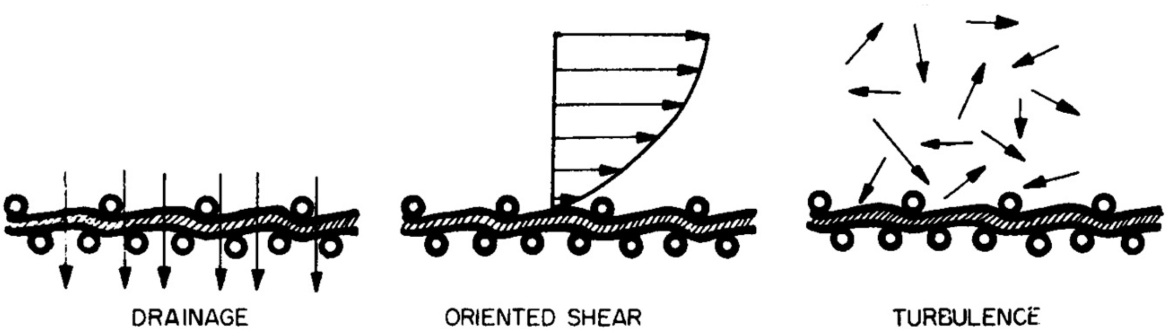

Figure 1. *Illustration of the three hydrodynamic processes during sheet forming [2]*

Sheet forming at industrial level starts with the deposition of an aqueous suspension of pulp fibres (at approx.. 1 wt%) on the forming fabric at the head box. There are three possible conditions regarding the jet-to-wire ratio. The jet is faster than the wire speed (= rush), the jet has the same speed as the wire or the wire has a higher speed (= drag).

If there is a speed difference like drag or rush, the oriented shear effect in the z-direction, which is the drainage direction, increases. As a consequence the fibers are aligned along this oriented shear, which causes the fiber orientation in industrially produced papers. The degree of anisotropy of fiber orientation (or fiber orientation index) is the result of the level of drag and rush and even changes of jet to wire speed ratio between 0,96 and 1,02 already have a huge influence on the degree of fiber orientation anisotropy. In case of undesired cross-flows (perpendicular to the paper machine direction), which are caused by uneven flow conditions over the width of the paper machine, a velocity gradient in the paper machine cross direction (CD) leads to a deviation of the main fiber direction from the machine direction. The angle of this deviation of the main fiber direction from the machine direction is called the fiber orientation angle. In general fiber orientation can just be manipulated as long as the fibers on the papermachine wire are still in an aqueous suspension at low constistency and thus freely movable. [2], [3]

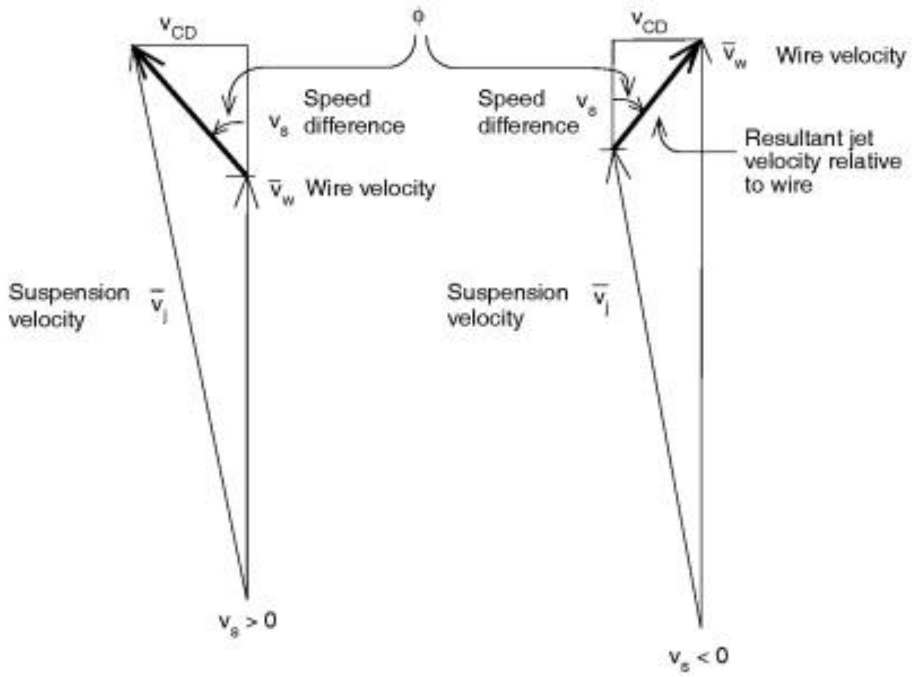

***Figure 2.** The direction of suspension flow relative to wire determines fiber orientation angle[3]*

Figure 2 shows the resulting jet velocity relative to the wire speed for drag and rush and the difference caused by drag or rush. With a jet to wire ratio below 1, the resulting orientation angle Φ is mathematically negative, with a value above 1 Φ it is mathematically positive.

Figure 3 illustrates the two stages of fiber mat formation on a paper machine wire. At typical consistencies for industrial sheet forming (approx. 0,5 to 1 wt%) in a first phase (filtration regime) a fiber mat is formed close to the wire while the suspension above this fiber mat still has a lower consistency and the fibres are freely movable and thus fiber orientation and formation can still be influenced. In the second phase of sheet formation (thickening regime) most of the water has been removed and the fibres form a continuous network and are not able to move freely anymore. Further drainage during sheet formation only happens by taking water from the interstices in the fiber network, which is called thickening. On a Foudrinier paper machine this transition from filtration to thickening can be observed by the water line. There are several effects regarding the two-sidedness of paper caused by this dewatering of the fiber mat depending on the sheet forming method. While a laboratory sheet has a fines and filler distribution which has the highest content at the wire side, an industrial formed sheet has the highest filler and fines content at the top side due to hydrodynamic forces applied though forming foils.[4]

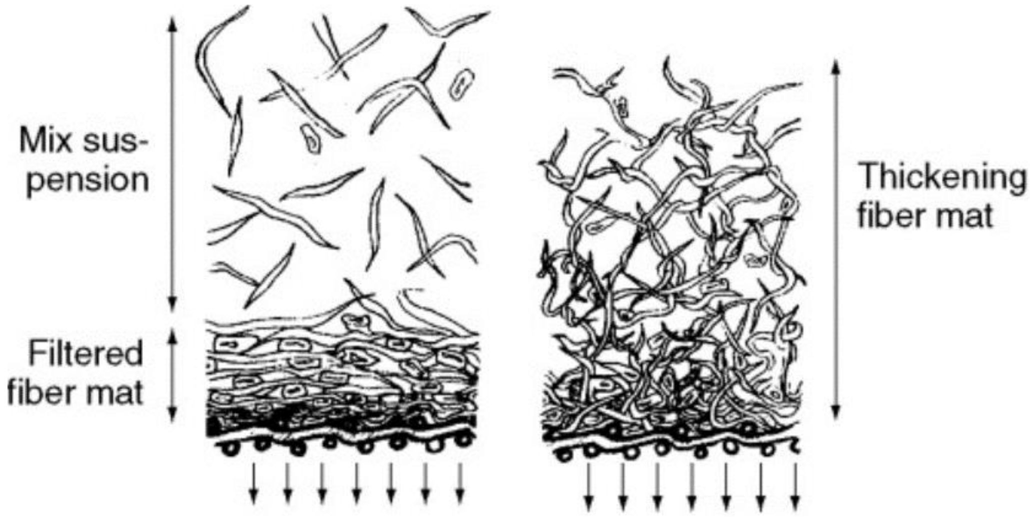

Figure 3. *Fiber mat generation and thickening effects in sheet forming.[3, Fig. 30]*

Degree of fiber orientation and fiber orientation angle are usually expressed with a polar diagram. **Figure 4** shows the principle of this diagram. A completely isotropic paper (as e.g. laboratory handsheets) without any preferred fiber orientation would end up as a circle in this diagram. Fiber orientation of real industrial papers always show an ellipse in the diagram, where "a" is defined as the principal axis and is an indicator for the number of fibers in the main fiber direction and "b" as the conjugate axis which indicates the number of fibers in the direction perpendicular to the main fiber direction. The fiber orientation angle α is defined as deviation of the main axis from the machine direction[4], [5]. Ideally this fiber orientation angle α should be 0.

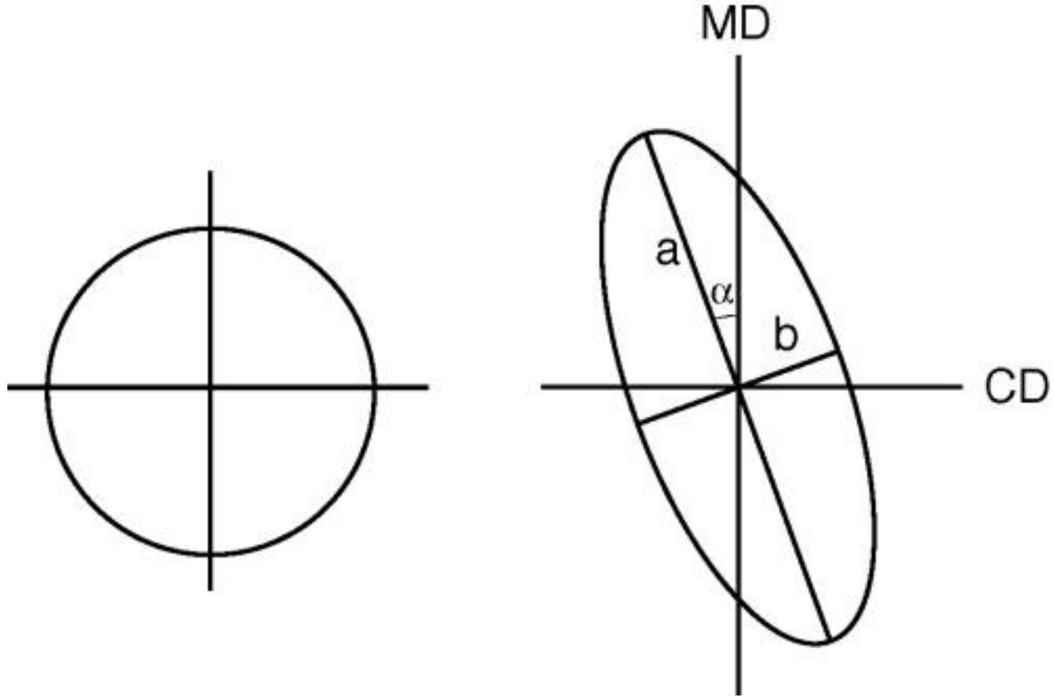

***Figure 4**. Definition of a fiber orientation angle [3, Fig. 19]*

As already mentioned the fiber orientation index, which is often defined as the elastic modulus ratio $^{E_{MD}}/_{E_{CD}}$ is not only a two dimensional problem. Due to differences in the velocity gradients in z-direction depending on former type or to hydrodynamic forces of foils and forming rolls and the resulting effects of the drainage velocity, the fiber orientation index is not constant in z- direction. Gapformer machines show the best results regarding two-sidedness due to their fast and homogeneous dewatering on both sides, while Fourdrinier paper machines can create a strong two-sidedness.[5] **Figure 5** shows this effect for the different former types.

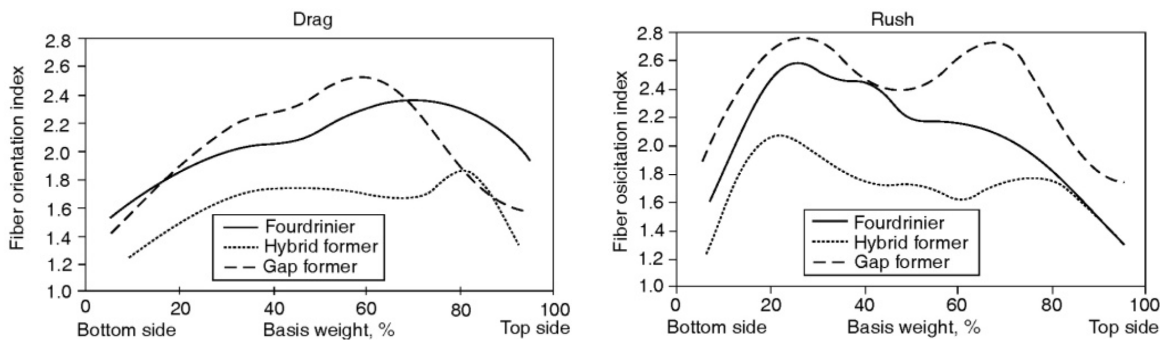

***Figure 5**. Variation of fiber orientation index through sheet thickness on three pilotformers for small jet-to-wire speed difference for drag and rush.[5, Ch. 1]*

As all the used model papers within this thesis were produced on Fourdrinier paper machines, the fiber orientation index of them is not constant in z-direction. A two sidedness of these papers regarding filler and fines content and regarding the fiber orientation has to be expected. **Figure 6** shows the possible effect of fiber orientation differences between top and bottom side on curl. The curled samples at the right side indicate the curl when dried for a machine direction (MD) and a cross direction (CD) strip.

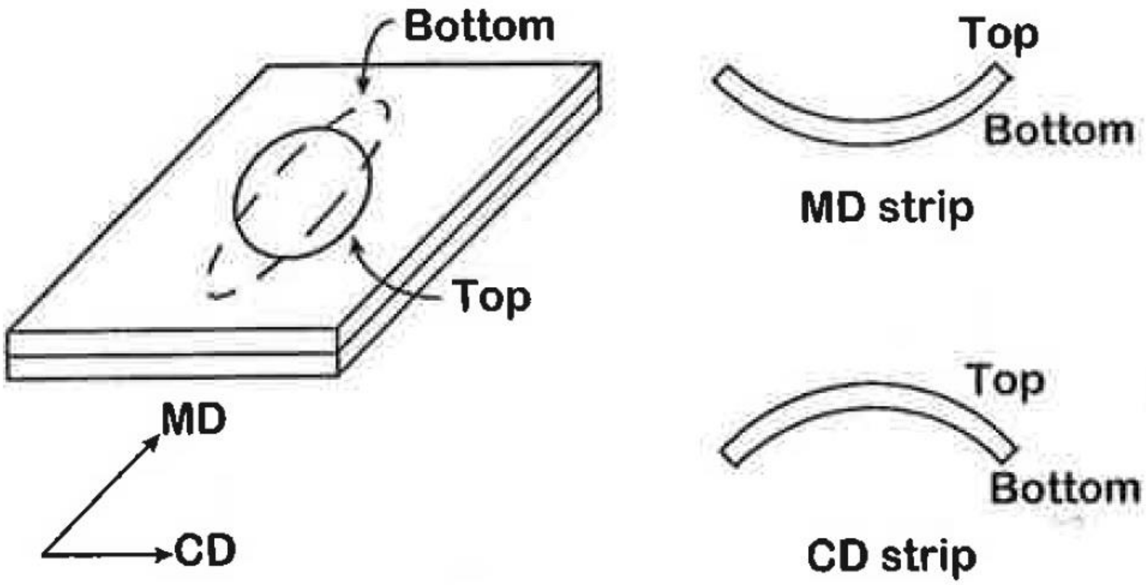

Figure 6. *Sketch of a curl caused by twosidedness of fiber orentation of an fourdrinier machine. The dashed ellipse at the bottom side indicates a more oriented sheet in machine direction. The top side does not have this strong fiber orientation.[1]*

2.2 Mechanism of curl

Hygroexpansion of a cellulose fiber is not the same in the main dimension of the fiber and the fiber does not swell equally. It swells into its longitudinal direction only 2 to 4 %, while it swells in width direction between 10 to 30 %[5]. Due to the fiber orientation of an industrially produced paper and th swelling behaviour of fibers some kind of curl must always happen, if the paper is wetted or driedfrom one side [1]. **Figure 7**shows the different types of curl.

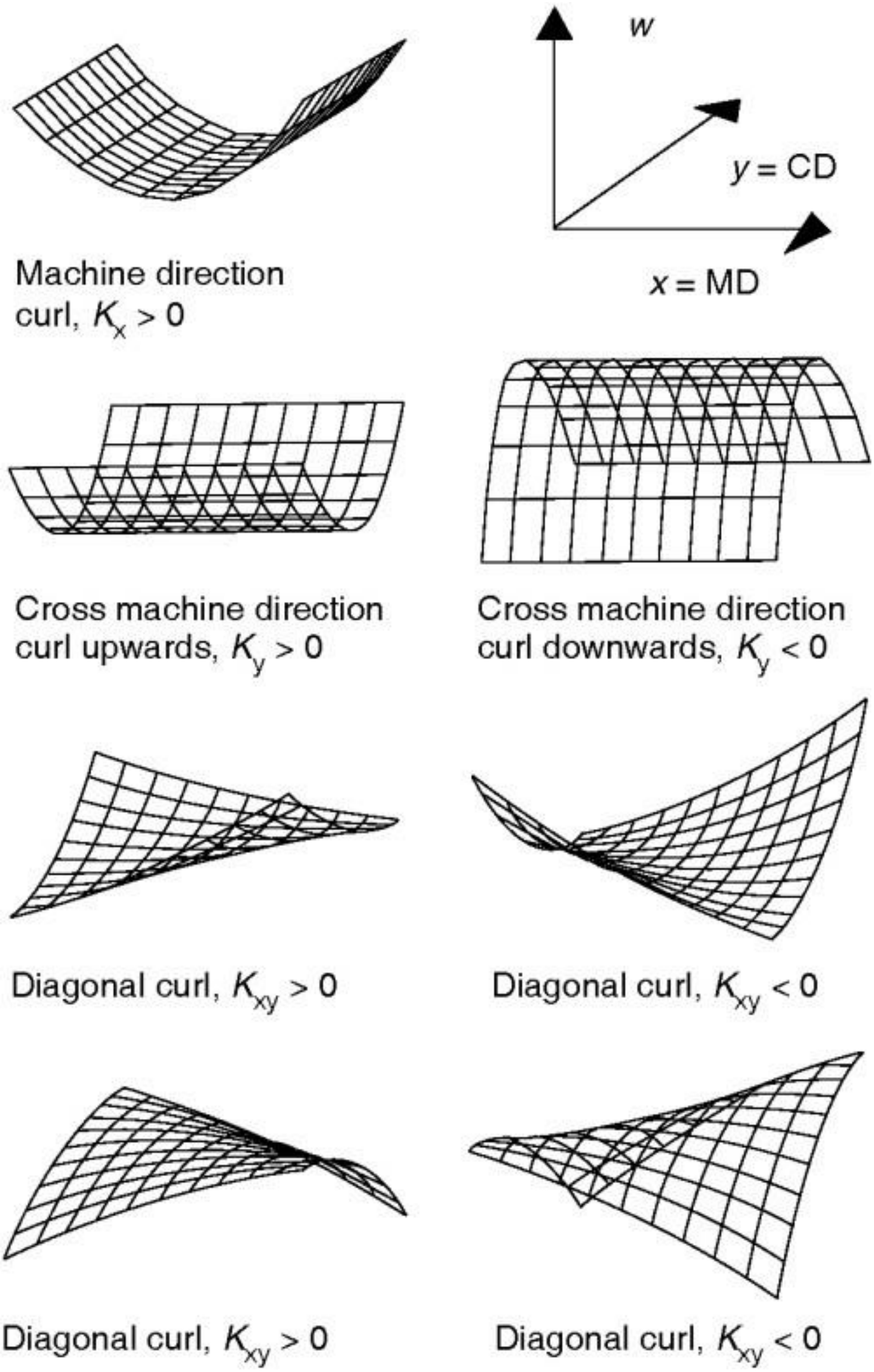

Figure 7*. Types of curl.[5, p. 330]*

There are three curl types:

- machine direction curl
- cross direction curl
- diagonal curl

These three curl types can also be described in a mathematical equation:

***Equation 1**. Mathematical definition of curl[5]*

$$w(x,y) = \frac{1}{2}K_x x^2 + \frac{1}{2}K_y y^2 + \frac{1}{2}K_{xy} xy$$

It sums up the three parts of quadratic curves, where K_x, K_y, K_{xy} represent the curl-factors in the three mathematical parts of the whole curl as listed in **Figure 7** having the unit of a curvature $[1/m]$.

According to paper and fiber physics, curl can be grouped into four different curl types:[1]

- structural curl (reversible curl)
- curl as a result of differential dried in strains release (irreversible curl)
- curl caused by different moisture/ temperature histories between top and bottom side (viscoelastic curl))
- roll set curl

2.2.1 Structural curl (reversible curl)

Structural curl is defined as a reversible curvature of paper due to paper two-sidedness[6]. Several effects can cause this paper two-sidedness. On the one hand, it can be related to differences regarding filler content at top and bottom side of the paper and its resulting difference in hygro-expansion, on the other hand curl can be caused by different fiber orientation indexes and angles at top side and bottom side of the paper. Due to the fact, that fibers have a stronger swelling behaviour in the cross direction, oriented paper sheets always shrink and expand stronger in conjugate axes of the fiber orientation polar diagram, which corresponds mostly to the cross direction of the paper web. Their swelling and expansion in the principal axis of fiber orientation (machine direction) can be neglected.[7]

If the fiber orientation (degree of anisotropy or fiber orientation angle) has a difference at the top or bottom side, the paper curls [1], [4], [7] (see also **Figure 8** and **Figure 9**)

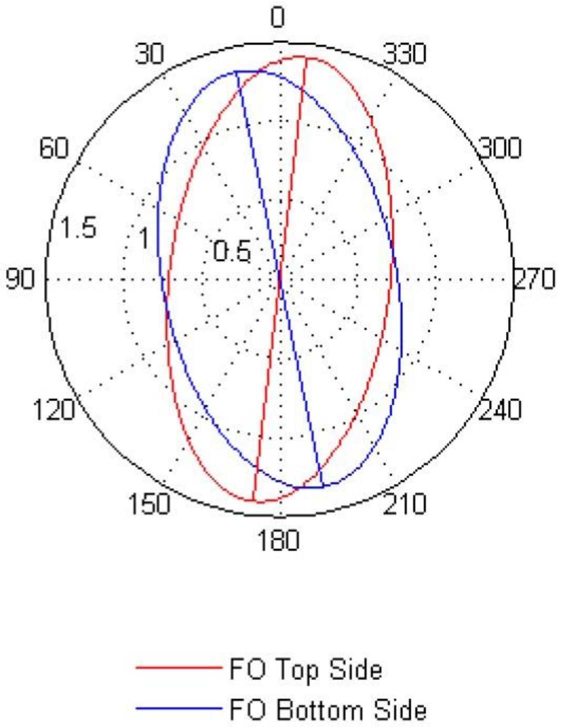

***Figure 8**. Polar diagram of structural curl, which results in a diagonal curl (twist).*

The structural curl, which results as a diagonal twist, is caused by differences in hygroexpansion on the two sides because of differences in fiber orientation angle and is defined using Equation 2 (see **Figure 8**):

- Difference in fiber orientation angle $(\phi_{TS} - \phi_{BS})$ at the top- and the bottom side
- Difference in hygroexpansion of the paper $(H_{MD} + H_{CD})$
- Paper thickness t reduces the curl

***Equation 2.** Diagonal Curl (Twist)[5, Ch. 9]*

$$K_{xy} = \frac{2(\phi_{TS} - \phi_{BS})\,(H_{MD} + H_{CD})}{t}$$

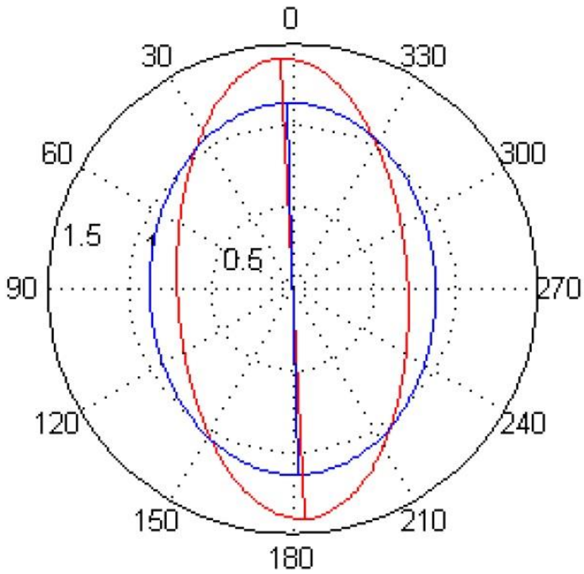

***Figure 9**. Polar diagram of structural curl, which results in a CD curl (twist)*

The structural curl, which results as a cross direction twist, is caused by differences in hygroexpansion on the two sides because of differences in fiber orientation anisotropy and is defined using Equation 3 (see **Figure 9**):

- Fiber orientation anisotropy difference$(A_{TS} - A_{BS})$
- Hygroexpansion of the paper in cross direction H_{CD}
- Paper thickness t reduces the curl

***Equation 3**. cross direction curl[8]*

$$K_y = \frac{H_{CD}(A_{TS} - A_{BS})}{t}$$

2.2.2 Curl as a result of differential dried in strains release (irreversible curl)

This curl type results from stetting free the dried in strains of industrially produced paper by raising the moisture content. This curvature is irreversible. The dried in strains are a result of the one sided drying effects of paper and can be controlled by adjusting the different drying temperatures in the post drying section of a paper machine.[1]

As shown in **Figure 10** the irreversible curl can be triggered by changing the relative humidity and thus the moisture content of the paper. Starting with drying the paper, the curvature of the paper increases. In a second step, the moisture will be adjusted to the start level and as a result, the curvature reduces again. A third step increases the moisture above the start level. This sets free the dried in strains. Afterwards reducing and increasing the moisture leads to a reversible curl. The irreversible curl which was triggered between the steps two and three cannot be reversed.[1]

As can be observed in **Figure 11** starting with moistening sets free the dried in strains immediately.

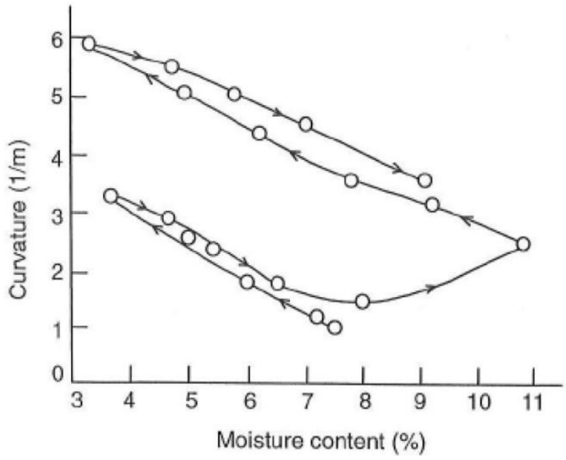

Figure 10. Triggering the irreversibel curl by starting with drying.[1]

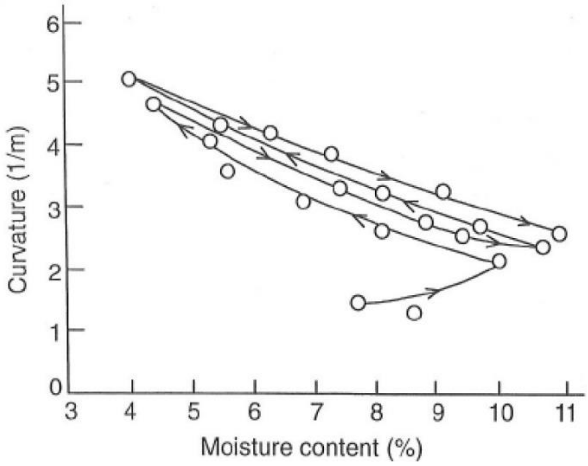

Figure 11.. Triggering the irreversibel curl by starting with wetting.[1]

2.2.3 Curl caused by different moisture/ temperature histories between top and bottom side (viscoelastic curl)

Paper is a material, which has viscoelastic behaviour. This behaviour indicates that every deformation has a vicious and an elastic deformation part. If paper is wetted on one side, this viscoelastic curl can be triggered. **Figure 12** points out Uesakas theory.[1]

The paper has an equal moisture content of 5% on top- and on the bottom side (**Figure 12** a). A one sided wetting leads to hygroexpansion (swelling) of this paper top side, while the bottom side does not swell (**Figure 12** b). Caused by this one-sided hygroexpansion the bottom side will be stretched (**Figure 12** c) and during the drying process, the expanded top side shrinks to its starting position. Due to the reason, that the stretching of the bottom side is irreversible (the vicious part), the result of a one sided wetting is a positive curl towards the top side. **Figure 12** d shows the result of the one sided wetting after reaching moisture equilibrium again. The curl leads towards the top side caused by a bending moment of the bottom side.[1]

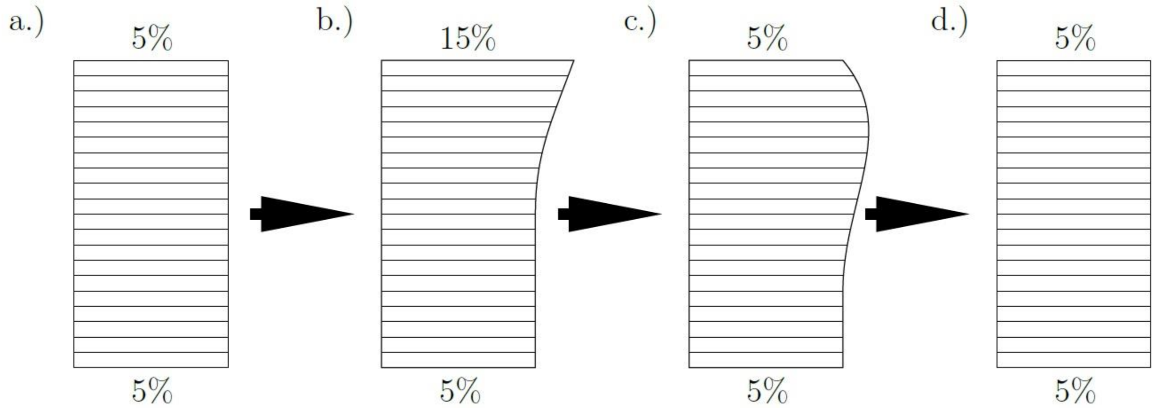

***Figure 12**. Theory of viscoelastic curl. [1]*

According to this theory, a one sided wetting curl leads to a positive curl, and a one sided drying curl leads to a negative curvature. In theory, one-sided wetting and drying from the back side should compensate the curl behaviour. **Figure 13** exemplifies this theory. However, there is not just one predominant curl mechanism, but different mechanisms overlie. In the end, the curl after printing in many cases does not go back.

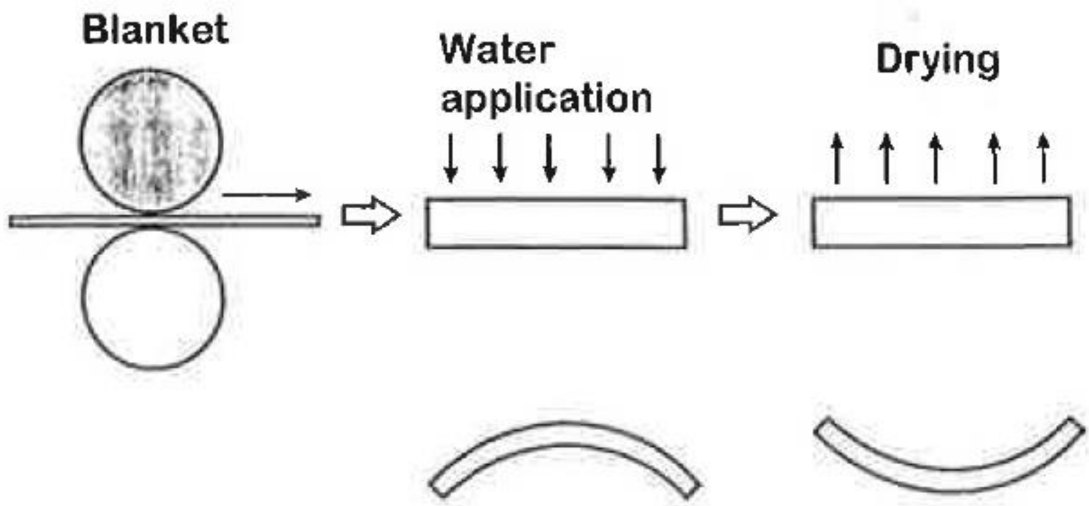

***Figure 13**.Curl in offsetprinting according to the viscoelastic curl behaviour.[1]*

2.2.4 Roll set curl

Roll set curl is related to a viscoelastic curvature stress relaxation. If the paper is guided along rolls with small diameters, viscoelastic curvature in machine direction happens. To control this roll set curl, de-curl mechanisms are used. As a fact this roll-set curl is caused by viscoelastic relaxation. Surrounding conditions, which have high temperature and high humidity increase this type of curl.[1]

2.3 Fundamentals of inkjet printing

This part of the chapter should link paper porperties of uncoated fine paper and inkjet printing. Due to the reason, that this thesis deals with curl triggered by inkjet orienting, its focus is set on curl and paper properties, not in printing itself. Hence, this part should only give a short overview on inkjet printing.Inkjet printing technologies can be divided into two groups regarding the drop generation:[9]

- drop on demand
- continuous drop technology

While the continuous inkjet technology produces a permanent drop flow where the ink drops are deflected and recycled, if the drop is not needed on the substrate, drop on demand technologies produce the ink drop right at the moment when it is needed. The triggering of the drop with drop on demand technology can be done with piezo electric or thermal systems [9]. Regarding printing quality, drop on demand systems have a better printing quality. Continuous inkjet systems are used for printing bar codes at packaging mills or other fast needed information with low quality requirements[10].
Regarding ink systems, two different inks are used:

- dye ink
- pigment ink

Dye inks are colorized liquids, while pigment inks use colorized pigments which are stabilized within a carrier liquid. In consequence of the small particle size of the pigments within the pigment ink, a pre treatment with salts at the paper mill of with primer liquids within the printing press, which include coagulants, are used as a pre-treatment in order to support the agglomeration on the paper surface and increase the colour gamut.[9], [11], [12]

2.4 Influence of ink types and paper properties on print quality

All four model paper which were used during this thesis are wood free uncoated fine papers. They differ in their surface treatment and their sizing. The following chapter should compare theses papers and their properties to the print quality, which could be achieved by using them. Also different ink types were used during this thesis. Pigment ink (with and without primer) and dye ink. Therefore the influence of these ink types on print quality is also shown in this chapter.

Table 1 *Paper types and their differnt treatment*

paper type	description oft the treatment
AKD sized paper	internal sizing, hydrophobization
pigmented paper	surface coating with anorganic pigments in surface sizing, no internal sizing
unsized paper	natural fine paper, no internal sizing, inkjet treated with salts in sizepress
calendered paper	smoothed surface though thermal compression, otherwise same paper as unsized paper

Two very important factors for print quality are colour gamut and optical density. To achieve a high optical density, the contact angle Θ has to be higher than 90 degrees.[13] It is commonly known that coated (and calendered) papers have a contact angle above 90°. Therefore increase of optical density and colour gamut by raising the contact angle is mostly relevant for papers without surface coating. There is a good correlation between optical density and colour gamut for inkjet printing. This effect has shown up with several papers and several coatings. Hence the R^2 has a value of 0,9752 [14]

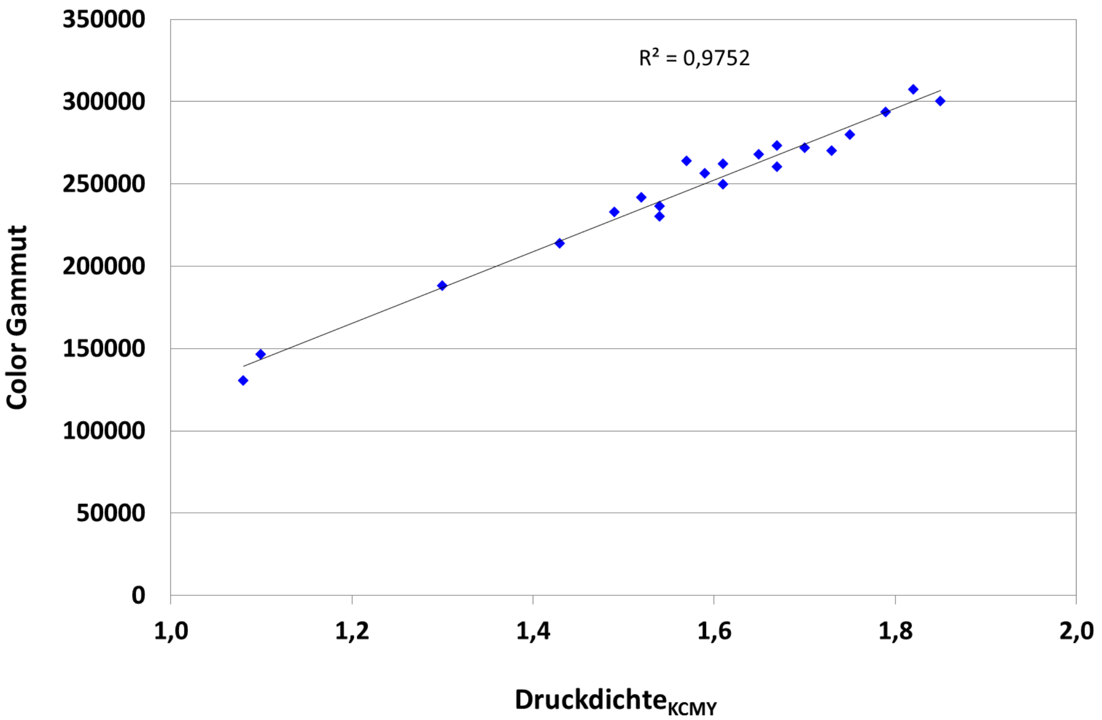

Figure 14 *Correlation for print density and colour gamut [14]*

If liquid is applied at paper, a wetting delay happens [13], [15]. This wetting delay is relevant for printing techniques which has a low impact velocity e.g. drop on demand technologies[15], [16]. With continuous inkjet printing the wetting delay was found not to be relevant. This is a result of high-speed optical analyses of a drop impact on different papers and a rough plastic sheet with known surface properties verifying the printing distance and drop velocity. Concerning colour density a 98% correlation of dot size at 120 ms after the impact and final dot size was found, but the final intensity of the drop reached the final level at 1500 ms.[17]. This effect of sizing and colour density can also be observed in the following figures. Five laboratory hand-sheets were produced out of 85% eucalyptus (35°SR) and 15 % mason pine (35°SR) and treated with different sizing agents, finishings and printed with dye ink. The average ink permeability was measured via a Confocal Laser Scanning Microscopy. The following **Figure 15** shows the dye-ink-distribution of all papers. [18]

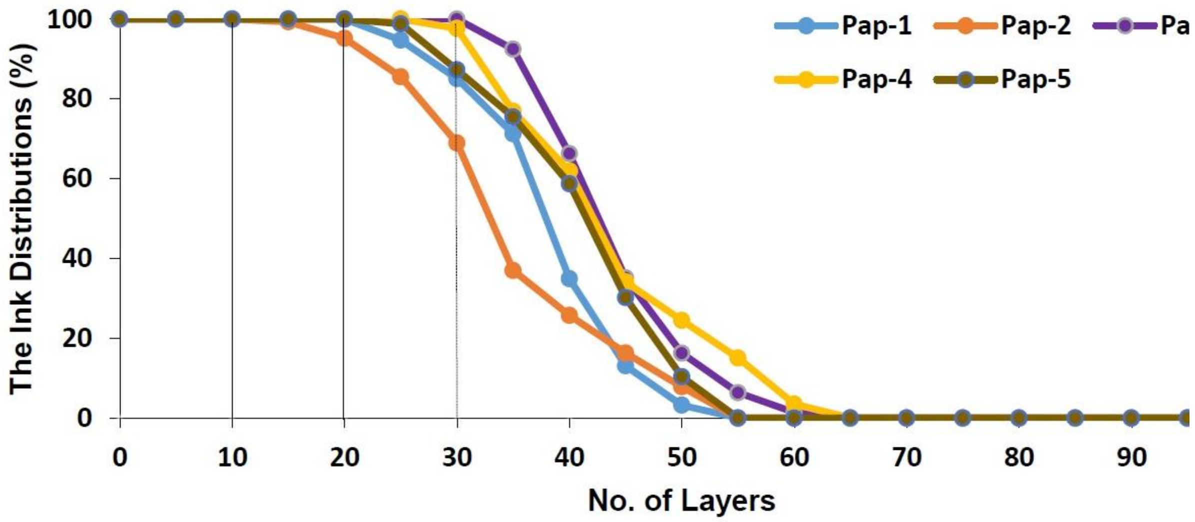

Figure 15 *Water based ink distribution of the lab-sheets listet in Table **2** [18]*

Table 2 defines the experimental datasheets for the papers shown in Figure 15. Paper 1 was used as reference paper, paper 2 was internally sized and paper 3 filled with PCC, paper 4 had both, paper 5 was further treated with calendering as finishing.[18]

Table 2 *Surface treatment of the hand sheets [18]*

	AKD sizing	PCC filler	calendering
Paper 1	0	0	0
Paper 2	1	0	0
Paper 3	0	1	0
Paper 4	1	1	0
Paper 5	1	1	1

With regards to the optical density, there is clear evidence, that sizing has an effect on it. The addition of PCC without sizing has a negative influence. The combination of PCC and sizing and calendering shows the best result. The already mentioned relationship between contact angle Θ and the variation of the paper properties is shown in Figure 16 and Figure 17 below.[18]

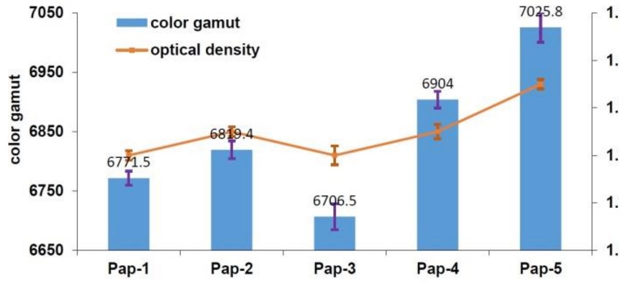

Figure 16. *Optical density (OD) and colour gamut of yellow with different surface treatments [18]*

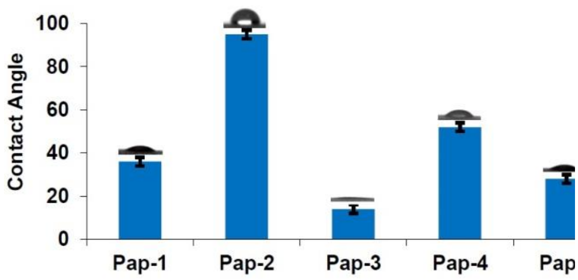

Figure 17. *contact angle and shapes of the deoinized water droplets depending on different surface treatments [18]*

The calendering impact can be observed when comparing papers 4 and 5. They have the same sizing and filler amount. Calendering reduces significantly the contact angle and increases the optical density. [18]

The variation of pulp type and filler content does not influence the colour gamut and optical density. These findings are based on a trial at a laboratory paper machine where the hardwood content was varied by 10% and the filler content had a variation of 6%. There have also been experiments with different hardwood and softwood contents in combination with a variation of the refining intensity. The result was that a variation of filler and fibers does not have an impact on colour gamut. The adding of salt on the surface ($CaCl_2$), also called ColorLock® increases the gamut with the usage of pigment ink, but not with dye ink.[19], [20].The printing of Primer at the Inkjet Printing Press has similar effects than $CaCl_2$ application at the size press in the paper machine. Primer also salts like $CaCl_2$ and increases the colour gamut.[9]

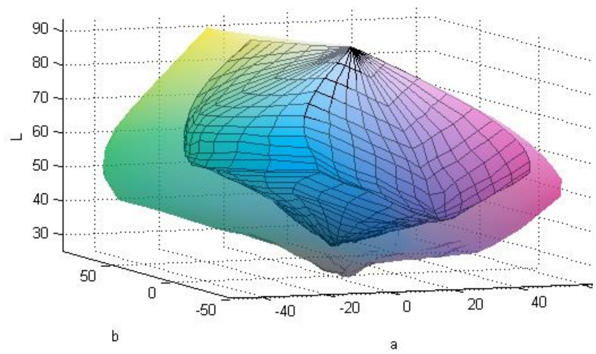

Figure 18. *Colour gamut volume for prints with pigment ink with and without ColorLock® [19]*

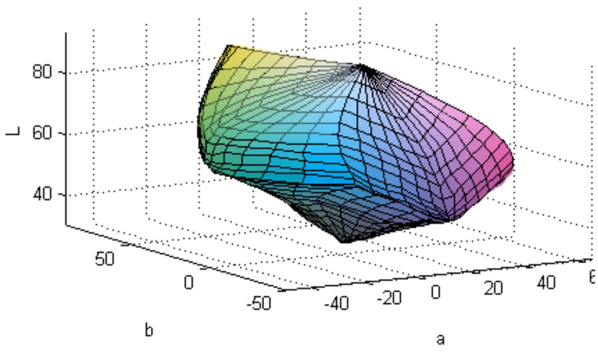

Figure 19. *Colour gamut volume for prints with dye ink with and without ColorLock® [19]*

Figure 20 and **Figure 21**compare the microscopy images of a 10% half tone value printed surface two papers. The used ink was pigment ink, the paper at Figure 20 has no Salt application, Figure 21 has a high amount of salt. The print dots seems to be smaller and more distinct for the paper J with surface fixation.[20]

Figure 20. *Microscopy image of paper G (no surface fixation) [20]*

Figure 21. *Microscopy image of paper J (high surface fixation) [20]*

If pigment inks are used the colour density can be raised with high amounts of salts that prevent the ink particles from penetrating into the paper and helps the ink to form a complex on the surface. Calendering also significantly improves the colour density.[21]

3 Materials and methods

3.1 Investigated papers

This thesis is one out of four master theses carried out within the CD Laboratory for Fiber Swelling and Paper Performance dealing with curl problems. While the first one is dealing with laboratory produced papers and its influence on paper (wet) curl, the second one deals with dried in strains of industrial produced papers and tries to localize papermachine- adjustments and its effects on it. The other two theses try to analyze curl from the printing side. One of these two theses analyses the effect of blanco printing deformation on an industrial cut-sheet printer (Canon VarioPrint i300), while this thesis investigates the effect of inkjet printing on curl of industrially produced papers.

These industrially produced model papers were all uncoated woodfree fine paper grades, produced by Mondi. The aim, while producing theses papers, was to obtain papers out of one production run, which had no significant variation regarding the quality parameters.

The focus was therefore set on a problem-free production. The papers were cut out of the center of the paper web regarding the cross direction curl and its tendency to increase at the edges.

All four model papers (see **Table 3**)) were produced on Fourdrinier paper machines at the Mondi Kematen paper mill, which is localized in Lower-Austria, three of them actually were produced on the same paper machine.

***Table 3**. List of the used model papers and its properties*

Paper type	Description of the treatment
unsized paper	natural fine paper, no internal sizing
pigmented paper	surface coating with anorganic pigments
calendered paper	unsized paper smoothed surface by thermal compression
AKD sized paper	hydrophobization of the paper surface

As can be observed in **Table 3**, all of this four model papers were produced using different treatments and therefore have different paper properties, which should have an influence on curl. The first three papers were produced on the same paper machine, while the AKD sized paper was produced on another machine. Regarding the first three papers, the raw materials of the base paper (short fiber and long fiber pulp, degree of refining) are identical. In addition, the AKD sized paper from the second machine was produced using the same raw materials. The calendered paper is the same as the unsized paper, but on line smoothed. **Table 4**. lists the most relevant paper properties of the four model papers.

Table 4. *Paper properties of the model papers*

Properties	Unit	AKD sized	unsized	pigmented	calendered
Grammage	[g/m²]	77,2	78,5	79,9	85,6
Filler content	[%]	13,52	21,51	22,98	22,56
Coat weight	[g/m²]	0	0	4	0
HSI* treatment ($CaCl_2$)	[ ]	No	Yes	Yes	Yes
Hg porosity	[%]	20,6	38,8	23,6	not available

* HSI…High speed inkjet

3.1.1 Hygroexpansion of the model papers

In order to observe the behaviour of theses papers regarding printing and drying, which deals with wetting and drying, hygro- (exposure to different relative humidities) and hydroexpansion (exposure to water) was measured.

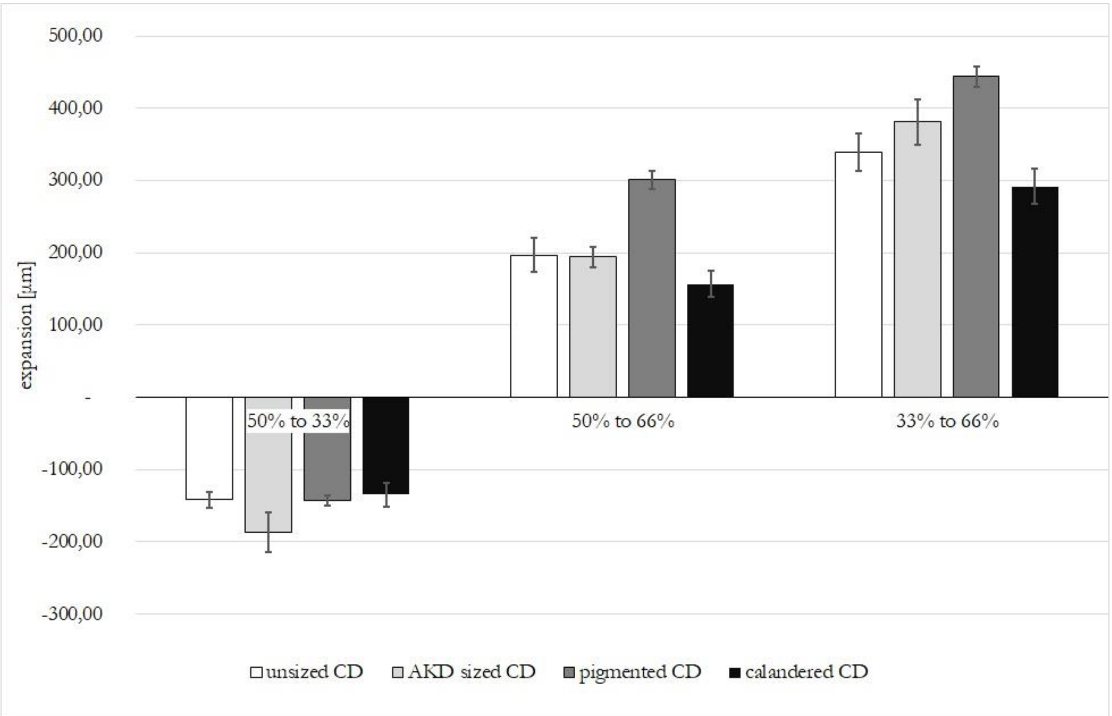

Figure 22. *Hygroexpansion of the four model papers mesaured according to DIN ISO 8226-1; number of samples n=5 each; eror bars erpresent 95% confidence interval*

Figure 22. shows the result of the hygroexpansion measurement. The method measures the shrinkage and the expansion of paper due to a change of the relative humidity while the temperature is kept constant. The measurement starts at standard conditions with 50% relative humidity and 22,5 °C. First the humidity is decreased to 33%. This value should be kept constant as long the paper does not expand or shrink anymore. Afterwards a relative humidity at 66% should be reached. The temperature should be kept constant.
As a result, two papers, the unsized and the AKD sized paper have almost the same hygroexpansion form 33 to 66% while the pigmented and the calendered papers expand significantly different.

3.1.2 Hydroexpansion of the model papers

Figure 23. *Hydro expansion measurement*

The measurement of the hydroexpansion shows the shrinkage or expansion of paper when immersed in water under a constant stress of 5 N/m.
The paper- strip has a length of 10 cm and a width of 3 cm. When the measurement starts, the bowl filled with deionized water moves upwards and the paper is immersed in water. Immediately, the constant force of 5 N/m is applied and the shrinkage or elongation of the paper is measured. The duration of the measurement is 80 s and its resolution is one value every 0,2 s. **Figure 24** shows the expansion of the papers in machine direction. The yellow frame indicates the time- frame relevant for the printing and drying process, which was used in this thesis. In short, the expansion in machine direction is almost completely developed after this time

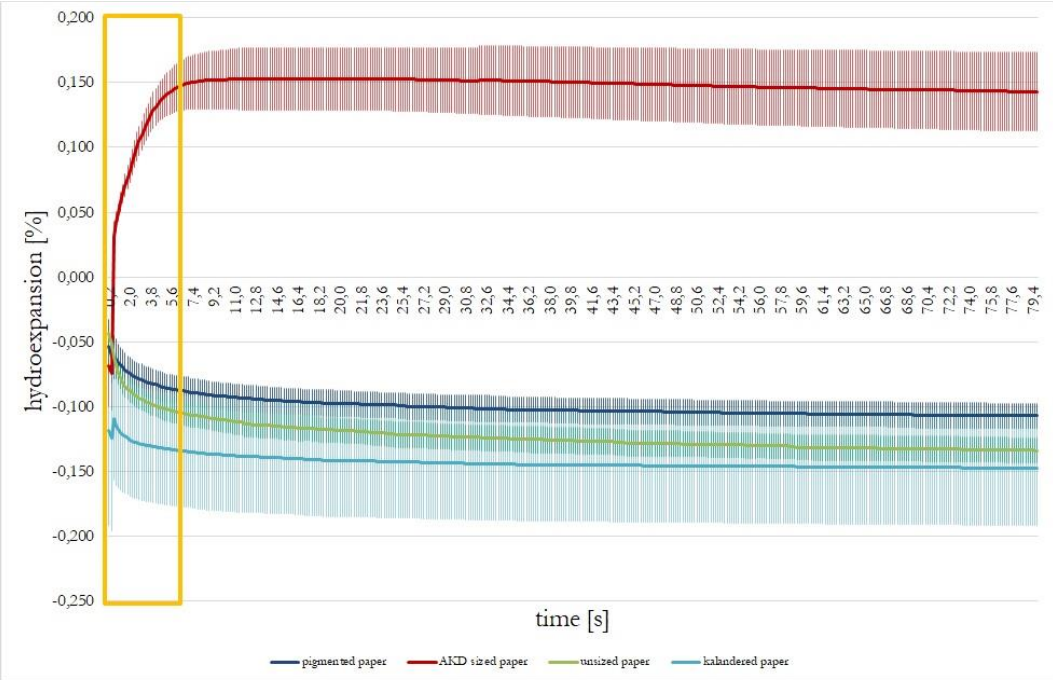

Figure 24. *Hydroexpansion of the four model papers in machine direction; number of samples n=6 each*

The three model papers without internal sizing shrink because of the dried in strains, while the AKD sized paper expands.

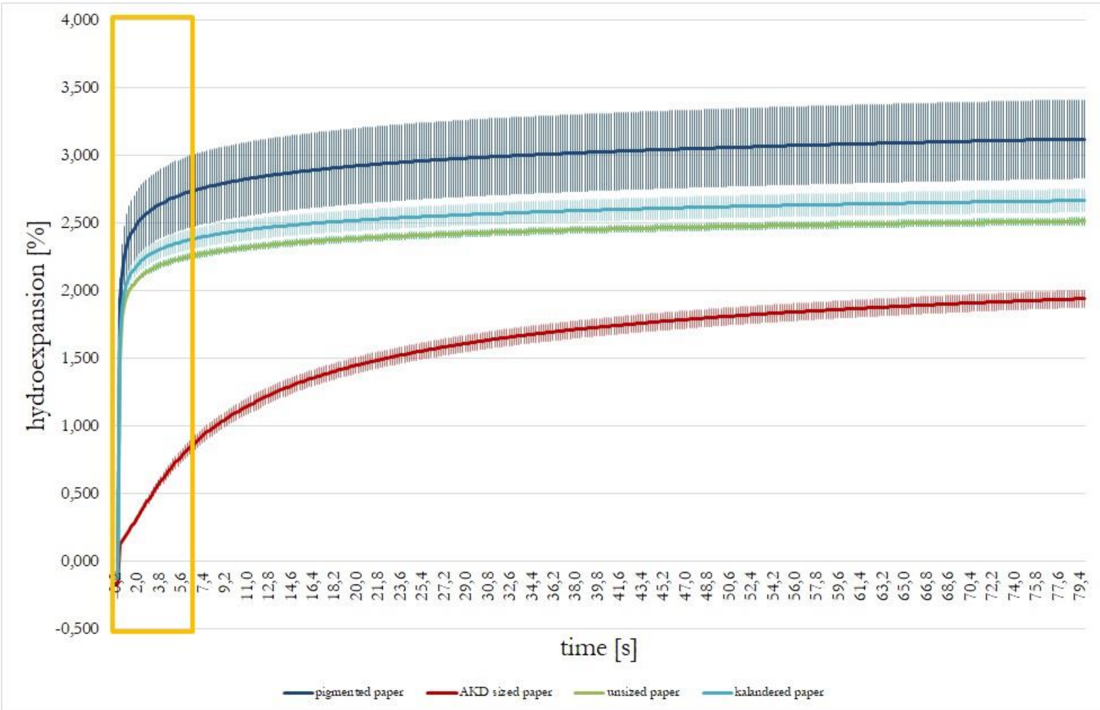

Figure 25. *Hydroexpansion of the four model papers in cross direction; number of samples n=6 each*

Figure 25 points out the difference of the hydroexpansion in cross to machine direction. First of all, by looking at the scale of the y-axis, the expansion is at a significantly higher level. One reason for this is the higher expansion or swelling of a cellulose fiber in cross direction [4].
Also the effect of sizing can be observed. While the three model papers without sizing reached almost their maximum level of expansion within the relevant time frame for printing, the AKD sized paper only reached half of the final expansion value.
Similarly to the hygroexpansion experiments, the pigmented paper has the highest value with 3 % hydroexpansion. The unsized and the calendered paper stay stable at 2,5 % while the AKD sized paper stabilizes at 2 % expansion.

3.2 Production of printed samples using the IPTS

3.2.1 Development of the method

The shortcut IPTS stands for ink-paper-testing-system and it is a laboratory print system developed by Océ-Printing-Sytems at Poing. Its idea is to obtain printed paper-samples on the lab scale by using industrial print heads, which are normally used in high speed roll inkjet printing systems without using a full roll inkjet printing press.
The reason for this development is a higher flexibility and less need of paper, because this system uses A4 sheets.

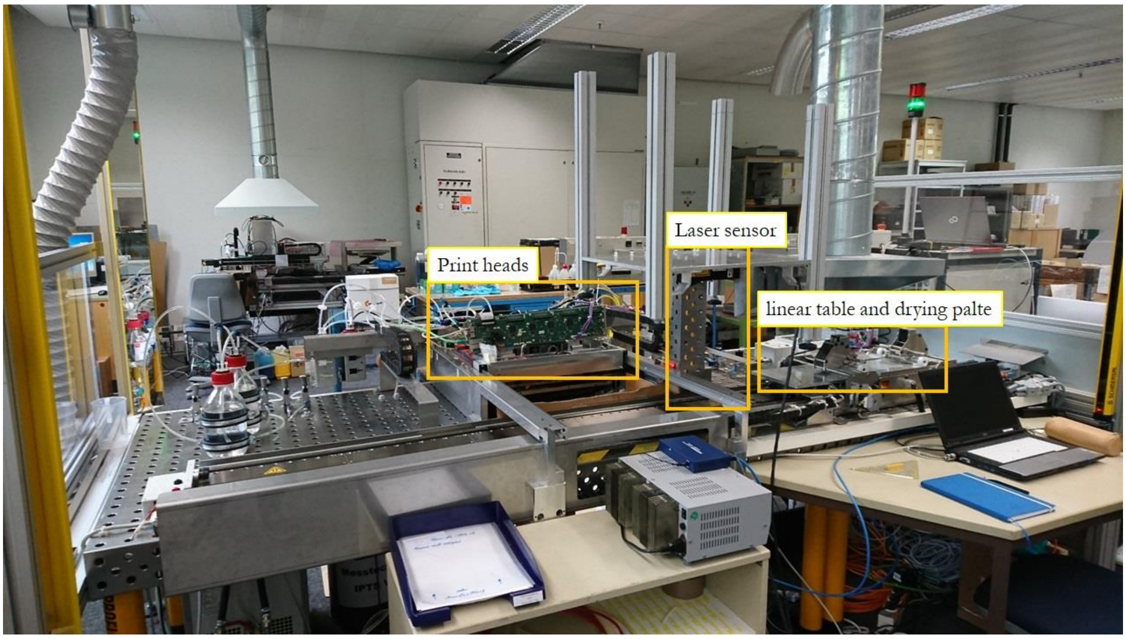

***Figure 26**. IPTS overview and its main components*

Figure 26 shows an overview of the IPTS and its main components. The main parts are:

- the print head carriage with possibility to mount five print heads, in general
  - one for primer application
  - four for the inks (CMYK)
- the linear table with the vacuum drying plate
- the laser sensor to evaluate curl mounted on top with sensor direction towards the linear table

The printing with the IPTS is a single sheet printing. One A4 sheet is placed on the linear table. The linear table is perforated. Before the printing starts, vacuum is applied to the table to firmly hold the paper. Afterwards, the head carriage is put in printing position and the linear table moves the paper under the print head and printing starts. The speed of the linear table during printing is 1333 mm/s, which represents the web speed in inkjet roll printing. Right after printing, the paper is transferred to the drying plate. The yellow framed transfer-rolls in **Figure 27** move the paper sheet instantly to the drying plate. This hot plate dries the paper sheet from the backside with 129 °C. Right after the sheet has arrived at the plate, a vacuum area on this plate is activated. This vacuum increases the heat transfer by creating full contact between the paper and the plate. After the set drying time the transfer-rolls on the other side of the plate transfer the dried paper from the plate.

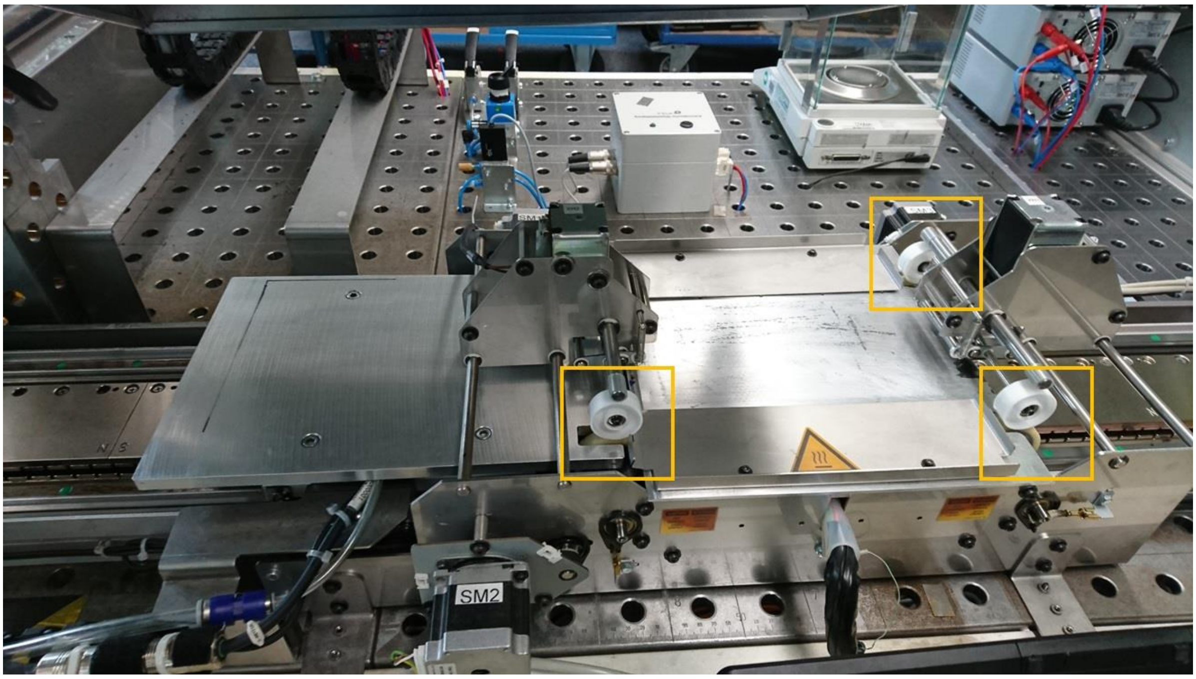

***Figure 27**. Linerar table and vacuum drying plate in tranfer position*

One print head, which is used in industrial inkjet presses has a printing width of ~ 113 mm. To obtain a wider printing area, several print heads are mounted on an industrial printer, overlapping in cross direction. The IPTS just uses one print head for each colour or primer. Hence, the width of the print is 11,3 cm; so an unprinted edge is the outcome.

Figure 28 exemplifies this maximum possible full tone printing. Some pretrials regarding curl with this setup were performed, but the results were not satisfying regarding triggering curl behaviour, because of the unprinted edges. In ordet to obtain a full tone print without unprinted edges, a new method had to be developed. As a consequence of the yellow framed vacuum area which is 11,5 x 20,5 cm in size, and the width of the laser spot of the sensor, which is visible at **Figure 28** to **Figure 31**, the chosen sample dimension for all tests is 10 x 17 cm.

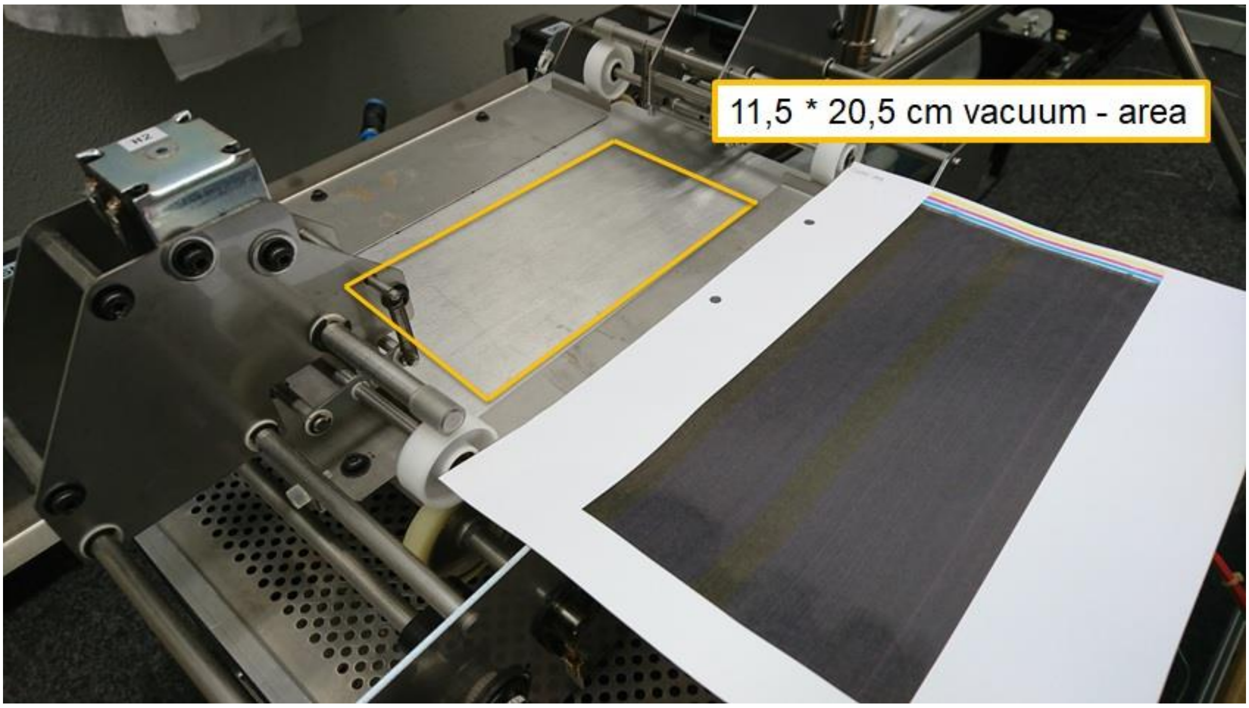

***Figure 28**. Maximum possible fulltone printing area and vacuum area of the drying tabel. Its limited by the width of the print head and a safety disnatce in order not to print at the linear table. Inside of the yellow feeld, the drying table has a perforation and sucks the paper during the drying process in order to get a good contact.*

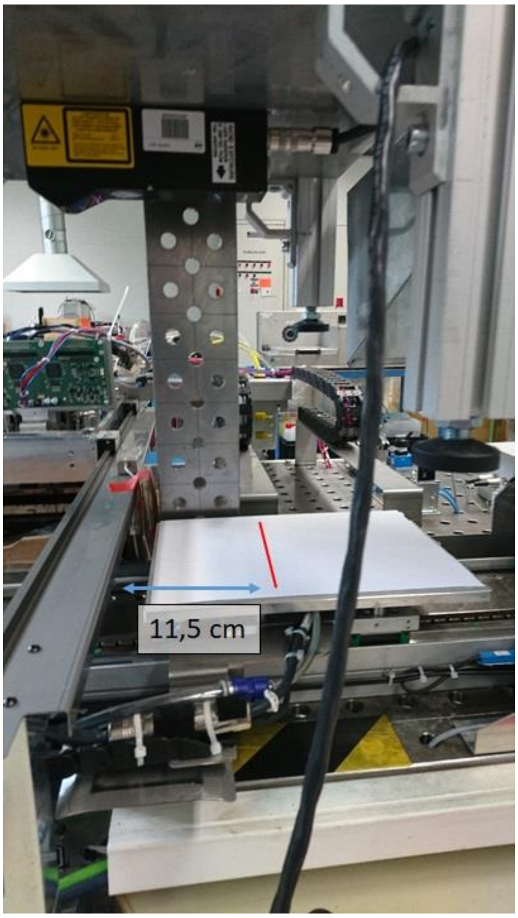

Figure 29.*Laser Sensor with linear table in position.*

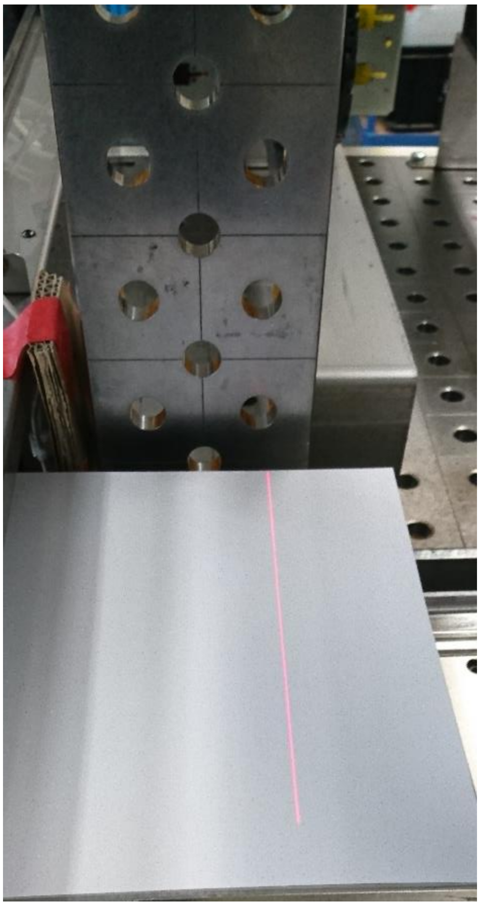

Figure 30. *Laser spot on the paper sheet.*

On the left side at**Figure 29**, the beam of the print head carriage can be seen. The gap between the linear table and this beam, which is shown in **Figure 31**, is approximately 1 cm. A measurement of the curled sample in the length direction was not possible because of the beam of the print head carriage. The curl sample touched this beam.

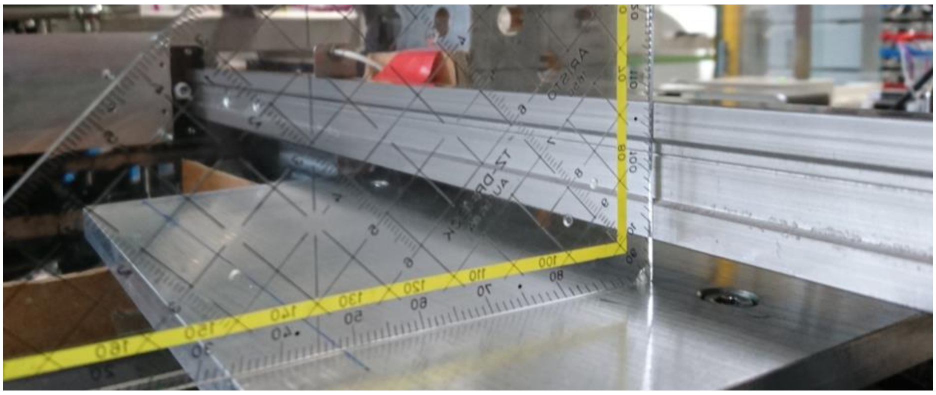

Figure 31. *Picture of the beam and the linear table below it.*

With the chosen sample length of 17 cm the beam has an overlay at every side at ~ 5 mm. And with the chosen sample length width of 10, the curled sample never touched the beam during the measurement. (**Figure 29**). In **Figure 32**. the chosen sample size and its cover is displayed. With this chosen sample size, full tone printing without unprinted edges was possible.

***Figure 32**. Picture of the chosen sample size and the cover*

The cover is needed to protect the linear table from the ink.

With this arrangement, the previously described printing process was not longer possible regarding the transfer of the paper sheet to the hot plate. The transfer rolls could not be moved towards the middle of the sheet due to mechanical reasons.

As a consequence this transfer had to be done manually using forceps. This manual transfer using forceps had to be done carefully. With some practice, the best way to do it was to use two forceps to move the sample without clamping it. Clamping led to plastic deformation, which is unwanted.

3.2.3 Preparation of paper samples out of the A4 sheets

***Figure 33**. Paper samples out of one A4 sheet*

Figure 33 demonstrates how the right size samples were prepared. Each paper sheet was removed from the original ream individually to secure, that top and bottom side of the sheet could not be confounded. Afterwards the top side and the paper grade was marked. The paper was cut in the shown way. The outcome of one A4 sheet is three 10 x 17 cm samples. Two with the long side in machine direction and one was cut out of the remaining lower part in cross direction. To compare nearly the same paper, these two MD sheets were compared to each other to show the effect of slightly different positions at the paper machine

3.2.4 Description of the used standard printing method

The standard print heads, which were used for mostly all experiments were piezo electric print heads with a 1200 dots per inch resolution. This print heads can generate three different drop sizes regarding the set fire impulse. Therefore, the variation of the print coverage can be done in two ways. The first way is by triggering not all 1200 nozzles, the second is using different drop sizes. When both ways are used, it is a so called multi-layer print job. When just the triggering of the nozzles results in different coverage and the drop size is kept constant, the name of the print job is depending on the used fire impulse. For instance the use of fire impulse level “2” results in used drops with around 3 pl. This printing job would be called a bi-level print job. All used print jobs in the experiments are bi-level print jobs.

As a result the developed standard method for the generation of curl samples is the following:

- each sample is cut out of A4 paper sheets, the top side is marked
- analysis of the untreated paper using the laser sensor
    - 20 mm/s speed of the linear table
    - 2 measurements with the laser sensor with 60 Hz
- printing process
    - 1333 mm/s speed
    - all colours in row
- manually transfer with two forceps from the linear table to the drying plate
- drying with the hot vacuum plate always from backside
    - analysis of the treated paper with laser sensor with 60 [hz]
    - 20 mm/s speed
    - 3 measurements right after the drying process
    - 20, 40, 60 seconds after the drying process

Figure 34 shows the workflow chart of the already described experiment.

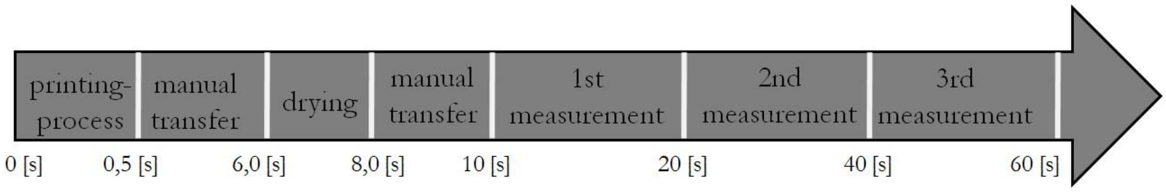

Figure 34*. Timeline and workflow chart of the standard printing and drying experiment. The times on the x-axis are not true to scale to allow better readability.*

3.2.5 Calculation and description of the ink amount with the used print jobs

3.2.5.1 Latex pigment ink print jobs

Table 5. lists the drop size and the resulting ink amounts for each ink type. All experiments, which used latex-pigment ink, used a combination of all four inks with and without primer. According to this table, the maximum possible ink amount would be 39,3 g/m² ink. This amount would be far too much ink and has no relevance in industrial printing.

Table 5. *Drop sizes and wet ink amounts for latex-pigment-ink*

ink	fire impulse level	dots per inch	drop size [pl]	wet ink amount per area [g/m²]
cyan	2	1200	3,9	9,40
key	2	1200	4,1	9,88
magenta	2	1200	4,0	9,64
yellow	2	1200	4,3	10,36

In order to get sharp and clear effects, one print job, which was used for the pretrials had a high wet ink amount. **Table 6** lists all generated bi- level print jobs which were used in this thesis. By using the area of the 10 x 17 cm paper samples , **Table 6**. shows a full list of all print-jobs using latex-pigment ink and the applied wet mass of ink to the sample.

Table 6. *List of all uses latex- pigment- ink print jobs*

Print job	applied wet mass to sample [g]	applied wet mass per area [g/m²]
4 x 70% coverage	0,668	39,292
4 x 50% coverage	0,334	19,646
4 x 40% coverage	0,267	15,717
4 x 25% coverage	0,167	9,823
4 x 20% coverage	0,134	7,858
4 x 17% coverage	0,114	6,680
4 x 10% coverage	0,067	3,929
4 x 5% coverage	0,033	1,965

3.2.5.2 Primer print jobs

There were two different primer amounts, which were used in the thesis. The standard primer amount was used in order to apply the primer first on the paper and all four inks afterwards in row. This was done during the pretrials. The second print job was generated to get as much possible primer amount on the paper to compare just primer printing to printing with the same ink amount without primer. **Table 7** shows a list of these two primer print jobs.

***Table 7**. List of primer print jobs*

ink	fire impulse level	dots per inch	drop size [pl]	wet primer amount [g/m²]
primer	1	600	3,0	2,00
primer	3	600	12,0	6,69

In **Figure 7** these 2 primer jobs and the one latex pigment ink print-job already listed in **Table 6**. are shown. As can be observed, the 4x17% coverage latex pigment ink print job was generated to obtain exactly the same amount of ink on the paper and to compare it to just primer printing (see chapter 4.5).

Table 8. *List of all primer printjobs*

Print job	applied wetmass at sample [g]	applied wet mass [g/m²]
100%, 3 [pl]	0,034	2,009
100%, 12 [pl]	0,114	6,696
4 times 17% coverage	0,114	6,680

3.2.5.3 Dye ink print jobs

Due to physical and technical reasons, printing of dye ink at Océ is only possible with 600 dpi heads. Also the drop sizes have a different value for dye ink. The approach in the experiments with dye ink printing was to compare similar ink amounts of dye ink to latex pigment ink. Unfortunately, just two primer heads for 600 dpi printing were available. Therefore the ink amount generated with four 1200 dpi print heads had to be reached with two 600 dpi print heads. The first dye ink print job had to apply a comparable ink amount to the smallest latex-pigment ink job, the second one had to print as much dye ink as possible with the 600 dpi print heads. **Table 9** lists these two chosen print jobs.

Table 9. *Print jobs used for dye ink*

ink amount	latex pigment ink		dye ink	
low ink amount	4 x 5 % coverage	1,956 g/m²	2 times 13 % coverage	1,984 g/m²
high ink amount	4 x 40 % coverage	15,717 g/m²	2 times 100% coverage	14,243 g/m²

3.2.6 Description of the method used for storage at 0% relative humidity

This experiment was chosen to obtain results from storing printed samples at nearly 0% relative humidity (RH).

To reach a climate with nearly 0% RH level, standard plastic boxes were bought at a shop. This standard plastic boxes hat to have the correct dimensions to allow storage of the printed paper samples. To make the boxes as airthight as possible a seal was placed between the lid and the box and a plastic tape was used to further improve air tightness (see Figures 26 and 27).

Figure 35*. Empty storage box with the sealing at the top.*

Figure 36*. Storage boxes filled with samples and sealed with sealing tape*

The 0% RH level was reached using silica gel. **Figure 36** shows a picture of the printed samples within the boxes at 0% RH. To control the humidity hygrometers were put inside of each box. The humidity stayed constant below values of 1% during all experiments. In order to avoid direct contact between the samples and the silica gel, plastic sheets as a barrier were put between the samples and the gel. A second indicator was also used to control humidity. The gel itself has an indicator, which colorizes the gel red if the moisture level becomes too high. As can be observed in Figure 27, the gel is blue. This also indicates that the humidity was below 1%.

3.2.7 Description of the backside water application experiment

This experiment was performed in order to analyze the influence on short-term curl of moistening the backside of the unprinted sample with exactly the same amount of water as printed on the top side. Right before the printing, the backside of the sheet was wetted with the this amount of water. To get a homogeneous wetting a rod coater with two different rods was used. These two different rods were used in order to see, whether there is an increasing or decreasing effect with higher or lower liquid amounts. These used two rods were the "white rod" with a 0,05 mm groove and the "red rod" with a 0,15 mm groove. The corresponding film thicknesses for water at the given rod- pressure and speed for these two rods is 4 µm for the white rod and 12 µm for the red rod. **Table 10** and 9 list the results of the pretrials regarding the water uptake levels of the four different model papers. There was no significant difference regarding water uptake with regards to paper two-sidedness; therefore the values of just one side are shown. To check the homogeneity of water application a small amount of red dye ink was put into the water and the colour density of the samples was checked. There was no significant difference in the colour density. The setup of the experiment is demonstrated in **Figure 37** to **Figure 39**.

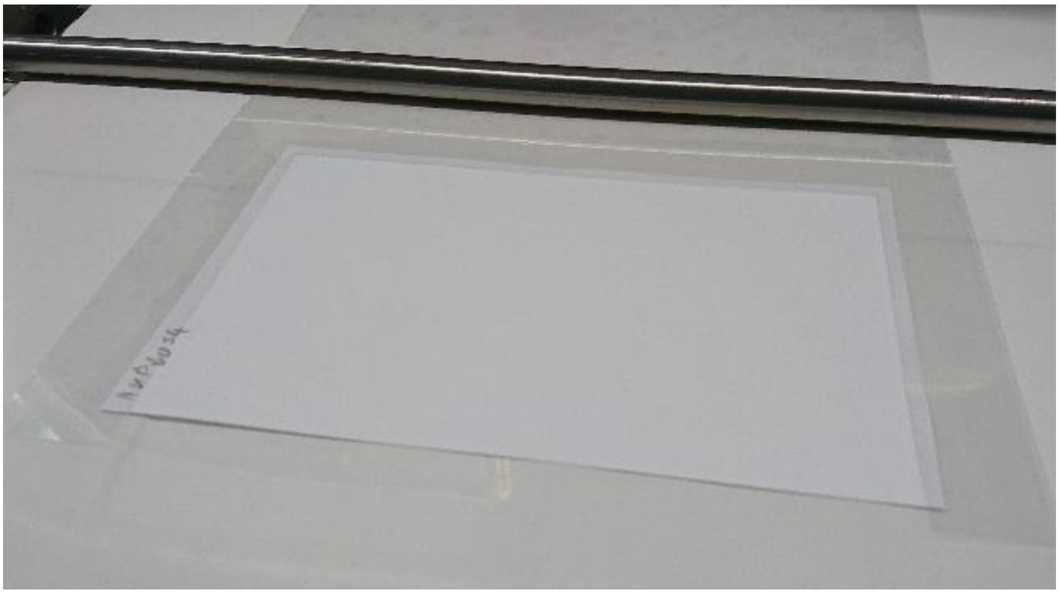

***Figure 37**. Paper sample for the rod coater. The sample is supported by a plastic film at the backside to allow easier transfer of the per-wetted sample to the IPTS. A second plastic sheet which is cut at the egdges defined the area for the water application. Addition of a small amount dye ink helped in the pretrials to check the homogeneity of the water application.*

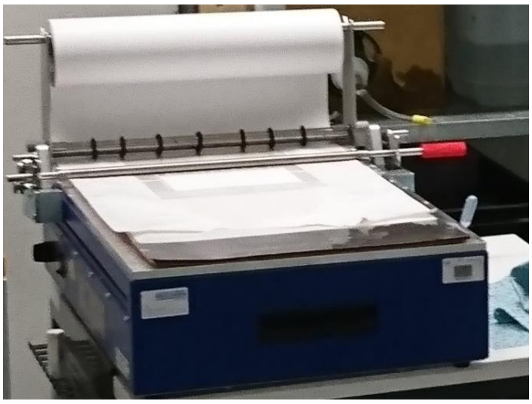

***Figure 38**.Picture of the rod- coater*

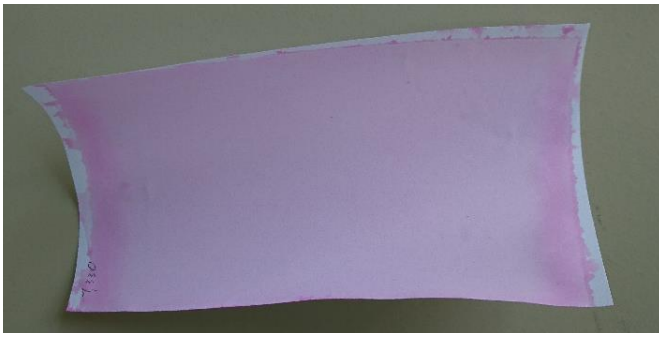

***Figure 39.** Wetted papersheet with dye ink as indicator.*

Table 10. Result of the pretrials for low water amounts (white rod)

	mass of the paper [g]	mass of the paper wet [g]	water take up [g]
unsized	1,345	1,480	0,135
	1,315	1,445	0,130
	1,320	1,455	0,135
			0,133
AKD sized	1,341	1,451	0,110
	1,330	1,447	0,117
	1,330	1,450	0,120
			0,116
pigmented	1,340	1,472	0,132
	1,344	1,512	0,168
	1,344	1,473	0,129
			0,143
calendered	1,515	1,680	0,165
	1,565	1,740	0,175
	1,531	1,721	0,190
			0,177

Table 11. *Result of the pretrials for higher water amounts (red rod)*

	mass of the paper [g]	mass of the paper wet [g]	water take up [g]
unsized	1,347	1,614	0,267
	1,370	1,624	0,254
	1,333	1,694	0,361
			0,294
AKD sized	1,332	1,521	0,189
	1,342	1,615	0,273
	1,344	1,635	0,291
			0,251
pigmented	1,362	1,656	0,294
	1,363	1,642	0,279
	1,364	1,661	0,297
			0,290
calendered	1,454	1,776	0,322
	1,463	1,787	0,324
	1,467	1,806	0,339
			0,328

Based on these results from the wateruptake pretrials the corresponding print jobs from the series using latex pigment inks (see **Table 7**. List of primer print jobs) were chosen. **Table 12** shows the chosen print-jobs for the two experiments per model paper with backside water application.

Table 12. *List of print jobs with backside water application and corresponding print job using latex pigment ink*

	low liquid amount		high liquid amount	
	water uptake [g]	chosen print job and wet ink amount [g]	water take up [g]	chosen print job and wet ink amount [g]
unsized	0,133	4x20%; 0,134	0,294	4x40; 0,267
AKD sized	0,116	4x17%; 0,114	0,251	4x40; 0,267
pigmented	0,143	4x20%; 0,134	0,290	4x40; 0,267
calendered	0,177	4x25%; 0,167	0,328	4x50; 0,334

3.2.8 Description of the hot air drying experiments under defined stress

All drying experiments where done with conductive drying by a hot plate from the backside. However, the newest Océ printing press in the market as well as most of the non digital printing presses like heatset offset and rotogravure use hot air drying with air foils, so one experiment was defined to evaluate the effect of hot air drying. The problem in planning this experiment was to take the influence of a defined stress in the machine direction into account. The solution was a clamp that has exactly the weight of 160 g. When the sample is clamped on one side, e.g. to the grid in the drying oven and the other side - being loaded with the 160 g clamp - hangs freely, the resulting force is approximately equivalent to the stress in a printing press.
Taking the mass of 160 g and a sample width of 10 cm the result is a defined stress of 160 N/m.

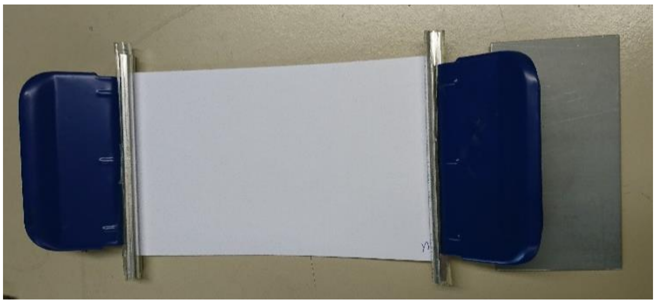

***Figure 40**. Picture of the clamped sample.*

***Figure 41**. Picture of the lower clamp which has exactly 160 g*

Figure 40 and **Figure 41** show the designed clamps. The workflow of the hot air drying experiment is as follows:

- each sample is cut out of A4 paper sheets, the top side is marked
- analysis of the untreated paper with laser sensor
    - 20 mm/s speed of the linear table
    - 2 measurements with the laser sensor with 60 Hz
- printing process
    - 1333 mm/s speed
    - all colours in row
- manually clamping of the printed sample on both sides
- drying under defined stress for 15 seconds at 150 °C in an oven with circulating air

- analysis of the treated paper with laser sensor with 60 Hz
    - 20 mm/s speed
    - 3 measurements right after the drying process
    - 20, 40, 60 seconds after the drying process

***Figure 42**. Result of the hot air drying experiment with 4x70 % ink and primer application*

Figure 42 illustrates a result of the hot air drying experiments. Due to the reason that these results are not fitting to the rest of the experimental results, they will not be further discussed in the results and conclusions section of this thesis. It is unclear why all papers curl like the sample shown in **Figure 42**. Also an influence of the clamping cannot be excluded. The results of these experiments and the long-term curl will be documented in the Appendix.

3.3 Evaluation of the curl samples

3.3.1 Evaluation of the laser-sensor data using MatLab

After measuring the curl samples with laser sensor at 60 Hz the result of each measurement is a data-matrix. The first step was a simplification of this huge matrix to a 256 x 256 matrix. The number of rows and the number of columns of each matrix was calculated and simplified to a quadratic matrix with 256 values. This happened directly after the measurement at Poing with an existing Perl script. After this step, the evaluation was performed using MATLABMATLAB. **Figure 43**show the raw data profile.

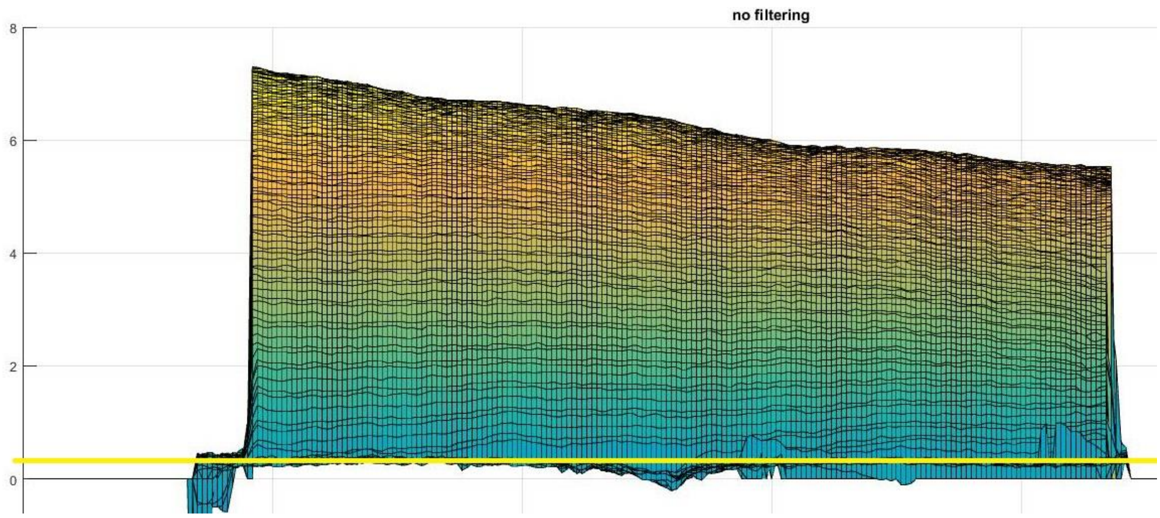

***Figure 43**. Curl matrix without filtering. The yellow line indicates the offset of the Y-Axis and the linear tabel.*

The first step after reading the matrix is a median filter application. This was done due to the reason to get a smoother surface using the exponential fit. The next step was to fit the Y- axis to the desk level in order to have them synchronized. In order not to falsify the matrix the chosen filter is a median filter, not a means filter. Therefore, each remaining value after the filtering is a real measured height value and not a calculated mean value.

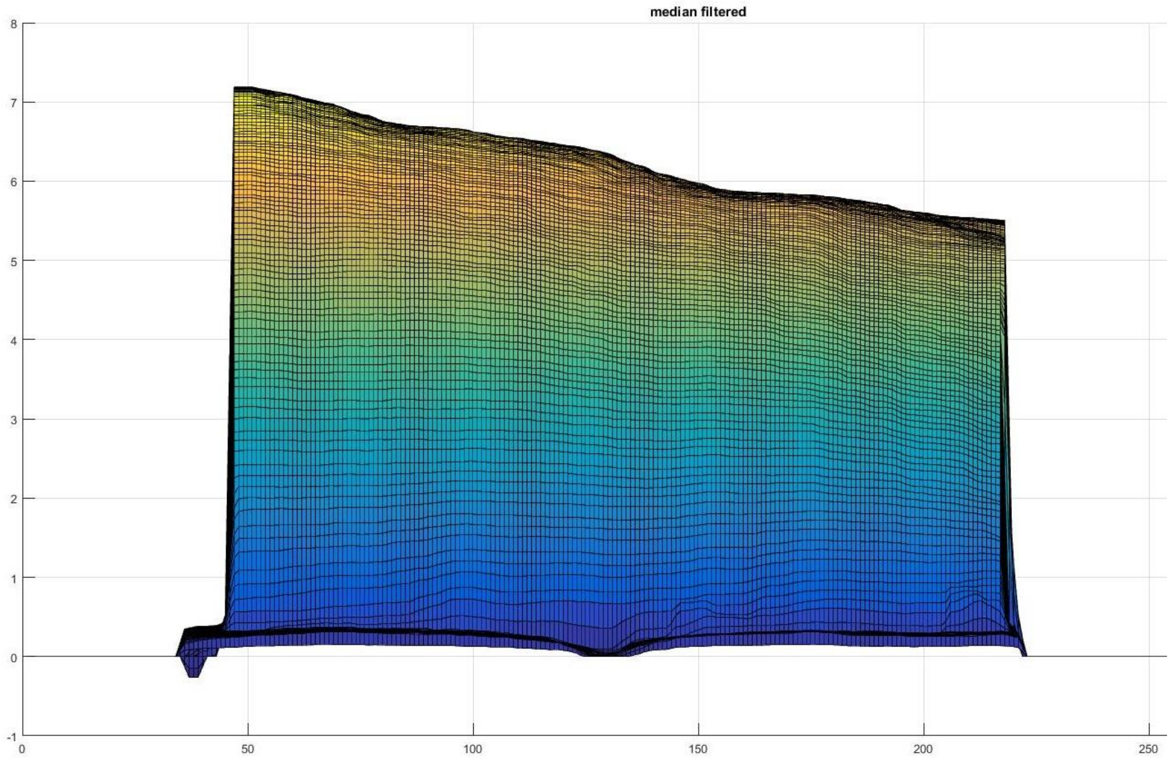

Figure 44. *Curl matrix with median filter application*

Using the results after median filtering (see **Figure 44**), a fitting procedure was applied. **Equation 4** shows this fitting function taking account the three curl types discussed in chapter 2.2 Mechanism of curl which is the base for the MATLAB fitting procedure.

Equation 4*. Curl- Fit equation which is used in the fitting procedure in MATLAB [1], [6]*

x- curl	$z = x^2 * k_x$
y- curl	$z = y^2 * k_y$
diagonal- curl	$z = x * y * k_d$
Total curl	$z = x^2 * k_x + y^2 * k_y + x * y * k_d$
Total curl with displacement	$\boldsymbol{z = (x-a)^2 * k_x + (y-b)^2 * k_y + (x-a) * (y-b) * k_x + c}$

where the <u>displacement constants</u> (explained at **Figure 45**) are:

$$a \rightarrow displacement\ x^{+};\ b \rightarrow displacement\ y^{+};\ c \rightarrow displacement\ z^{+}[m]$$

and the <u>curl- values are:</u>

$$k_x;\ k_y;\ k_d\ \left[\frac{1}{m}\right]$$

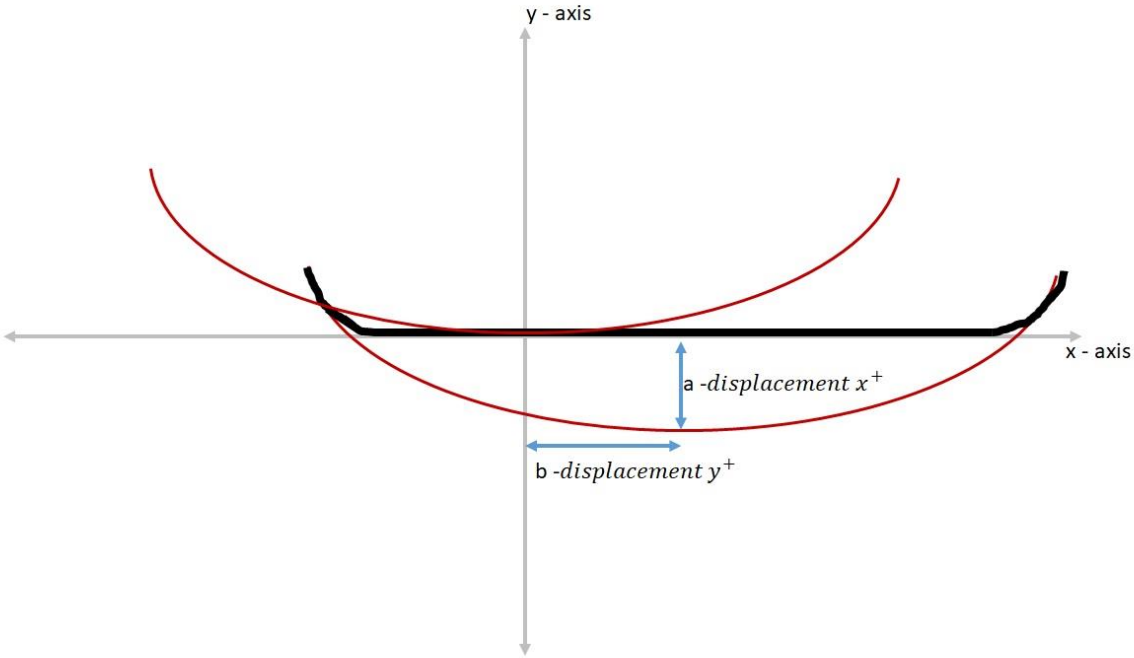

***Figure 45**. sketch of the fit principle in 2 dimensions. The curl sample (black fat line) has a fit within a parabolic eyuation. The result is the red parabel. Its displacement to the x and y axis are characterized with the constants a and b. Due to a better understanding the third dimension fit, which uses the same priciple, is not shown*

Further, the algebraic sign-convention for the curl and the axes have to be defined. A mathematical positive curl is present if the sample rolls from the plate with its edges, a negative curl is present if the sample rolls from the plate with its middle part. **Figure 46** and **Figure 47** illustrate the definition of positive and negative curl.

***Figure 46**. Sketch of a positive curl sample after printing. The red colour indicates the printed side.*

***Figure 47**. Sketch of a negative curl sample after printing. The red colour indicates the printed side.*

In addition, the axes of curl have to be defined. A x-curl is defined as a rising of the edges or the body along the x-axes. **Figure 48** shows an image of a paper with a negative y-curl. It is a y-curl, as it rises along the y-axis, and it is negative because the sample rolls away from the plate with its middle part. Alternatively, **Figure 49**. indicates a positive diagonal curl.

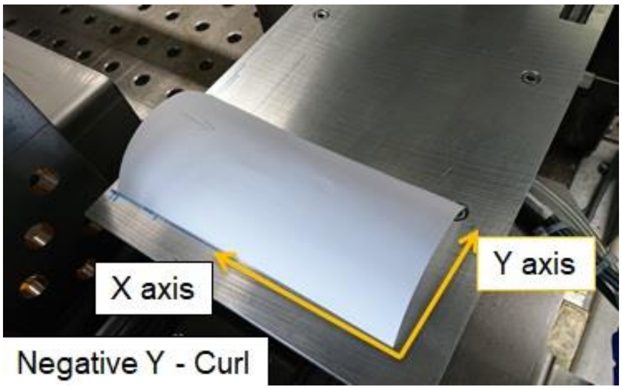

***Figure 48**. Illustration of a paper showing negative y-curl.*

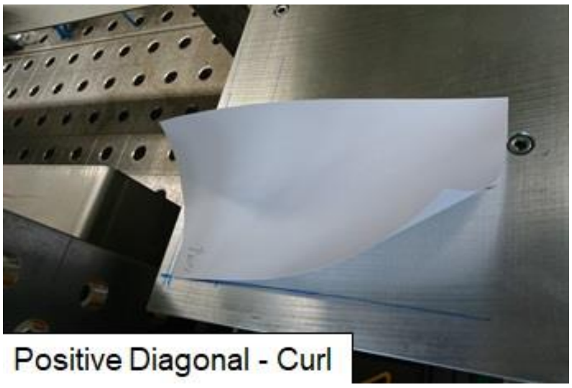

***Figure 49**. Illustration of a paper showing positive diagonal curl*

Figure 50 to **Figure 53** are the result of a typical high ink amount printing on an AKD sized paper. While **Figure 50** demonstrates the negative curl, which is the result of top side printing on an AKD sized paper, **Figure 52** represent a positive curl of an AKD sized paper. The values below the two charts at and represent the fitting values from the MATLAB fit based on Equation 4, the coefficient of determination of the fit and the displacement constants. The values below are the result of the mathematical fit with X curl, Y curl and Diagonal Curl representingk_x, k_y and k_d and X disp Y disp and Z disp representing a, b and c.

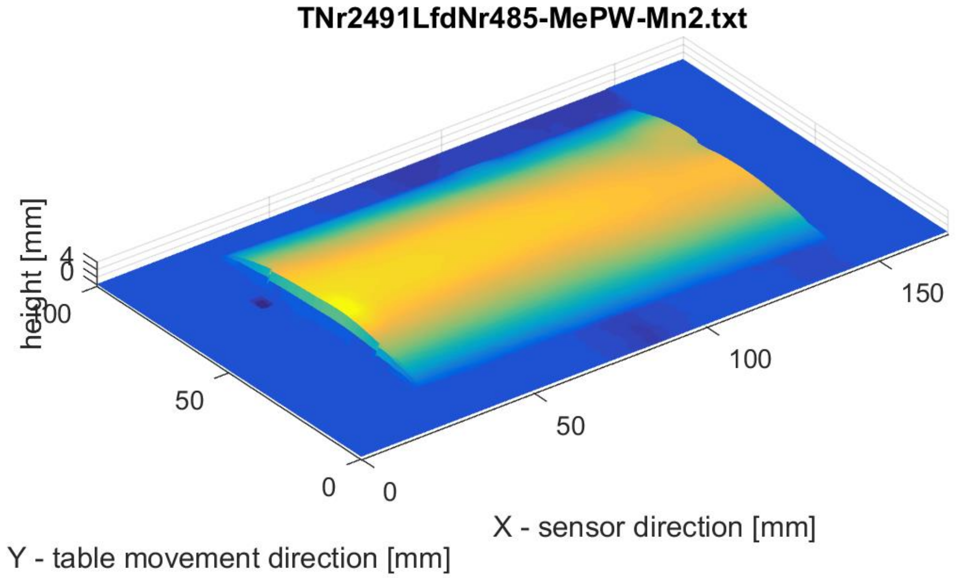

Figure 50. *Curl picture of the median filter and the MATLAB fit of a negative culred paper sample*

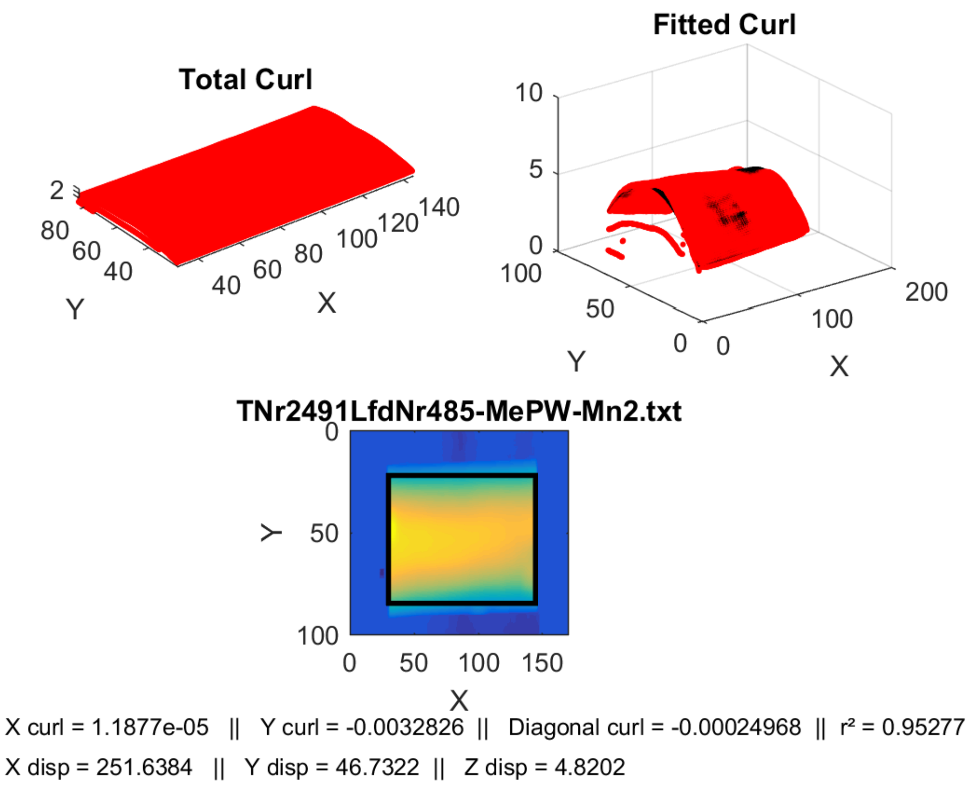

Figure 51.*Result of the MATLAB fit. The picture in upper left corner shows the fitted total curl, in the upper right corner with black the fitted figure and with the red points the measured values. The picture below shows the set frame for the fit.*

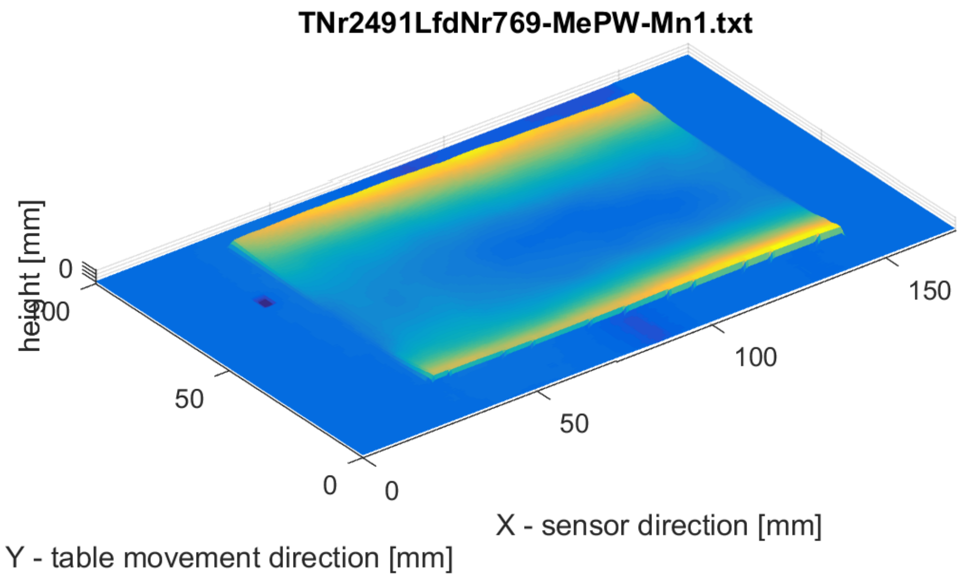

Figure 52. *Curl picture of the median filter and the MATLAB fit of a positive culred paper sample*

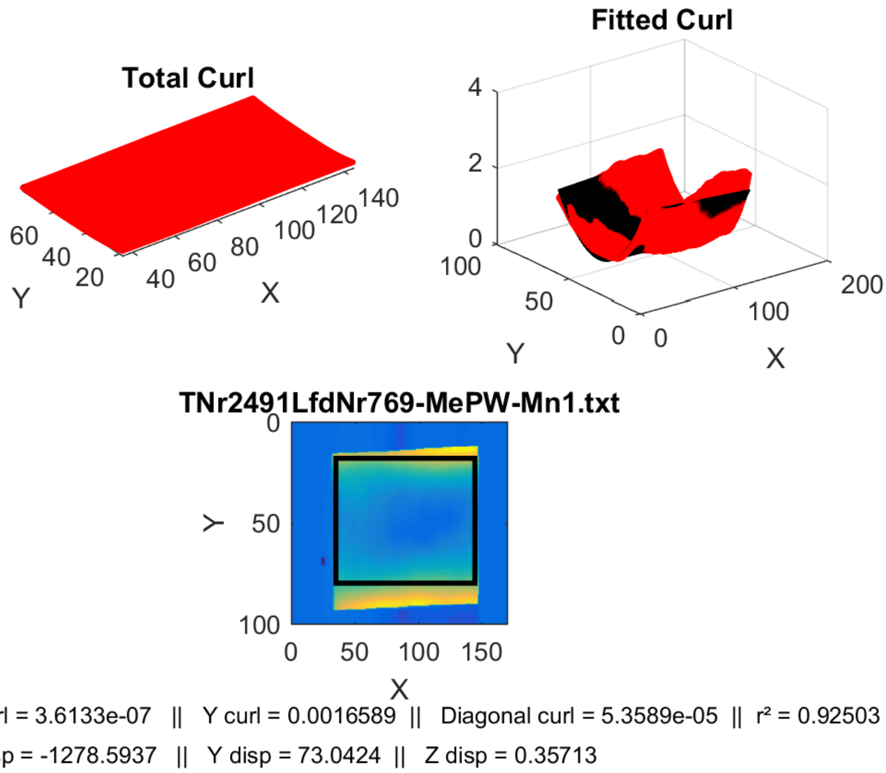

Figure 53. *Result of the MATLAB fit. The picture in upper left corner shows the fitted total curl, in the upper right corner with black the fitted figure and with the red points the measured values. The picture below shows the set frame for the fit.*

The second result of this measurement and the fit is the curl height function. It is a graph, which represents the maximum value in each column of the matrix. The red marked point indicates the maximum rise of the sample. This red marked point and the curl values were used afterwards for the graphs depicting the results.

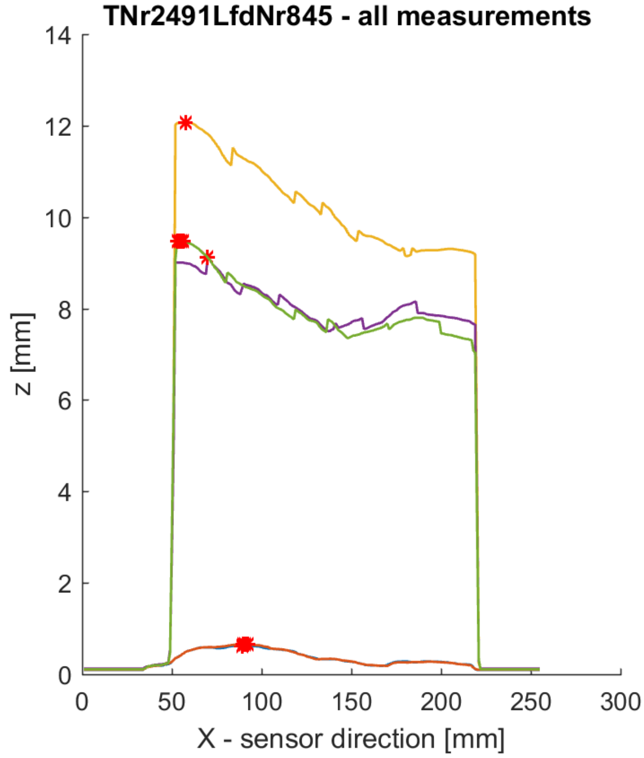

Figure 54. *Curl height trend of the printed sample. The first two measurements are the base paper measurements, the three following represent the measurment after printing.*

3.3.2 Validation of the method and its limits

To identify the standard deviation and the reproducibility of the developed curl analysis methods, hand curled paper sheet and a metal standard were produced. These standards were measured several times regarding the curl factors and the curl height. The standard deviation of the curl fit parametersshows some fluctuation, the maximum curl height and the position of this value does not fluctuate.

- variation coefficient of curl fit parameters: 12,5 % $\pm 1\ \sigma$
- variation coefficient of maximum curl height and its position: <1 % $\pm$ 1 σ

Figure 55 and **Figure 56**show the results of these validation measurements.

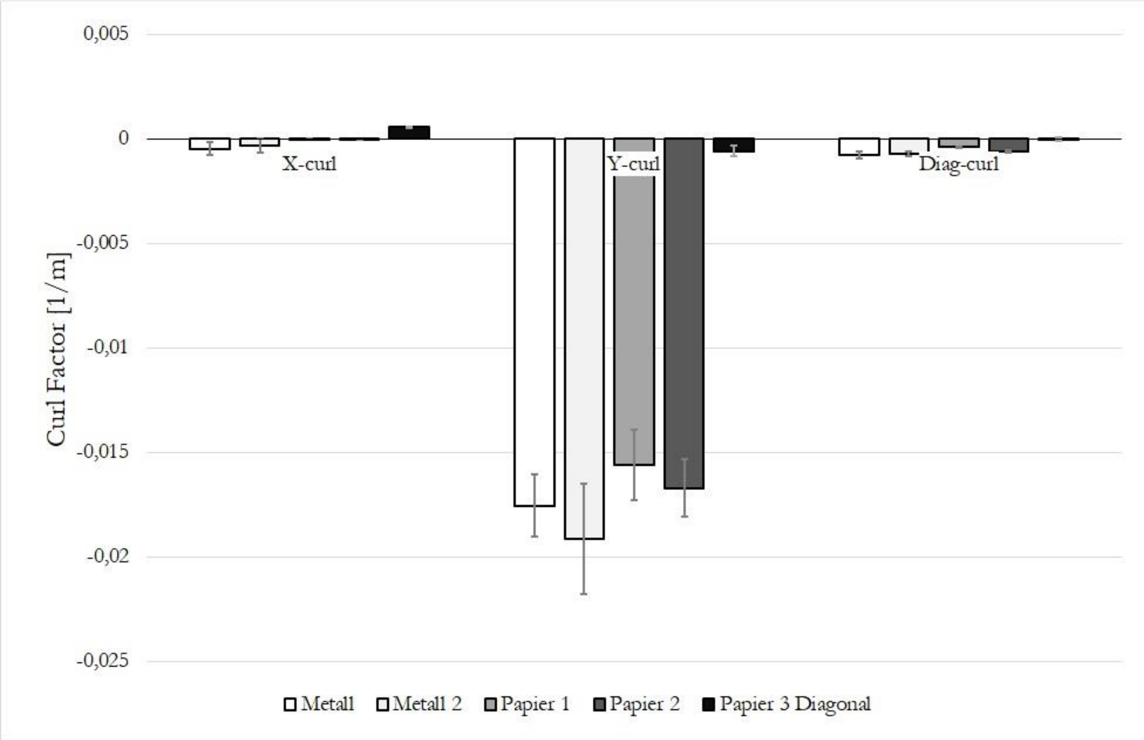

***Figure 55**. Curl values MATLABobtained using the MATLAB procedure for the differnt hand formed curl samples and the metal curlstandard; number of samples n=7; error bars depict the standard deviation.*

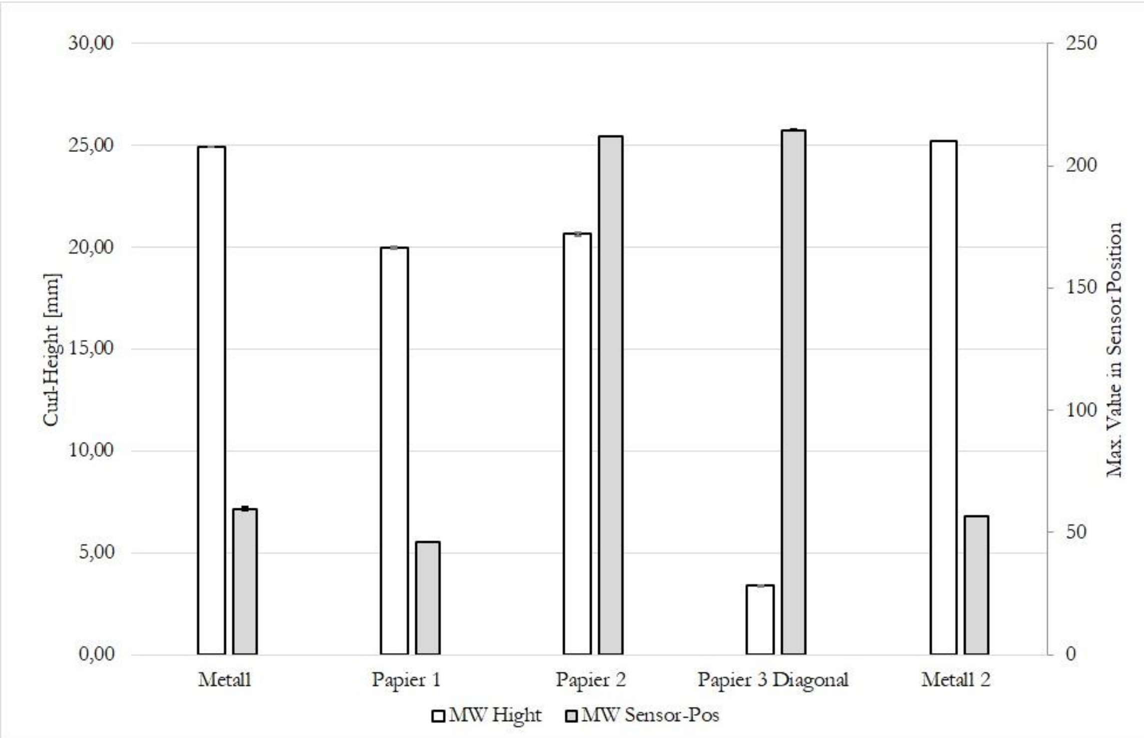

***Figure 56**. The average maximum curl height and the position of this curl height; number of samples n=7; error bars depict the standard deviation*

Nevertheless, the developed method has one drawback. Each fit has to be controlled manually regarding its correctness. Especially in the rare cases where the type of curl is unclear, the MATLAB routine fits a result, which has a better coefficient of determination than the actual curl behaviour, but still it is wrong.

One good example for this drawback is the primer printing experiment performed with calendered paper. **Figure 57** depicts a curled sample of a calendered paper.

Visually a negative curl is observed.

Nevertheless, as can be seen in **Figure 59** the fiting routine detects a positive curl, because of the curvature in the center of the sample. The MATLAB routine neglects that the edges are not rolled upwards which should be the indication for a positive curl. This problem is caused by the mathematical definition of the curl formula itself, which is a second order function. The type of curvature depicted in **Figure 57** and **Figure 58**, however, can only be represented by a function of a higher order.

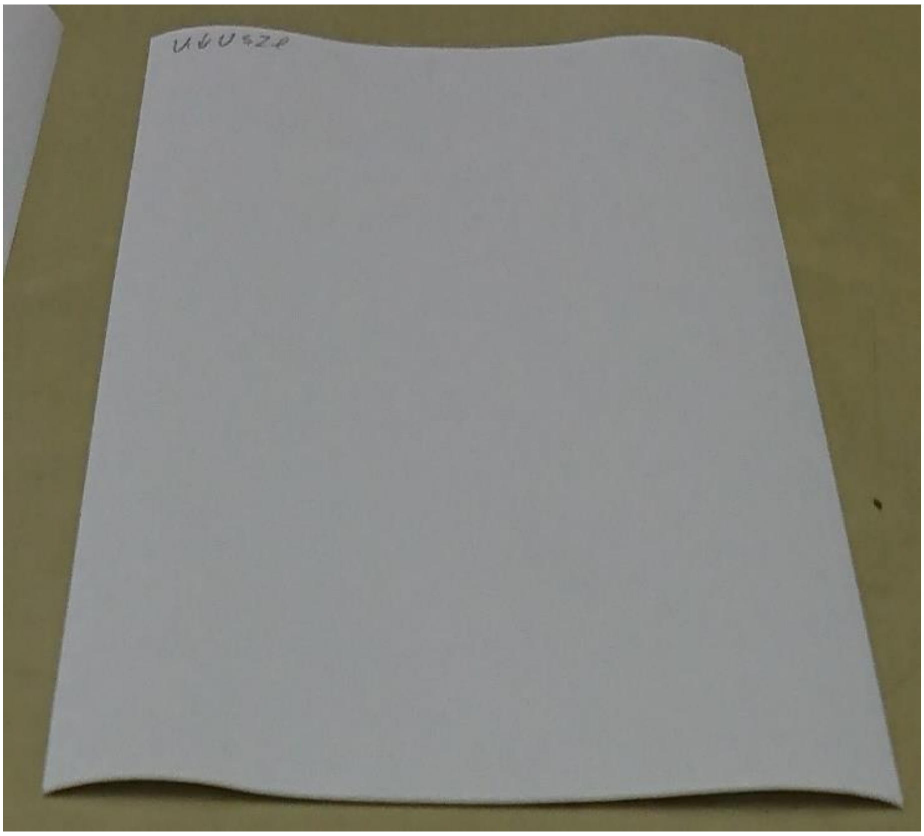

***Figure 57**. Long- term- curl of just primer application on a calendered paper after 12 hours. It is good to see, that the curl is negative. The edges are not lifted.*

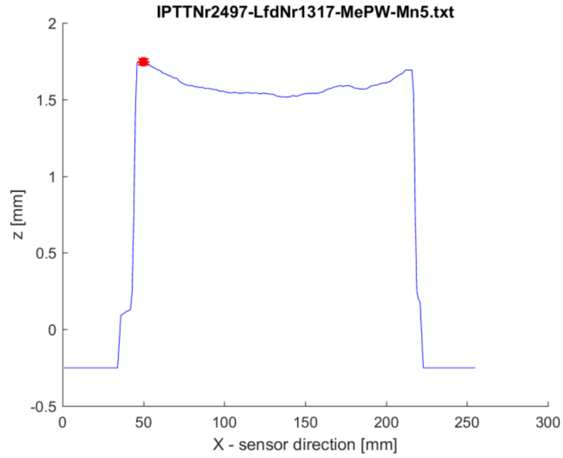

Figure 58. The curl height function of this sample. It also indicates a negative curl

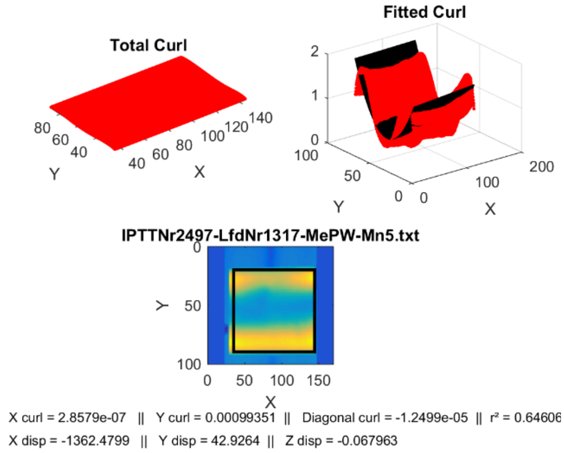

Figure 59. Wrong fit with the mathematical positive curl. However the r² is at 0,65

3.3.3 Explanation of the diagrams based on the data of the MatLab fitting routine

The generation of the charts, which are used in the results part, will be explained on the basis of the first experiment, which was high ink amount printing with primer. As already mentioned the results out of the MATLAB fit are the maximum curl height and the curl parameters itself.

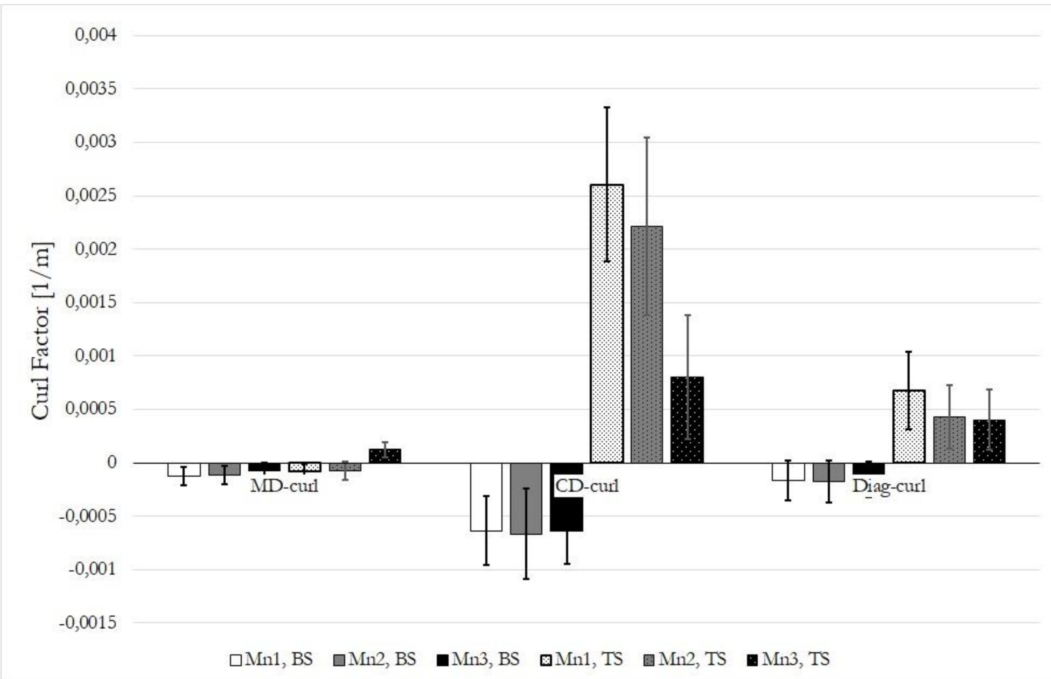

***Figure 60**. Curl parameters of the unsized paper, printed with 4 times 70 % ink coverage and primer; number of samples n=11 each. Error bars depict 95% confidence interval.*

Figure 60 shows the curl parameters for the unsized paper. 11 samples were prepared in the way a depicted in **Figure 34**. Therefore, this chart represents 22 samples. 11 for top side printing and 11 for backside printing.

The three bar-groups represent the three curl parameters. A negative bar value indicates a negative curl (e.g. **Figure 46**/ **Figure 47**), a positive bar value indicates a positive curl. The full tone bars represent the measurements printed on back- side; the dotted bars represent the top- side printed samples.

White bars indicate the first measurements after 20 seconds (Mn1), each grey bar the second measurement after 40 seconds (Mn2) and the black bars the last measurement after 60 seconds (Mn3). **Figure 61** depicts the second group of results obtained by the MATLAB program, the final maximum curl height. As can be see this curl height decreases within the first 60 seconds.

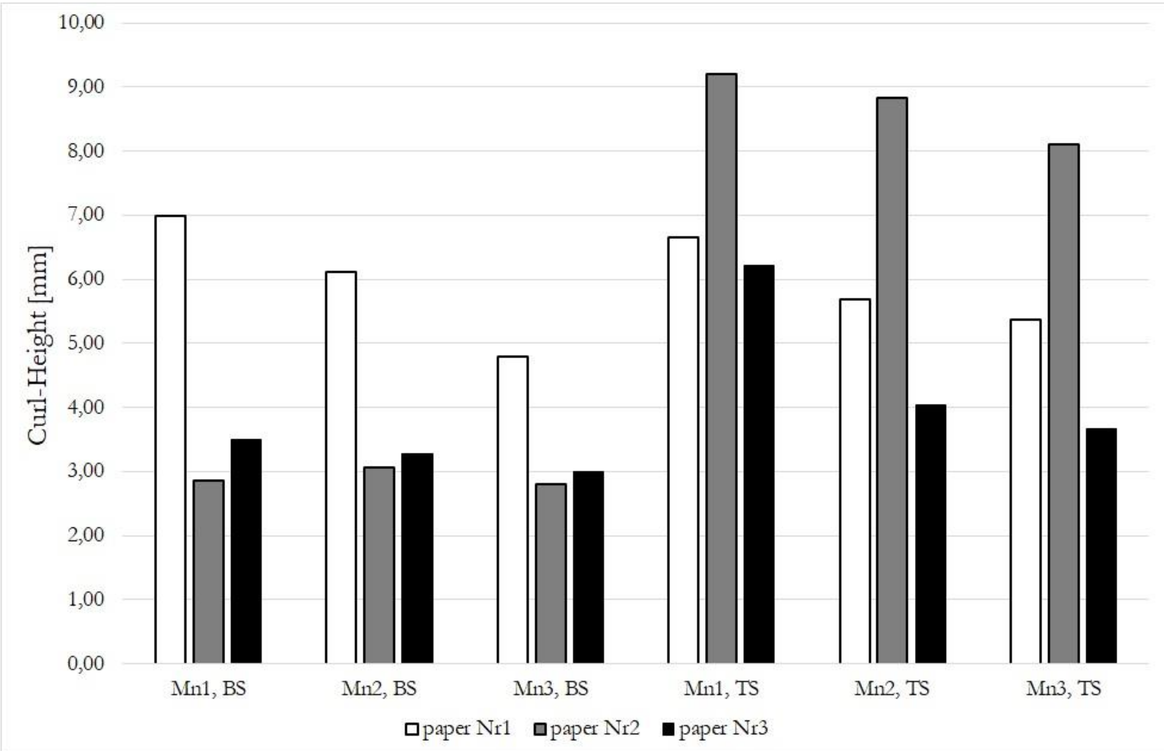

***Figure 61**. Curl height trend for three out of the 11 samples of the unsized paper for back side and top side printing.*

This evaluation was performed for all four papers. **Figure 62** and **Figure 63** thus sum up the measurement results for a total of 88 samples.

Figure 62, which sums up the curl parameters, shows the mean value of the three measurements after 20, 40 and 60 s for bottom- and top side. This was done as the interest focusses on the

behavior of within the first 60 seconds. Due to this the confidence intervals are wider because the curl parameters change during this three measurements.
To distinguish between the bottom- and top-side the bars representing the top side printing are dotted bars again. The different paper grades are depicted in different grey shades.

The same method was applied to the curl- height values in **Figure 63**. Four bars represent the measurement of one paper side, three of them the measuremnet after 20, 40 and 60 seconds. The last bar represents the mean value of the first 3 bars and its confidence error bar with α=0,05.
The charts shown in **Figure 62** and **Figure 63** both show important information. The goal was to merge these two charts into one in order to reduce the amounts of diagrams needed to illustrate the results of the high number of printing tests and to thus allow a better readability and easier understanding of the results in this thesis.

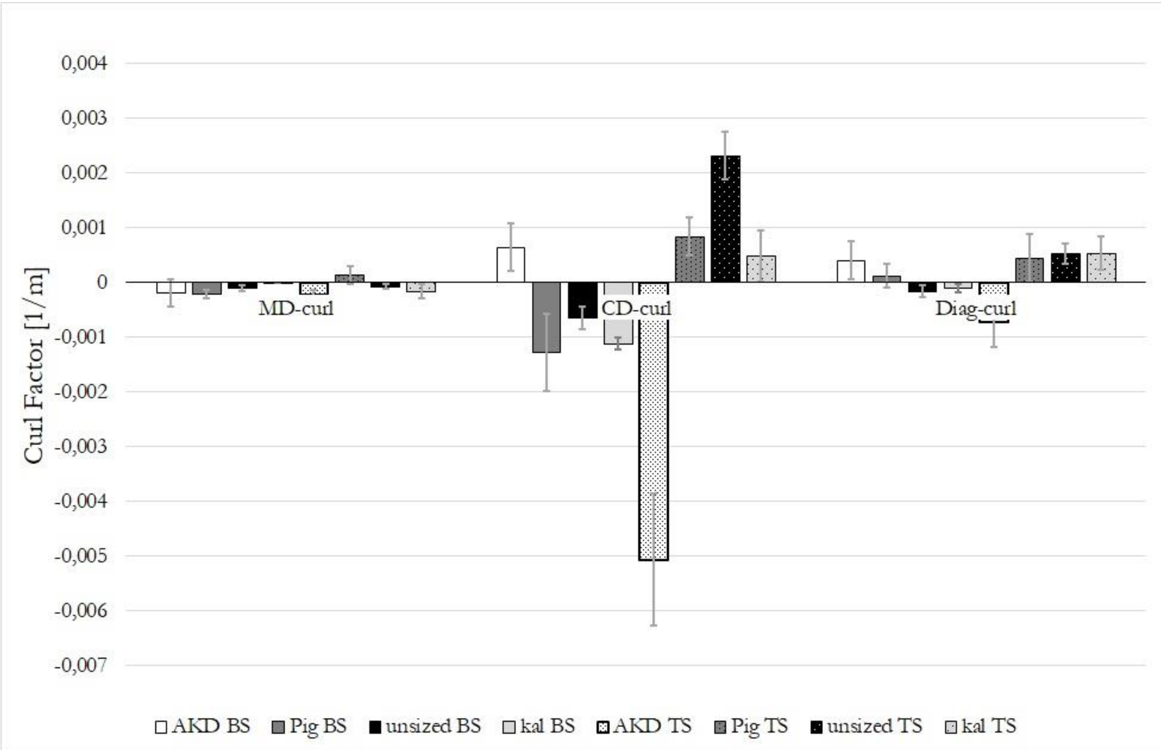

***Figure 62**. Curl parameters of all four papers printed with 4x70% coverage with latex pigment ink; number of samples n=11 each. Error bars depict 95% confidence intervals*

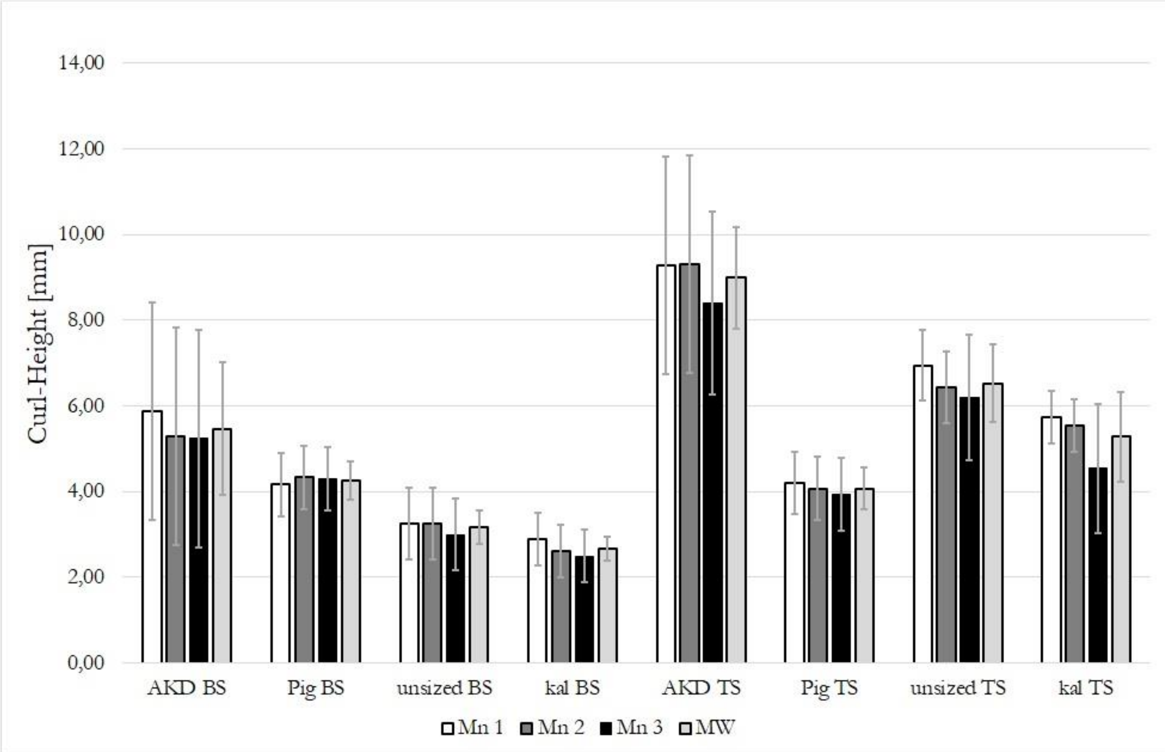

Figure 63*. Curl- height of all four papers*

The result of this merging of the two diagrams can be seen in **Figure 64**. The curl height is expressed as the sum of the three curl parts. Each paper grade is represented by two bars, one for the top and one for the bottom side printed samples. The overall height of each bar indicates the average value of the curl height measurements.

The three curl types are now merged into to curl height based on their ratio. The error bars are the error bars of the curl height measurement. To illustrate the procedure the calculation of the values depicted in **Figure 64** will be demonstrated in the following for the AKD sized paper printed on the bottom side (bar labelled AKD BS in **Figure 62**):

For this paper sample the mean values of all measurements regarding curl parameters and a curl heights for the bottom side printing within the first 60 seconds (i.e. after 20, 40 and 60 s) and the confidence interval for the curl height are listed in **Table 13**.

Table 13*. Mean values of AKD sized paper printed on bottom side*

MD_{curl} [1/m]	CD_{curl} [1/m]l	$Diag_{curl}$ [1/m]	curl- height [mm]	CI (α=0,05)
-0,000185165	0,000643552	0,000399099	5,47	1,551419657

Assuming, that the machine direction (MD), the cross direction (CD) and the diagonal curl should amount to 100 % their ratio is calculated using Equation 5:

$$MD_{ratio} = \frac{MD_{curl}}{(|MD_{curl}|+|CD_{curl}|+|Diag_{curl}|)} \quad \textbf{Equation 5}$$

Using this ratio, the MD curl part of the mean curl height value can be calculated according to Equation 6. The CD curl part and Diagonal Curl part is calculated following the same principle according to Equation 7 and 8 respectively:

$$MD_{part} = Curlheight_{mean} * \left[\frac{MD_{curl}}{(|MD_{curl}|+|CD_{curl}|+|Diag_{curl}|)}\right] \quad \textit{\textbf{Equation 6}}$$

$$CD_{part} = Curlheight_{mean} * \left[\frac{CD_{curl}}{(|MD_{curl}|+|CD_{curl}|+|Diag_{curl}|)}\right] \quad \textit{\textbf{Equation 7}}$$

$$Diag_{part} = Curlheight_{mean} * \left[\frac{Diag_{curl}}{(|MD_{curl}|+|CD_{curl}|+|Diag_{curl}|)}\right] \quad \textit{\textbf{Equation 8}}$$

Table 14*. Result of the curl- part calculation for the AKD sized paper printed on the bottom side*

MD_{Part} [mm]	CD_{Part} [mm]	$Diag_{Part}$ [mm]	curl- height [mm]	KI (α=0,05)
-0,82	2,87	1,78	5,47	1,5514

Summing up the three curl parts listed in **Table 14**results in the curl height of this sample.

This procedure is carried out for each of the paper samples resulting finally in the diagram depicted in **Figure 64**.

This type of presentation of the results is used throughout 4 Results of the experiments in order to allow a condensed depiction of the main findings of the trials.

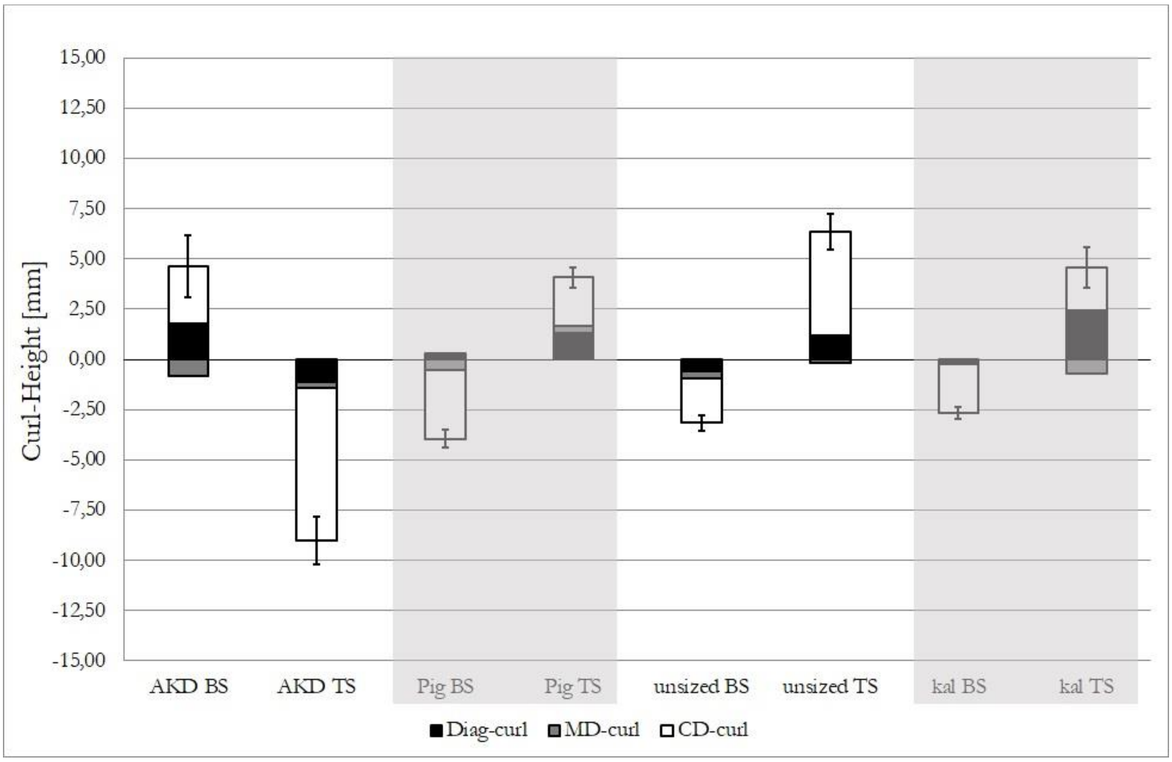

***Figure 64**. Curl- height as a function of the curl factors which result from the MATLAB fit. Plot for all four papers printed with 4x70% coverage with latex pigment ink; number of samples n=11 each. Error bars depict 95% confidence intervals for curl height*

4 Results of the experiments

For each of the experiments the result of the preceding trial has been used to form the research question of the following experiment. This it is advisable to read the entire chapter as a whole instead of individual sections.

4.1 Blanco printing

Blanco printing or sometimes in printing industry also called "just fixation" means the application of thermal fixation to the paper without previous printing. The experiments were done with the standard thermal fixation method of the IPTS. The paper was stored under standard conditions (50% RH and 22,5 °C) for at least 24 hour before doing this experiment.
These IPTS standard-drying conditions are:

- 123 [°C] surface temperature of the vacuum heating plate
- Residence time of 2 [s] at the hot plate
- Sutured pressure at ~ 0,6 [bar]

Previous experiments which compared printing and thermal fixation at two and four seconds duration showed, that the paper is absolutely bone-dry after this standard drying time of two seconds. Therefore this trial and all other experiments were just done with two seconds residence time.
As can be observed in **Figure 65**, the curl after thermal fixation of three out of the four model papers depends on the respective paper side.
The three parts of each bar represent the machine direction, the cross direction and the diagonal direction part of the curl and are the result of the already described Mat Lab fit. The total height of each bar represents the mean value of the maximum curl height out of three measurements, which were done after 20 seconds, 40 seconds and 60 seconds after the fixation. The AKD sized paper, the unsized and the pigmented paper flip the side of the curl. Taking a closer look at this graph, the yellow arrows show the direction of this change. The change direction is the same for the pigmented and the unsized paper, which were produced on the same paper machine. The direction of change of the AKD sized paper is contrary to the other three model papers.

It is also clearly visible, that the dominant curl part of all four papers is the cross-direction (CD) part. The calendered paper does not flip the side by drying from back- or top side. In addition, its average curl height value (1,25 mm on back side and 1,35 mm on top side) is at a tiny level.

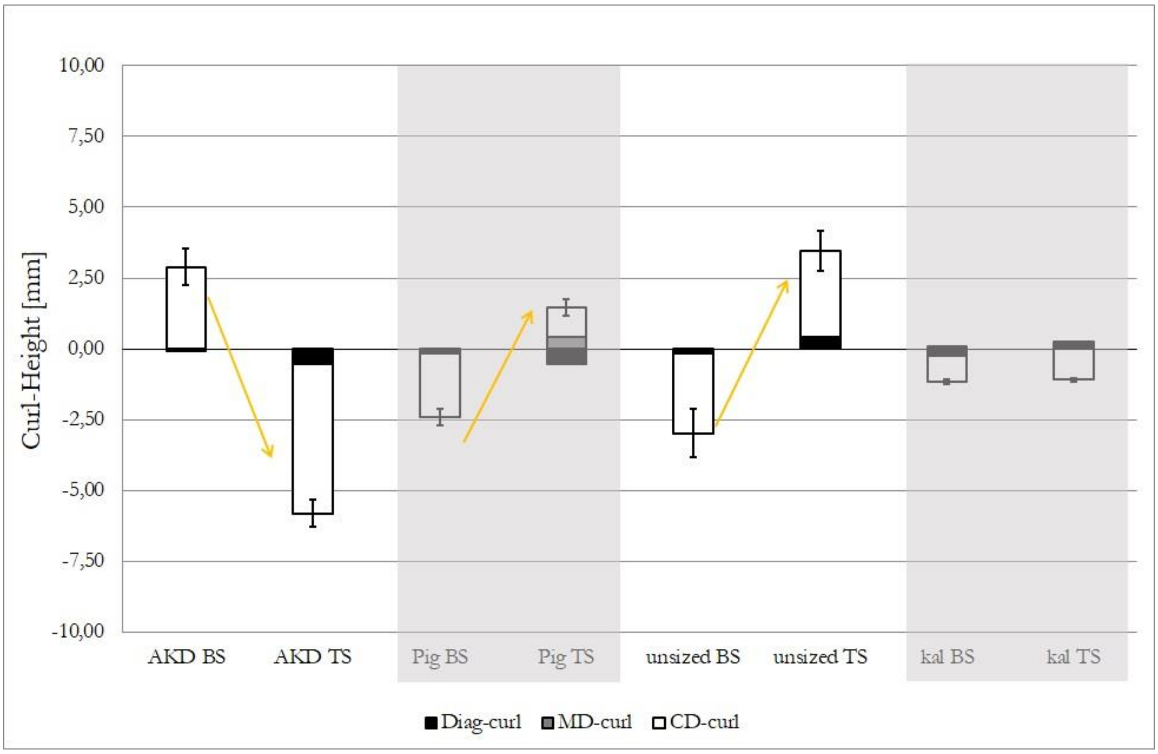

Figure 65*. Short term curl of a 2 seconds fixation experiment with all four model papers; number of samples n=5 each. Error bars represent confidence intervall α=0,05*

Additionally, a long-term measurement of the curl was carried out. The following four charts show the maximum curl height at different times after the blanco printing, which is the result of the laser sensor measurement. The red marked spot locates the maximum curl height of the entire sheet. The measurements at 20, 40 and 60 seconds are alse the result in **Figure 65**.

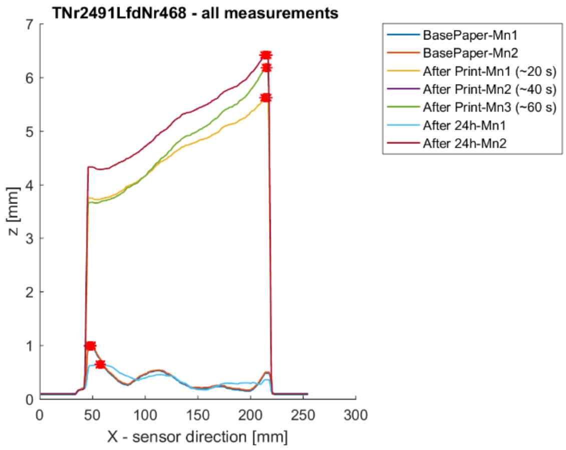

Figure 66. *Maximum curl height of one AKD sized paper before fixation, right after fixation and 24 hours after fixation*

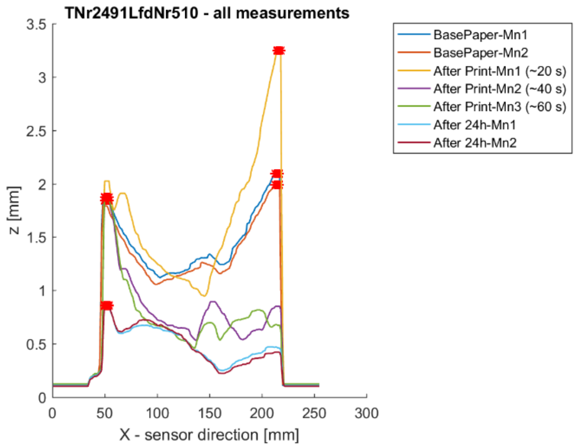

Figure 67*. Maximum curl height of one pigmented paper before fixation, right after fixation and 24 hours after fixation*

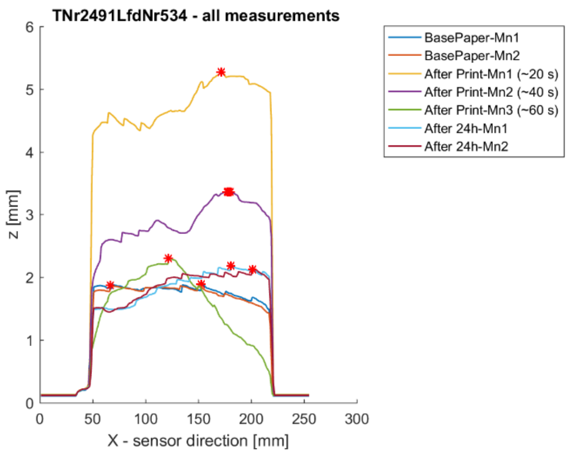

Figure 68 *maximum curl height of one unsized paper before fixation, right after fixation and 24 hours after fixation*

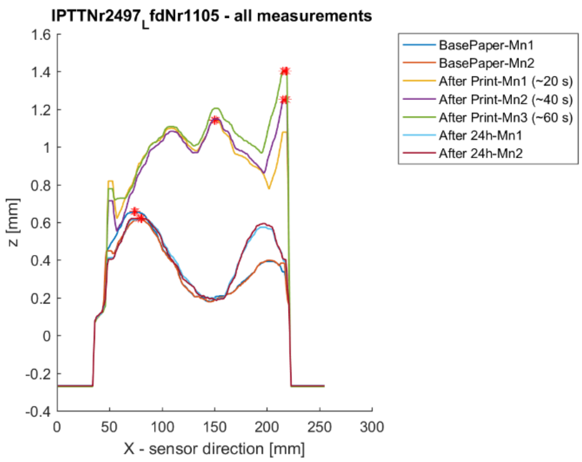

Figure 69 *maximum curl height of one calendered paper before fixation, right after fixation and 24 hours after fixation*

Measurement number (Mn) one and two are two base paper measurements of the same paper before blanco printing. The next three Mesurements (within the charts as shortcut Mn) are those, which were done after 20, 40 and 60 second after fixation, and the last two are paper measurements after 24 hours storage at 50% HR and 22,5 [°C]. All four charts showed that the curl height of all four papers is after 24 hours at the same level as before the blanco printing. This means that the curl triggered by thermal fixation without printing is fully reversible.

The comparison of this reversible Short-Term-Curl of all four model papers also shows the difference of them regarding the curl- height and the curl form. As can be observed in **Figure 66** and the curl- form of an unsized and an AKD Sized paper is smooth, while the curl-form of the calendered paper (**Figure 69**) is more uneven and the curl form of the pigmented paper (**Figure 67**) is most uneven. The Curl height of the AKD sized paper is more or less stable during the first 60 second while the curl height of the unsized paper after 60 seconds is lower than 50% of the start value.

<u>Conclusion</u>:
This corresponds with theory, that a pure drying curl is reversible and has no long time effects.
→ no irreversible curl released.

4.2 Conventional printing with latex pigment ink

This conventional printing experiments which that means all four colours are printed in sequence with and without primer, was done to check the influence of ink amount on curl.

4.2.1 High ink amount of latex pigment ink with primer application

To see a sharp effect, the fist experiments were done with a very high ink amount. The chosen ink amount was four times 70% over all coverage full tone printing of all four colour. This sums it up to an ink coverage value of 240%. Standard full tone printing in a commercial reel- to- reel printer has maximum ink coverage of 160%. All designed print jobs are bi-level print jobs. This means, the print heads were driven with fire two impulses and there is just one drop size of 3 [pl].
Figure 70 lists the result of the Short-Term-Curl of this high ink amount experiment with primer of all four model papers. The error bars represent a confidence interval of an α=0,05. It is clearly visible that this Short-Term-Curl is depending on the paper side and flips its side with back- and top side printing. However, contrary to just blanco printing, the calendered paper also flips its side when the printing side is changed.

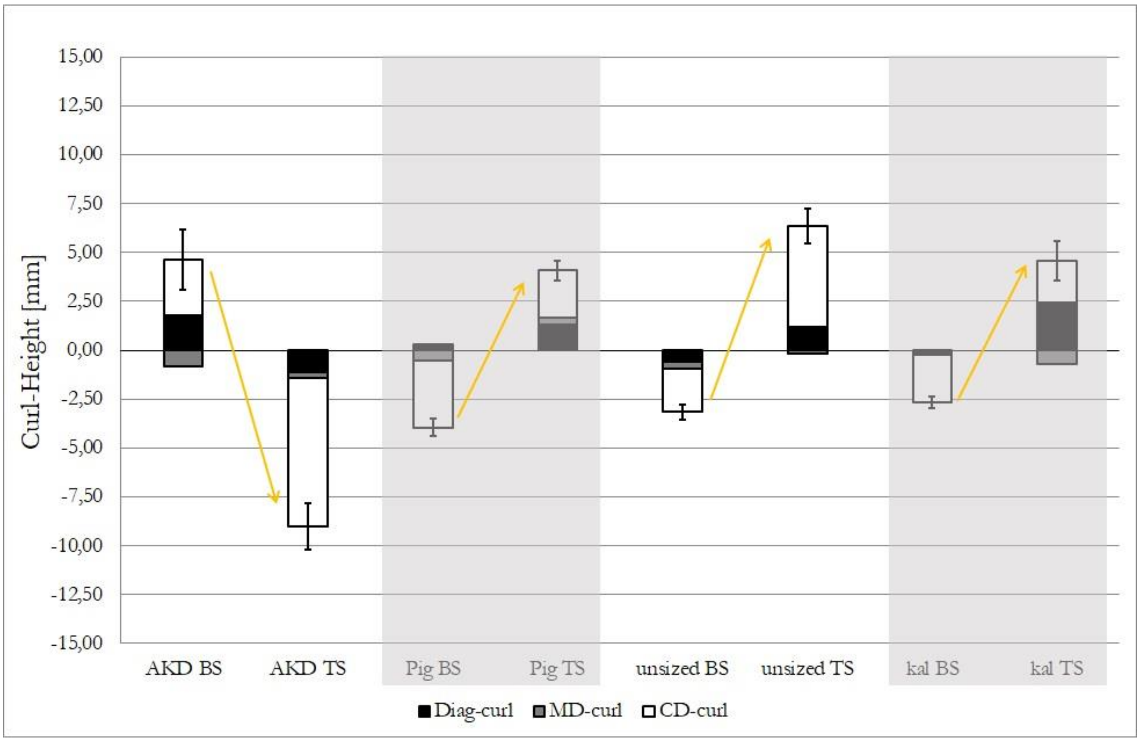

***Figure 70**. hort term curl of the 240% ink couverage experiments of all four model papers with primer; number of samples n=11 each.*

In order to observe of the long- term- curl behaviour all samples were stored under standard conditions at 50% RH and 22,5 [°C] for several hours. **Figure 71** is a picture of this storage after 24 hours. Two of the papers, the pigmented and the unsized paper formed extremely high curl after 24 hours. A measurement of them was no longer possible. The other papers, the AKD sized and the calendered one ended up in conditions that allowed measurements.

The result of this measurement of the short- and long-term behaviour of one AKD sized paper can be observed at **Figure 73**. The grey-lighted part marks the bottom side, the white part the top side. The red boxes represent the short-term-curl values. (20. 40 and 60 [s] after printing and fixation). The green boxes represent the long-term-curl values, which were measured 24 hours after printing.

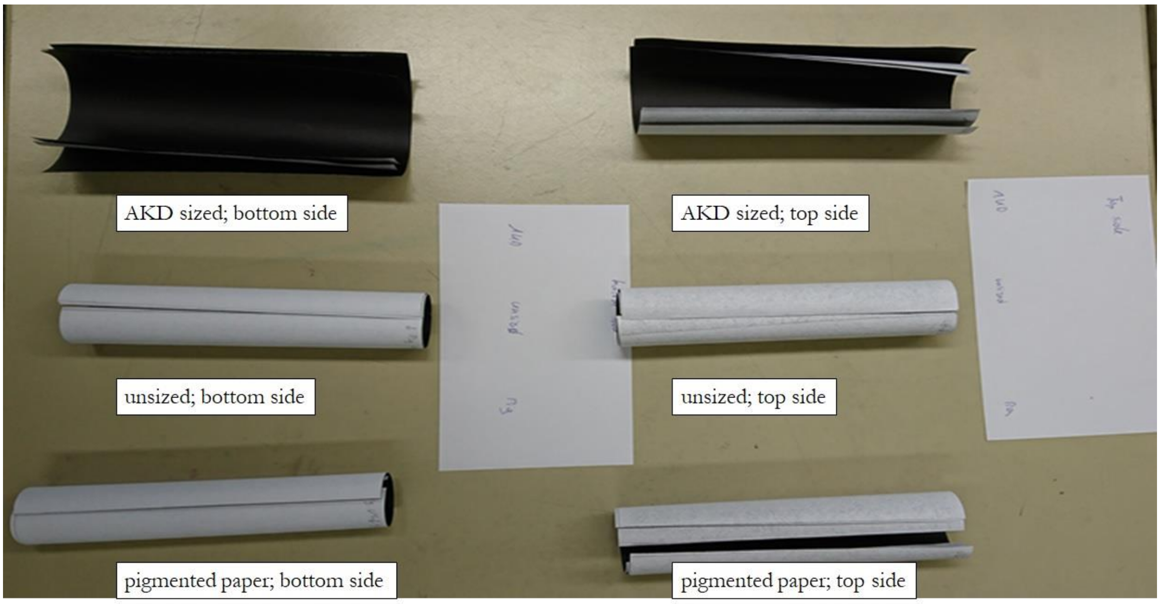

Figure 71*.Three of the four modell papers after 24 hours storage at standard conditionswith 50 % RH and 22,5 [°C].*

The short-term-curl flips its side with the back side and top side. By looking at the yellow arrows, it can be observed that the curl value and height after 4 hour is for both paper sides at the same level and that it is positive. The long-term-curl of both paper sides develops to the printed side and is always positive. This can also be observed with the pictures of the measured paper at **Figure 72**. The long- term- curl thus seems to be governed by the printing side, it always turn to the siede the print was applied on.

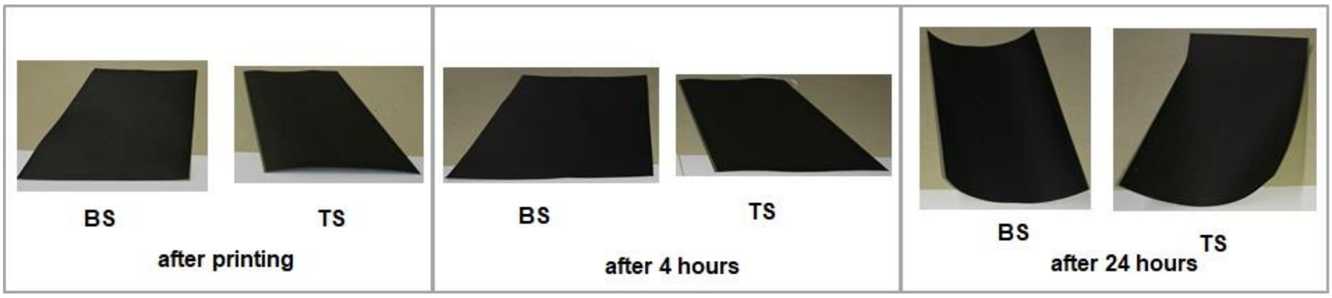

Figure 72*. Pictures of the measured AKD sized paper after 4 and 24 hours.*

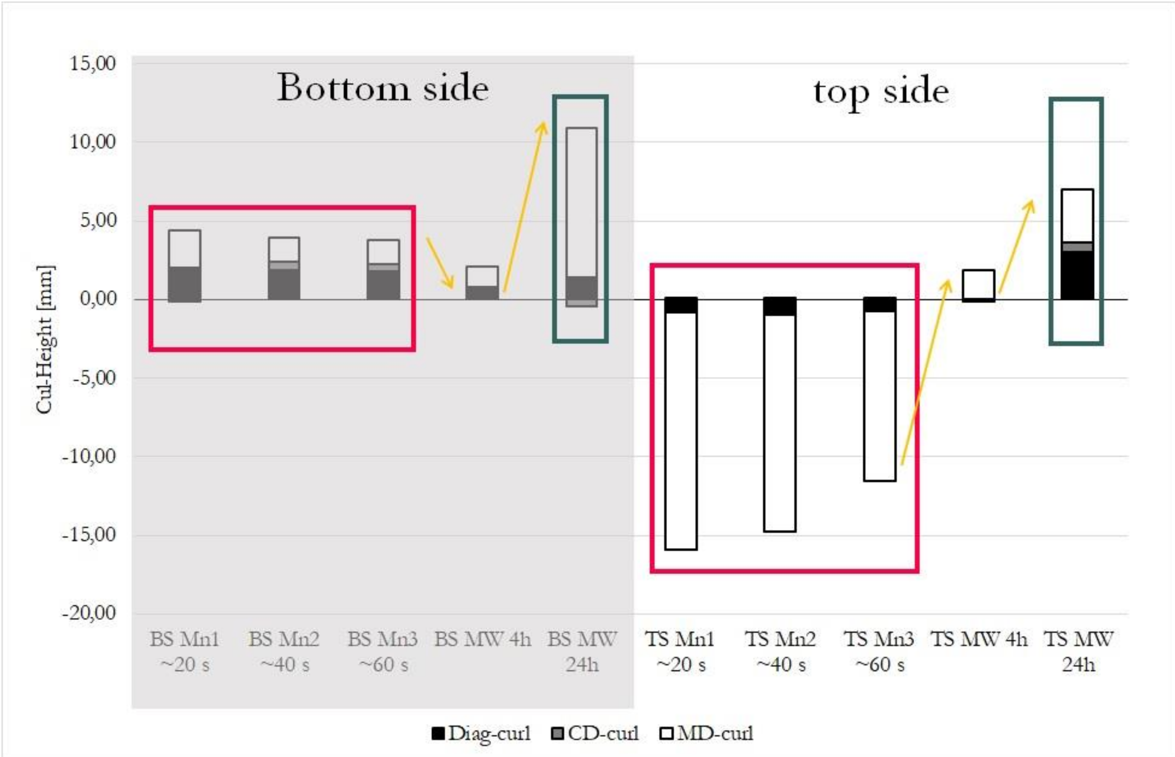

***Figure 73**. Short-, and Long- Term Curl Behaviour of one AKD sized paper sample.*

4.2.2 High ink amount of latex pigment ink without primer application

In order to observe the influence of primer on short- term- curl, this high ink amount experiments (240% coverage) were also done without primer. Due to the reason, that the calendered paper was not available at the time of these experiments, the values for this paper are missing. In general, the results at **Figure 74** have the same tendencies as the printing with primer. The side flips, the AKD sized paper flips to the opposite side than the other papers. By observing the total curl height, we see a significant difference. The curl height of the short-term curl without primer is higher for pigmented paper at both sides (BT, BS) and the curl height of the AKD sized and the unsized paper without primer is higher for the bottom side and lower for the top side. **Table 15** lists this difference.

Table 15. *Influence of primer on short-term curl height*

		without primer [mm]	with primer [mm]	Δ [%]		without primer [mm]	with primer [mm]	Δ [%]
AKD	top side	5,141	9,002	-49,6	bottom side	9,653	5,468	+76
pigmented	top side	4,731	4,073	+18,9	bottom side	7,706	4,267	+81
unsized	top side	2,789	6,528	-60,6	bottom side	13,753	3,464	+400
calendered	top side		5,278		bottom side		2,607	

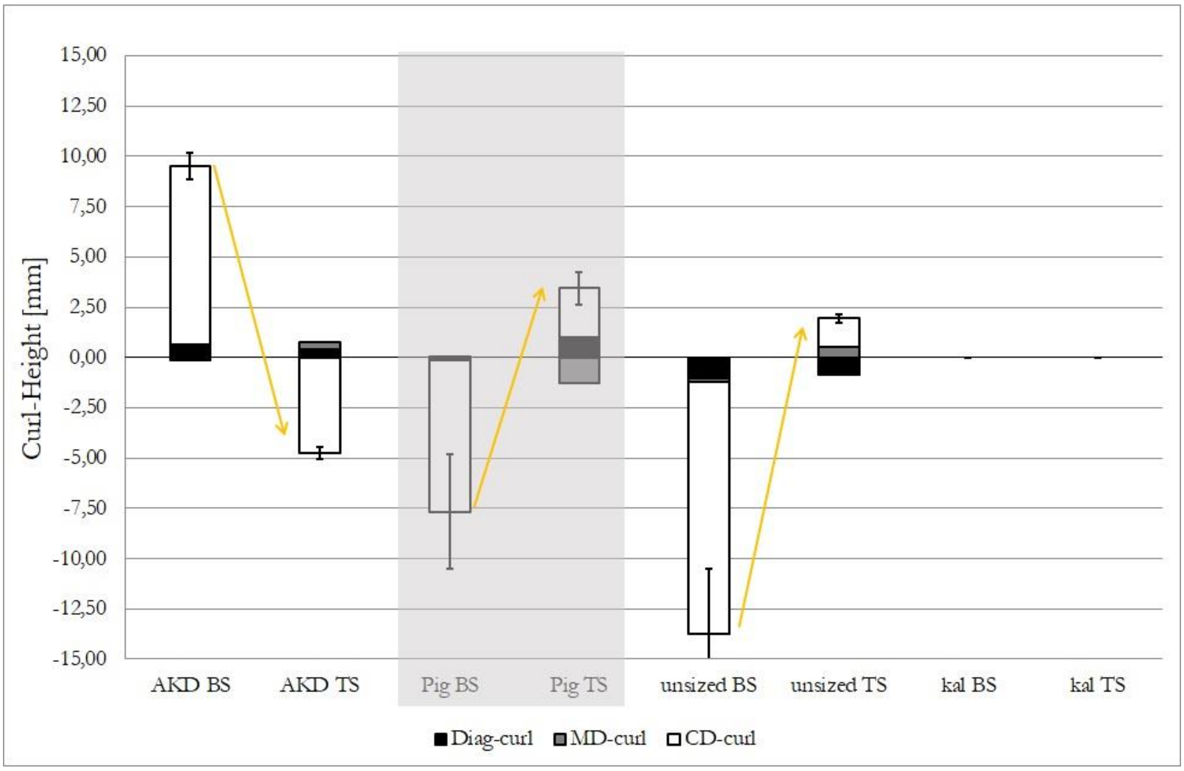

Figure 74. *Short- term- curl of the high ink amount experiments of all four model papers without primer; number of samples n=4 each, 95% cofidence intervals.*

Conclusion:

Primer strongly decreases bottom side curl, the effect on top side is inconclusive, with a tendency on curl raise.

4.2.3 Variation of typical ink amounts of latex pigment ink without primer application

The following four graphs show the result of the ink variation experiments with ink amount, representative for inkjet printing. Very high ink amount in industrial printing can go up to 160% of coverage [9].

The chosen two ink amounts are:

- 4 times 5% ink coverage (20%) 1,965 g/m² ink
- 4 times 40% ink coverage (160%) 15,717 g/m² ink

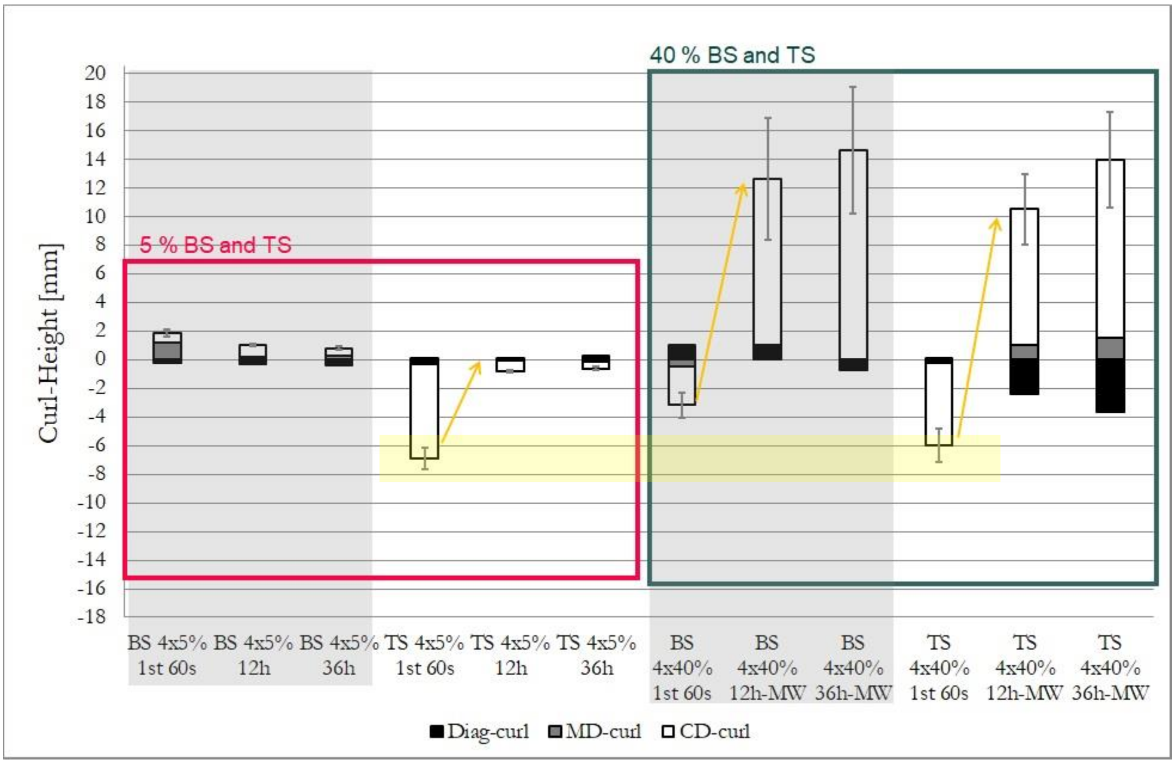

***Figure 75**. Result of the variation of the ink amount without primer on short and long-term curl of AKD sized paper.; number of samples n=5 each*

Figure 75. shows the result of this experiment with the AKD sized paper. The two different ink amounts are marked with the red and green box. For each ink amount, there are six bars, three representing the bottom side and three of them the topside. The first of these three bars represents the short-term-curl and is the mean value of three measurements within 60 [s], the second one shows the curl after 12 hours and the last one after 36 hours storage time at 50% RH and 22,5 [°C]. As the yellow arrows indicate, the long- term curl always is a strong positive curl, no matter if the

paper was printed on top- or bottom side. The long-term-curl is always positive and to the printed side with all four model papers. Its height depends on the ink amount. With high ink amount, it is increasing.

The short-term-curl with low ink amount is depending on the paper side and flipping with top side and backside. With 15,717g/m² ink, this phenomenon cannot be dedicated for all papers. But with rather high ink amounts, (240%) and with other all other ink amounts applied at the experiments, the flipping is showing up again.

The curl height of the Short-term-curl of the top side of the AKD sized paper has no significant difference with change of the ink amount. (**Figure 73**) The light yellow lightened box helps indicating this. The outcome of this experiment with the other three model papers ended up with similar results except that the ink amount there has an effect on the curl-height of the short-term-curl. **Figure 76**. points out this difference. For the other three papers a higher ink amount leads to stronger short- term- curl.

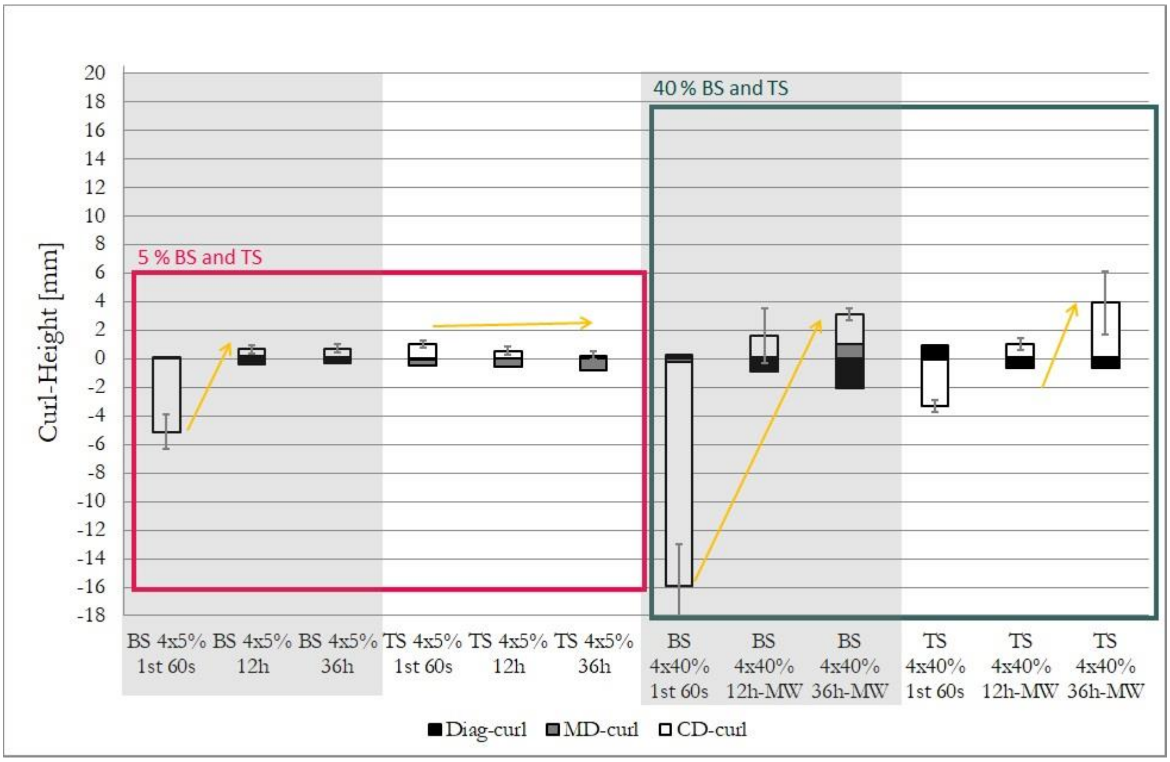

Figure 76*. Result of the variation of the ink amount without primer on short and long-term curl of unsized paper; number of samples n=5 each*

However, as with the AKD sized paper, with low ink amounts and very high ink amounts (e.g. last chapter) the short-term-curl is depending on the paper side and flips side with bottom and top side.

Pigmented and the calendered paper show the same tendencies as the unsized paper. The absolute curl height is different.
Regarding the curl Height and the curl itself, the AKD sized paper has the weakest intensity.

Table 16. *Average curl height for 4x40% ink application*

	top side [mm]		bottom side [mm]	
	av. curl-height	KI α=0,05	av. curl-height	KI α=0,05
AKD	17,613	±3,30	15,389	±4,39
pigmented	3,933	±2,71	5,704	±0,619
unsized	4,561	±2,22	5,185	±0,436
calendered	6,665	±2,20	6,402	±1,11

With focus at the AKD sized paper, **Figure 77** visualizes this difference shown with the previous charts and **Table 16**.

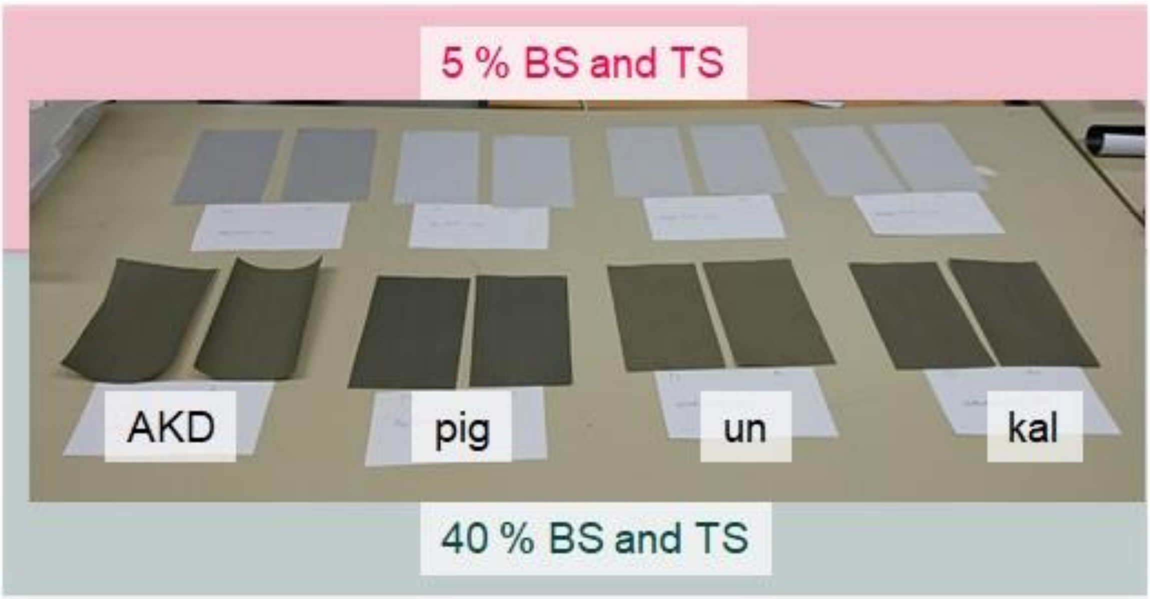

Figure 77*. Picture of the curl samples after 36 hours storage with 50 RH and 22,5 [°C]*

4.3 Conventional printing with latex pigment ink and storage with 0 % RH

The paper samples were kept in a box with 0 % relative humidity right after printing for 24 hours. The result was the same for all four model papers except the curl height in its absolute values.

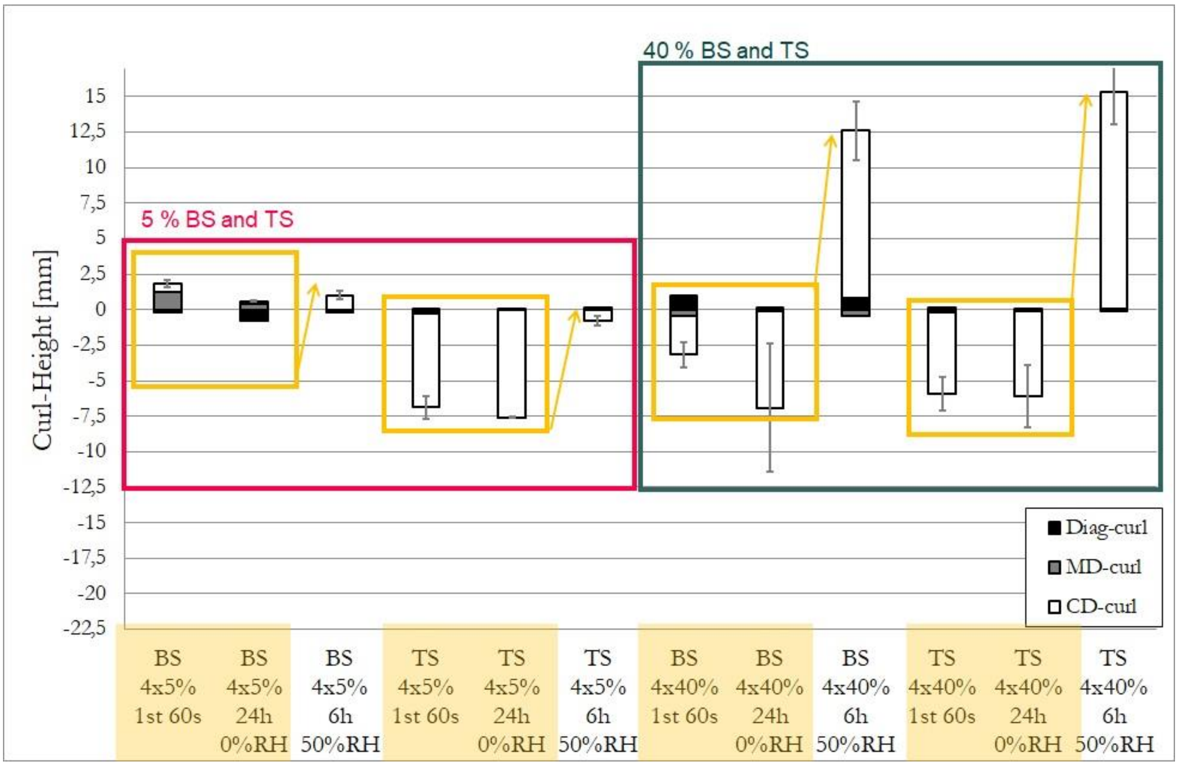

Figure 78. *Result of the ink variaition experiments with storage at 0 %RH afterwards for the AKD sized model paper; number of samples n=5 each*

Just as in the previous charts, so in **Figure 78**. too, the red and green squares mark the different ink amounts. The yellow box and the light yellow lightning in the legend mark the two bars right after printing and after 24 hours storage at zero percentage relative humidity. We clearly see that a storage without humidity in the air freezes the short-term curl.

The yellow bars indicate the development of the long-term curl after reconditioning of the samples at 50 % RH for six hours. The temperature was kept constant at 22,5 [°C]. Only after reconditioning to 50% RH the long- term- curl is developing.

Figure 79 lists the final curl height of all four model papers after the reconditioning step for six hours at 50% RH. The grey-lighted areas should help to differ between the four model papers. Each white bar represents the bottom side printed paper, a dark bar represents the top side printed paper. In consequence of the overlapping confidential error bars, there is no significant difference at the final curl height except the bottom side of the unsized paper. Nevertheless, the error bars of the final curl height after the 0 % humidity treatment are huge. This can be explained with the time frame of the measurement. The samples were put out of the silica gel box to do the measurement. It takes ~70 seconds to do it. (e.g. **Figure 34**). During this time, the paper is still at 50% RH and the reconditioning starts. As a matter of fact, that diffusion is driven by the concentration gradient, which has the highest level at the start, the reconditioning during the first 60 seconds is fast.

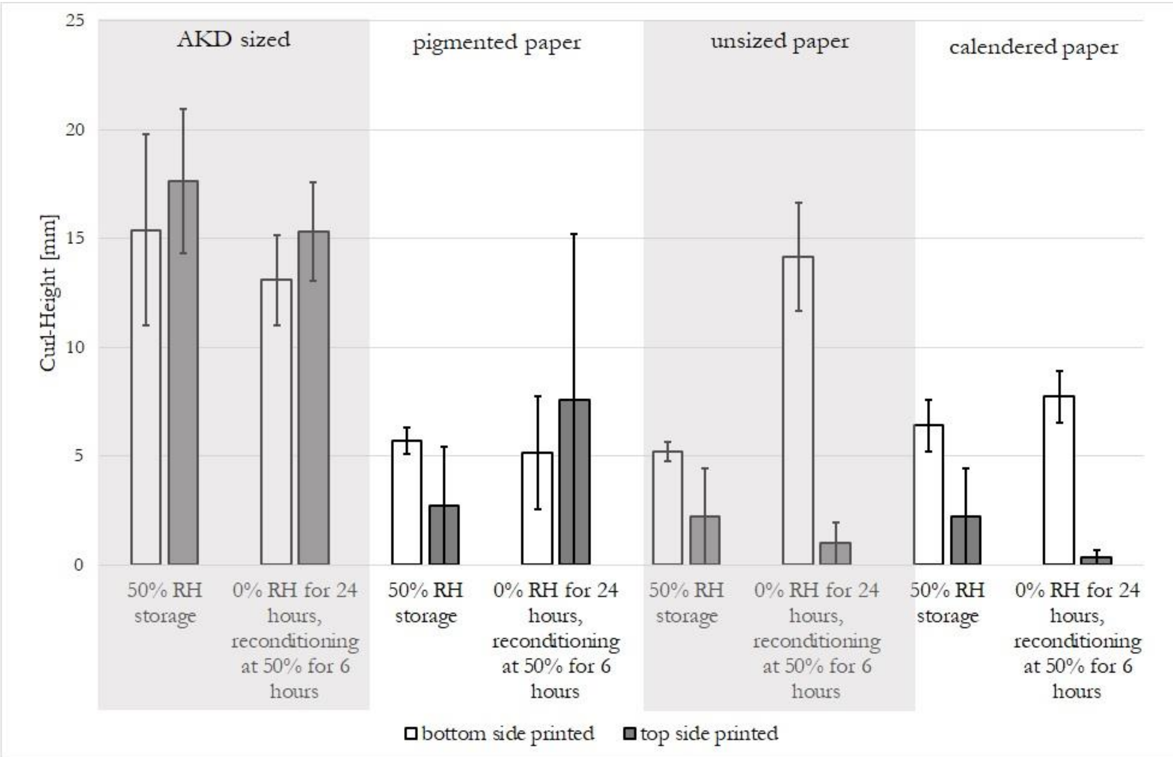

***Figure 79**. Different final curl heights with 4x40% (15,717 g/m²) after reconditioning with 50% HR compared to final curl height without treatment with 0% RH..*

Conclusion:

The 0% RH storage delays the development of the long- term curl. As long as the paper is at 0% RH the long- term curl does not develop. Only after reconditioning to 50% relative humidity, the long- term curl develops.

The reconditioning to 50% is necessary to develop the long- term curl.

4.4 Conventional printing with dye ink

In addition to uncouple the one sided wetting effect from the on sided drying effect on the hot plate, a experiment with free air drying at 50 % RH and 22,5 [°C] was started. Instead of drying the printed sample on the hot plate with standard conditions, the drying happened a free air without conductive heating from the backside.

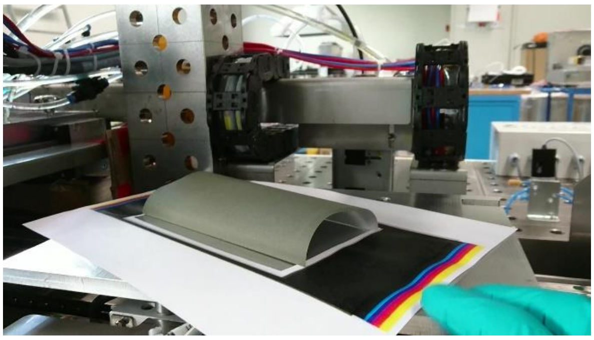

Figure 80. *One sided wetting curl of AKD sized paper right after printing.*

Figure 81*. Collapsed AKD sample 21 seconds of free air drying.*

Right after the printing, the one-sided wetting curl happens. **Figure 80**. shows this for the printed AKD sample. This curl can be observed as the short-term curl. On the contrary to the short-term-curl right after printing and drying on the vacuum plate, this one sided wetting curl does not flip side, it is always to the printed side. Its stability regarding time is short. After several seconds this one sided wetting curl collapses, **Figure 81**. shows this collapse. After several seconds this collapse takes place for all papers except the pigmented model paper.

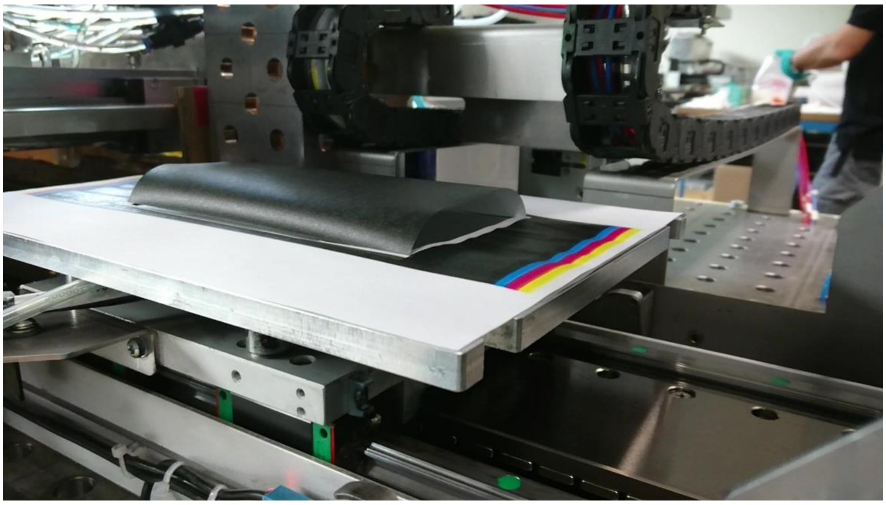

Figure 82*. One sided wetting curl of pigmented paper right after printing*

Figure 82. is the image of the one sided wetting curl (which has no side-dependence) of the pigmented paper. Here the curl also occurs directly after printing. However, the curl does not collapse upon drying and remains stable.

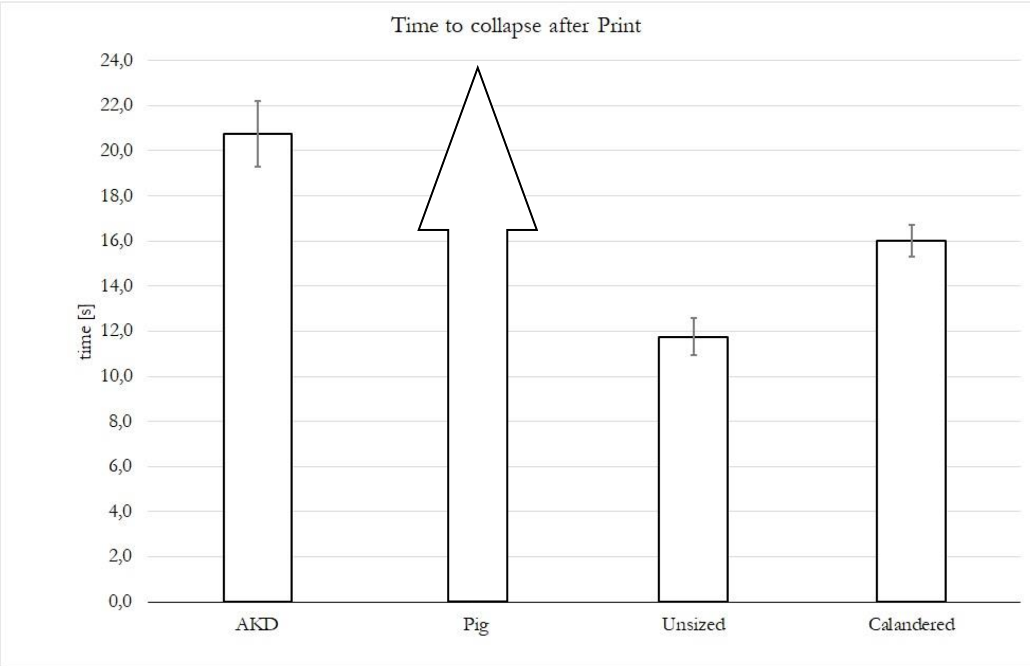

Figure 83. *Collapse time of the one sided wetting curl of the model papers; number of samples n=4 each*

Figure 83. is a chart of this collapse time. The AKD sized paper has the longest resting time, while the unsized model paper has the shortest one, the pigmented does not collapse at all.

The result of this free air drying experiment regarding the long- and short-term-curl is represented at the figures on page - 67 - **Figure 84**. In general, for all papers the short- and the long-term-curl is negative and remains negative. For small ink amounts there is no significant change in the curl height and direction. This indicates the yellow cross out at **Figure 84** in the 5% ink amount box. Otherwise, the long-term-curl for large ink amounts starts negative and after several hours it is increasing. There is no significant difference for the top- and bottom side regarding the curl direction and curl height. After 36 hours, the top side as well as the bottom side have a strong and well-defined negative MD curl. This behaviour of the AKD sized model paper is similar to the unsized and the calendered one. **Figure 85** shows the result of this experiment for the pigmented model paper. Hence the one sided wetting curl does not collapse and it remains at the level as the picture within **Figure 82** indicates. This strong one-sided wetting curl remains and increases during the first 12 hours of the long-term investigation. This growth of the negative long-term-curl is not at the same, but the final level is similar to the other three model papers, because it starts at higher curl level. By taking a closer look at the variation of the curl height, this long- term growth of the pigmented paper curl it is not statistically representative. It remains at about the level of the never collapsed short-term-curl.

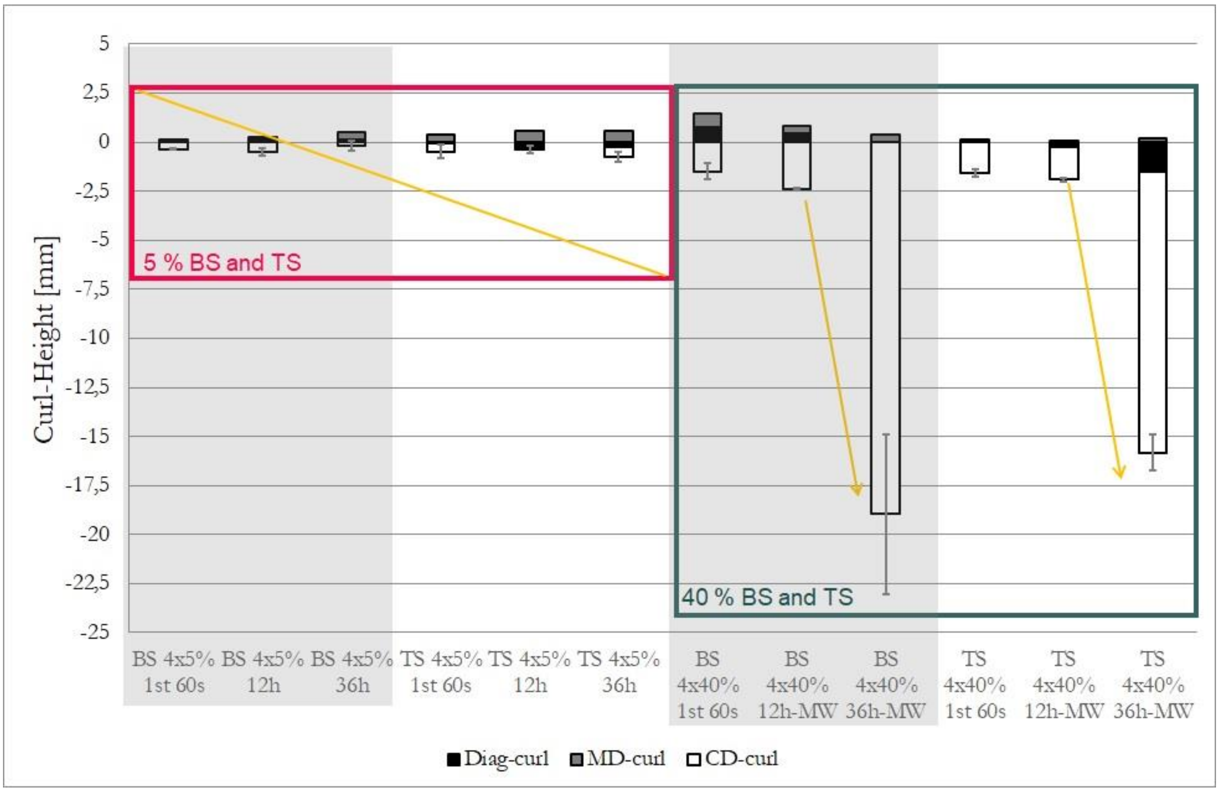

Figure 84. *Short- and long-term curl free air drying of AKD sized paper; n=2 each;*

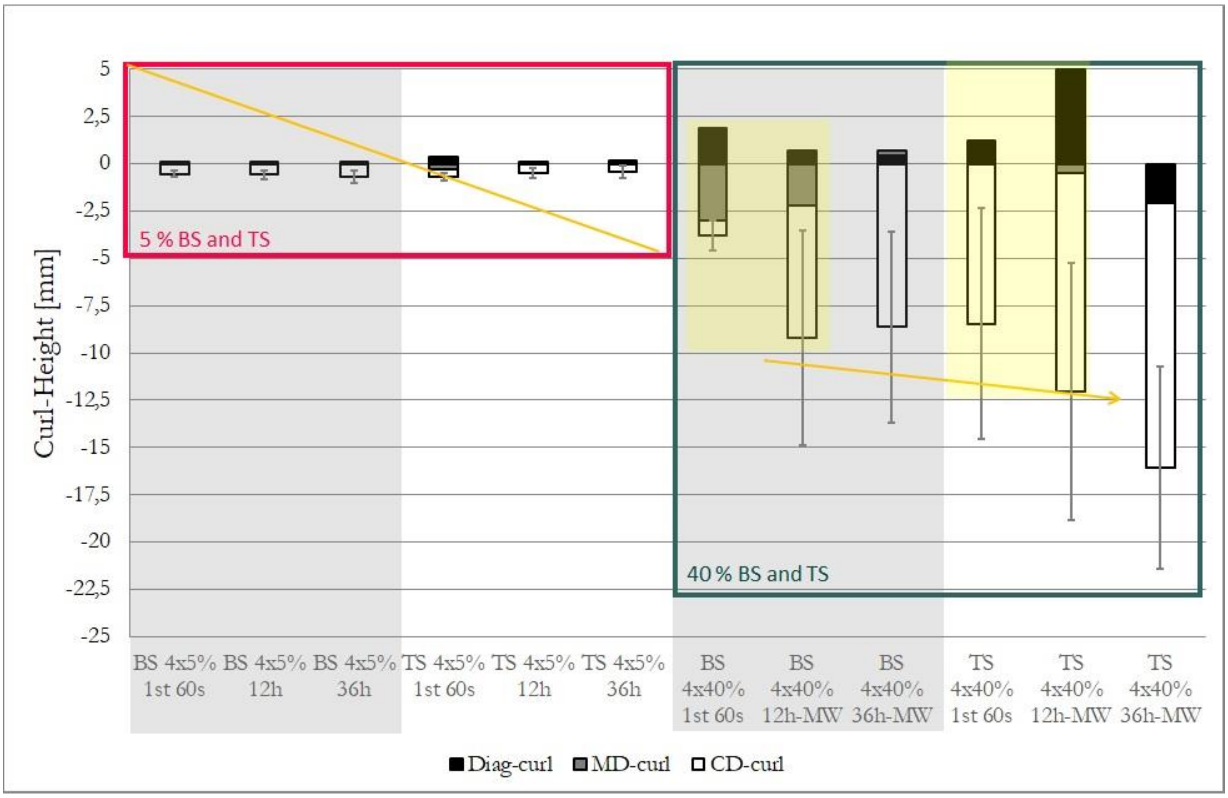

***Figure 85**. Short- and long-term curl free air drying of pigmented paper; number of samples n=2 each;*

<u>Conclusion</u>:

The behaviour of three papers is very particular. First the wetting curl develops within 2-3 seconds after printing. Then the curl collapses after 10 to 30 seconds of air-drying. Finally the curl comes back after 12 hours with the same intensity and direction as the initial wetting curl. The pigemted paper does not collapse at all and its curl stays negative.

4.5 Application of primer without ink

As already described, the goal of this experiment was to apply the maximum possible amount of primer and a comparable amount of ink to see, if there is a different behaviour of primer printing compared to ink. As the primer is composed of salt and water, we expected a behaviour similar to the inks, maybe weaker.

The maximum possible primer amount and the correspondent ink amount is:

- 100% Primer with 12 [pl] drops 6,696 g/m²
- 4 times 17% ink coverage pigment ink 6,680 g/m²

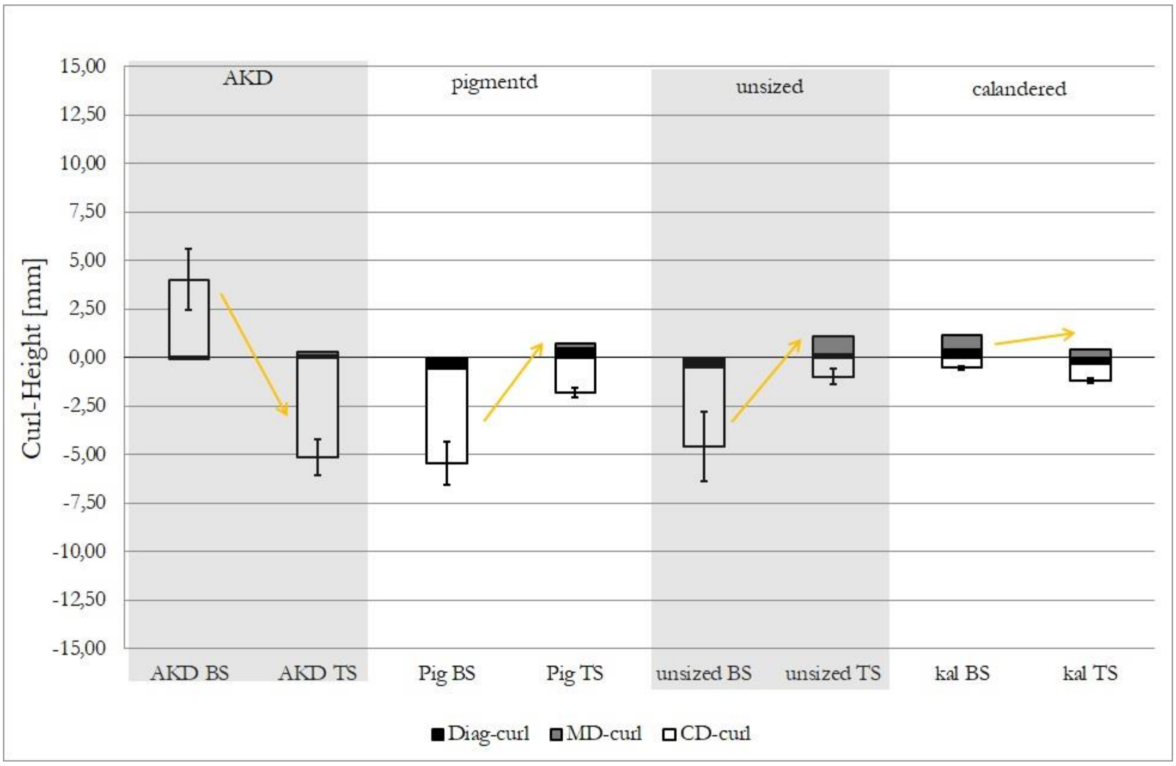

Figure 86. *Short-term-curl of 4x17 ink coverage; number of samples n=4 each.*

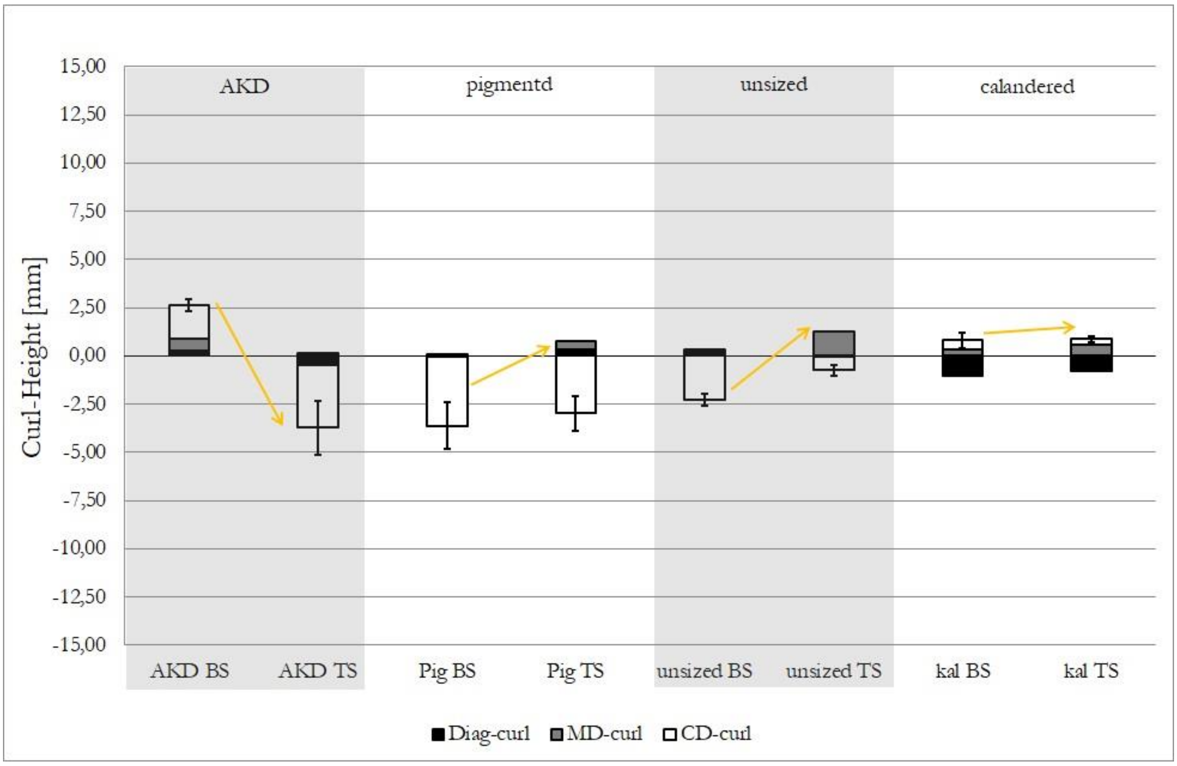

Figure 87. *Short-term-curl of the maximum possible amount of primer printing; number of samples n=4 each*

Figure 86 represent the short-term-curl of the correspondent ink amount. Figure 87. shows this short- term- curl for just primer application. As the yellow arrows help with the indication, the short-term curl is as expected, flips its side and does not differ from the effect that is observed for printing the same amount of ink

Regarding the long-term curl evaluation after applying of 6,7 g/m² pigment latex ink, the results are similar to those shown at page - 60 -. The final long- term curl is positive, has no side-dependence on top- or bottom side and the value of the height is between the four times 5% and the four times 40% ink amount.
Suspiciously, the long-term-curl of the primer printed samples behave different from the ink- printed samples can be observed at the figures at page - 70 -, a strong negative curl develops after several hours. Each paper is represented with three bars. The first indicates the short-term-curl, which is also listed at **Figure 87**. The next bar stands for the curl after 8 hours conditioning time at 50% RH and 22,5 [°C], the last one for the curl value after 24 hours storage. The number of samples at the long-term curl measurement is just one, but there were several samples printed and they showed the same tendency.

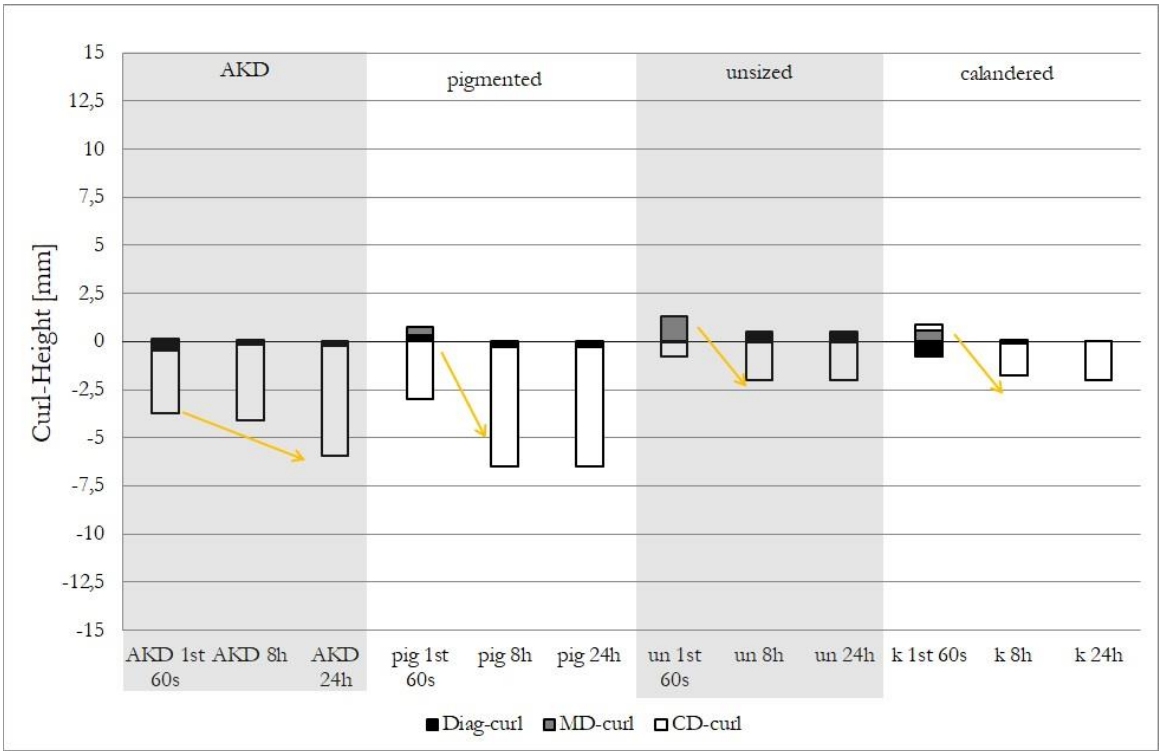

Figure 88. *Long-term-curl of top side primer printed of all four model papers; ; number of samples n=1 each*

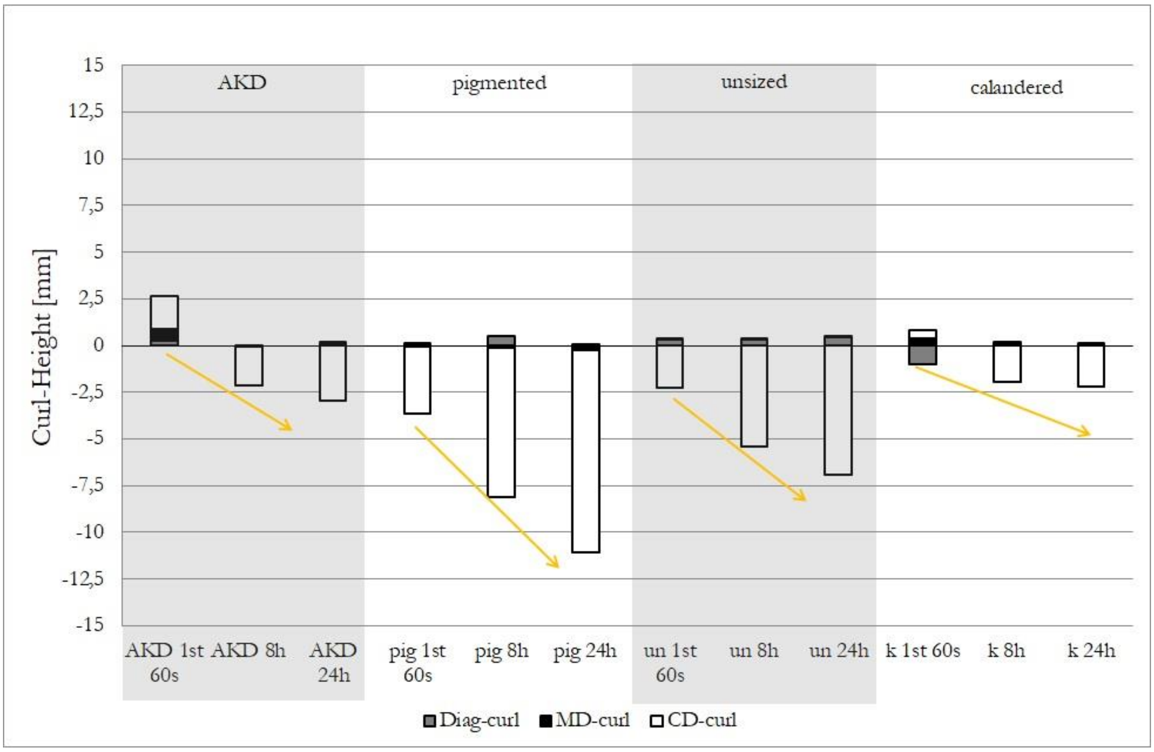

Figure 89.*long-term-curl of bottom side primer printed; number of samples n=1 each.*

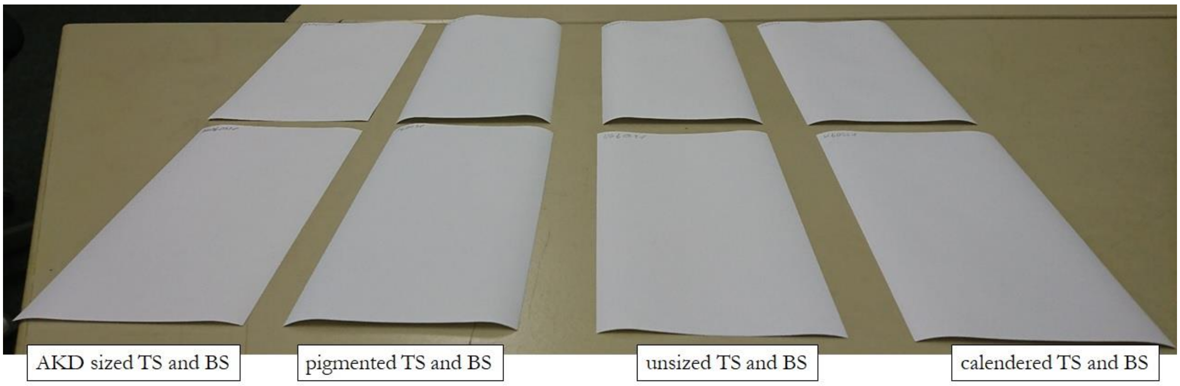

Figure 90. *Picture of the measured samples of just primer application after storage for 24 hours at 50% RH.*

This strong negative curl can also be observed in Figure 90. The result of the charts at page - 70 - is also observable with pure eye and emphasizes, that the final curl height of the pigmented paper the highest.

<u>Conclusion</u>:

Primer application shows the same short- term- curl behaviour but a completely different long- term- behaviour than printing with the correspondent latex- pigment- ink amount. The long- term- curl of just primer application is negative. The pigmented paper, which has normally the weakest curl height, has the highest long- term- curl height if just primer is applied.

4.6 Conventional printing with dye ink

To get an indication of the influence of the latex and the pigments in the latex-pigment ink, the variation of different ink amounts were also done with dye ink. As already mentioned, the printing of dye ink needs different IPTS settings. Different print-heads have to be used. These different print heads have other wave forms and can just print with 600 dots per inch. On account of technical and administrative reasons, the usage of only two print heads instead of four was possible. To get comparable printing results, the two print jobs for dye ink are oriented at the ink amount of latex-pigment-ink printing jobs.

Table 17*. Ink amounts for latex-pigment-ink and dye-ink*

ink amount	latex pigment ink		dye ink	
low ink amount	4 times 5 % coverage	1,956 g/m²	2 times 13 % coverage	1,984 g/m²
high ink amount	4 times 40 % coverage	15,717 g/m²	2 times 100% coverage	14,243 g/m²

Table 17 links the generated Bi-level-print-jobs with the calculated amounts. As a result of the usages of only two dye heads, the pint job, which uses higher ink amounts can not reach the ink amount level of the correspondent latex-pigment-ink-job. It is ~1,5 g/m² lower. Being a representative result for all four model papers, **Figure 91**. shows the experimental results to dye ink printing.

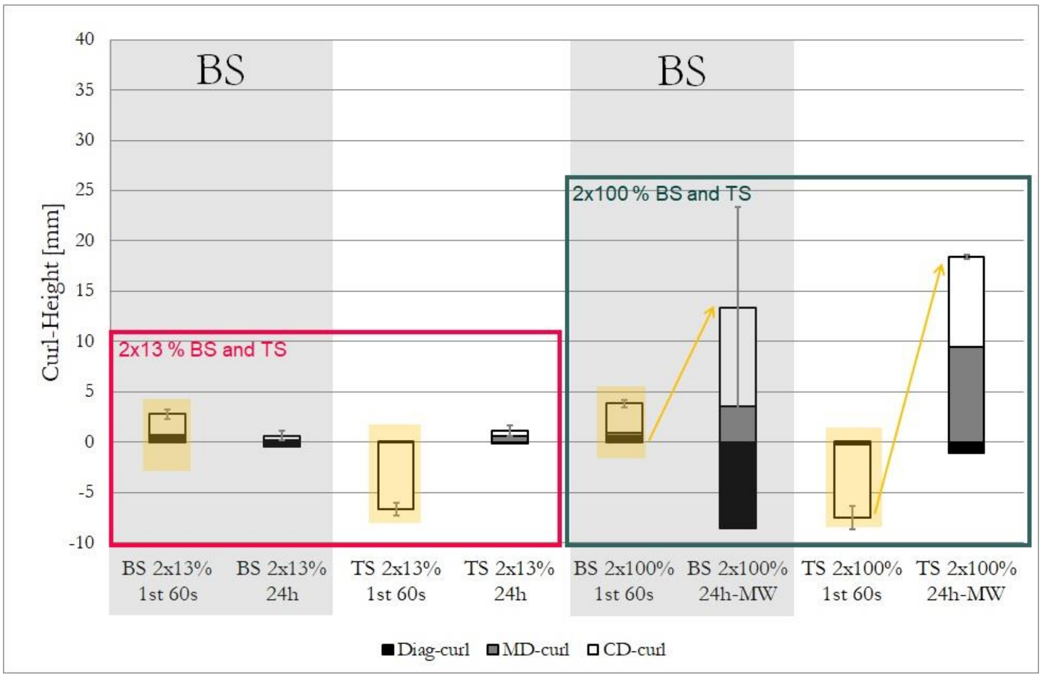

Figure 91. *Long-, and short-term curl for dye ink with AKD sized paper; number of samples n=2 each.*

Just as with pigment ink printing, the short-term-curl, which is represented in the first bar, flips its side and depends on top- or bottom side. This highlights the yellow areas. It is also clearly visible, that the long-term curl is always positive and increases with higher ink amounts.

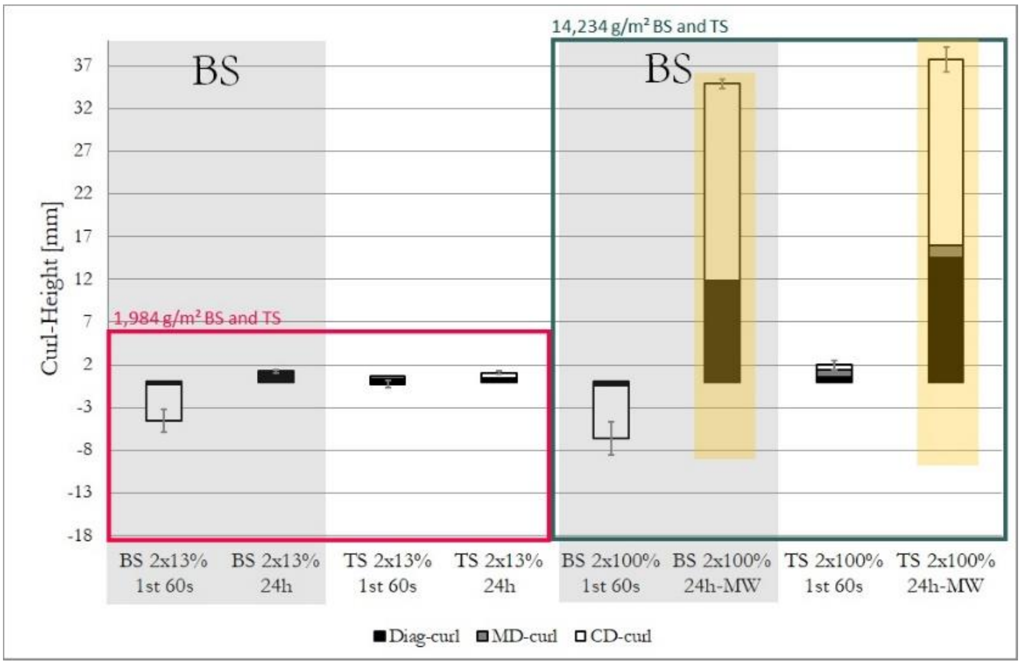

Figure 92. *Short-, and long-term-curl of unsized model paper samples printed with dye ink.*

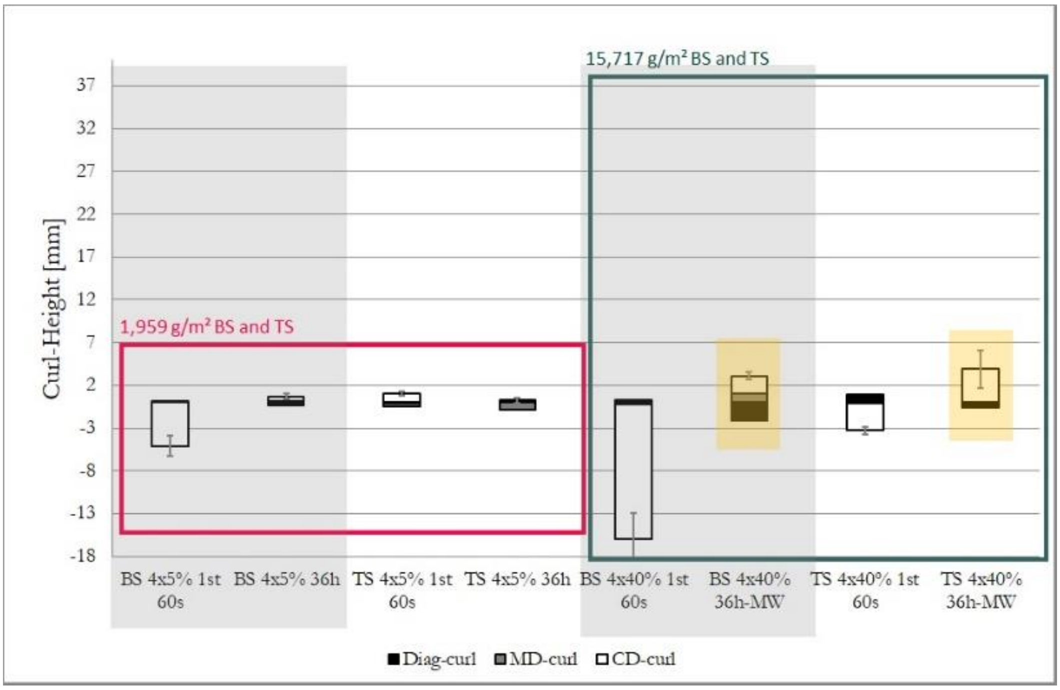

Figure 93*.unsized model paper samples printed with latex pigment-ink; number of samples n=4 each.*

Figure 92 and **Figure 93** compare the different ink systems with printing on unsized paper to each other. It exemplifies for all model papers the difference of those two ink systems. Both have a short and a long-term-curl. The short term curl of both system flips its side depended on bottom side and top side, and is well defined as CD curl.
Nevertheless, the long-term-curl of the dye-ink-system is stronger and more undefined regarding the MD and the diagonal component. The yellow-lighted boxes in both charts indicate this.

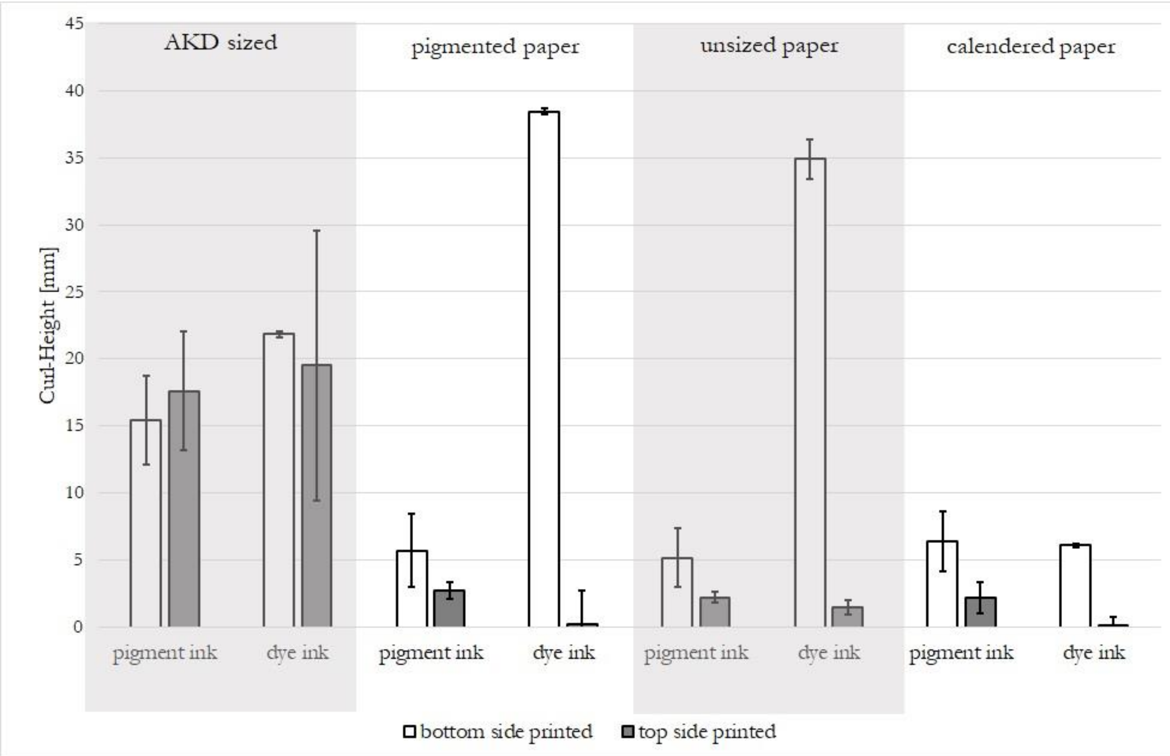

***Figure 94**. Average curl height with high ink amount dye and latex-pigment-ink printing; number of samples latex n=4 each; number of samples latex n=2 each.*

As a result of this experiment, **Figure 94**. lists the final curl height of the long-term-curl of both systems 24 hours after printing. The curl height for two out of the four model papers is at a much higher level with dye ink printing although not considering, that the printed dye ink amount is ~1,5 g/m² lower. However are needs to consider that the solids content of the pigmented ink is higher.

This undefined and quite high long-term-curl can be observed in **Figure 95** to **Figure 98** for all four papers.

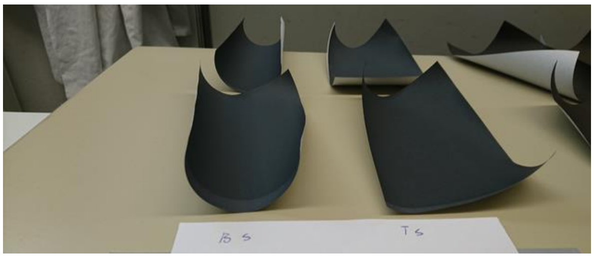

Figure 95. *Picture of the long-term-curl of AKD sized paper samples printed with dye ink*

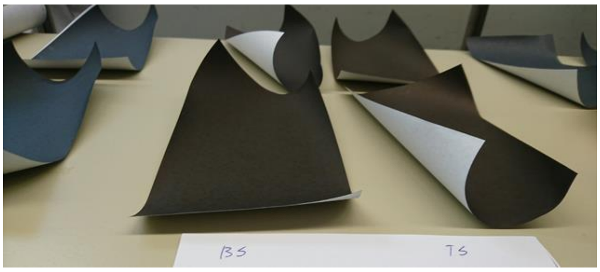

Figure 96. *Picture of the long-term-curl of pigmented paper samples printed with dye ink*

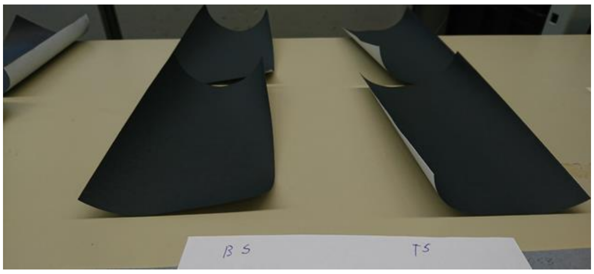

Figure 97. *Picture of the long-term-curl of calendered paper samples printed with dye ink*

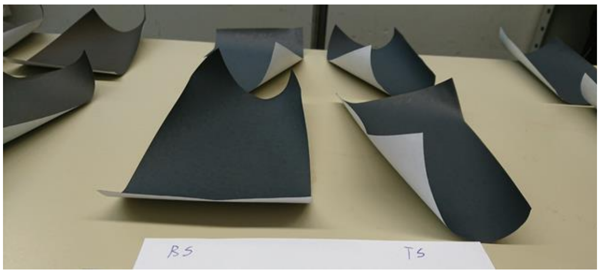

Figure 98. *Picture of the long-term-curl of unsized paper samples printed with dye ink*

<u>Conclusion</u>:

The curl develops similar but stronger for dye ink. Thus, it can not be related to the formation of a closed latex film at the paper surface for the latex ink.

4.7 Backside water application

This last experiment was done to investigate if there is a difference in the curl behaviour if the same amount of water is applied at the backside right before printing. The idea here is that according to the classic theory, backside water application should decrease the curl (which is caused by front side ink appliance and backside heating). This experiment was done for two water amounts

- A small amount of water at the backside and the corresponding ink amount at the other side with ~ 0,13 g water uptake of the paper sample
- A high amount of water at the backside and the corresponding ink amount at the other side with ~ 0,25 g water uptake of the paper sample

Table 10. Result of the pretrials for low water amounts (white rod) and **Table 11** at page - 34 - list the water amounts and **Table 12** links this to the print jobs.

Table 12. *List of print jobs with backside water application and corresponding print job using latex pigment ink*

	low liquid amount		high liquid amount	
	water uptake [g]	chosen print job and wet ink amount [g]	water take up [g]	chosen print job and wet ink amount [g]
unsized	0,133	4x20%; 0,134	0,294	4x40; 0,267
AKD sized	0,116	4x17%; 0,114	0,251	4x40; 0,267
pigmented	0,143	4x20%; 0,134	0,290	4x40; 0,267
calendered	0,177	4x25%; 0,167	0,328	4x50; 0,334

The ink amount of every paper is different and depends on the water take up volume, which was measured previously in pre experiments. (e.g. material and methods)

4.7.1 Backside water application with small ink and water amounts

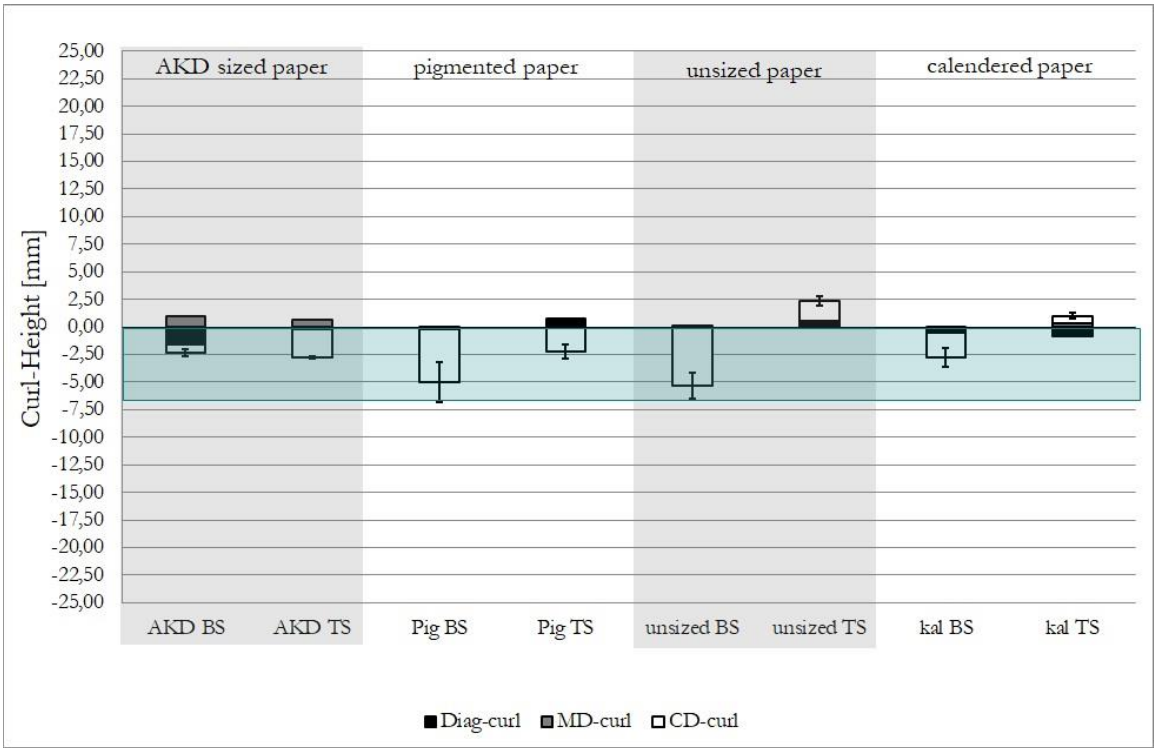

Figure 99. *Short-term-curl of the four model papers printed with the reference ink amount* *<u>without</u>* *backside water application; number of samples n=4.*

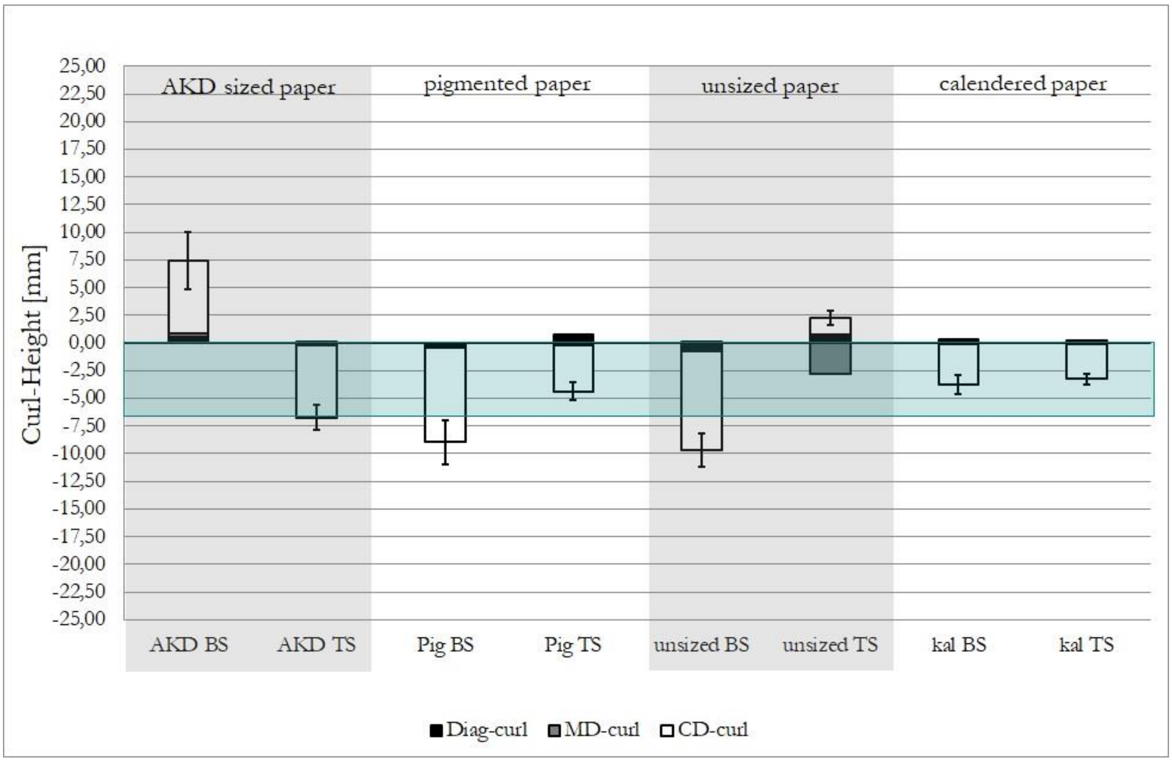

Figure 100*.Short-term-curl printed with the same ink amount as with the reference print at Figure 99* *<u>with water application at the backside</u>**; number of samples n=4.*

Considering the error bars, the curl height of the short-term-curl does not change significantly. However, an indication of the experiment with low liquid amounts can be observed by taking notice of the light blue bar which overlays both plots. This highlights the tendency that the negative curl is stronger with backside application. The flip of the side of the curl happens also with backside water application. This is fitting with the theory that backside water application should promote negative curl.

4.7.2 Backside water application with high ink and water amounts

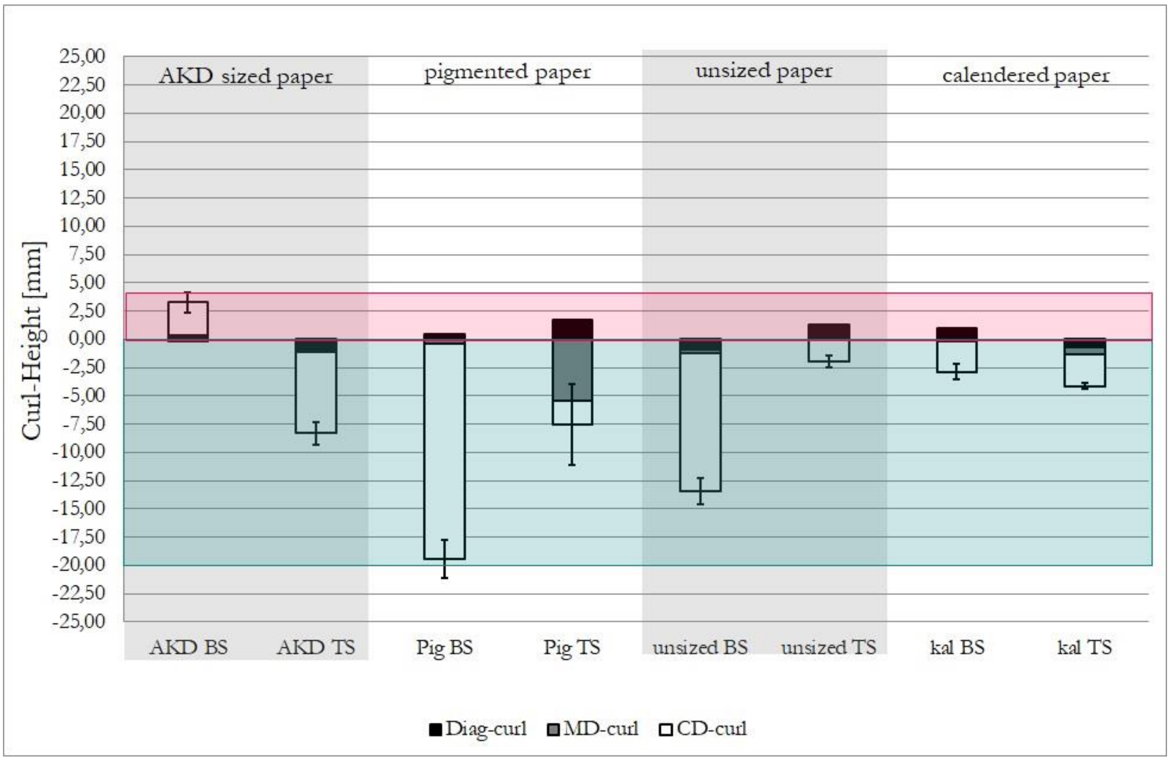

Figure 101*.Short-term-curl of the four model papers printed with high the reference ink amount <u>without backside water application</u>; number of samples n=4 each.*

Figure 101 conveys the reference ink amount for the high liquid amount experiment, which can be observed at **Figure 102**. As the light green boxes indicate, with high liquid amounts on top and on backside the negative curl is at a lower level, but on the other hand, as can be observed with the light red box the positive curl is intensified. The does not correspond to theory which would predict strong negative curl.

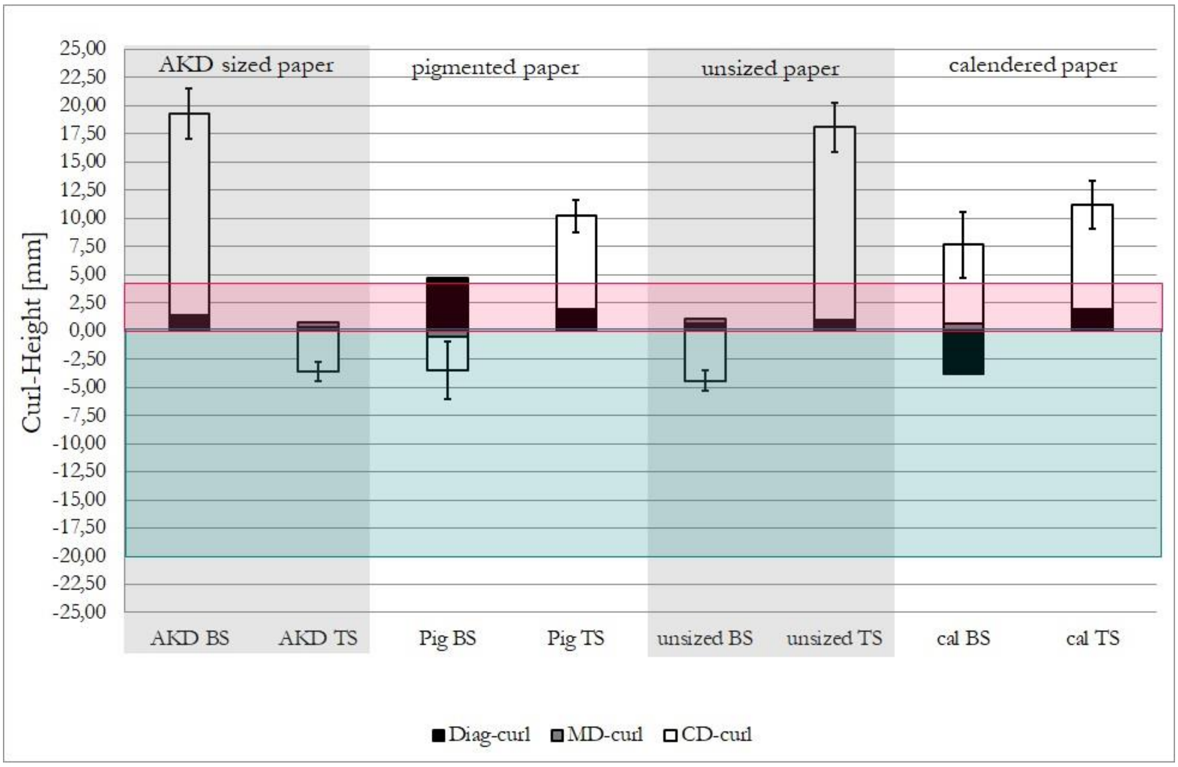

Figure 102*.Short-term-curl of the four model papers printed on top the same high ink amount as with the reference print at Figure 101 <u>with water application at the backside</u>; number of samples n=4 each.*

The following **Figure 103** and **Figure 103** sum up the result for the curl height from both experiments. It does not distinguish between the curl direction and just focuses on the average short-term-curl height.

Expecting that the liquid amount is at the same level on top and on bottom side, higher liquid amounts on both sides:

- have a negative effect short- term- curl height for AKD sized, unsized and calendered paper
- have hardly an effect on short- term- curl for the pigmented paper

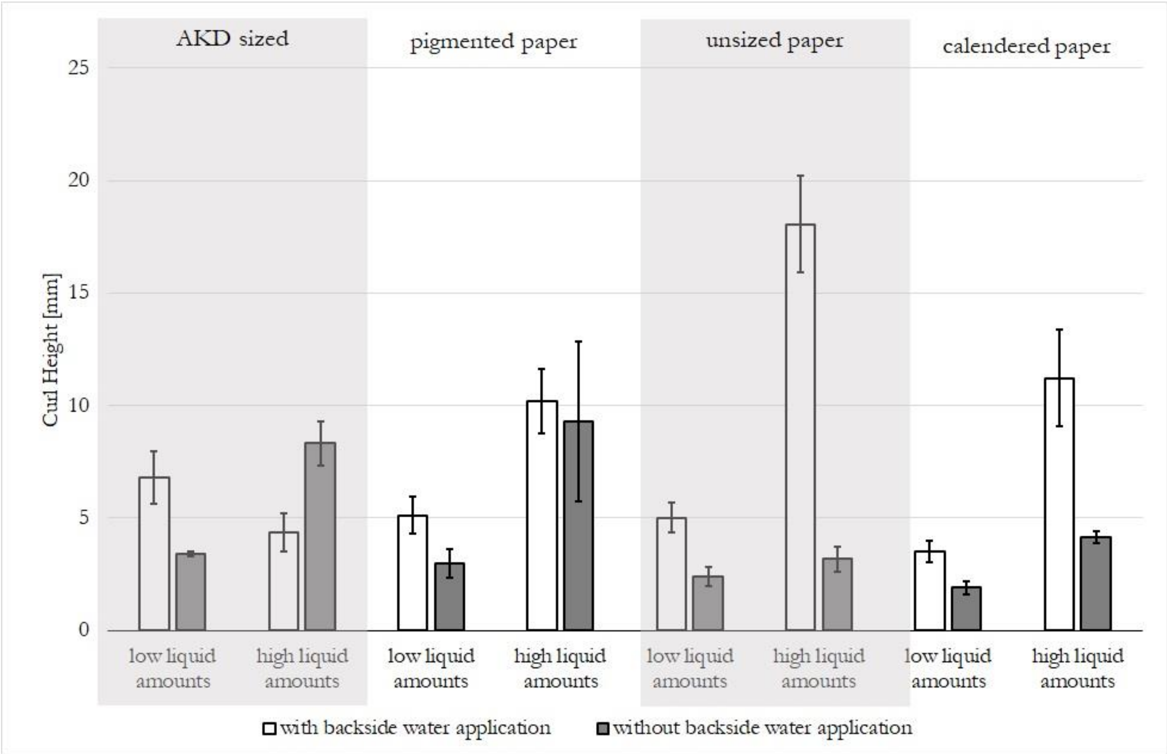

***Figure 103**. Summary of the average curl height of short- term- curl with and without backside water application. <u>Printing side = Top side</u>; number of samples n=4 each.*

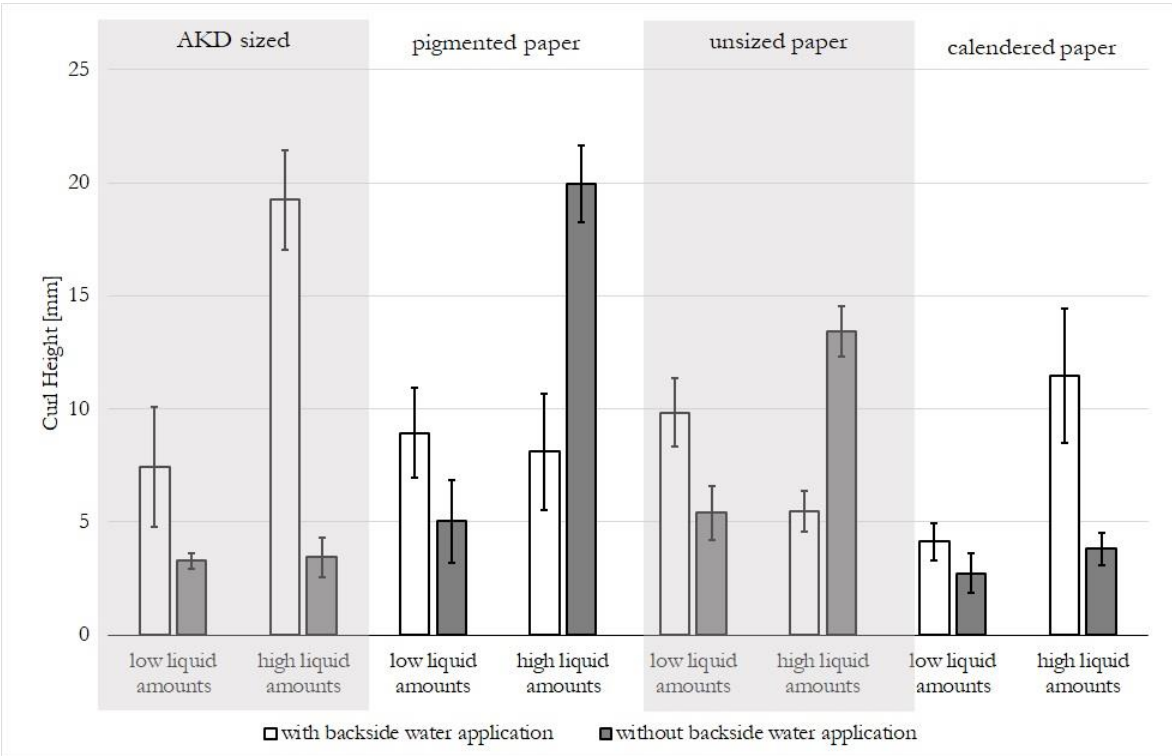

***Figure 104**.Summary of the average curl height of short- term- curl with and without backside water application. <u>Printing side = bak side</u>; number of samples n=4 each.*

In general, with higher water amounts, the short-term-curl height increases. Considering the curl- height charts at **Figure 103** and **Figure 104** the backside water application significantly raises the curl height with high and low liquid amounts for the unsized and the calendered paper at top side printing, the pigmented paper shows the same tendencies, but for high liquid amounts the raise is not significant.

The AKD sized paper has a strong curl- height increase if the bottom side is printed. Considering that the curl direction of the AKD sized paper is inverse to the others, all paper grades show an increase of curl height for a positive curl.

There are also tendencies that the negative curl is decreased. With high liquid amounts this can be shown significantly for the AKD sized, the pigmented and the unsized paper.

An effect of backside water application on the long-term-curl has not been detected.

<u>Conclusion</u>:

Backside water application did not reduce the curl. – It even showed tendencies to increase it. This is not according to theory where it should systematically pulls the curl towards the negative side. It pulls the curl strongly towards the positive side.

4.8 Result Matrix

The matrix table on the next page shows a compact summary, which is aimed to showing the big picture of the results and is also an introduction for reading the conclusions.

The sequence of this matrix is in the same order like the results presented in this chapter. Each result of the last leads to the question investigated in.

- the green framed box in the first column describes the name of the experiment
- the dark red framed box in the second column describes the research question intimidating the experiment.
- the yellow framed summarizes the result of the chapter which described the experiment.

experiment	reason for investigation	result
blanko – printing	investigation of one sided drying curl	one sided drying curl is fully revesible
conventional printing with latex pigment ink	Investigation of curl behaviour and its time dependence	there are two independent curl types, the short- term- curl flips it side, the long- term- curl points always to the printed side
conventional printing and sample-storage at 0% RH	influence of humidity on long-term-curl	0% RH freezes the short-term-curl, reconditioning at 50% RH releases long-term-curl
conventional printing and free-air-drying	separation of the one- sided- wetting and one- sided- drying effect	one- sided- wetting + free air drying points always away from the printed side for short- and long- term curl
just primer application	influence of primer on short- and long-term-curl	just primer printing leads to a NEGATIVE long-term curl (and flipping side in short-term- curl)
conventional printing with dye ink	influence of latex in latex pigment ink on curl	ST curl and LT curl are the same like with printing with latex- pigment- ink; LT-Curl is stronger with dye ink
backside water application	does the same amount of liquid on the other side prevent the ST-curl?	prevents negative ST-Curl, intensifies positive ST-Curl, ~no effect on long-term-curl

5 Conclusions

5.1 Conclusions on short-term-curl

The following **Figure 106**. illustrates all short term curl results for 15,6 g/m² and 27,5 g/m² ink application in a condensed presentation of all results except the backside water application experiment.

The average curl-height is shown negative or positive regarding the negative or positive curl detection of the CD curl. Fitting problems according the fit equation of the MATLAB-fit have been corrected manually after looking at every fit picture. For better readability, the splitting of the total curl height into the three curl parts (MD, CD and diagonal) is not shown anymore.

It is clearly visible, that the short-term-curl flips with changing the printing side. The AKD sized paper always has the curl in the opposite direction than the other papers.

Figure 105 should help with the interpretation of the following chart. Each paper is represented with seven bars. These seven bars are the result of the average curl height of one experiment.

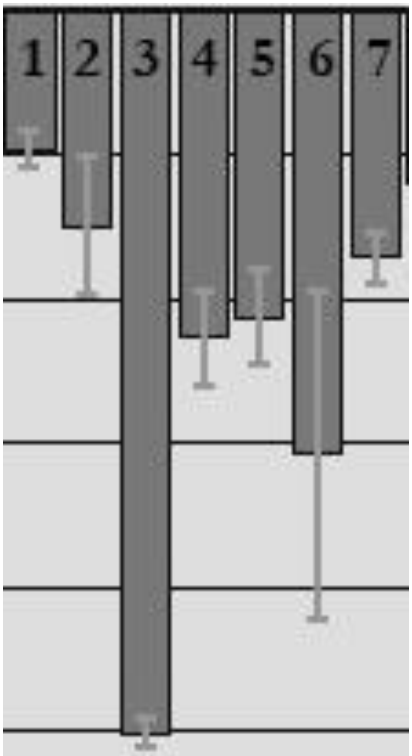

Figure 105. *Legend of the result chart*

Its direction corresponds to the side the CD- curl is pointing to, which is the general curl direction. If not stated differently, the drying was 2 seconds form the back side on a hot plate with 129°C.

1. blanco printing (2s drying)
2. 6,696 g/m² just primer application
3. 15,717 g/m² conventional printing with latex- pigment- ink
4. 15,717 g/m² printing with latex- pigment- ink and free air drying
5. 14,243 g/m² conventional printing with dye- ink
6. 27,505 g/m² conventional printing with latex- pigment- ink without primer
7. 27,505 g/m² conventional printing with latex- pigment- ink with primer

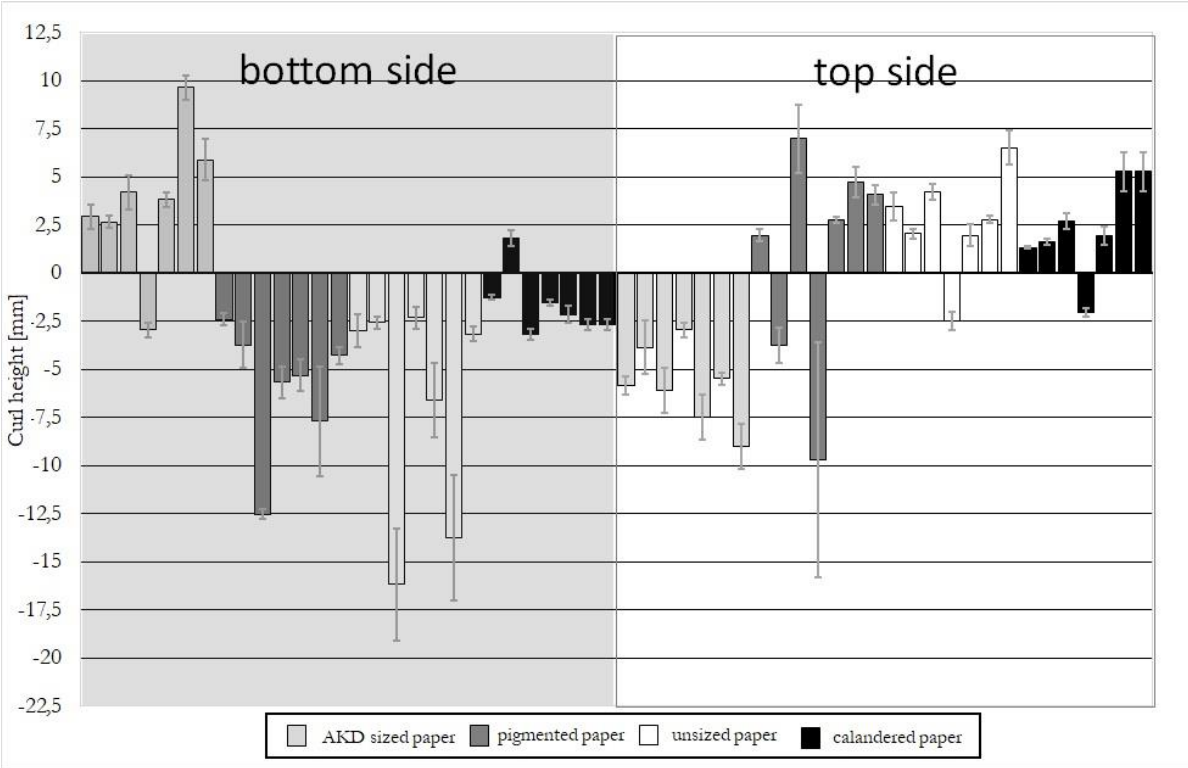

***Figure 106**. summary of all short-term-curl-results for all model papers*

All bar plots flip side if the printing side is changed except the one sided wetting curl of the free air-drying, which is represented by every fourth bar of one paper-group. This is always negative. Summing up the relevant results of all experiments done regarding the short-term-curl-effect gives the following list:

blanco printing

- fully reversible
- flipped side with back- and tops side printing

ink variation (dye and pigment)

- curl raises with higher ink amount
- flipped side with back- and tops side printing

application of just primer

- shows same effect in short-term like pigment ink
- flipped side with back- and tops side printing

backside water application

- prevents negative short- term- curl
- intensifies positive short- term- curl
- flipped side with back- and tops side printing

There is one effect out of this list, which happens always. This dominant effect is the curl-flipping effect when changing the printing side. This effect in combination with the result of the blanco-printing-experiment, which showed that the short- term- curl can also be activated with just drying from one side, and that this curl is fully reversible, leads to the conclusion, that the short-term-curl must be a structural curl. Apparently a structural two sidedness in the paper (FO, filler, fines, sizing, two sidedness regarding former type) leads to a curl which is caused by the structural two sidedness. The curl always goes towards the same side of the paper no matter where the wetting/ drying is applied to. The AKD sized paper apparently has a different structural two sidedness; it is produced on a different paper machine than the other papers.

This short-term-curl is a structural Curl caused by

- two-sidedness of the paper
- difference on filler distribution on top and on bottom side
- difference of fiber-orientation-angle on top or bottom side
- difference of fines content in base paper
- ….

It intensifies with:

- higher ink amount
- backside water application on top side

It can be reduced with:

- usage of primer with latex-pigment-ink printing

In general, structural curl can be minimized by reducing the swelling/ shrinkage of the paper sheet. We also see this in the experiments -the short- term curl is indeed reduced by reduced liquid amounts (dye vs. pigment ink) and by using primer. Primer contains of salt ($CaCl_3$) which inhibits the swelling of the fibers.

5.2 Conclusions on long-term-curl

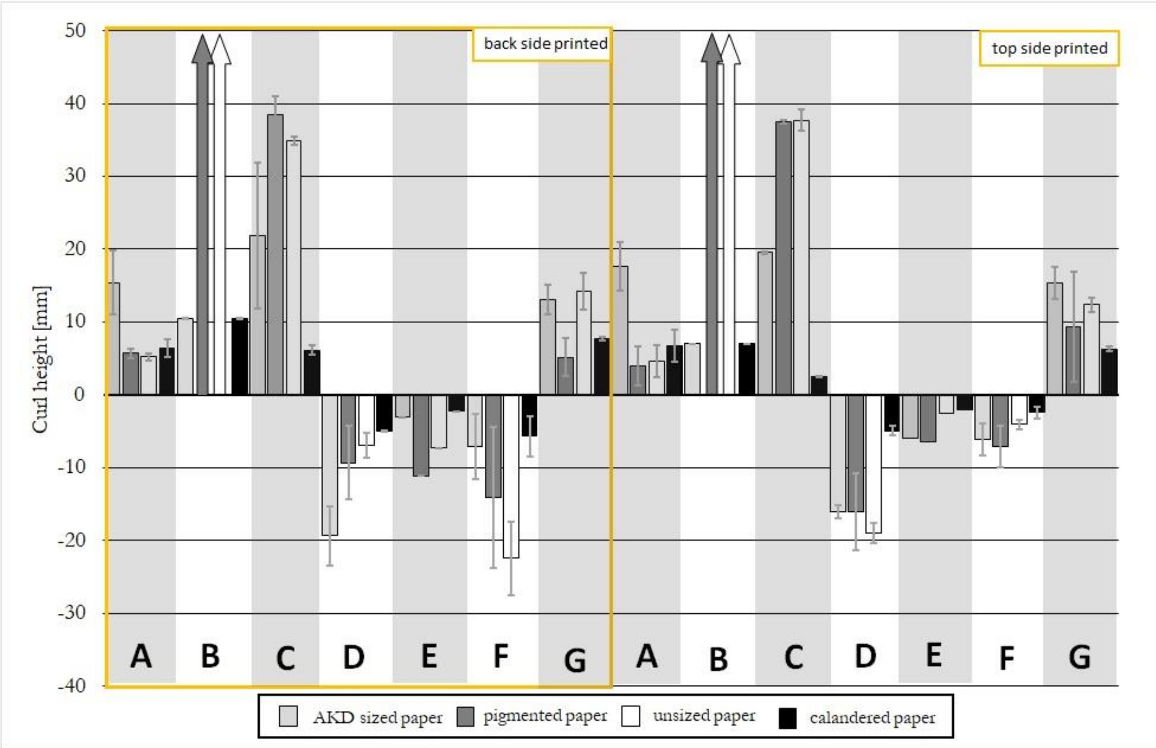

***Figure 107**.Summary of all long-term-curl-results for all model papers.*

Figure 107 represents all results for the long-term-experiments done during this work. Similarly to the short-term-curl chart at **Figure 106** the splitting of the total curl height into the three curl parts (MD, CD and diagonal) is not shown anymore. The average curl-height is shown negative or positive regarding the negative or positive curl direction of the CD curl.

The letter A to G represent the experiment in which a long- term investigation was done. **Table 18** indicates these experiments.

***Table 18**. List of the long- term- curl experiments*

letter	experiment	letter	experiment
A	160% latex pigment ink without primer	E	just primer printing
B	240% latex pigment ink with primer	F	LT curl after 24 hours at 0% RH
C	200% dye ink	G	LT curl of the 0% RH smples after 6 hours reconditioning at 50% RH
D	160% latex pigment free air drying		

Fist attention is attracted due to the reason, that every long-term-curl except the free air drying curl, which represents "D", the primer application bar, which represents "E" and the curl after the storage at 0% relative humidity "F"s positive.
However, there is no two-sidedness at all. The long- term- curl of bottom side and top side printed samples has the same direction regarding its main component (the CD curl). Printing with ink in combination with hot plate drying leads always to a positive long- term- curl. Both ink types have this positive curl. The arrows at the end of the high ink amount values of the pigmented and the unsized model paper should indicate that the curl is too strong to be measured. (e.g. **Figure 71**)
The blanco printing experiment is not listed at the long- term- curl chart because there is no long- term- curl with just heating. It is fully reversible.

Summing up the relevant results of all experiments done regarding the long-term-curl-effect gives the following list:

blanco printing	• NO longterm-curl
ink variation (dye and pigment)	• curl raises with ink amount • the long- term- curl is always POSITIVE
application of just primer	• long- term- curl is NEGATIVE and stronger as with the same ink amount
backside water application	• NO effect on long- term- curl • remains POSITIVE
Free air drying	• long- term- curl redevelopes • it stays NEGATIVE

In contrast to the short- term- curl, the classification of the long-term-curl to a curl-type is not possible yet. Two obligatory conditions must happen in order for long- term curl to develop:

- long-term-curl just happens if the sample was printed or wetted
  - the curl depends on the side of wetting and NOT on the paper side.
- long-term-curl needs relative humidity to develop (see page- 63 -)
  - 0 % RH freezes the short- term- curl
  - reconditioning with 50 % RH leads to long-term-curl

Printing with ink and drying on a hot plate always leads to a positive final long-term-curl. The strength of the long-term-curl triggered by conventional printing with different inks can be sorted from the worst to the best:

- dye – ink
- latex – pigment – ink without primer
- latex – pigment – ink with primer

This corresponds to the expected amount of swelling.

➔ Dye- ink – no solids content, more liquid.

➔ Latex- pigemt- ink – high solids content

➔ Primer – salts – more swelling

It is unclear why the long- term- curl is negative for air drying and for printing only primer. The mechanism why and how the long- term- curl is working is not understood. **Figure 108** should summarize the written conclusions as a pictogram.

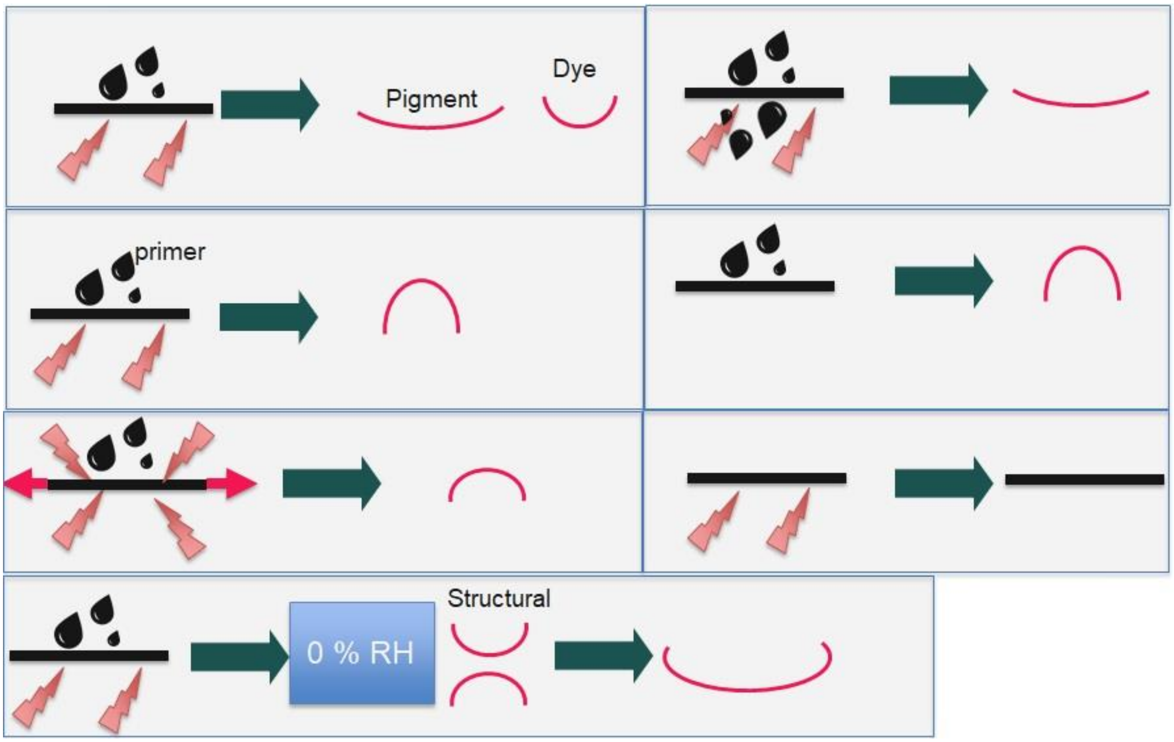

***Figure 108**. Pictogram of the long- term- curl behaviour*

5.3 Conclusions on the paper type regarding long- and short- term- curl

5.3.1 Influence of the different paper types on short- term- curl

During this work, four different model papers were used. This four model papers had different finishing and sizing in order to investigate these effects on curl. **Table 19** lists these differences.

***Table 19**. Paper types and their differnt treatment*

paper type	description oft the treatment
AKD sized paper	internal sizing, hydrophobization
pigmented paper	surface coating with anorganic pigments in surface sizing, no internal sizing
unsized paper	natural fine paper, no internal sizing, inkjet treated with salts in sizepress
calendered paper	smoothed surface though thermal compression, otherwise same paper as unsized paper

Regarding short-term curl, **Figure 109** lists the average curl height of the short- term-curl with different amount of latex- pigment- ink without primer.

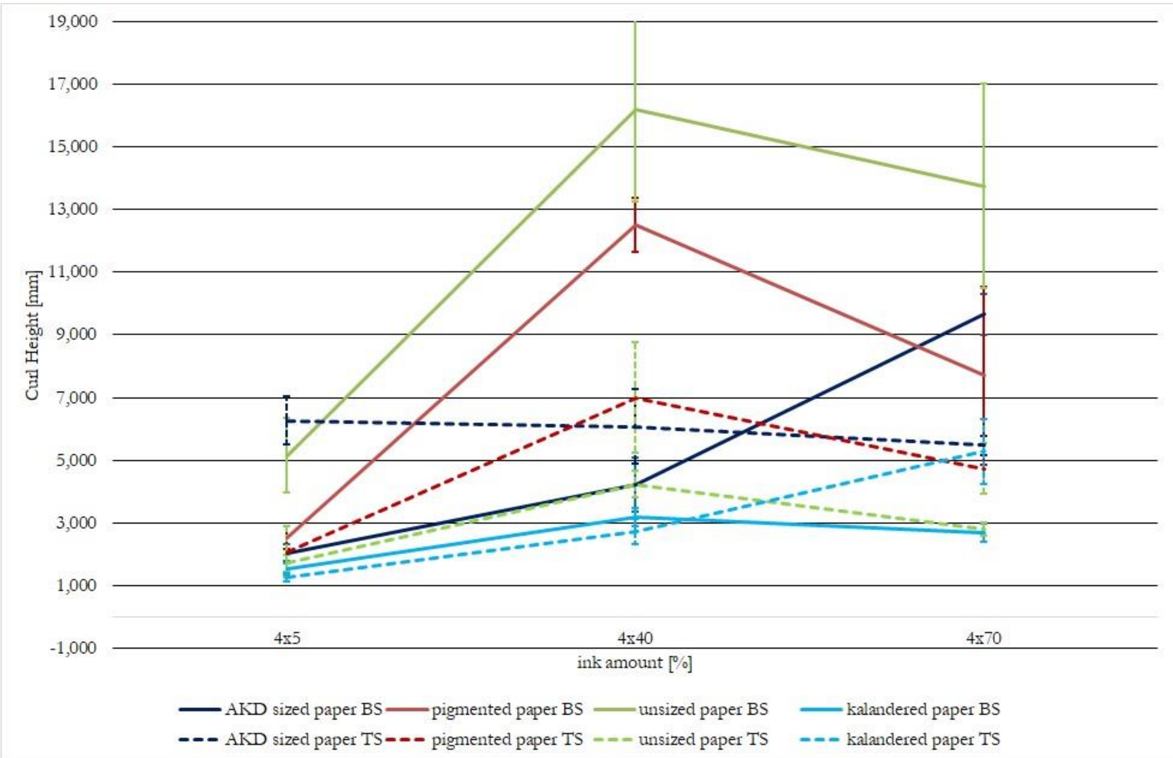

***Figure 109**. Final short-term-curl-height of all four model papers*

The unsized and the pigmented paper have stronger curl behaviour. The top side of these two papers has better curl values than the bottom side. In question of these two papers, the conclusions regarding short- term- curl are:

- the pigmented and the unsized paper have less curl behaviour on top and on bottom side. Also they have strong overall curl.
- the final curl height raises with higher ink amounts to a certain level, where it stays constant.

The decrease of the curl height can NOT be explained with an increase of curvature. Actually, the curvature stays at the same level. It is unclear why the long- term- curl is decreasing. Considering the error bars, which indicates a 95% confidence interval of the curl height, the deviation of the curl height at high ink amounts is wide, but the intervals do not overlap. Thereupon, the curl height on short- term- curl decreases at very high ink amount.

Regarding the other two model paper types no strong two sidedness of the curl height can be detected. The curl height of the top side of the AKD sized paper does not increase with higher ink amounts. The curl height of the calendered paper raises slightly and simultaneously on top and on bottom side with higher ink quantity.

The impact of paper-treatment on short- term-curl can be figured out in a list of this four model paper form the from the worst to the best:

- unsized model paper
- pigmented model paper
- calendered model paper
- AKD sized model paper

5.3.2 Influence of the different paper types on long- term- curl

The conclusions on short- term- curl can be adopted to the long- term- curl can in several ways. **Figure 110**. represents all height values for latex- pigment- ink without primer. There are two papers where curl measurement at high ink levels is still possible (AKD sized and calendered paper) and two, where the curl height measurement is not possible (pigmented and unsized paper) for 4x70% ink coverage (see **Figure 71** at page - 57 -). The arrows at the end of the curl height graph of these papers indicate that behaviour.
While the curl height of the calendered paper increases with higher ink amounts, the AKD sized paper decreases at rather high levels.

At 160% and 280% coverage, which represents 15,7 and 27,5 g/m^2 wet ink appliance, a significant two sidedness can be seen regarding the pigmented, the unsized paper and the AKD sized paper. A higher curl height value is measured for the top side of the unsized and the pigmented and the bottom side of the AKD sized paper. Considering, that the AKD sized paper always has the curl in the opposite direction than the other papers, all three papers have a higher long- term- curl value at the paper side which has the mathematical positive curl. (see. Figure 106. summary of all short-term-curl-results for all model papers). This seems logical because the curl does not have to flip its side form short- to long- term curl.

The curl height of the calendered paper raises slightly and simultaneously on top and on bottom side with higher ink quantity till 15,717 g/m^2. At last, the curl height of the top side decreases, while the bottom side still grows.

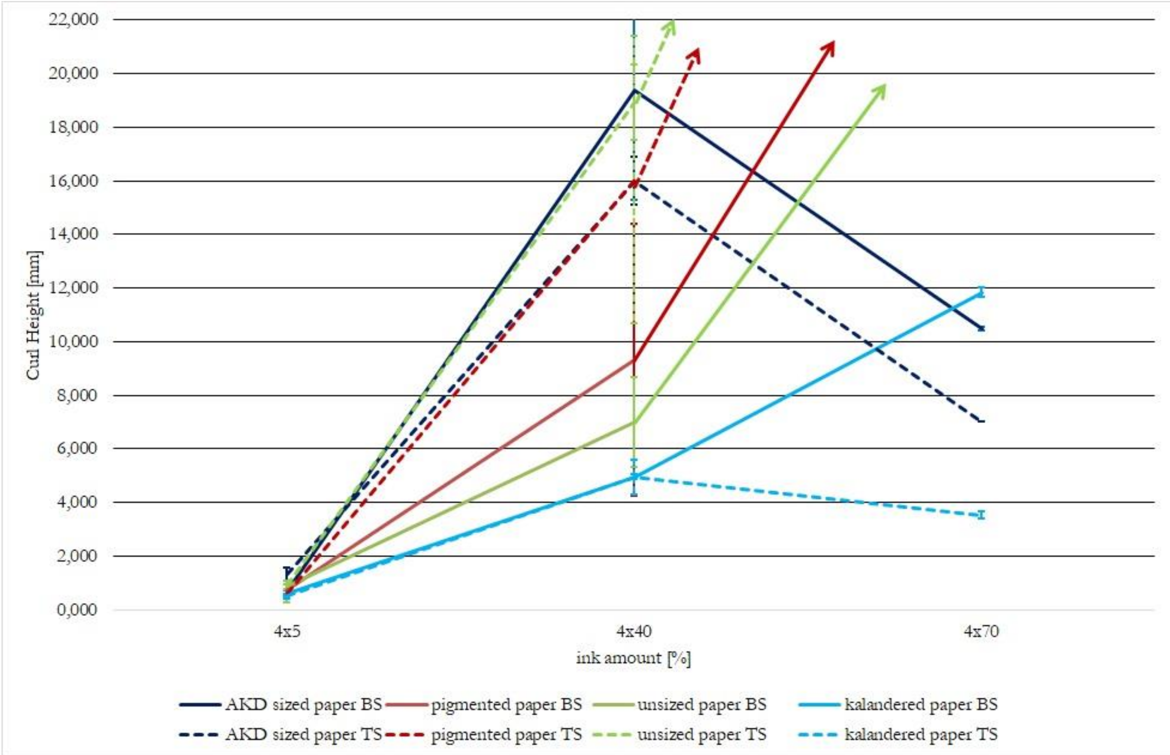

***Figure 110**. Final long-term-curl-height of all four model papers*

Finally, the conclusion is similar to the short- term- conclusion. It is a list of this four model paper from the worst to the best:

- unsized model paper
- pigmented model paper
- calendered model paper
- AKD sized model paper

One idea to explain this logic sequence of the papers is the resistance to liquid take up or the contact angle between the liquid and the paper surface. The unsized paper has the lowest contact angle and hardly no resistance to liquid take up. The pigments hinder the liquid take up, but also interact with the liquid. The calendered paper has a smoother surface and a smoother contact angle. Accordingly, the liquid penetration resistance is higher. The AKD sized paper has a hydrophobization and its contact angle is at the highest level.

5.4 Summary

To sum it up, the conclusion are:

- Short- term- curl is a structural curl and caused by two-sidedness of the paper and paper properties
- Long- term- curl is not possible to distinguish but some observed facts as preconditions must be the case:
    - long-term-curl just happens if the sample was printed or wetted
    - long-term-curl needs relative humidity to develop
- The list of model papers from the worst to the best regarding their curl behaviour
    - unsized model paper
    - pigmented model paper
    - calendered model paper
    - AKD sized model paper

The short- term- curl is a structural curl which could be characterized by the observed curl-flipping effect when changing the printing side. This effect in combination with the result of the blanco-printing-experiment, which showed that the short- term- curl can also be activated with just drying from one side, and that this curl is fully reversible, leads to this conclusion.

Apparently a structural two sidedness in the paper (FO, filler, fines, sizing, two sidedness regarding former type) leads to a curl which is caused by the structural two sidedness. The curl always goes towards the same side of the paper no matter where the wetting/ drying is applied to. The AKD sized paper apparently has a different structural two sidedness; it is produced on a different paper machine than the other papers. In general, structural curl can be minimized by reducing the swelling/ shrinkage of the paper sheet. We also see this in the experiments -the short- term curl is indeed reduced by lower liquid amounts (dye vs. pigment ink) and by using primer. Primer contains of salt ($CaCl_3$) which inhibits the swelling of the fibers.

The mechanism of the long- term curl behaviour and how the long- term- curl is working is not fully understood In contrast to the short- term- curl, the classification of the long-term-curl to a curl-type is not possible yet. Two obligatory conditions must happen in order for long- term curl to develop. A long-term-curl just happens if the sample was printed or wetted and long-term-curl needs relative humidity to develop.

The curl depends on the side of wetting and NOT on the paper side. A storage at 0 % RH freezes the short- term- curl and reconditioning with 50 % RH triggers this long-term-curl. Printing with ink and drying on a hot plate always leads to a positive final long-term-curl. It is unclear why the long- term- curl is negative for air drying and for printing only primer.

The rating of the four used model papers regarding their curl behaviour concludes that the AKD sized shows the best results, followed by the calendered and the pigmented paper. The unsized paper has the worst curl behaviour. This sequence does not change for long- or short- term curl behaviour. One idea to explain this logic sequence of the papers is the resistance to liquid take up or the contact angle between the liquid and the paper surface. The unsized paper has the lowest contact angle and hardly no resistance to liquid take up. The pigments hinder the liquid take up, but also interact with the liquid. The calendered paper has a smoother surface and a smoother contact angle. Accordingly, the liquid penetration resistance is higher. The AKD sized paper has a hydrophobization and its contact angle is at the highest level.

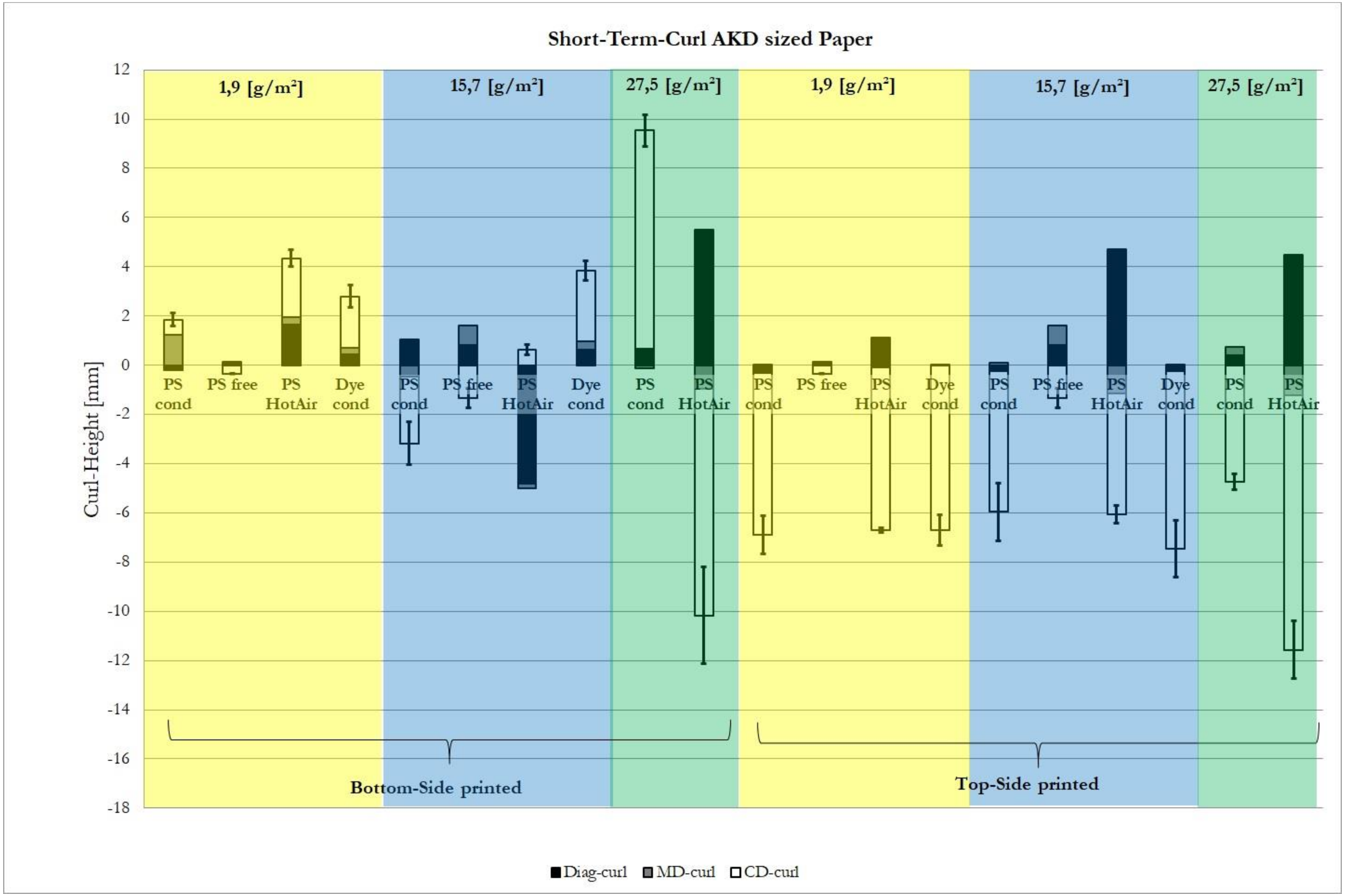

***Figure 111**. Short- term- curl results of all erxperiments done for AKD sized paper*

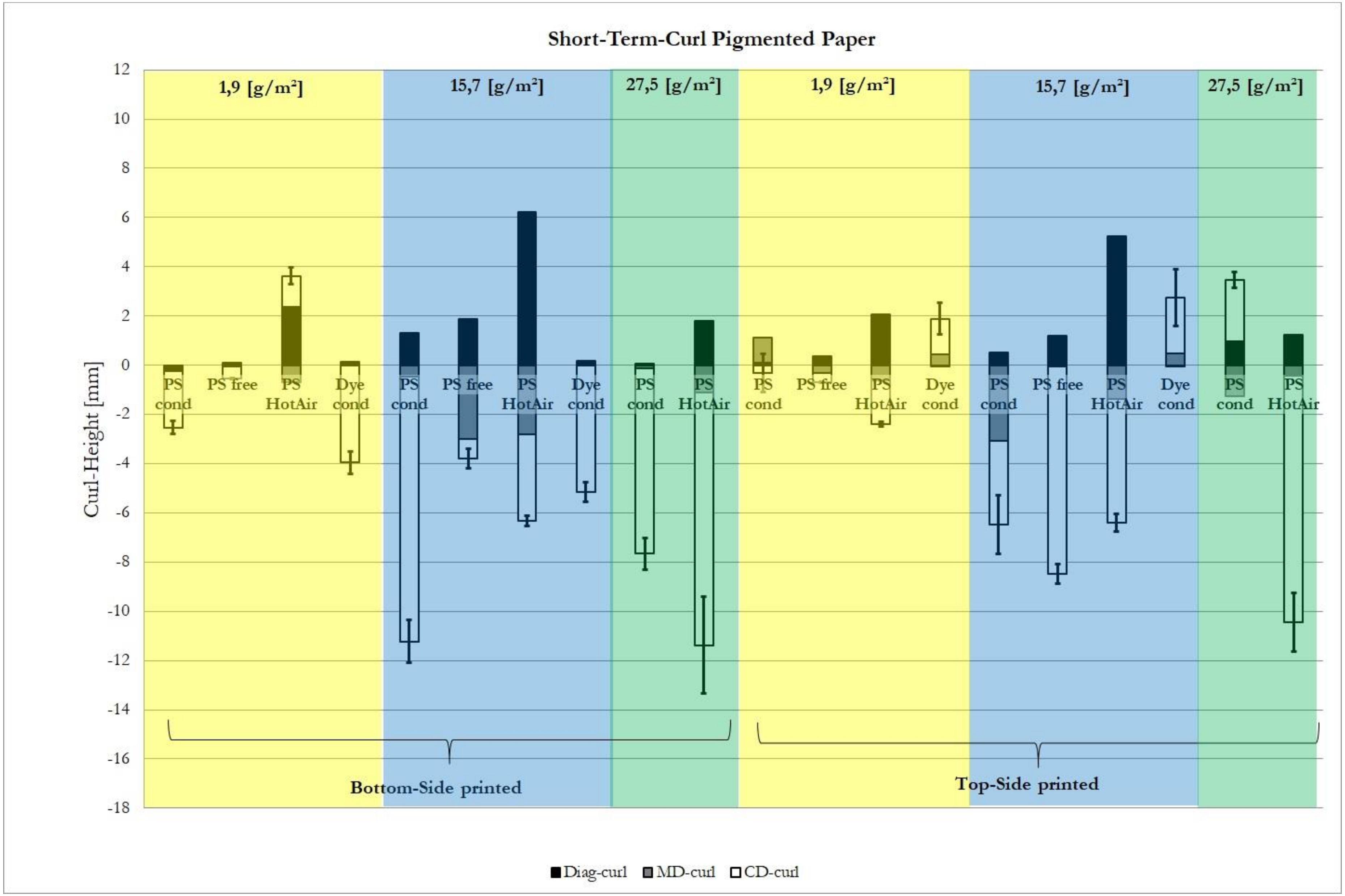

Figure 112. *Short- term- curl results of all erxperiments done for pigmented paper*

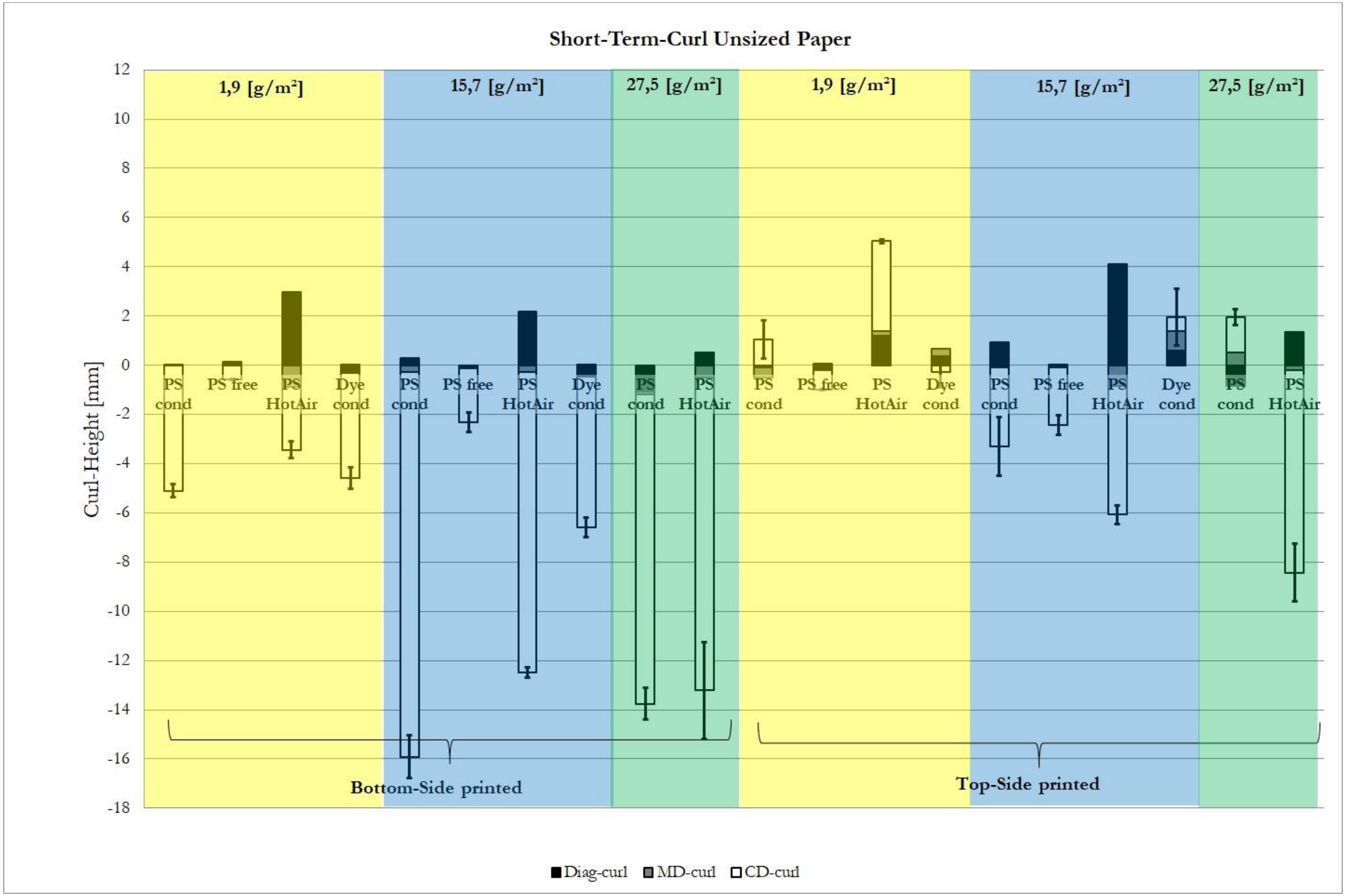

Figure 113. *Short- term- curl results of all erxperiments done for unsized paper*

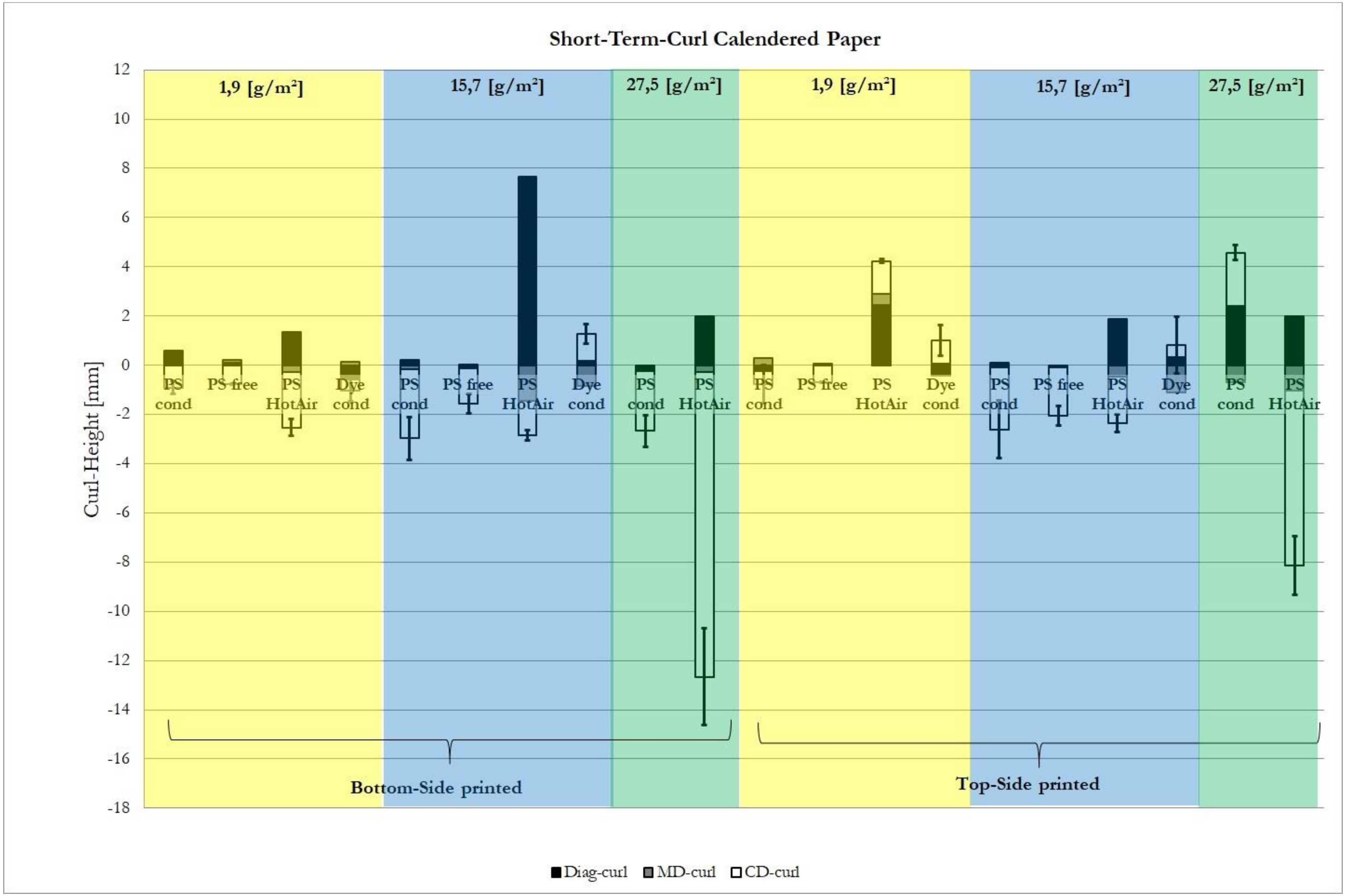

***Figure 114**. Short- term- curl results of all erxperiments done for calendered paper*

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[21] A. Lundberg, J. O rtegren, and O. Norberg, "Aggregation of Color Pigments by Surface Fixation Treatment," *J. Imaging Sci. Technol.*, vol. 55, no. 5, p. 50605, 2011.

6.2.2 List of figures

6.2.3 List of tables

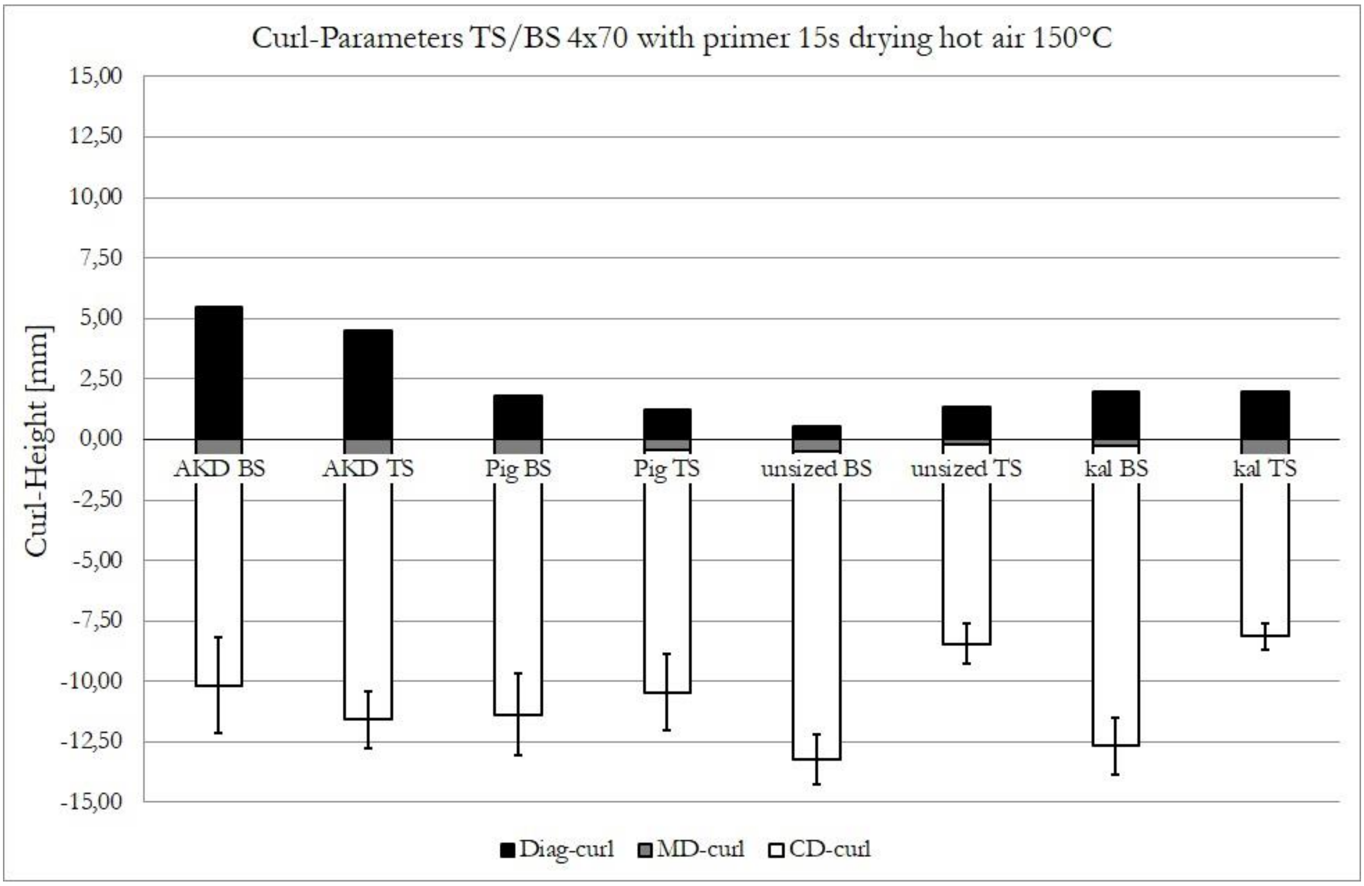
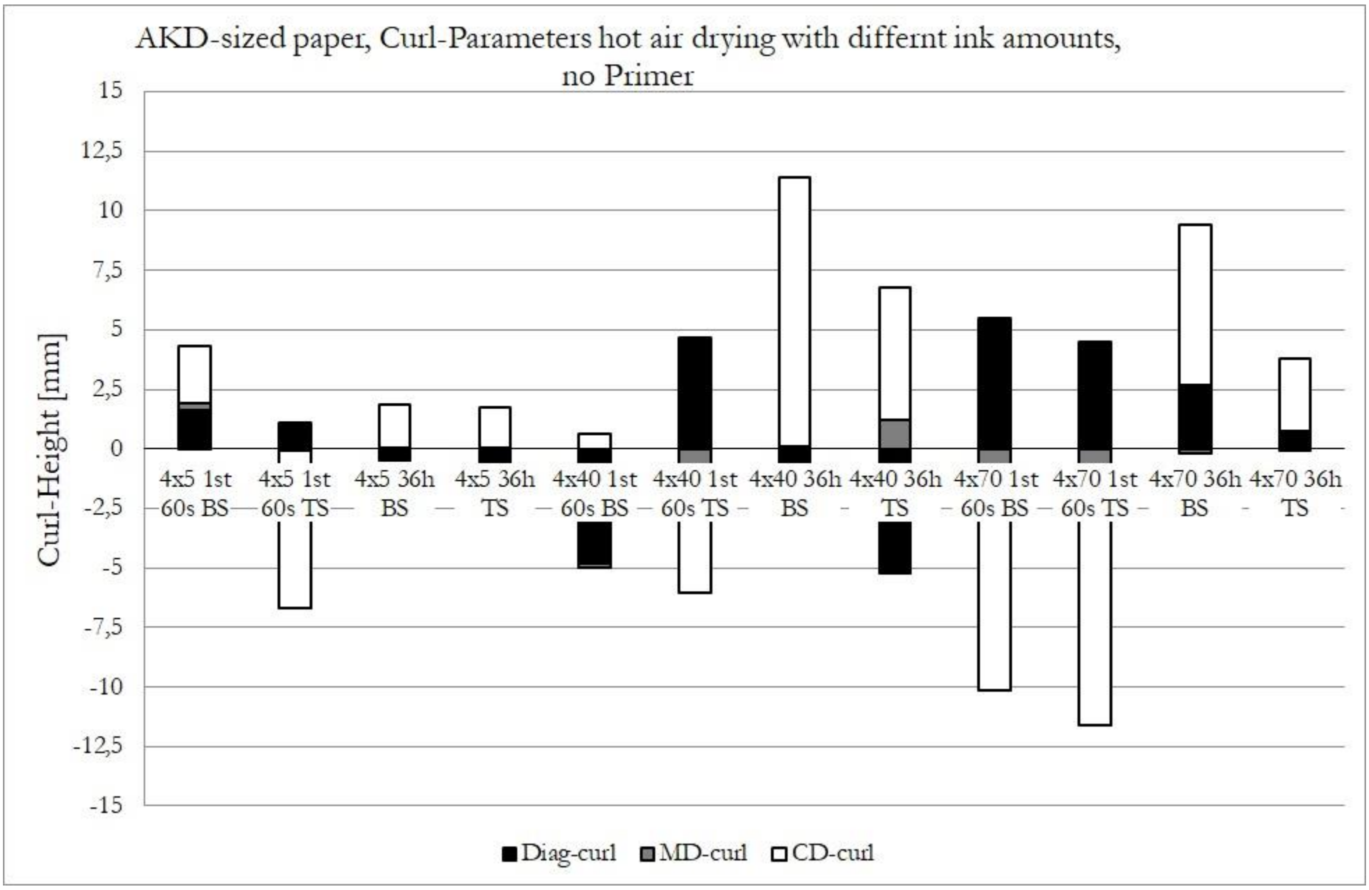
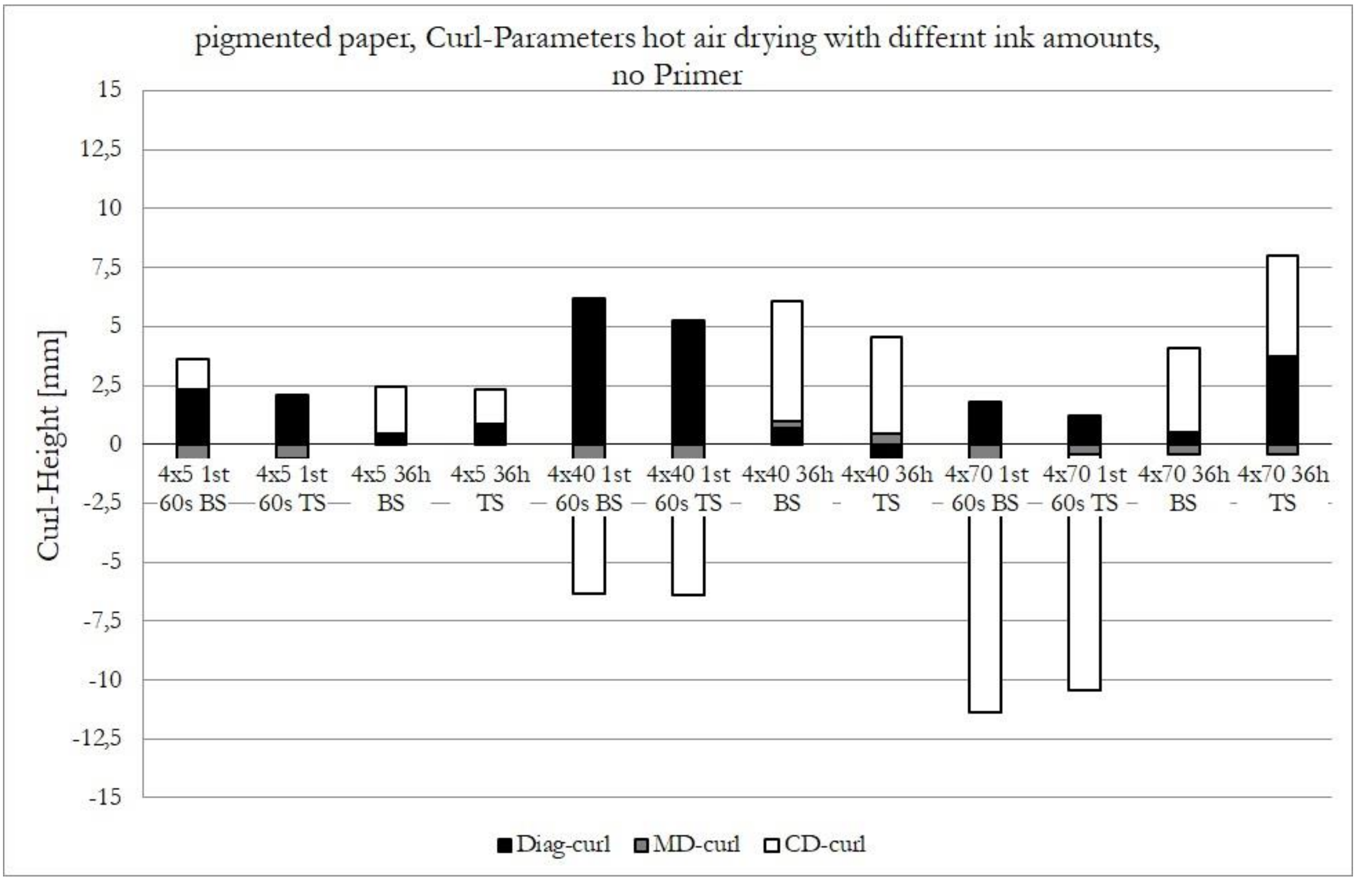
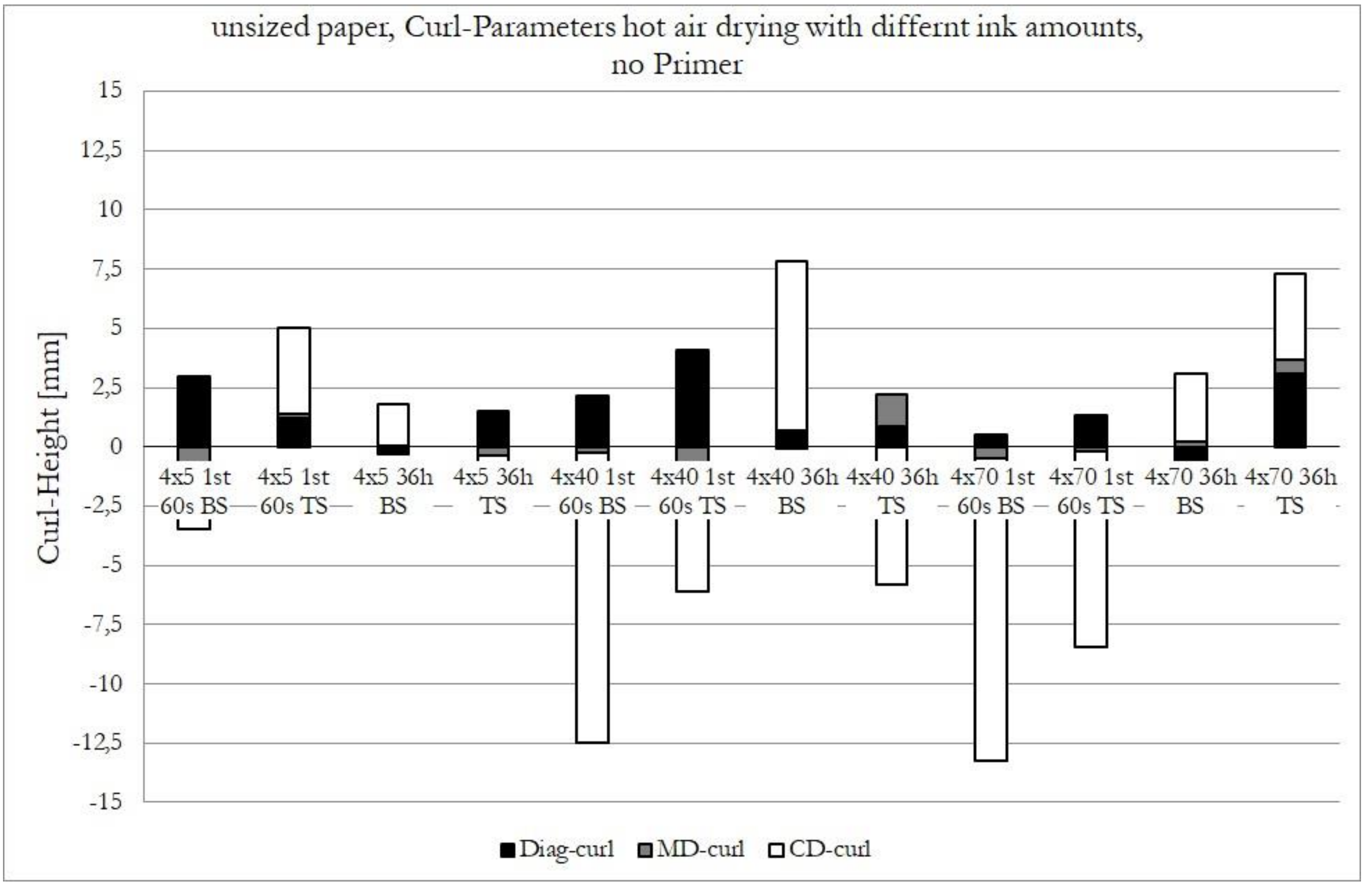
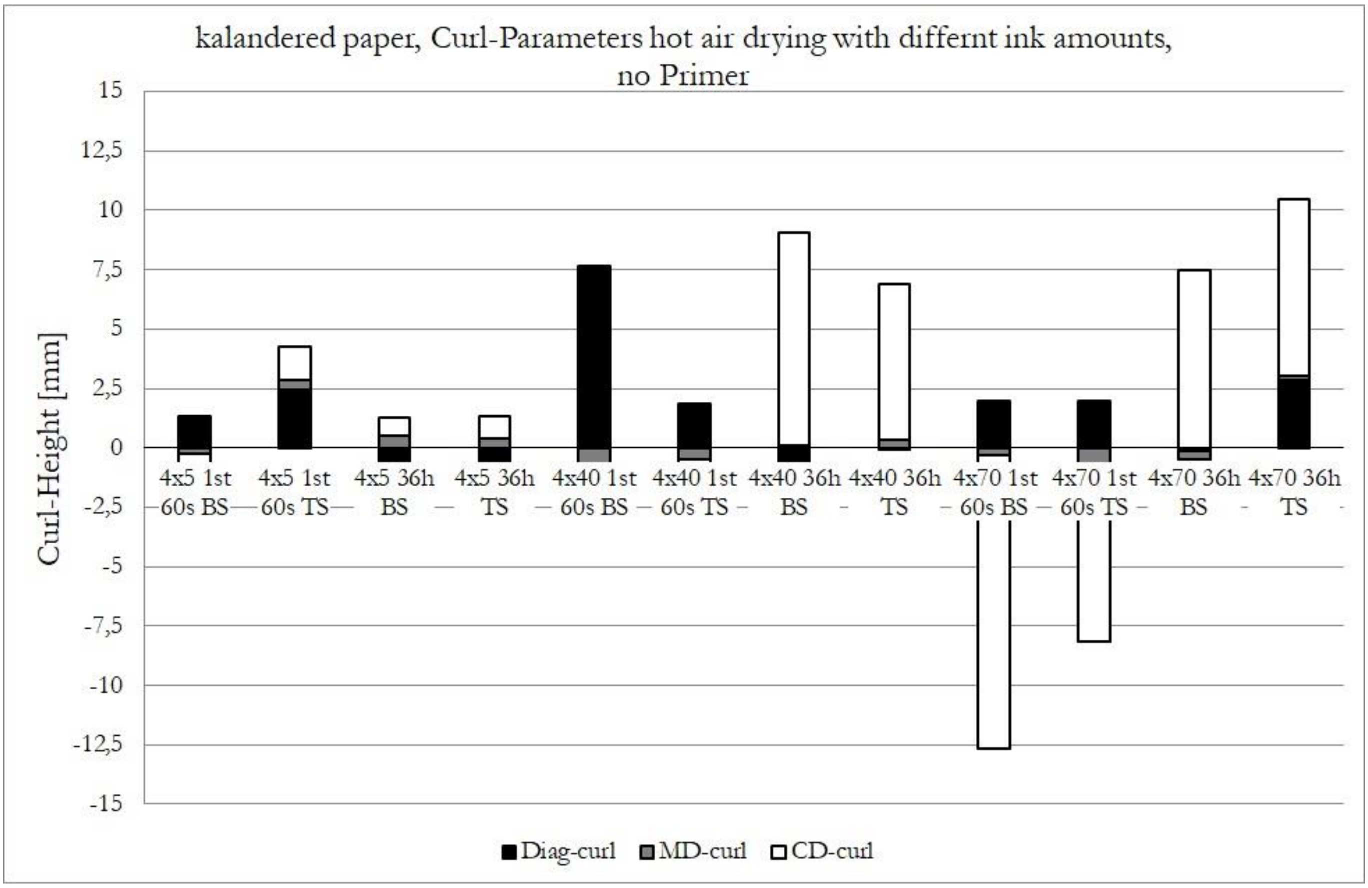


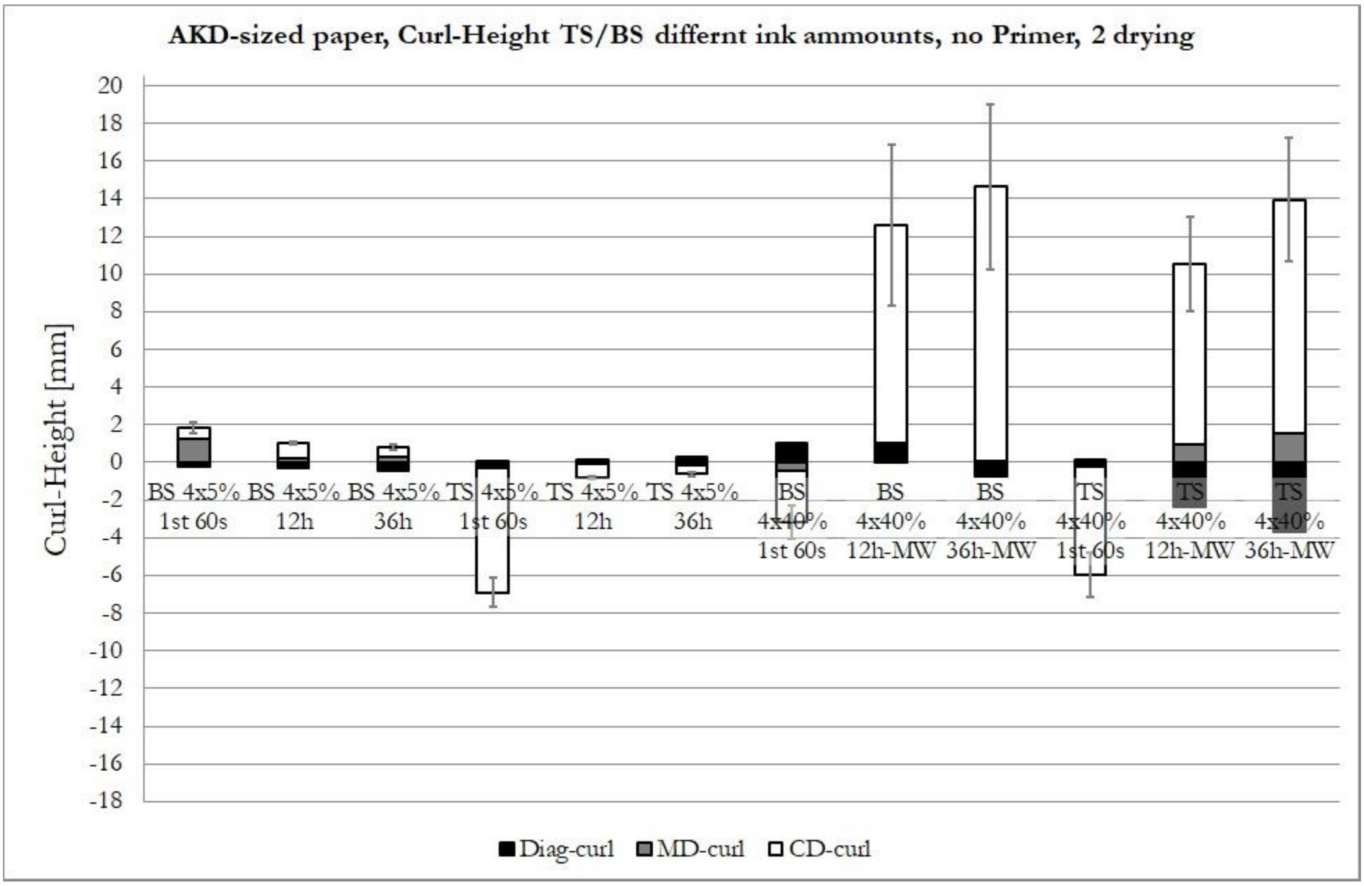
***Figure 115**. Result of the short term curl of the hot air drying under defined stress. number of samples n=9 each*

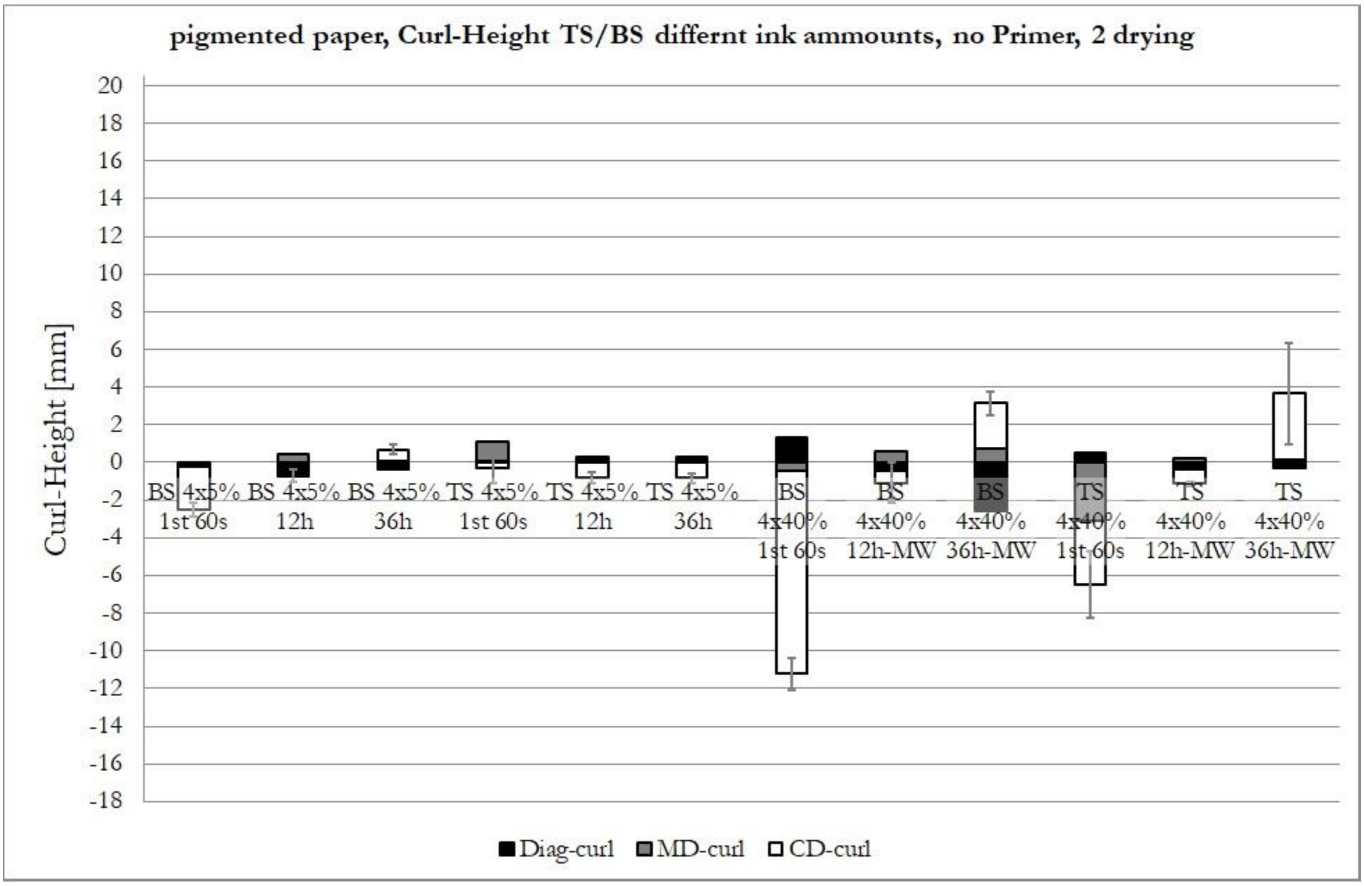


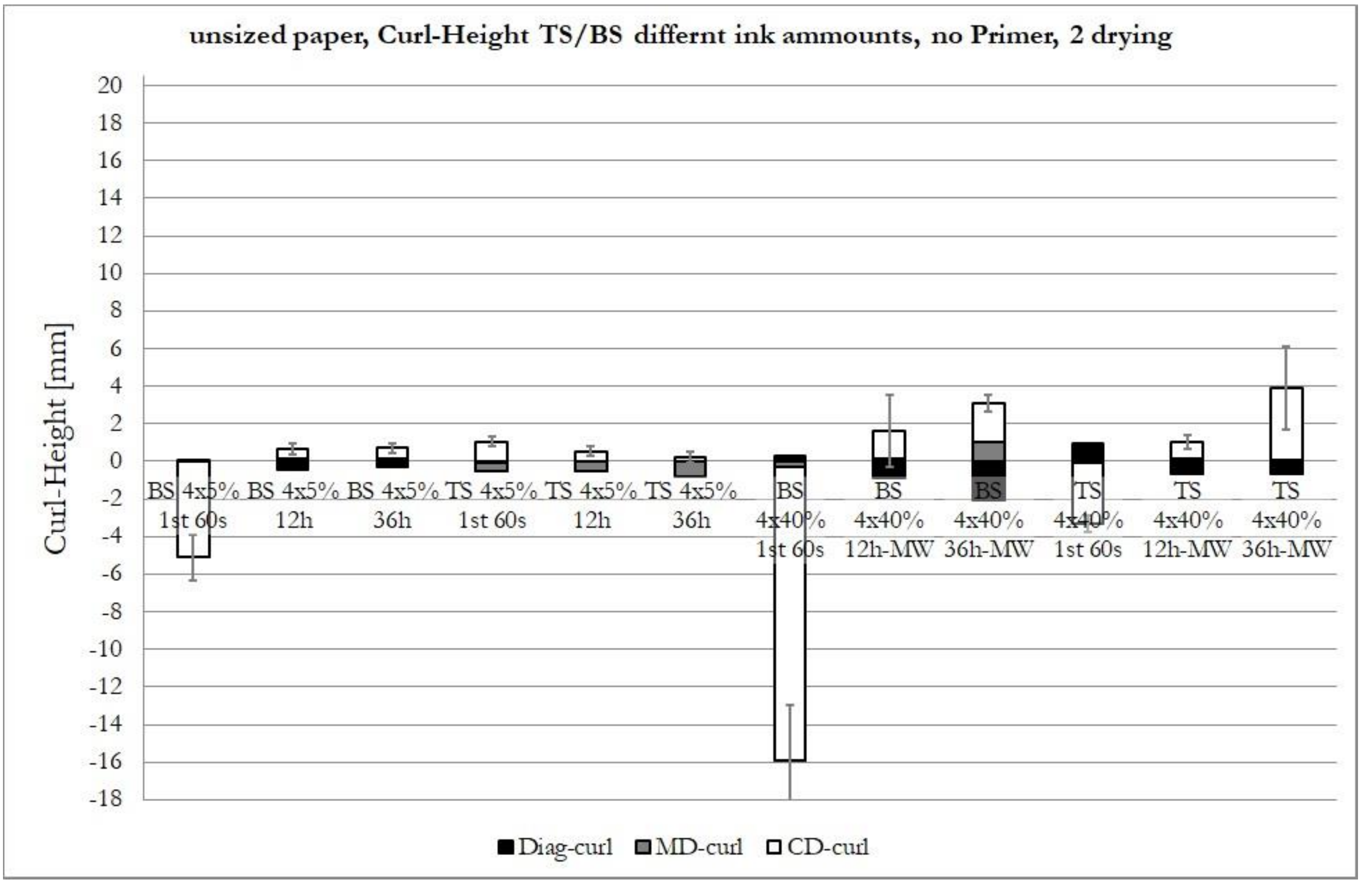

pigmented paper, Curl-Parameters hot air drying with differnt ink amounts, no Primer
Curl-Height [mm]
15
12,5
10
7,5
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
4x5 1st 60s BS
4x5 1st 60s TS
4x5 36h BS
4x5 36h TS
4x40 1st 60s BS
4x40 1st 60s TS
4x40 36h BS
4x40 36h TS
4x70 1st 60s BS
4x70 1st 60s TS
4x70 36h BS
4x70 36h TS
Diag-curl
MD-curl
CD-curl

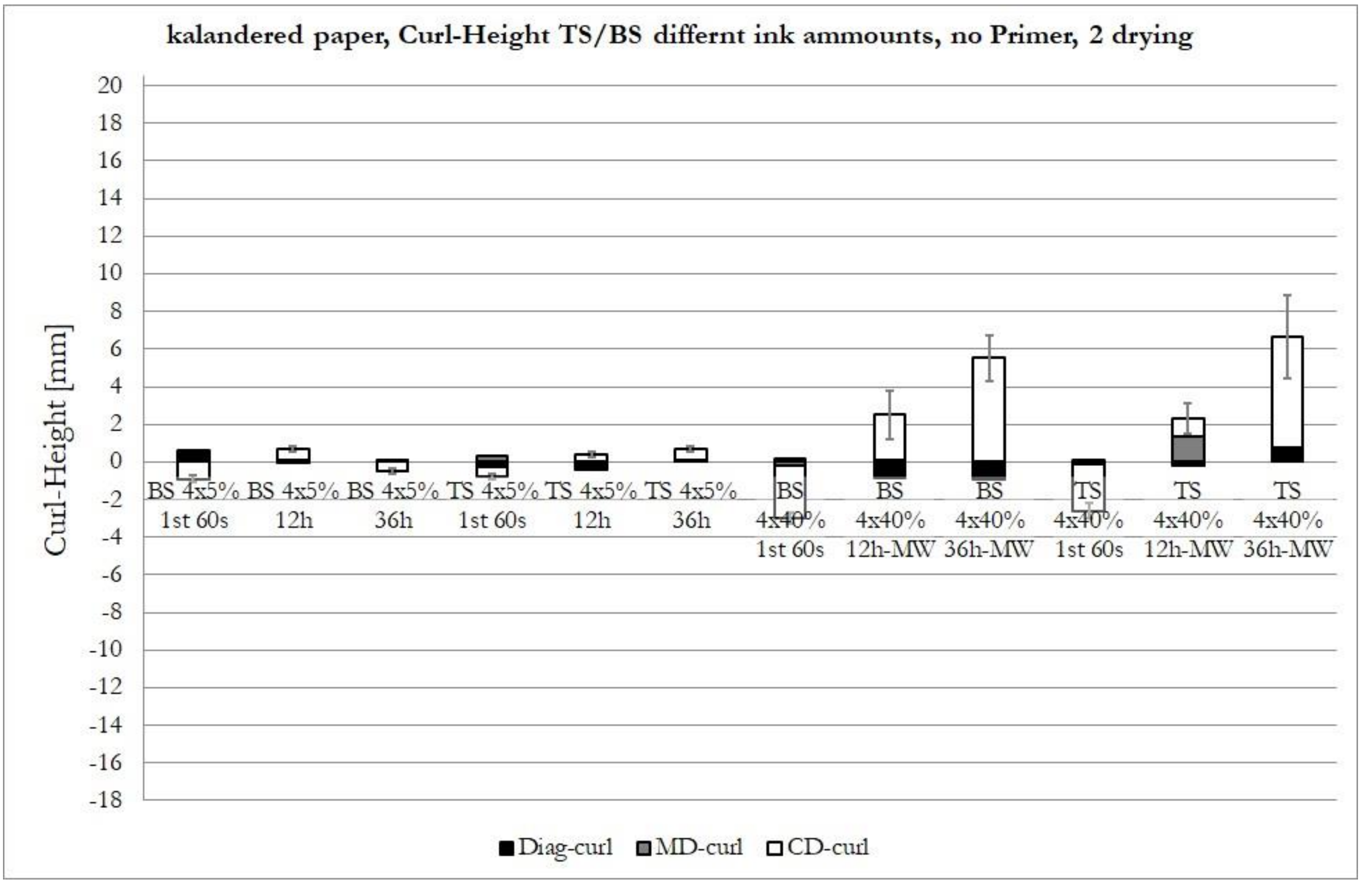

unsized paper, Curl-Parameters hot air drying with differnt ink amounts, no Primer
Curl-Height [mm]
15
12,5
10
7,5
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
4x5 1st 60s BS
4x5 1st 60s TS
4x5 36h BS
4x5 36h TS
4x40 1st 60s BS
4x40 1st 60s TS
4x40 36h BS
4x40 36h TS
4x70 1st 60s BS
4x70 1st 60s TS
4x70 36h BS
4x70 36h TS
Diag-curl
MD-curl
CD-curl

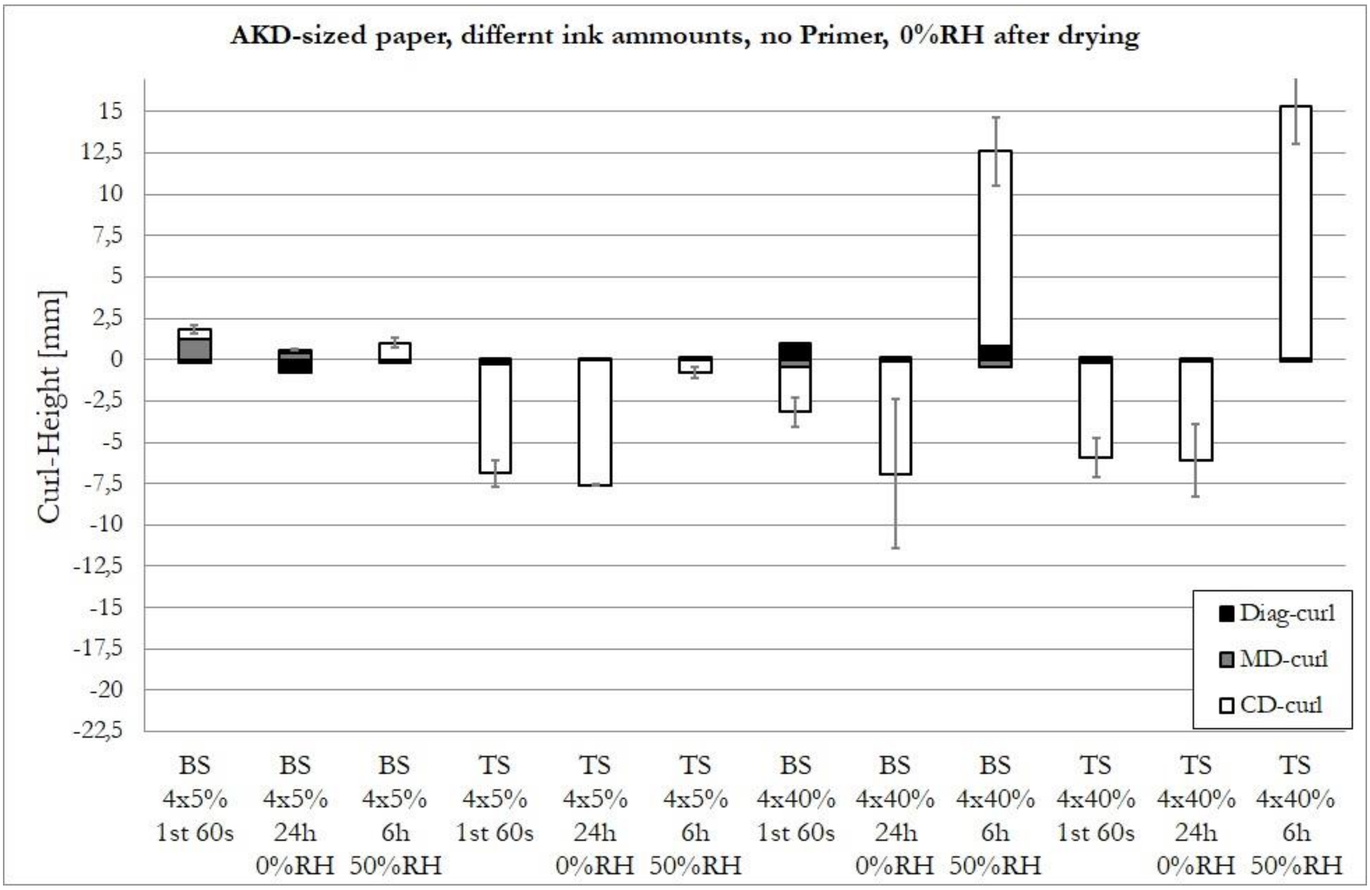

kalandered paper, Curl-Parameters hot air drying with differnt ink amounts, no Primer
Curl-Height [mm]
15
12,5
10
7,5
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
4x5 1st 60s BS
4x5 1st 60s TS
4x5 36h BS
4x5 36h TS
4x40 1st 60s BS
4x40 1st 60s TS
4x40 36h BS
4x40 36h TS
4x70 1st 60s BS
4x70 1st 60s TS
4x70 36h BS
4x70 36h TS
Diag-curl
MD-curl
CD-curl

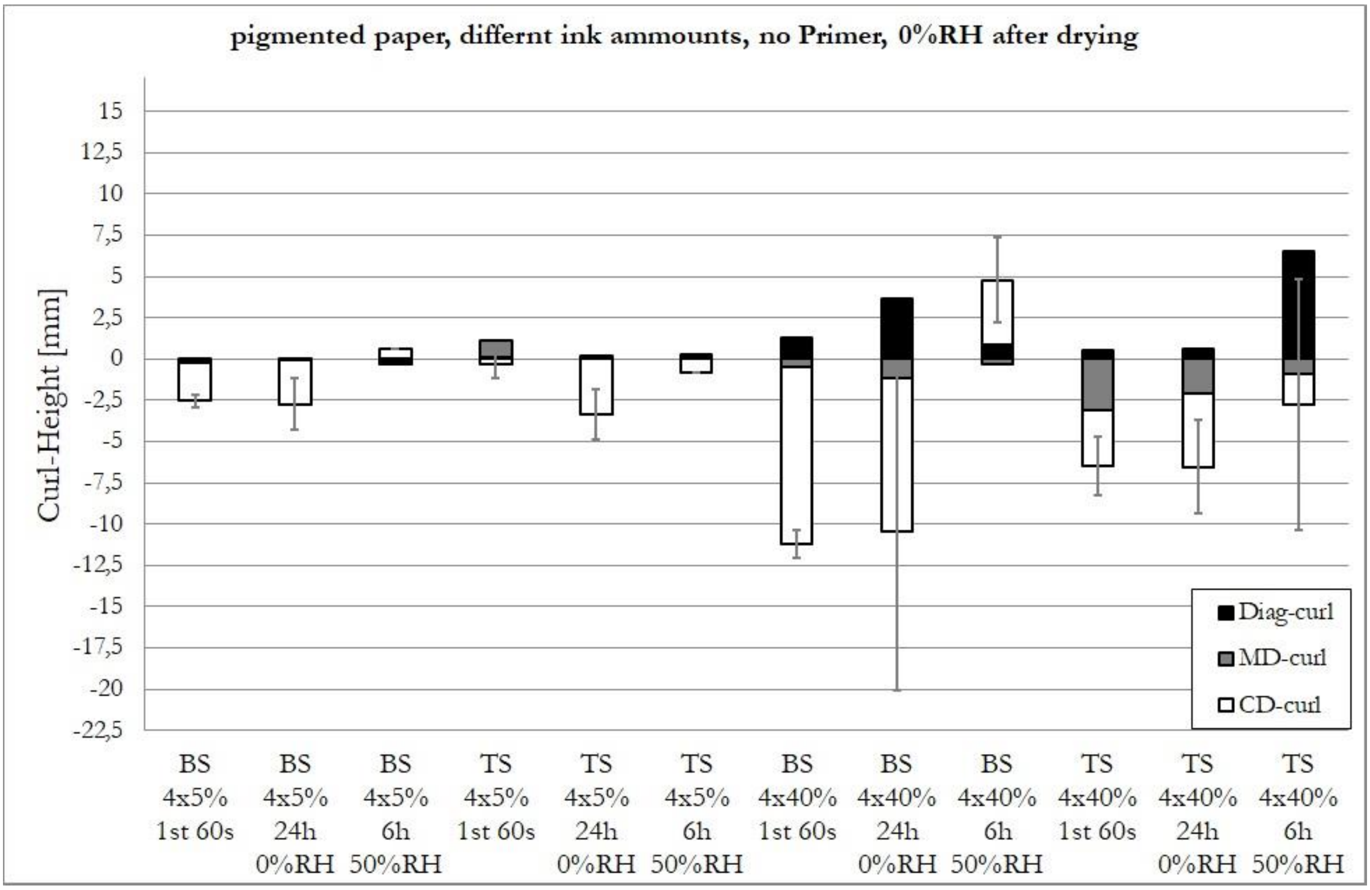

AKD-sized paper, Curl-Height TS/BS differnt ink ammounts, no Primer, 2 drying
Curl-Height [mm]
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
BS 4x5% 1st 60s
BS 4x5% 12h
BS 4x5% 36h
TS 4x5% 1st 60s
TS 4x5% 12h
TS 4x5% 36h
BS 4x40% 1st 60s
BS 4x40% 12h-MW
BS 4x40% 36h-MW
TS 4x40% 1st 60s
TS 4x40% 12h-MW
TS 4x40% 36h-MW
Diag-curl
MD-curl
CD-curl

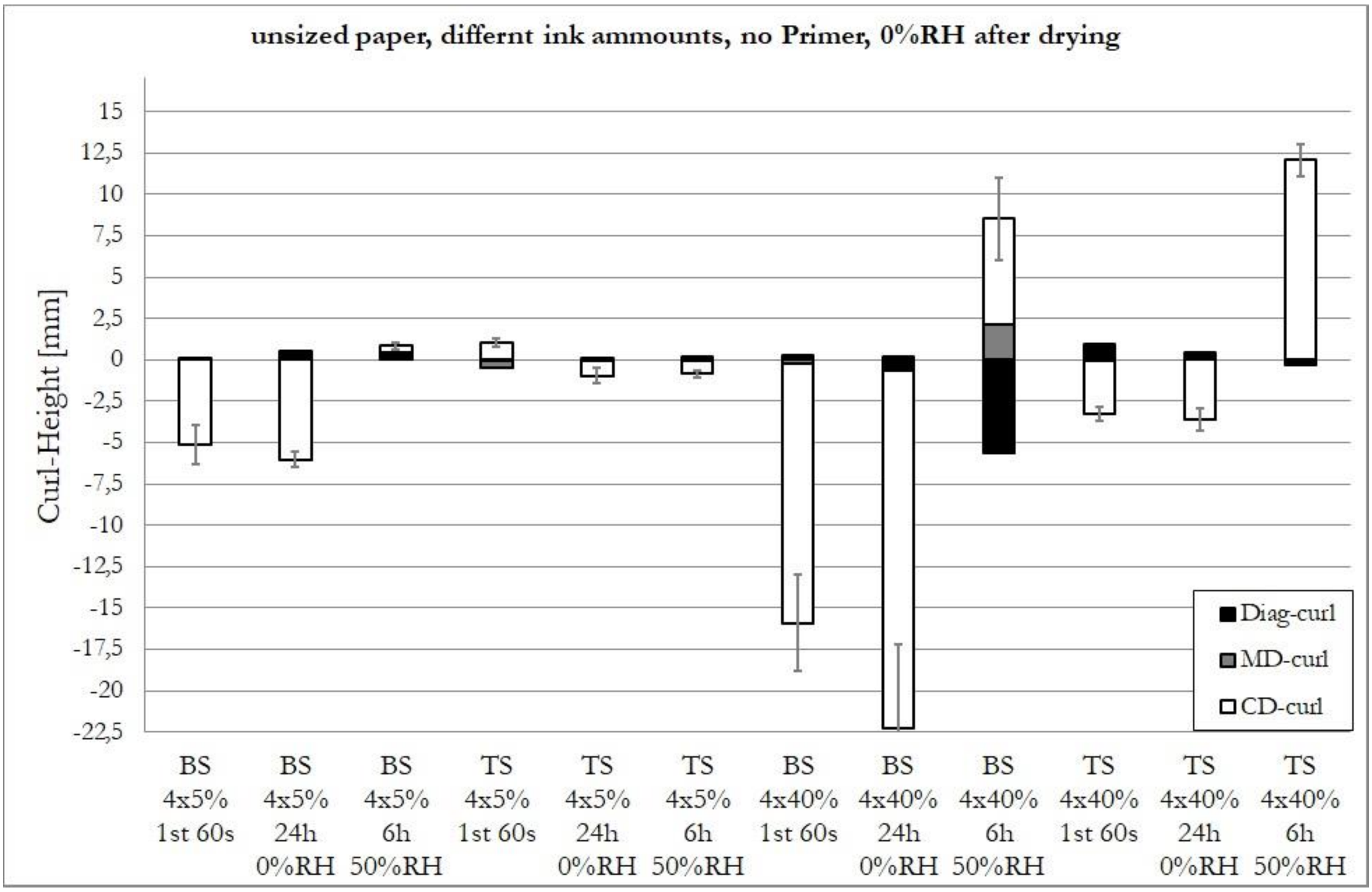

pigmented paper, Curl-Height TS/BS differnt ink ammounts, no Primer, 2 drying
Curl-Height [mm]
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
BS 4x5% 1st 60s
BS 4x5% 12h
BS 4x5% 36h
TS 4x5% 1st 60s
TS 4x5% 12h
TS 4x5% 36h
BS 4x40% 1st 60s
BS 4x40% 12h-MW
BS 4x40% 36h-MW
TS 4x40% 1st 60s
TS 4x40% 12h-MW
TS 4x40% 36h-MW
Diag-curl
MD-curl
CD-curl

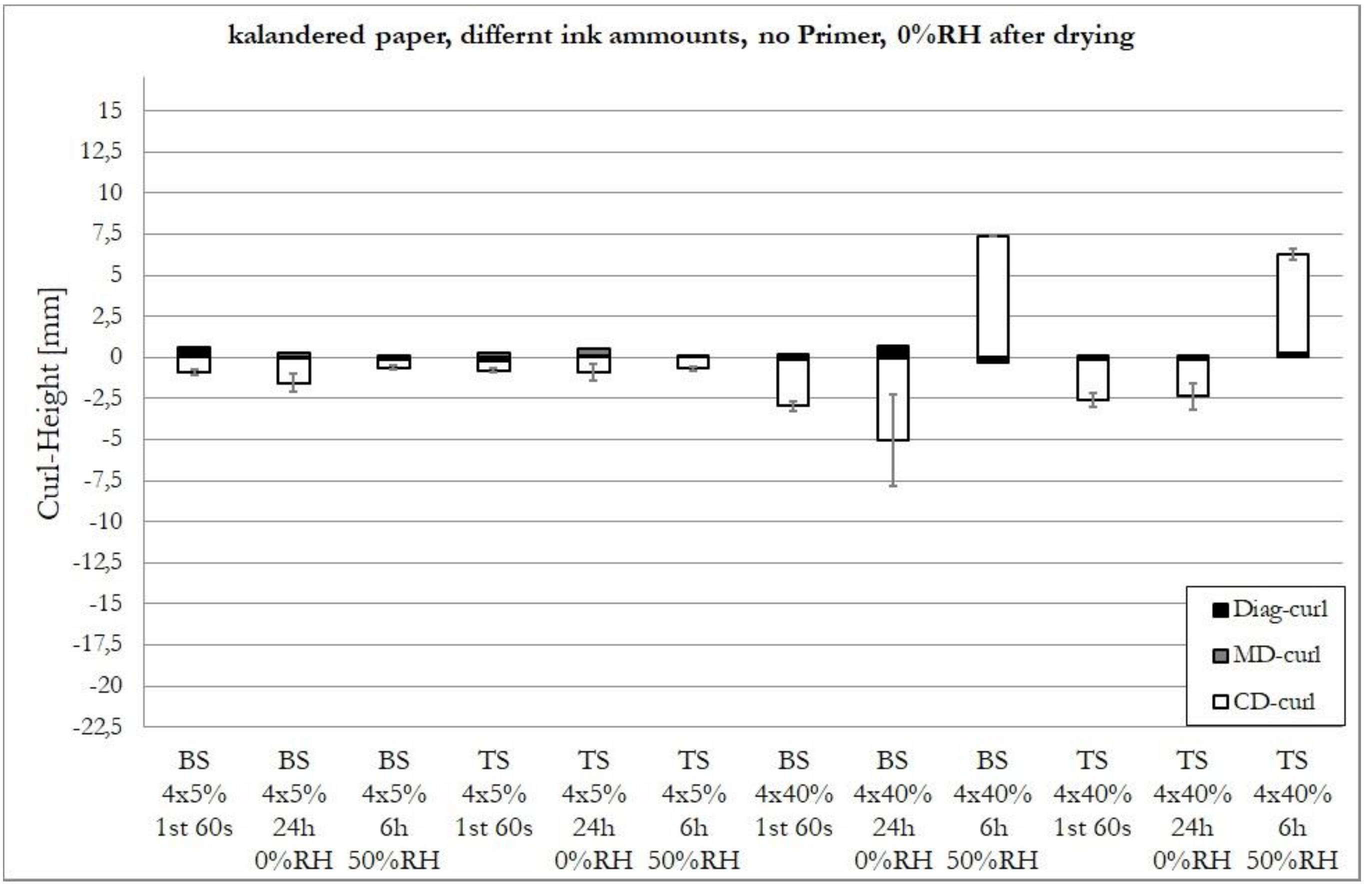

unsized paper, Curl-Height TS/BS differnt ink ammounts, no Primer, 2 drying
Curl-Height [mm]
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
BS 4x5% 1st 60s
BS 4x5% 12h
BS 4x5% 36h
TS 4x5% 1st 60s
TS 4x5% 12h
TS 4x5% 36h
BS 4x40% 1st 60s
BS 4x40% 12h-MW
BS 4x40% 36h-MW
TS 4x40% 1st 60s
TS 4x40% 12h-MW
TS 4x40% 36h-MW
Diag-curl
MD-curl
CD-curl

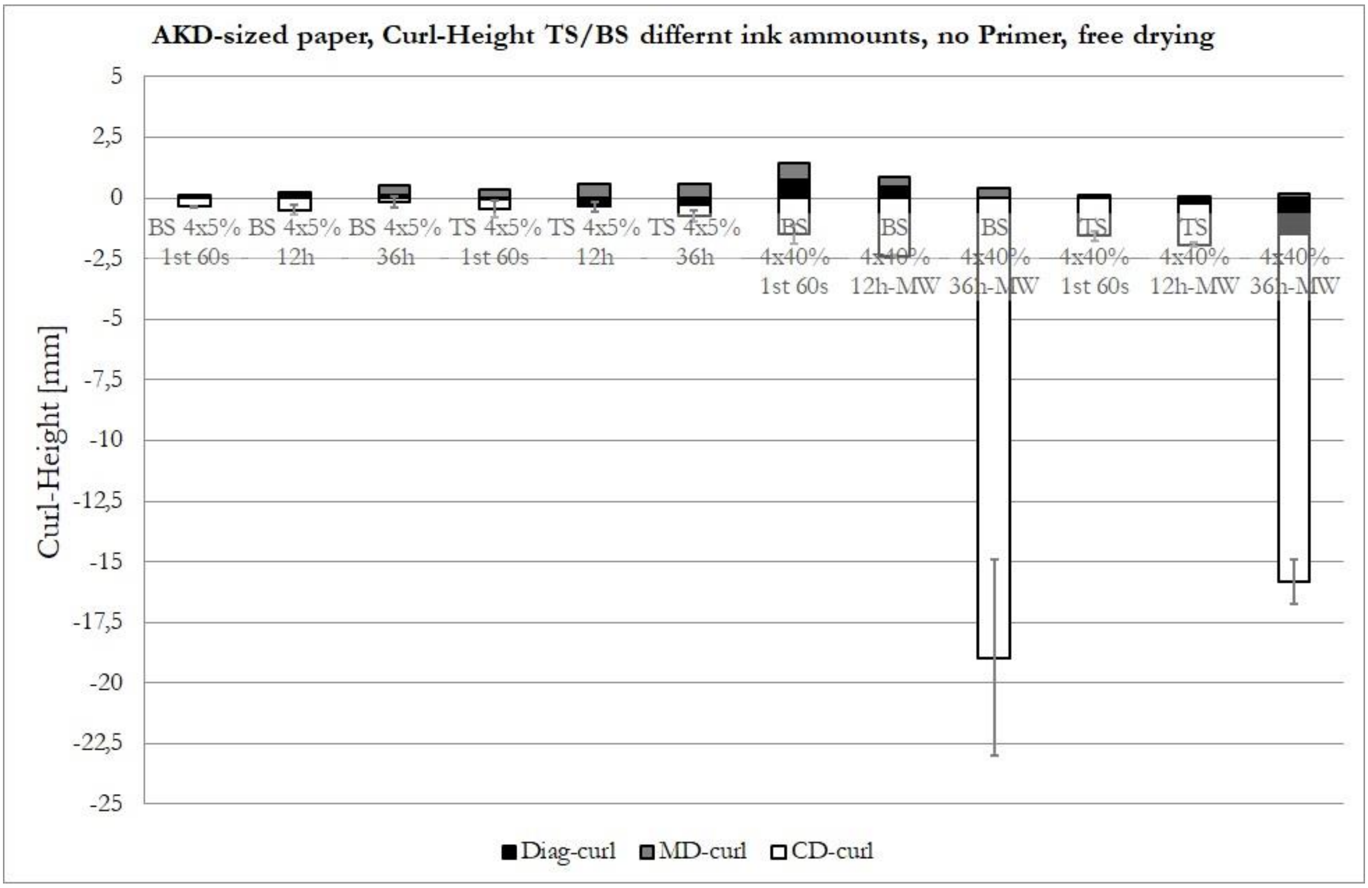

kalandered paper, Curl-Height TS/BS differnt ink ammounts, no Primer, 2 drying
Curl-Height [mm]
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
BS 4x5% 1st 60s
BS 4x5% 12h
BS 4x5% 36h
TS 4x5% 1st 60s
TS 4x5% 12h
TS 4x5% 36h
BS 4x40% 1st 60s
BS 4x40% 12h-MW
BS 4x40% 36h-MW
TS 4x40% 1st 60s
TS 4x40% 12h-MW
TS 4x40% 36h-MW
Diag-curl
MD-curl
CD-curl

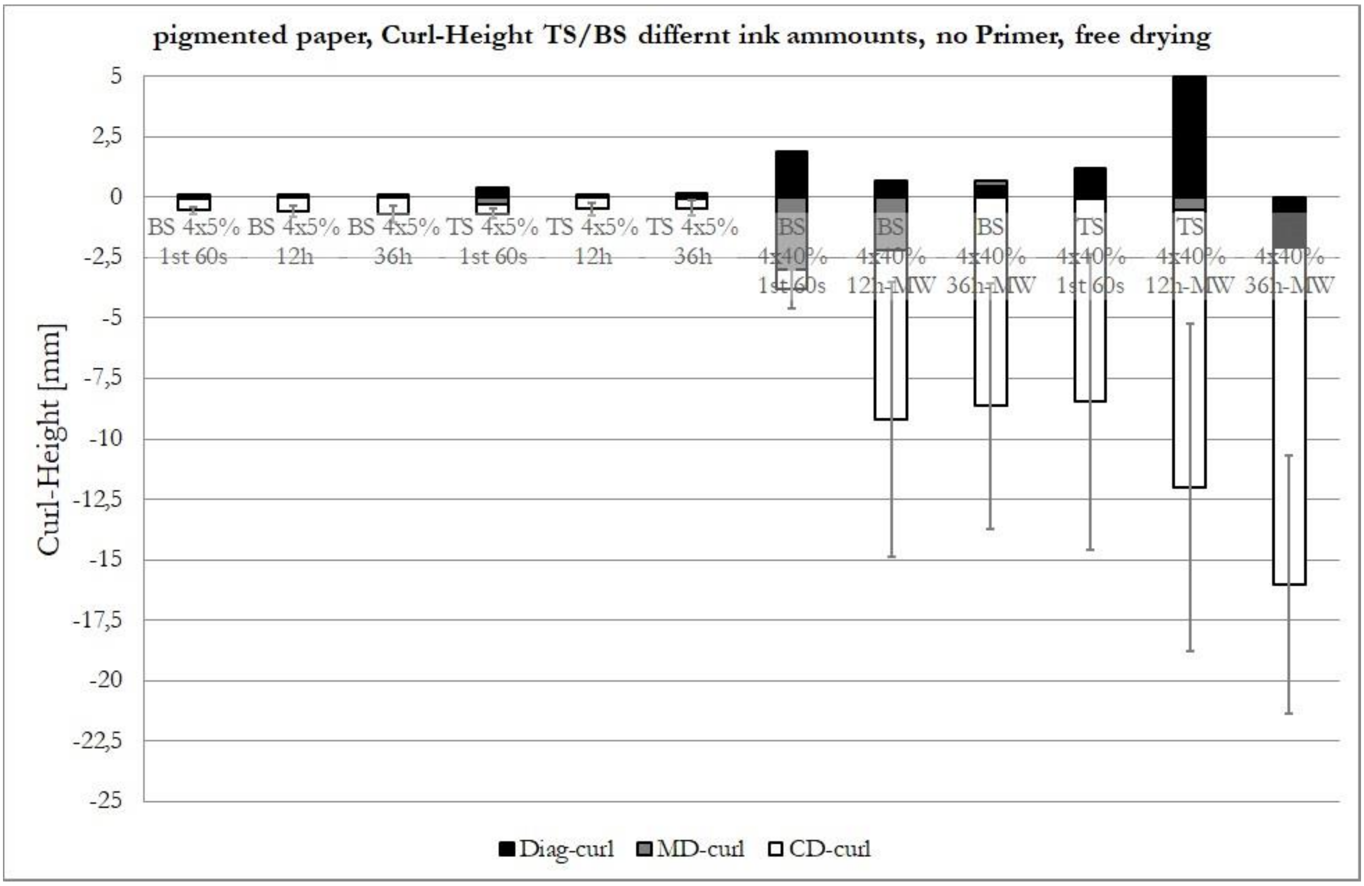

AKD-sized paper, differnt ink ammounts, no Primer, 0%RH after drying
Curl-Height [mm]
15
12,5
10
7,5
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
-17,5
-20
-22,5
Diag-curl
MD-curl
CD-curl
BS 4x5% 1st 60s
BS 4x5% 24h 0%RH
BS 4x5% 6h 50%RH
TS 4x5% 1st 60s
TS 4x5% 24h 0%RH
TS 4x5% 6h 50%RH
BS 4x40% 1st 60s
BS 4x40% 24h 0%RH
BS 4x40% 6h 50%RH
TS 4x40% 1st 60s
TS 4x40% 24h 0%RH
TS 4x40% 6h 50%RH

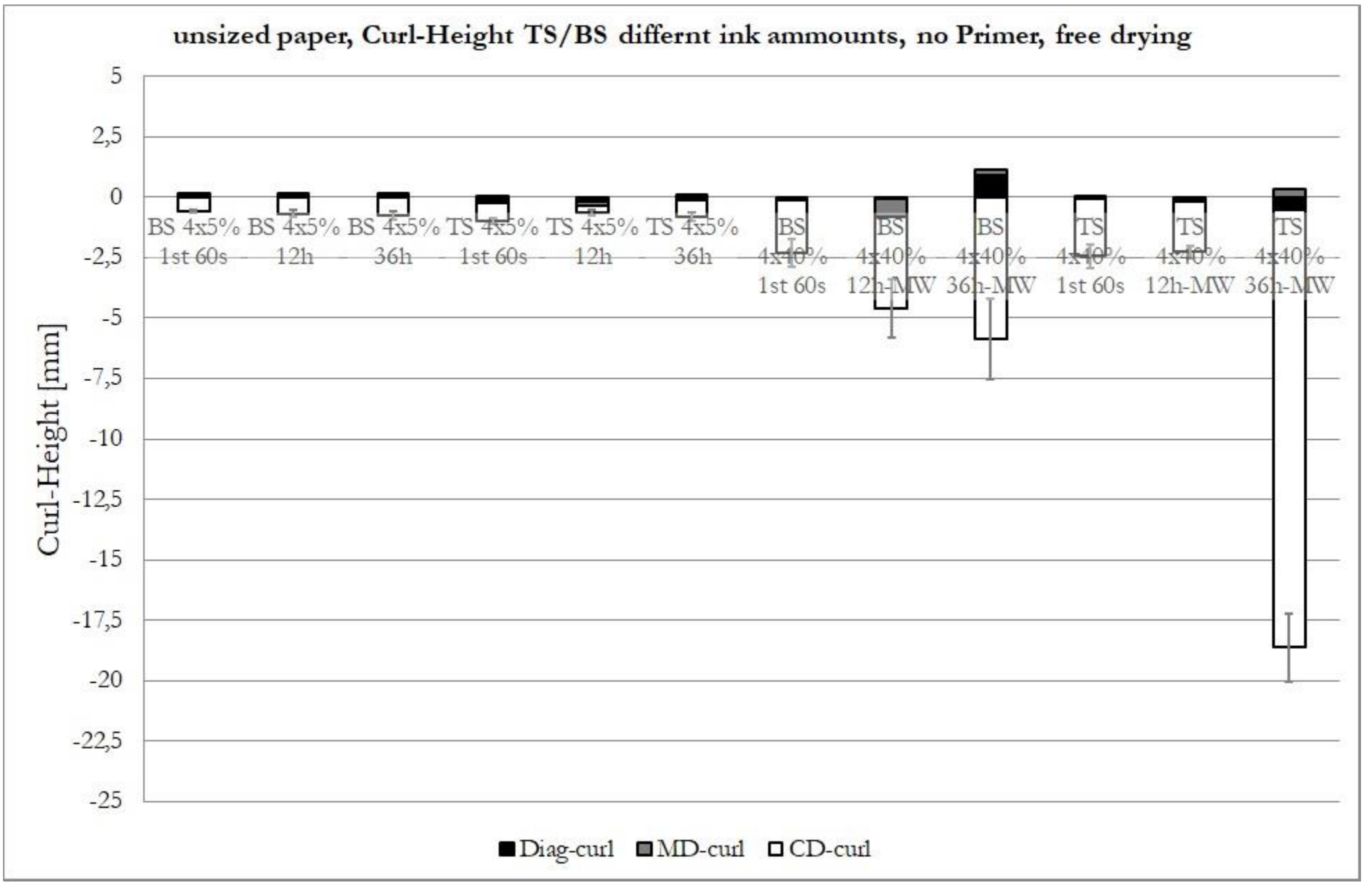

pigmented paper, differnt ink ammounts, no Primer, 0%RH after drying
Curl-Height [mm]
15
12,5
10
7,5
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
-17,5
-20
-22,5
Diag-curl
MD-curl
CD-curl
BS 4x5% 1st 60s
BS 4x5% 24h 0%RH
BS 4x5% 6h 50%RH
TS 4x5% 1st 60s
TS 4x5% 24h 0%RH
TS 4x5% 6h 50%RH
BS 4x40% 1st 60s
BS 4x40% 24h 0%RH
BS 4x40% 6h 50%RH
TS 4x40% 1st 60s
TS 4x40% 24h 0%RH
TS 4x40% 6h 50%RH

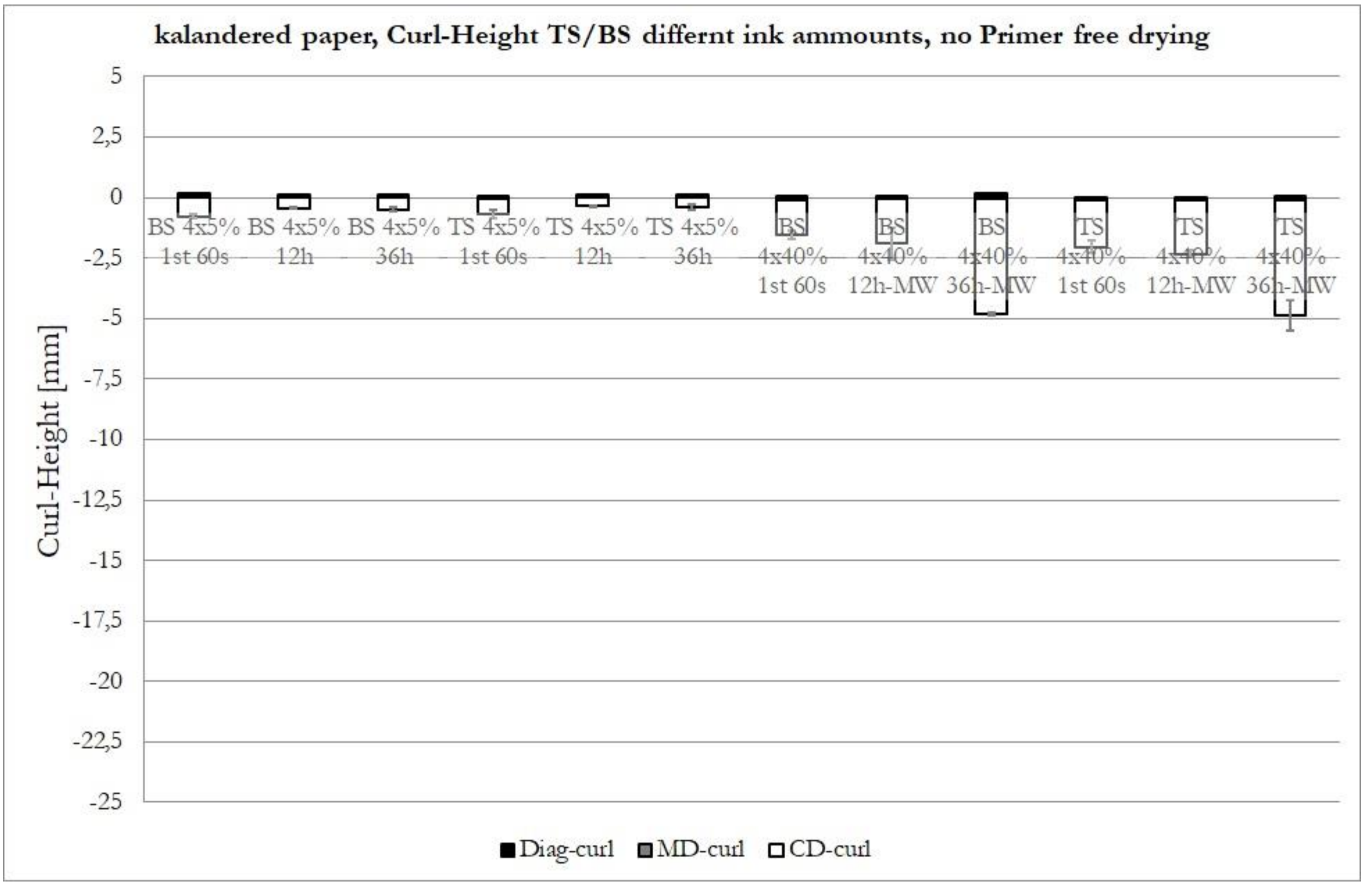

unsized paper, differnt ink ammounts, no Primer, 0%RH after drying
Curl-Height [mm]
15
12,5
10
7,5
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
-17,5
-20
-22,5
Diag-curl
MD-curl
CD-curl
BS 4x5% 1st 60s
BS 4x5% 24h 0%RH
BS 4x5% 6h 50%RH
TS 4x5% 1st 60s
TS 4x5% 24h 0%RH
TS 4x5% 6h 50%RH
BS 4x40% 1st 60s
BS 4x40% 24h 0%RH
BS 4x40% 6h 50%RH
TS 4x40% 1st 60s
TS 4x40% 24h 0%RH
TS 4x40% 6h 50%RH

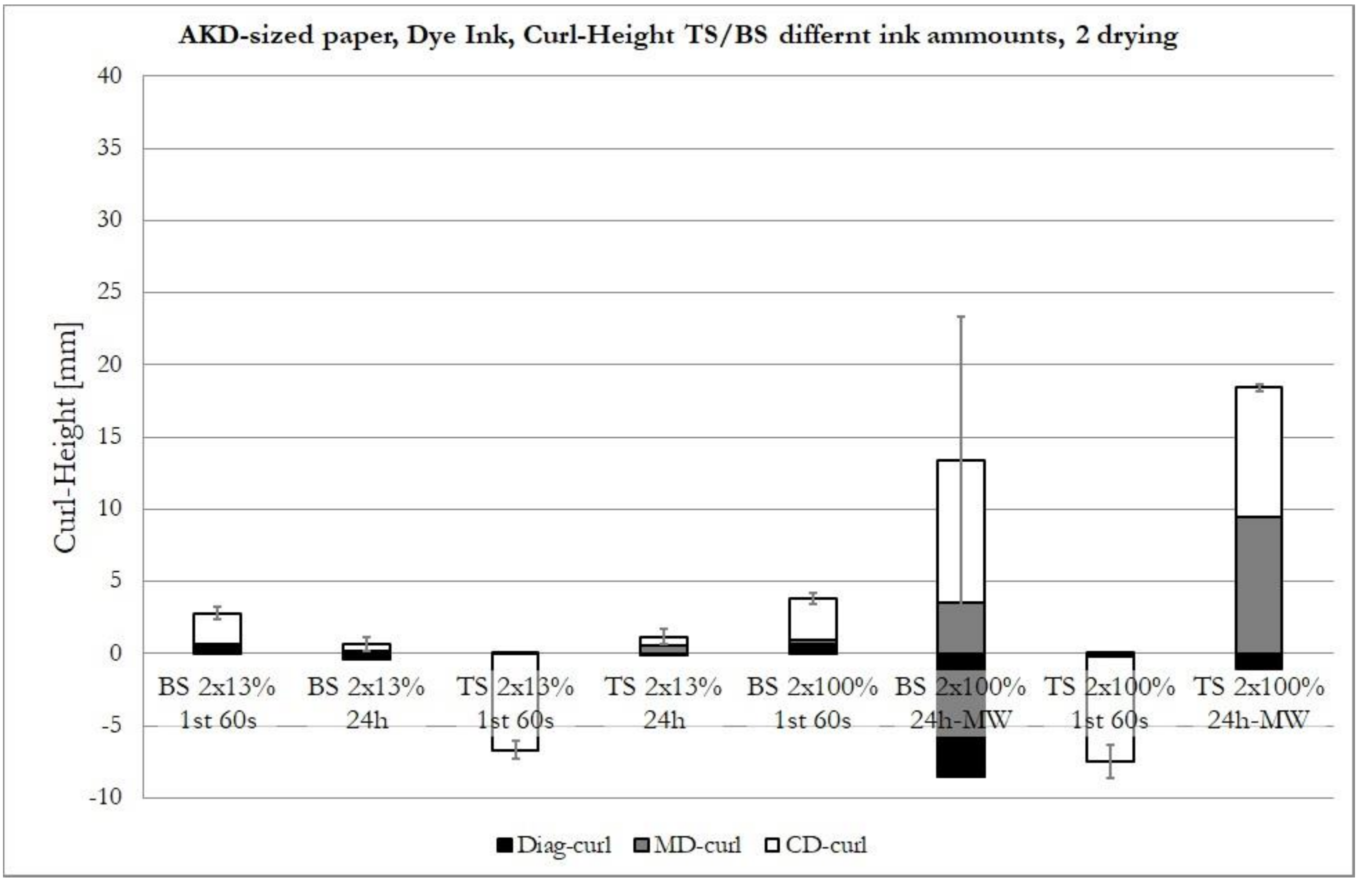

kalandered paper, differnt ink ammounts, no Primer, 0%RH after drying
Curl-Height [mm]
15
12,5
10
7,5
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
-17,5
-20
-22,5
Diag-curl
MD-curl
CD-curl
BS 4x5% 1st 60s
BS 4x5% 24h 0%RH
BS 4x5% 6h 50%RH
TS 4x5% 1st 60s
TS 4x5% 24h 0%RH
TS 4x5% 6h 50%RH
BS 4x40% 1st 60s
BS 4x40% 24h 0%RH
BS 4x40% 6h 50%RH
TS 4x40% 1st 60s
TS 4x40% 24h 0%RH
TS 4x40% 6h 50%RH

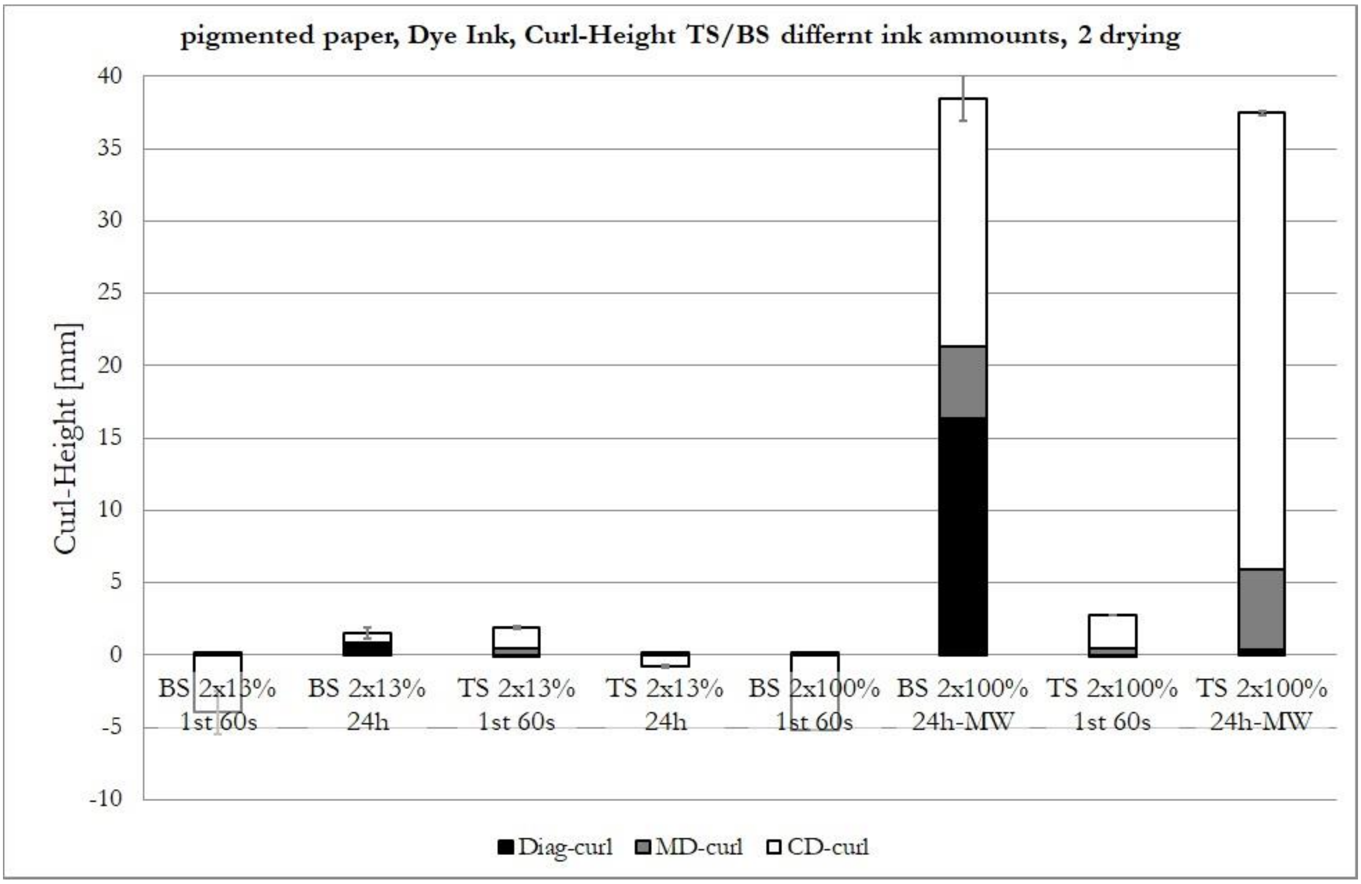

AKD-sized paper, Curl-Height TS/BS differnt ink ammounts, no Primer, free drying
Curl-Height [mm]
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
-17,5
-20
-22,5
-25
BS 4x5% 1st 60s
BS 4x5% 12h
BS 4x5% 36h
TS 4x5% 1st 60s
TS 4x5% 12h
TS 4x5% 36h
BS 4x40% 1st 60s
BS 4x40% 12h-MW
BS 4x40% 36h-MW
TS 4x40% 1st 60s
TS 4x40% 12h-MW
TS 4x40% 36h-MW
Diag-curl
MD-curl
CD-curl

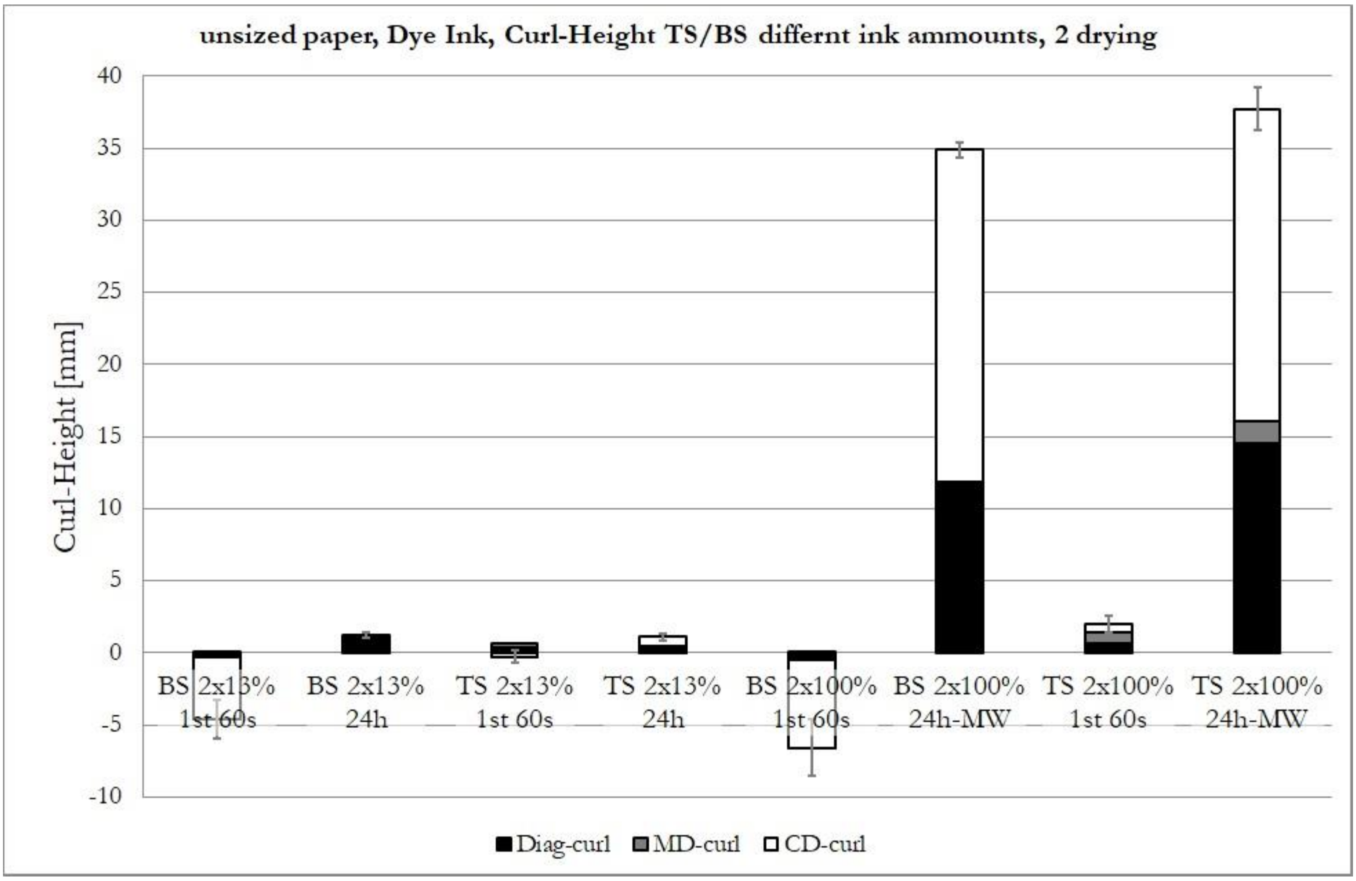

pigmented paper, Curl-Height TS/BS differnt ink ammounts, no Primer, free drying
Curl-Height [mm]
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
-17,5
-20
-22,5
-25
BS 4x5% 1st 60s
BS 4x5% 12h
BS 4x5% 36h
TS 4x5% 1st 60s
TS 4x5% 12h
TS 4x5% 36h
BS 4x40% 1st 60s
BS 4x40% 12h-MW
BS 4x40% 36h-MW
TS 4x40% 1st 60s
TS 4x40% 12h-MW
TS 4x40% 36h-MW
Diag-curl
MD-curl
CD-curl

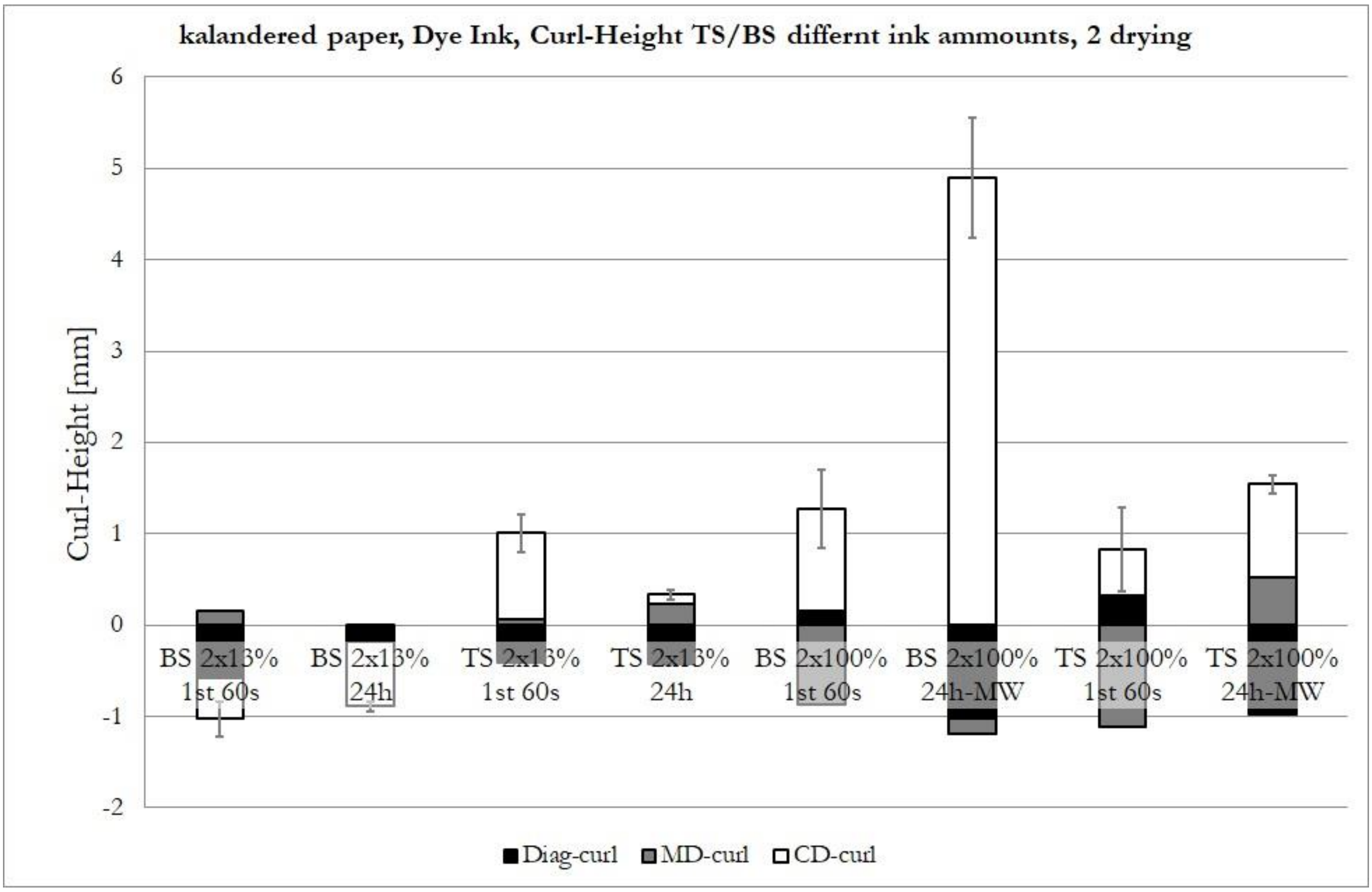

unsized paper, Curl-Height TS/BS differnt ink ammounts, no Primer, free drying
Curl-Height [mm]
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
-17,5
-20
-22,5
-25
BS 4x5% 1st 60s
BS 4x5% 12h
BS 4x5% 36h
TS 4x5% 1st 60s
TS 4x5% 12h
TS 4x5% 36h
BS 4x40% 1st 60s
BS 4x40% 12h-MW
BS 4x40% 36h-MW
TS 4x40% 1st 60s
TS 4x40% 12h-MW
TS 4x40% 36h-MW
Diag-curl
MD-curl
CD-curl


kalandered paper, Curl-Height TS/BS differnt ink ammounts, no Primer free drying
Curl-Height [mm]
5
2,5
0
-2,5
-5
-7,5
-10
-12,5
-15
-17,5
-20
-22,5
-25
BS 4x5% 1st 60s
BS 4x5% 12h
BS 4x5% 36h
TS 4x5% 1st 60s
TS 4x5% 12h
TS 4x5% 36h
BS 4x40% 1st 60s
BS 4x40% 12h-MW
BS 4x40% 36h-MW
TS 4x40% 1st 60s
TS 4x40% 12h-MW
TS 4x40% 36h-MW
Diag-curl
MD-curl
CD-curl


AKD-sized paper, Dye Ink, Curl-Height TS/BS differnt ink ammounts, 2 drying
Curl-Height [mm]
40
35
30
25
20
15
10
5
0
-5
-10
BS 2x13% 1st 60s
BS 2x13% 24h
TS 2x13% 1st 60s
TS 2x13% 24h
BS 2x100% 1st 60s
BS 2x100% 24h-MW
TS 2x100% 1st 60s
TS 2x100% 24h-MW
Diag-curl
MD-curl
CD-curl


pigmented paper, Dye Ink, Curl-Height TS/BS differnt ink ammounts, 2 drying
Curl-Height [mm]
40
35
30
25
20
15
10
5
0
-5
-10
BS 2x13% 1st 60s
BS 2x13% 24h
TS 2x13% 1st 60s
TS 2x13% 24h
BS 2x100% 1st 60s
BS 2x100% 24h-MW
TS 2x100% 1st 60s
TS 2x100% 24h-MW
Diag-curl
MD-curl
CD-curl


unsized paper, Dye Ink, Curl-Height TS/BS differnt ink ammounts, 2 drying
Curl-Height [mm]
40
35
30
25
20
15
10
5
0
-5
-10
BS 2x13% 1st 60s
BS 2x13% 24h
TS 2x13% 1st 60s
TS 2x13% 24h
BS 2x100% 1st 60s
BS 2x100% 24h-MW
TS 2x100% 1st 60s
TS 2x100% 24h-MW
Diag-curl
MD-curl
CD-curl


kalandered paper, Dye Ink, Curl-Height TS/BS differnt ink ammounts, 2 drying
Curl-Height [mm]
6
5
4
3
2
1
0
-1
-2
BS 2x13% 1st 60s
BS 2x13% 24h
TS 2x13% 1st 60s
TS 2x13% 24h
BS 2x100% 1st 60s
BS 2x100% 24h-MW
TS 2x100% 1st 60s
TS 2x100% 24h-MW
Diag-curl
MD-curl
CD-curl

6.2.4 MatLab code

import-file

```
clear all;
close all; clc;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ACHTUNG: cropping region Definition: [y_lowB, y_upB, x_lowB, x_upB]
% Y - tabel movement (10,75) ; X - Sensor (25, 160)
% Std-value [10,70, 20,155] for culZ
% std-value [10,80, 35,145] for Poing2
% std-value [10,68, 50,130] for Poing2 airdrying
% Std-value [15,70, 20,155] for raw papaer
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%
%LfdNr:
i = 283;

% Range for Y - tabel movement
y_lowB = 10;
y_upB = 82;
% Range for  X - Sensor
x_lowB = 36;
x_upB = 140;


% IPTTNr2497_LfdNr1117_MePW_Mn1
% TNr2491LfdNr283_MePW_Mn1

path='E:\Dropbox\Dropbox\Diplomarbeit\Auswertungen\Poing2\Daten_roh\Refernz_Metall\';
measurement={ ...
              ['TNr2491LfdNr' num2str(i) '_MePW_Mn1.txt'], [y_lowB, y_upB, x_lowB,
x_upB];  ...
              };

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Abfang den Lizenz vom Server --> Trycatch, sobald lizend verfügber, ausführung
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% ['TNr2491LfdNr' i '_MePW_Mn6.txt'], [45,81, 35,145]
 zahl=0;
try
    licence = fittype('a*x^2+b*exp(n*x)');
    test = cfit(licence,1,10.3,-1e2);
catch
while 1
 clc;
 warning('License nicht zur Verfügung');
 zahl=zahl+1;
 zahl,  zahl/6

 pause(10)
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%
%   Ausführen Anlalyse  %
%%%%%%%%%%%%%%%%%%%%%%%%%

delete([path,'results.xlsx']);
```

```
xlswrite([path,'results.xlsx'],{path},1,'A1');
xlswrite([path,'results.xlsx'],{'file','X-curl','Y-curl','Diag-curl','displ x','displ
y','displ z','R² fit', ...
    ' ','Y - table movement direction [mm]','max. Cul-Hight'},1,'A3');

for line=1:1:size(measurement,1)
    [fit,hmax] = Curl(path, measurement{line,1}, measurement{line,2});
    xlswrite([path,'results.xlsx'],measurement(line,1),1,['A',num2str(line+3)]);
    xlswrite([path,'results.xlsx'], ...

[fit.x_curl,fit.y_curl,fit.Diag_curl,fit.disp_x,fit.disp_y,fit.disp_z,fit.RSq], ...
         1,['B',num2str(line+3)]);
    xlswrite([path,'results.xlsx'],hmax,1,['J',num2str(line+3)]);
end

msgbox('Auswertung fertig','Abschlussmeldung')
```

fit-program

```
function [result,maxcurl] = Curl (path, file, crop)

% define cropping region
y_lowB = crop(1);
y_upB = crop(2);
x_lowB = crop(3);
x_upB = crop(4);

% define curl function
% curl function definition
curl_function = @(x_c, y_c, diag_c, disp_x, disp_y, disp_z, x, y) ...
    x_c * (x-disp_x).^2 + diag_c * (x-disp_x).*(y-disp_y) + y_c * (y-disp_y).^2 +
disp_z;

% read datafile
region_ca = readtable([path,file],'Delimiter',';');
region_ca = table2cell(region_ca);

% Extraktionsbereich
matrixsize = size(region_ca);
start_row = 1;
% end_row = 255;
end_row = matrixsize(1 );
start_col = 11;
end_col = 265;

% parse data
data_extr = zeros(end_row-start_row+1,end_col-start_col+1);
for row = start_row:1:end_row
    for col = start_col:1:end_col
        try
        if isnan(region_ca{row,col})
            ; % do nothing
        elseif isempty(region_ca{row,col})
            ; % do nothing
        elseif isnumeric (str2num(region_ca{row,col}))
            s = strrep(region_ca{row,col},',','.');
            data_extr(row-start_row+1,col-start_col+1) = str2num(s);
        end
        % Einlesefehler abfangen
        catch
            showcol=num2str(col);
```

```
            showrow=num2str(row);
            showfile=num2str(file);
            msgbox(sprintf('%s', 'Einlesefehler in Reihe ', showrow, ' Spalte ',
showcol),showfile);
        end
    end
end


% figure;
% surf(data_extr); title('no filtering');


% filterung
med_filter_dim = 10;        % median filter intensity
%
data_filt1 = data_extr * NaN;
data_filt2 = data_extr * NaN;
for line = 1:1:size(data_extr,1)
    data_filt1(line,:) = medfilt1(data_extr(line,:),med_filter_dim);
end
for line = 1:1:size(data_filt1,2)
    data_filt2(:,line) = medfilt1(data_filt1(:,line),med_filter_dim);
end
% figure;
% surf(data_filt2); title('median filtered');

% sonst null wird mitberechnet im mean wert
baseline = mean(mean(data_filt2(lines_plate_start:lines_plate_end,:)));
data_filt_baseline = data_filt2 - baseline;
% data_filt_baseline(data_filt_baseline < 0) = 0;

% graphic for z max
figure;
fzmax=max(data_filt_baseline);
zmax=max(fzmax);
hold on
plot(fzmax,'b','LineWidth',0.5);
title(strrep(file,'_','-'));
ylabel('z [mm]');
xlabel('X - sensor direction [mm]');
[x yzmax] = find(fzmax == max(fzmax));
plot(yzmax,zmax,'r*','LineWidth',1);
print([path,file(1:end-4),' - max. Cul-Hight.png'],'-dpng','-r200');

hold off

% max. curl factor as matrix
maxcurl = [yzmax,zmax];

% de-skewing
sensor_dir_res = 170/254;
table_dir_res = 100/ (end_row-1) ;
[X,Y] = meshgrid(0:sensor_dir_res:170,0:table_dir_res:100);

figure;
surf(X,Y,data_filt_baseline,'LineStyle','none');
xlabel('X - sensor direction [mm]');
ylabel('Y - table movement direction [mm]');
zlabel('height [mm]');
title(strrep(file,'_','-'));
axis equal;
```

```
print([path,file(1:end-4),' - baseline.png'],'-dpng','-r200');

% crop fitting region
x_data = X( X > x_lowB & X < x_upB & Y > y_lowB & Y < y_upB);
y_data = Y( X > x_lowB & X < x_upB & Y > y_lowB & Y < y_upB);
curl_data = data_filt_baseline( X > x_lowB & X < x_upB & Y > y_lowB & Y < y_upB);
[fit] = FitCurlEqu (x_data, y_data, curl_data, curl_function);

% results plot
%
% curl data
figure;
subplot(2,2,1);
plot3(x_data, y_data, curl_data,'.r');
title('Total Curl');xlabel('X');ylabel('Y'); axis equal;

% fitted data
[X_cropped, Y_cropped] = meshgrid (x_lowB : 1 : x_upB, y_lowB : 1 : y_upB);
subplot(2,2,2);
curl_test = curl_function(fit.x_curl, fit.y_curl, fit.Diag_curl, ...
    fit.disp_x, fit.disp_y, fit.disp_z, X_cropped, Y_cropped);
surf(X_cropped,Y_cropped,curl_test);
hold on; plot3(x_data, y_data, curl_data,'.r');
title('Fitted Curl');xlabel('X');ylabel('Y'); % axis equal;

% cropping region
subplot('position',[0.38,0.20,0.20,0.25]);
imagesc([0 170],[0 100],data_filt_baseline);xlabel('X');ylabel('Y');
rectangle('Position',[x_lowB y_lowB (x_upB-x_lowB) (y_upB-y_lowB)],'LineWidth',2);
title(strrep(file,'_','-'));
text(-270, 145,['X curl = ',num2str(fit.x_curl),'    ||    Y curl =
',num2str(fit.y_curl), ...
    '   ||   Diagonal curl = ',num2str(fit.Diag_curl),'   ||   r² =
',num2str(fit.RSq)],'FontSize',9);
text(-270, 165,['X disp = ',num2str(fit.disp_x),'    ||    Y disp =
',num2str(fit.disp_y), ...
     '   ||    Z disp = ',num2str(fit.disp_z)],'FontSize',9);
print([path,file(1:end-4),'.png'],'-dpng','-r200');

result = fit;


clear variables;
close all;

% define curl function
% curl function definition
curl_function = @(x_c, y_c, diag_c, disp_x, disp_y, disp_z, x, y) ...
    x_c * (x-disp_x).^2 + diag_c * (x-disp_x).*(y-disp_y) + y_c * (y-disp_y).^2 +
disp_z;


% curl parameters
k_x = -0.01;     % X curl intensity
k_y = 0.01;     % Y curl intensity
k_diag = 0.0; % diagonal curl intensity
disp_x = 5;     % displacement from origin x-direction
disp_y = 10;     % displacement from origin y-direction
disp_z = 0;      % displacement from origin z-direction

% calculate curl
%
```

```
[X, Y] = meshgrid(-20:1:20,-30:1:30);
X_curl = k_x * (X-disp_x).^2;
Y_curl = k_y * (Y-disp_y).^2;
Diag_curl = k_diag * (X-disp_x) .* (Y-disp_y);

total_curl = X_curl + Y_curl + Diag_curl + disp_z;

% plot curl
figure;
subplot(2,2,1);
surf(X,Y,X_curl);
title('X Curl'); xlabel('X');ylabel('Y'); axis equal;
subplot(2,2,2);
surf(X,Y,Y_curl);
title('Y Curl'); xlabel('X');ylabel('Y'); axis equal;
% subplot('position',[0.3 0.1 0.37 0.37]);
subplot(2,2,3);
surf(X,Y,Diag_curl);
title('Diagonal Curl');xlabel('X');ylabel('Y'); axis equal;
subplot(2,2,4);
surf(X,Y,total_curl);
title('Total Curl');xlabel('X');ylabel('Y'); axis equal;

% fit curl function to data
x_data = reshape(X,[],1);
y_data = reshape(Y,[],1);
curl_data = reshape(total_curl,[],1);
[fit] = FitCurlEqu (x_data, y_data, curl_data, curl_function);

% results plot
%
% curl data
figure;
subplot(2,2,1);
plot3(x_data, y_data, curl_data,'.r');
title('Total Curl');xlabel('X');ylabel('Y'); axis equal;

% fitted data
subplot(2,2,2);
curl_test = curl_function(fit.x_curl, fit.y_curl, fit.Diag_curl, ...
    fit.disp_x, fit.disp_y, fit.disp_z, X, Y);
surf(X,Y,curl_test);
hold on; plot3(x_data, y_data, curl_data,'.r');
title('Fitted Curl');xlabel('X');ylabel('Y'); axis equal;
%
% parameters
%
mTextBox = uicontrol('style','text');
set(mTextBox,'String',['X curl = ',num2str(fit.x_curl),'   ||   Y curl =
',num2str(fit.y_curl), ...
    '  ||   Diagonal curl = ',num2str(fit.Diag_curl),'  ||  r² = ',num2str(fit.RSq)]);
set(mTextBox,'Position',[-70,30,700,30]);
set(mTextBox,'FontSize',12);
mTextBox2 = uicontrol('style','text');
set(mTextBox2,'String',['X disp = ',num2str(fit.disp_x),'   ||   Y disp =
',num2str(fit.disp_y), ...
    '  ||   Z disp = ',num2str(fit.disp_z)]);
set(mTextBox2,'Position',[-100,0,700,30]);
set(mTextBox2,'FontSize',12);


function [fit_result] = FitCurlEqu (x, y, z, curl_function)
```

```
% fit curl function to data
x_fit = reshape(x,[],1);
y_fit = reshape(y,[],1);
z_fit = reshape(z,[],1);
% [parameters, gof] = fit ([x_fit, y_fit], z_fit, curl_function, 'StartPoint', [0 0 0.1
0 0 0])
[parameters, gof] = fit ([x_fit, y_fit], z_fit, curl_function)

fit_result.x_curl = parameters.x_c;
fit_result.y_curl = parameters.y_c;
fit_result.Diag_curl = parameters.diag_c
fit_result.disp_x = parameters.disp_x;
fit_result.disp_y = parameters.disp_y;
fit_result.disp_z = parameters.disp_z;
fit_result.RSq = gof.rsquare;
```

Max height evaluation-program

```
clc; close all;


%%%%%%%%%%%%%%%%%%%%%%
%LfdNr:
 i = 1105;

path='E:\Dropbox\Dropbox\Diplomarbeit\Auswertungen\Poing3\Daten_roh\K_TS_2_4sdrying\';
measurement={ ['IPTTNr2497_LfdNr' num2str(i) '_MePW_Mn1.txt'];  ...
              ['IPTTNr2497_LfdNr' num2str(i) '_MePW_Mn2.txt']; ...
              ['IPTTNr2497_LfdNr' num2str(i+2) '_MePW_Mn1.txt']; ...
              ['IPTTNr2497_LfdNr' num2str(i+2) '_MePW_Mn2.txt']; ...
              ['IPTTNr2497_LfdNr' num2str(i+2) '_MePW_Mn3.txt']; ...
%               ['IPTTNr2497_LfdNr' num2str(i+2) '_MePW_Mn4.txt']; ...
%               ['IPTTNr2497_LfdNr' num2str(i+2) '_MePW_Mn5.txt']; ...
              ['IPTTNr2497_LfdNr' num2str(i+3) '_MePW_Mn1.txt']; ...
              ['IPTTNr2497_LfdNr' num2str(i+3) '_MePW_Mn2.txt']; ...
              };

%            read datafile

figure;
hold on;
i=1;
for line=1:1:size(measurement,1)
    file = measurement{line,1};

    region_ca = readtable([path,file],'Delimiter',';');
region_ca = table2cell(region_ca);

% Extraktionsbereich
matrixsize = size(region_ca);
start_row = 1;
% end_row = 255;
end_row = matrixsize(1 );
start_col = 11;
end_col = 265;

% parse data
data_extr = zeros(end_row-start_row+1,end_col-start_col+1);
for row = start_row:1:end_row
    for col = start_col:1:end_col
        try
        if isnan(region_ca{row,col})
            ; % do nothing
        elseif isempty(region_ca{row,col})
            ; % do nothing
        elseif isnumeric (str2num(region_ca{row,col}))
            s = strrep(region_ca{row,col},',','.');
            data_extr(row-start_row+1,col-start_col+1) = str2num(s);
        end
        % Einlesefehler abfangen
        catch
            showcol=num2str(col);
            showrow=num2str(row);
            showfile=num2str(file);
            msgbox(sprintf('%s', 'Einlesefehler in Reihe ', showrow, ' Spalte ',
showcol),showfile);
        end
    end
```

```
end

% filterung
med_filter_dim = 10;        % median filter intensity
%
data_filt1 = data_extr * NaN;
data_filt2 = data_extr * NaN;
for line = 1:1:size(data_extr,1)
    data_filt1(line,:) = medfilt1(data_extr(line,:),med_filter_dim);
end
for line = 1:1:size(data_filt1,2)
    data_filt2(:,line) = medfilt1(data_filt1(:,line),med_filter_dim);
end

% calculate reference height of metal plate

lines_plate_start = end_row - 10;
lines_plate_end = end_row - 1;



% sonst null wird mitberechnet im mean wert
baseline = mean(mean(data_filt2(lines_plate_start:lines_plate_end,:)));
data_filt_baseline = data_filt2 - baseline;

% graphic for z max

fzmax=max(data_filt_baseline);
zmax=max(fzmax);
hold on
p(i) = plot(fzmax,'LineWidth',1);

[x yzmax] = find(fzmax == max(fzmax));
plot(yzmax,zmax,'r*','LineWidth',1);

line= line+1;
i= i+1;
end

showtit=num2str(measurement{1,1}(1:end-13));
title(sprintf('%s',showtit, ' - all measurements '));
ylabel('z [mm]');
xlabel('X - sensor direction [mm]');
legend([p(1) p(2) p(3) p(4) p(5) p(6) p(7)],'BasePaper-Mn1','BasePaper-Mn2' ...
    ,'After Print-Mn1 (~20 s)','After Print-Mn2 (~40 s)','After Print-Mn3 (~60 s)' ...
    ,'After 24h-Mn1','After 24h-Mn2', 'Location','northeastoutside'  );
lgd.FontSize = 10;
lgd.lineSize = 1.2;
lgd.FontWeight = 'bold';

hold off
print([path,file(1:end-4),' - MaxCurl_RawPaper_Printpaer_all_Mn.png'],'-dpng','-r200');
```