Surface Sizing with Starch Solutions at Solids Contents up to 18%

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This study examined the surface sizing of uncoated fine paper with a metered size press at considerably higher starch solids contents than used conventionally. A broad range of rheological measurements of the studied starches and solids contents are presented also, along with a set of wet-film curves for various parameters of starch properties. Results from the study show that a wide variety of starch molecular weights can be used at increased starch solids content levels. Increasing the starch solids content, therefore, no longer is restricted to highly degraded starches only. An increased solids content in the starch solution reduces evaporation energy requirements, and less wetting of the paper web during sizing reduces the number of web breaks. Using high solids starch solutions also makes it possible to use the same surface treatment concept (e.g. same drying concepts and roll covers) for both sizing and coating operations.

La présente étude a porté sur le collage en surface du papier fin non couché, à l'aide d'une presse encolleuse doseuse à des teneurs en solides d'amidon considérablement plus élevées que d'ordinaire. Une vaste gamme de mesures rhéologiques des teneurs en solides et en amidon étudiées est aussi présentée, ainsi qu'un ensemble de courbes de pellicules humides pour différents paramètres des propriétés de l'amidon. Les résultats de l'étude indiquent qu'une grande variété de poids moléculaires de l'amidon peuvent être utilisés à des teneurs accrues en solides d'amidon. L'augmentation de la teneur en solides d'amidon n'est donc plus limitée aux amidons très dégradés. L'augmentation de la teneur en solides dans la solution d'amidon réduit les besoins d'énergie pour l'évaporation, et la réduction du mouillage de la feuille de papier lors de l'encollage réduit le nombre de cassures de la feuille. L'emploi de solutions d'amidon à haute teneur en solides permet aussi d'utiliser le même type de traitement de surface (par ex., le même type de séchage et de garniture de rouleaux) tant pour le collage que pour le couchage.

INTRODUCTION

Surface sizing is an operation in which a sizing agent is applied to the surface of the previously formed web [1]. The main role of surface size is to promote surface properties, e.g. by strengthening the surface and binding such particles as fibres and fillers to the surface. Starch is also expected to add internal strength to the sheet through liquid penetration in the z direction [2]. There are numerous techniques for applying starch on the paper surface, such as a pond size press, gate roll size press or a metered size press (MSP). The various technologies used in surface sizing are described widely in literature, e.g. by Grön and Rantanen [3].

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Application Conditions Influencing the Solids Content of the Starch Solution

The solids content of surface size varies typically within a range of 3–18%, depending on the application technology used. In pond sizing, where starch solids are used primarily to adjust the amount of dry starch in paper, the solids content is typically between 3 and 9% [4]. Today, the pond size press still adds certain quality advantages over film transfer technology through more complete starch penetration [3]. However, there is a clear trend toward the usage of film transfer technology (especially MSP) due to several disadvantages with the pond size press [5]. Following are some of the drawbacks of pond size press technology:

— A tendency for turbulence in the pond, creating flow instabilities and an uneven cross-machine direction (CD) starch distribution at higher speeds [6];
— High liquid pickup due to a low solids content to avoid pond instabilities, resulting in wetting and reduced strength properties [7];
— High demand for drying capacity at the afterdrying section due to high liquid pickup,

which often limits production capacity [7]; and
— Limited adjustment options for the starch solids content and the applied dry amount due to an almost constant liquid pickup determined by the dryness of paper and the level of internal sizing [8,4].

The MSP was introduced in the early 1980s to overcome runnability problems related to pond size presses [5]. It was then possible to deal with the problems noted above through:
— An increased size solids content that reduced afterdrying capacity requirements and the number of breaks;
— A reduced interdependence between starch solids content and pickup; and
— A reduced dependence of size press pickup on internal sizing and base sheet moisture content [4].

The starch solids contents for MSP sizing varies between 5 and 18% at size amounts giving 0.7–4 g/m² [4]. However, with modern high-speed fine paper and packaging board machines, this can lead to an uneconomical process due to high drying capacity demands of a

long afterdrying section. There is also an additional trend towards the use of versatile MSP units with both coating and surface sizing capabilities. In these cases, drying capacity needs to be overdimensioned for coating to be able to evaporate the water applied during surface sizing.

Influence of Application Conditions and Starch Z Distribution on Paper Properties

There are several studies in which the interdependence of z-directional strength properties and starch solution solids, explained by differences in starch penetration, is reported, such as a study by Bergh and Åkesson [9]. They reported that starch could be retained on the paper surface by increasing starch solids contents up to 15% when using a short dwell (SDTA) application technique. Solids contents of 5, 10 and 15% were used with ~0.5, 1.0 and 1.5 g/m² dry pickup, respectively. Küstermann [10] and Felder [11] studied surface sizing using MSP with varied solids contents and aiming for a constant wet-film amount. They did not report in their work the effect of an increased solids content while maintaining a low and constant applied dry starch amount.

There are, on the other hand, many studies of various application methods resulting in varied penetration behaviour also at comparable dry starch amounts and, consequently, in different internal and surface properties of paper. Hansson and Klass [7] investigated differences between the Billblade technique and pond size press with respect to starch penetration differences. It was found that blade application produced less starch penetration and increased the surface strength of paper.

Tehomaa et al. [12] compared SDTA blade application with MSP application for surface sizing and discovered clear differences in such fine paper properties as smoothness, porosity, stiffness, surface strength and opacity values using a constant dry pickup level. Here, it was found that Bendtsen air permeability decreased with blade application from 600 to 100 mL/min at a dry starch pick up of 2 g/m². In this study, the lower starch penetration at an equivalent starch amount resulted in more attractive quality potential for blade application than for MSP. However, the conclusion of the study was in favour of MSP technology due to its better runnability and higher productivity potential.

Starch Requirements for High Solids MSP Surface Sizing

Starches used for surface sizing are normally either native or modified starches, which are either physically or chemically modified through the introduction of functional groups [5]. There are many modification methods, such as oxidation, thermal modification, and ionization. Remmer and Eklund [13] have reported that the viscosity of the starch solution is the most important liquid parameter determining its sorption rate. They also claimed that the degree of cationic charge of the starch did not influence its sorption into the paper. Felder [11], on the other hand, used the cationic charge

as an explanation in discussing the differences in strength values (e.g. internal strength) when comparing test results obtained with cationic and enzymatically converted starch.

Certain properties are required of starch at the MSP metering and transfer stages, such as the ability to remain stable even at high solids contents [14]. The metering process is critical since the levelling and overall quality of the film directly influence paper properties. Here, the rheological properties of starch will be crucial in terms of its stability [15,16].

Paper properties, such as surface and internal strength, that are promoted by surface sizing have been controlled through starch modification to achieve various viscosity levels and the desired starch penetration. This modification has consisted of degrading the starch molecules to various degrees to get the desired rheological properties for the starch solution. But, if a starch molecule is broken down into short chains, it can turn into sugars with limited film-forming capacity and ability to enhance the desired paper properties. Then its functionality as a binder is considerably reduced, and so is its ability to work as a carrier for optical brighteners [17].

Reduced evaporation requirements and increased paper quality potential can be achieved by using high solids starch solutions. There is a consequent need to maintain the runnability and the film-forming capability of the process when applying thinner starch films on roll surfaces. Here, the combination of the controllable rheological properties of the starch solution with the required binding potential is of keen interest to this study.

A number of studies have been carried out on surface sizing with the MSP technique, even at high solids contents. However, increased solids contents have restricted the ability to maintain low dry starch amount, i.e. below 1.5 g/m² per side. This study is aimed at maintaining a steady application of dry starch to paper despite a high solids content, which is accomplished by optimizing the application conditions (e.g. roll cover hardness, grooved rod type, and smooth rod diameter). When applying starch solutions at high solids contents, more uniformity is required of the thin starch film. Therefore, the inclination was to use very finely grooved rod profiles and, at the highest solids contents, even smooth rods, which also extend the roll-grinding interval and rod-

TABLE I
STARCH PROPERTIES

Property	Solids Content (%)	Starch A	Starch B
Viscosity, Brookfield 100 rpm at 60°C (mPa•s)	8	27	35
	12	48	65
	15	60	95
	18	70	140
Average molecular weight, M_W (g/mol)		27 000	~ 50 000[1]
Degree of polymerization, DP		150	300
Degree of substitution, DS		0.031[2]	0.018[3]

[1]. Not measurable with the columns used in size exclusion chromatography.
[2]. Degree of substitution of carboxyl groups (DS_{COOH}).
[3]. Degree of substitution of quartenary ammonium groups (DS_{NH4}).

TABLE II
PROPERTIES OF BASE PAPER

Properties	Values
Grammage, g/m²	82
Ash content, %	14.7
Internal sizing, %	0.8
Density, kg/m³	736.5
Air permeability, Bendtsen, mL/min	775
Oil absorption, Cobb-Unger (10 s), g/m²	47.7
Surface strength, IGT (MD), m/s	1.32
Internal strength, Scott Bond, J/m²	147
Bending stiffness, MD, mNm	0.48
Bending stiffness, CD, mNm	0.15
Opacity, %	93.8
ISO brightness, %	93.9

TABLE III
MEASUREMENT METHODS AND STANDARDS

Methods	Standard
Grammage	SCAN-P 6:75
Density	SCAN-P 7:96
Ash content	SCAN-P 5:63
Oil absorption, Cobb-Unger (10 s)	SCAN-P 37:77
Air permeability, Bendtsen	SCAN-P 60:87
Bending stiffness	SCAN-P 64:90
Opacity	SCAN-P 8:93
ISO brightness	SCAN-P 3:93
Internal strength, Scott Bond	TAPPI T 833
Surface strength, IGT	SCAN-P 63:90

changing cycle.

EXPERIMENTAL
Materials
Starch

Two modified potato-based starches were used in our study (Raisio Chemicals Inc., Raisio, Finland). These starches were modified with a specific focus on stability, even at high solids contents, in the starch solutions.

A native potato starch was modified initially through oxidation with hypochlorite, and the content of carboxylic groups in the oxidized starch was ~1% (DS_{-COOH} = 0.031). The viscosity of this starch A (Raisamyl 01020) was 20 mPas (Brookfield 100 rpm, 60°C) at a concentration of 10%. Cationization was done by introducing quartenary ammonium groups, followed by oxidization of the starch. The degree of substitution (DS_{-NH4}) was 0.018. The viscosity of cationic starch B (Raisamyl 24520) was 100 mPas (60°C) at a concentration of 10%. Four parts of OBA (Optiblanc NF, 3V, Bergamo, Italy) were used in the starch solution. The starch properties are summarized in Table I.

Despite the fact that only the higher viscosity level starch was cationic, the cationic charge was not expected to affect the results through its penetration behaviour, as reported by Remmer and Eklund [13]. Bergh et al. [9] also reported that the viscosity of starch has the largest impact on its z distribution.

Base Paper

A woodfree base paper without surface sizing and a basis weight of 82 g/m² was used for the study. The properties of the base paper are presented in Table II.

Methods
Process

The trials were run as a coated two sides MSP application (OptiSizer, Metso Paper Inc., Järvenpää, Finland) at a speed of 1200 m/min and a linear load of 25 kN/m. The roll cover material was polyurethane with a hardness of 36 Pusey & Jones (P&J) and roll diameter of 950 mm. Film metering was performed with both 10 mm grooved rods and 15–35 mm smooth rods. The grooved rod profiles selected were

0.25/23, 0.20/20 and 0.35/30 (Metso Paper, Inc.) to produce the different film thicknesses needed to obtain a constant dry starch amount of ~1 g/m² per side with different starch solids contents. The rod type was selected based on wet film amount measurements [18]. Then, the trial was performed using a series of rod loads to obtain a set of film thicknesses. Here, the target was to produce surface sizing ~1 g/m² per side. For example, the highest solids content solutions were applied using 20 mm smooth rods for low-viscosity starch A and 15 mm smooth rods for high-viscosity starch B to achieve the targeted dry starch amount.

The remaining film on the bottom roll was measured at each trial point to determine the transfer ratio in the film transfer process. In measuring the remaining film, however, the scraping time was increased to 20 s (instead of 10 s used in measuring the applied film) due to the almost negligible remaining film amount.

A single-nip soft calender was used at a machine speed of 1200 m/min, a steel roll temperature of 60°C and a linear load of 45 kN/m. The top side of the paper was run against the steel roll. The hardness of the polymer roll was 90 Shore durometer and diameter 420 mm.

Measurements

Paper properties were measured based on the standards reported in Table III.

The rheological characterizations of the starch solutions were performed at starch solution temperatures of 20, 30, 40 and 50°C for each solids concentration (i.e. 8, 12, 15 and 18%). Flow in the low shear rate region (1–1500 s^{-1}) was studied with a rheometer based on Couette viscometric flow, where the inner cylinder is a stator and the outer cylinder rotates (Bohlin VOR rheometer, Bohlin Inc., Lund, Sweden). A yield stress, τ_β, describing the stress needed to obtain flow was calculated for the starch solutions according to the Bingham plastic flow model. An intermediate shear region (10^3–10^5 s^{-1}) was studied for the starch solutions with a rheometer based on Searle flow geometry, where the inner cylinder rotates and the outer cylinder is a stator (Hercules, HiShear rheometer, Kaltec Scientific Inc., Detroit, MI, USA). An air pressure region corresponding to a high shear region of 10^5–10^6

s^{-1} was used in the air pressure-driven capillary viscometer (ECV, Gradek Oy, Kauniainen, Finland), where the controlled shear stress measurements are based on a Hagen-Poiseuille viscometric flow. Stainless steel capillaries were used with a length of 100 mm and a diameter of 0.55 mm. The data were adjusted for entrance effects according to Hagenbach-Couette and end-wall effects according to the Rabinowitz-Weissenberg equation [19].

The total starch amount applied was measured from the paper samples using lithium chloride analysis [20], where a weighed portion of the sample is burned in a muffle furnace. The residue is dissolved with acids and the individual element concentration is determined then with inductively coupled plasma atomic emission spectroscopy.

Results are presented for both starches at starch amounts of 1.8 and 2.5 g/m² total applied starch. The specific starch amounts are obtained by creating a linear trend line from the measured paper properties as a function of the starch amount. Paper properties at given starch amount levels were then obtained by assigning the values of 1.8 and 2.5 to the trend line equations.

RESULTS
Effect of Solids Content on the Rheological Properties of the Starch Solution

The flow properties of the two starch solutions were determined in a shear rate region from 10^0 to 10^6 s^{-1}, with solids concentrations from 8 to 18% at a temperature of 40°C (Fig. 1). The reason for presenting the rheometer results at 40°C was the fact that it was difficult to maintain higher temperatures in the capillary during measurement. It was found that the main difference was due to initial property differences, where the higher molecular weight of the cationic starch B gave a more pronounced shear-thinning flow. It was obvious that the low-viscosity starch A did not show the same shear-thinning effect but rather gave a Newtonian flow even at solids contents of up to 18%. When the solids content of starch B was increased above 12%, its viscosity exceeded that of starch A in the same shear rate region. This means that the metering conditions for a
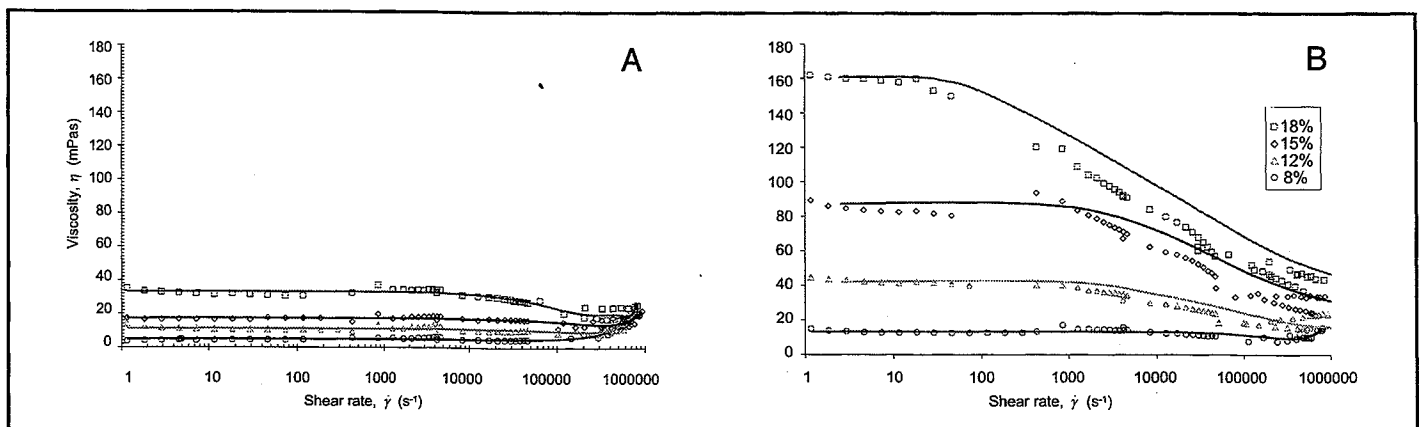

Fig. 1. Effect of the solids content (ϕ_c = 8, 12, 15 and 18%) of the starch solutions on viscosity (η) at shear rates $\dot{\gamma}$ from 10^0 to 10^6 s^{-1} (40°C) with (A) a low-viscosity starch A and (B) a high-viscosity starch B.

smooth rod need to be changed (i.e. higher rod pressure, smaller rod, etc.) to maintain the same size amount. It is also evident that the flow of the low-viscosity starch A becomes unstable at high shear rates (>500 000 s⁻¹), especially for the 8% solution (Fig. 1A). This increase in viscosity could be an effect of unstable solution flow in the capillary (i.e. non-laminar flow). The different high shear viscosity behaviour at a shear rate of 500 000 s⁻¹ is illustrated further in Fig. 2.

It was expected that the starch molecules would create a weak network that could develop initial yield stress prior to breaking. Yield stress was found to be low for both starch solutions, even up to 18% solids content. Also, for starch B, low yield stress was measured, which was surprising since the viscosity level was quite high (Fig. 3). Based on the results, excellent film forming and coverage also were found within the whole solids content range, which correlates with the weak starch molecule network (i.e. low-yield stress values).

When relating starch properties to process conditions, it was expected that yield stress might explain differences in the web release force for various starch solutions. Here, higher yield stress means that there is a higher force re-

quired to obtain flow in the starch, which in turn would affect the cohesion of the starch, resulting in a longer web release distance. If so, yield stress needs to be controlled to avoid an uneven web release at such solids contents or viscosity levels. No web release problem was detected in this study, even up to an 18% solids content with starch B, which could be supported by the low yield stress values.

Effect of Starch Solution Solids Content on the Starch Application Amount and Transfer Ratio

The wet film amount measurement results are presented in Fig. 4. Using these measurements, it was possible to determine the required pressure level and rod type to obtain a similar starch amount on either side of the sheet in the actual trial. As expected, the wet film amount measurements indicate a strong dependence between the wet film thickness and rod pressure.

The transfer ratio during the trial presented in Fig. 5 was determined by measuring the film remaining on the bottom roll during the trial. The higher viscosity starch gives a higher transfer to the sheet than the low-viscosity starch. When observing the transfer ratio val-

ues, one should note that the remaining films were extremely thin and that the film may not have been scraped off completely during measurement.

Effect of Starch Solution Solids Content on Starch Penetration

Increasing the solids content of the starch solution from 8 to 18% reduces starch penetration and leaves more starch on the paper surface. The dry starch amount applied on the paper surfaces illustrated in Fig. 6 was ~2.0 g/m², where both starches penetrated through the paper at 8% and remained on the surface at 18%. This has also been reported in a study by Bergh [2], where he found that a starch solution applied with a flooded nip size press at 15% solids content penetrated far less than at 4%, despite equal viscosities of the solutions. He explained this result as more rapid closing of the pores with a higher solids content. In our study, the solids content of the starches also dominated their penetration behaviour, but the high viscosity level of starch B seemed to enhance slightly the starch concentration on the paper surface. This can be seen when observing the starch penetration behaviour differences between the two starch types at starch solids
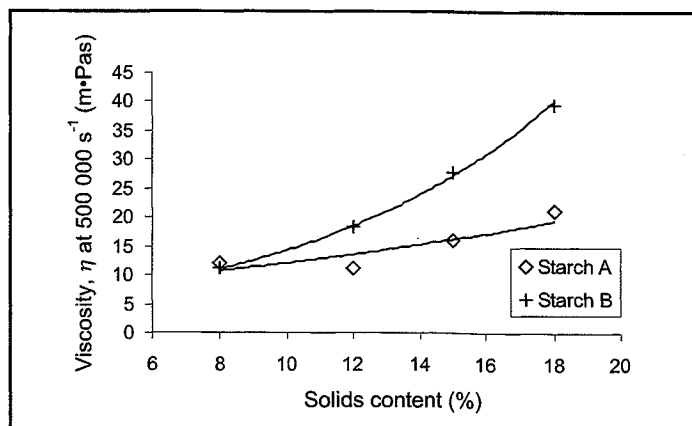

Fig. 2. Effect of the solids content of the starch solutions (ϕ_C = 8, 12, 15 and 18%) on viscosity (η) at a shear rate $\dot{\gamma}$ of 500 000 s⁻¹ and a temperature of 40°C with a low-viscosity starch A and a high-viscosity starch B.
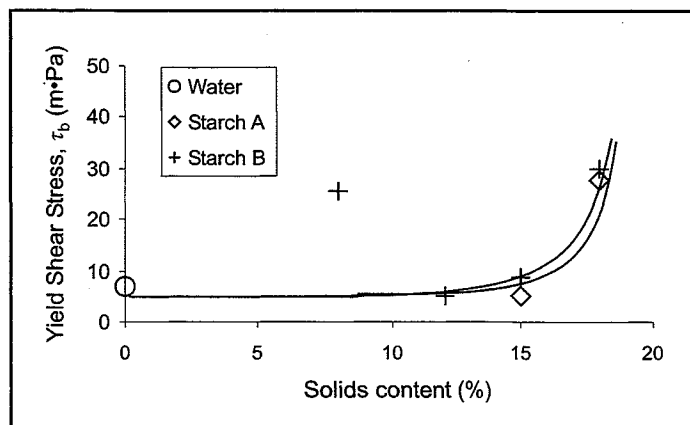
Fig. 3. Effect of the solids contents (ϕ_C = 8, 12, 15 and 18%) of starch solutions on yield stress (τ_B) with a low-viscosity starch A and a high-viscosity starch B.

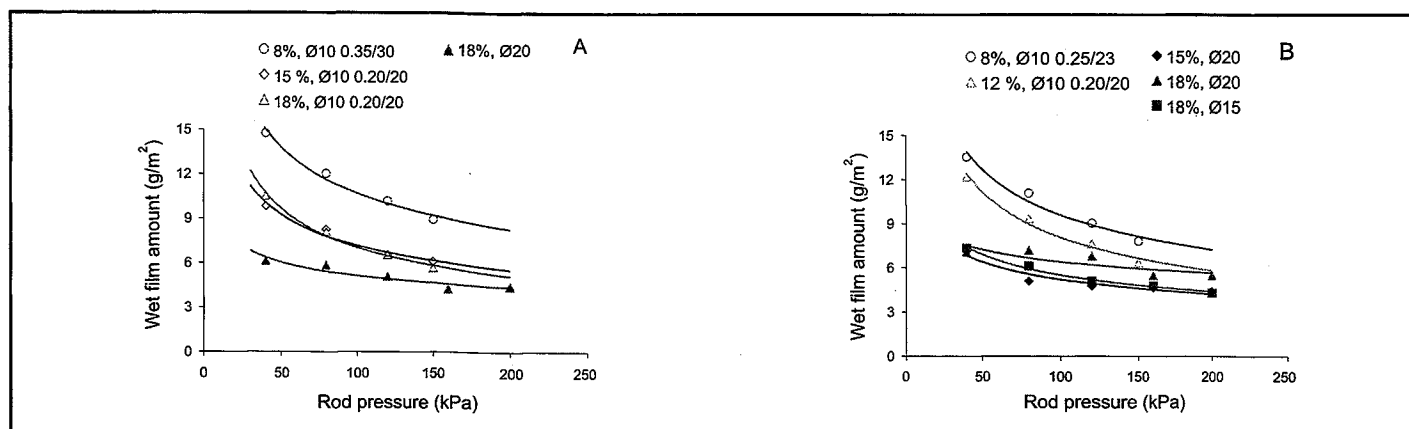Fig. 4. Measured wet-film amounts with (A) a low-viscosity starch A and (B) a high-viscosity starch B. 10 mm grooved rods (Ø10 mm) are presented with open symbols, while smooth rods (Ø15 and Ø20 mm) are plotted with filled symbols. The codes of the grooved rods represent the groove profile shapes used.

contents of 12 and 15%.

With the starch solids content levels mentioned, low-viscosity starch A seems to penetrate into the fibre network more than higher viscosity starch B. When observing these starch penetration differences, one must also recognize the fact that, when the dry starch amount is kept constant, the liquid volume added to the paper structure depends directly on the starch solids content used. For example, when the starch solids content is increased from 8 to 18%, the liquid volume added to the sheet is decreased by 56%, filling the pores mainly at the surface of the sheet. However, some of the penetration differences, especially between the two different starches at comparable solids contents and film amounts, may be explained by the effect of solids content on the viscous flow of the starch solution into the porous network of the sheet.

Effect of Starch Solution Solids on Paper Properties

An increased solids content increases the surface strength of paper since starch remains on the surface. The effect of the solids content is more evident with the higher viscosity starch B, which can be seen in Fig. 7. With the low molecular weight starch A, however, a drop in surface strength values can be observed with a low starch amount, whereas the higher molecular weight starch B, with potentially more binding power, gives increasing surface strength levels also with lower starch amounts.

The porosity of paper decreases by almost 50% in terms of Bendtsen air permeability with higher starch solids contents (Fig. 8). With both starches, air permeability was reduced from 800–600 to 400 mL/min at 18% solids content. The most evident reduction in air permeability was seen for the high-viscosity starch B.

At an increased starch solids content, the absorption of oil is reduced (Fig. 9). The reduced openness of the paper surface with a higher starch concentration on the sheet surface is naturally an explanation for this behaviour. The high-viscosity starch B gave an especially clear oil absorption reduction from 40 to 25 g/m^2 as the starch solids content was increased by 10 percentage points.

As expected, internal strength (e.g. Scott Bond) decreases as a result of decreased starch penetration at an increased solids content in the starch solution (Fig. 10). Starch B with its higher viscosity remains more on the surface than starch A, and internal strength can therefore be reduced even more. This effect can be seen for both starches, especially at a solids content of 15%. Also, the amount of the two starches applied has a very dramatic effect on internal strength at different solids contents. Here, the more viscous starch shows a larger impact on internal strength at solids contents between 8 and 18% as the applied starch amount increases. This can be explained by a further enhanced starch concentration on the surfaces.

The influence of solids content on paper stiffness can be seen more clearly in the CD di-

rection, where stiffness is increased at higher solids contents (Fig. 11). Again, this increased stiffness as a function of solids content can be explained by decreased penetration. This observation also agrees with previous studies [12], where the increased stiffness of the sheet was achieved with SDTA blade application and reduced starch penetration.

The solids content effect on the machine-direction (MD) bending stiffness is unclear for both starch solutions, due to a higher initial stiffness from 0.4 to 0.6 mNm. Here, it can be assumed that the ef-

fect of the MD fibre orientation is higher than that of the starch solution properties. In the CD direction, the situation is different and a
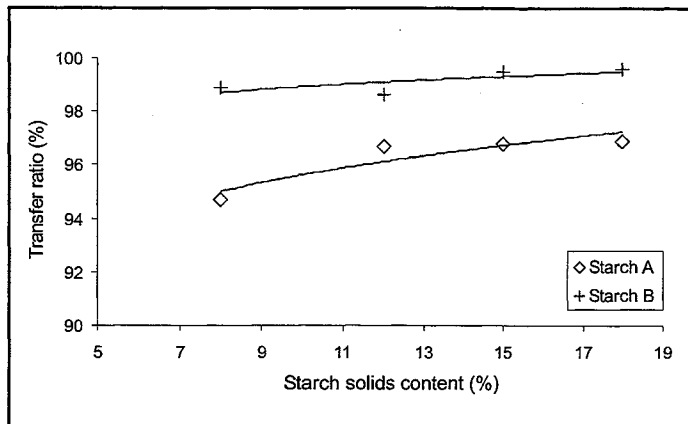

Fig. 5. Transfer ratio determined by measuring the film remaining in the film transfer process. The individual values plotted represent averages measured from a set of 4–5 test points at each solids content with a low-viscosity starch A and a high-viscosity starch B.
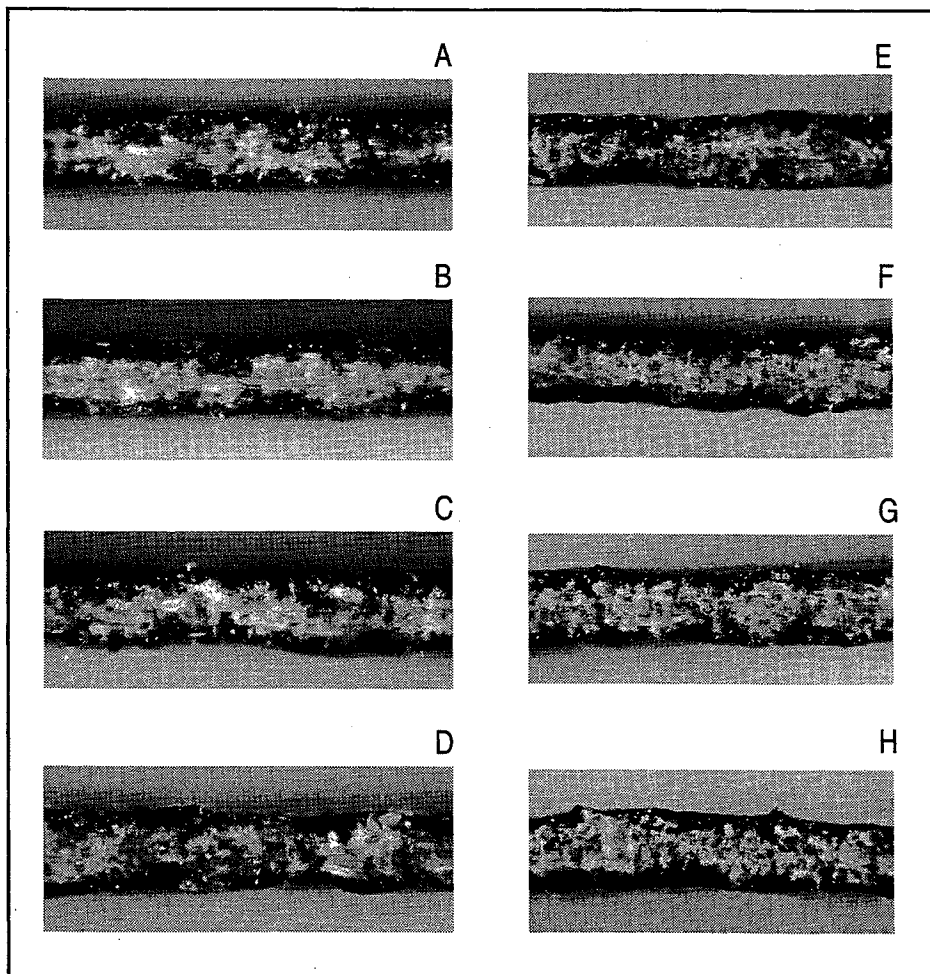

Fig. 6. Cross-sections of surface-sized paper with ~2.0 g/m^2 of total starch applied at different solids contents (8, 12, 15 and 18%) with a low-viscosity starch A (A–D) and a high-viscosity starch B (E–H). The iodine-stained starch can be seen as darker areas in the photographs. (A) Total starch amount = 1.8 g/m^2 at 8%, Br$_{100}$ = 27 mPa·s (60°C); (B) total starch amount = 1.8 g/m^2 at 12%, Br$_{100}$ = 48 mPa·s (60°C); (C) total starch amount = 2.0 g/m^2 at 15%, Br$_{100}$ = 60 mPa·s (60°C); (D) total starch amount = 1.8 g/m^2 at 18%, Br$_{100}$ = 70 mPa·s (60°C); (E) total starch amount = 1.9 g/m^2 at 8%, Br$_{100}$ = 35 mPa·s (60°C); (F) total starch amount = 2.0 g/m^2 at 12%, Br$_{100}$ = 65 mPa·s (60°C); (G) total starch amount = 2.0 g/m^2 at 15%, Br$_{100}$ = 95 mPa·s (60°C); (H) total starch amount = 1.9 g/m^2 at 18%, Br$_{100}$ = 140 mPa·s (60°C).

0.02–0.03 mNm improvement can be detected as a result of the increased starch solution concentration.

The penetration of starch also affects the optical properties of paper. As seen in Fig. 12, ISO brightness is increased as the starch solids content is increased. This can be explained by the fact that the optical brightener attached to the starch molecules is also more concentrated on the paper surface. One can support this observation when the different penetration behaviours of the two starches at solids contents of 12% are compared visually (Fig. 6). Here, the higher viscosity starch B remains more on the sheet surface compared to the low-viscosity starch A, especially at a solids content level of 12%. As seen in Fig. 12, the difference in the ISO brightness values between the two starches is most evident in this solids content region.

Starch solids content also affects the opacity of paper through the penetration behaviour of the starch (Fig. 13). Whereas no clear effect of the starch solids content can be seen with the low-viscosity starch A, with the higher viscosity starch B, the opacity of paper clearly is increased as starch remains more on the sheet surface. This may be explained by a more uniform starch layer on the sheet surface that weakens the optical contact between the sheet surfaces. Again, as opacity can be seen to decrease with increased starch amounts, the effect of starch filling the pores and, therefore, reducing scatter is supported.

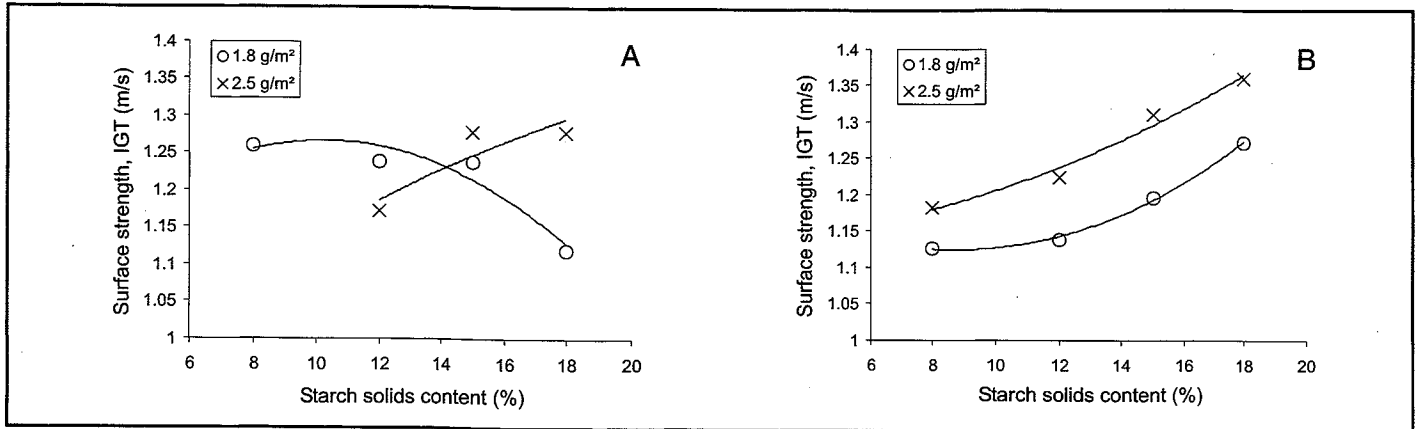## DISCUSSION

As reported, it is possible to apply solids

Fig. 7. Effect of solids content on surface strength (IGT) as a function of the total amount of starch applied with (A) a low-viscosity starch A and (B) a high-viscosity starch B.
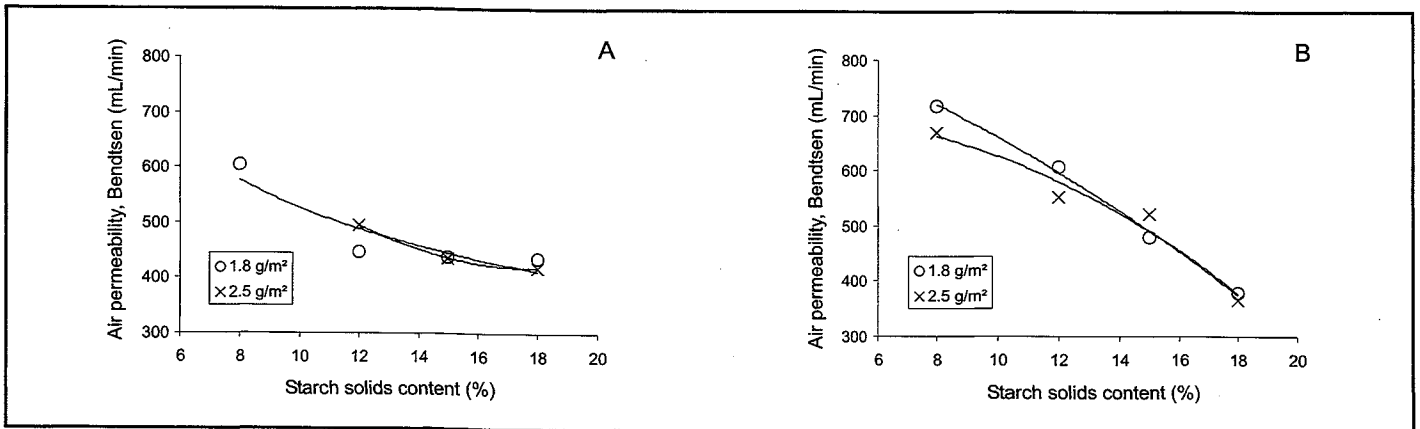

Fig. 8. Effect of solids content on air permeability (Bendtsen) as a function of the total amount of starch applied with (A) a low-viscosity starch A and (B) a high-viscosity starch B.
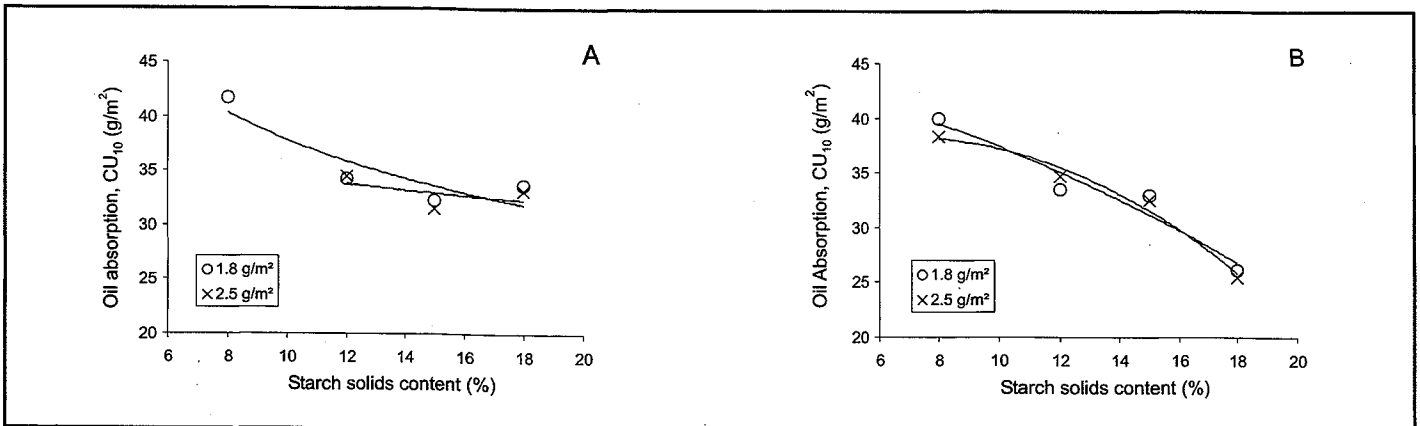

Fig. 9. Effect of solids content on oil absorption (Cobb-Unger, CU_{10}) as a function of the total amount of starch applied with (A) a low-viscosity starch A and (B) a high-viscosity starch B.

contents up to 18% without an increased dry starch amount. The results presented also show that it is possible to use a wide variety of starch viscosities and molecular weights with increased starch solids contents. Therefore, increasing the starch solids content is not necessarily restricted only to highly degraded starches with lower binding power potential.

Increased starch solids content levels helped to produce an improved transfer ratio with no MSP runnability restrictions due to web release from the roll after the nip.

When maintaining the starch amount while the starch solids content is increased, it is possible to achieve up to 50% savings in energy consumption and investment costs for the after-

drying section. In paper machines with online MSP application units, both surface sizing and coating capabilities may be desirable. In these cases, drying capacity needs to be over-dimensioned for coating to be able to evaporate the water applied during surface sizing. But, surface sizing using high solids contents could eliminate the need for additional drying
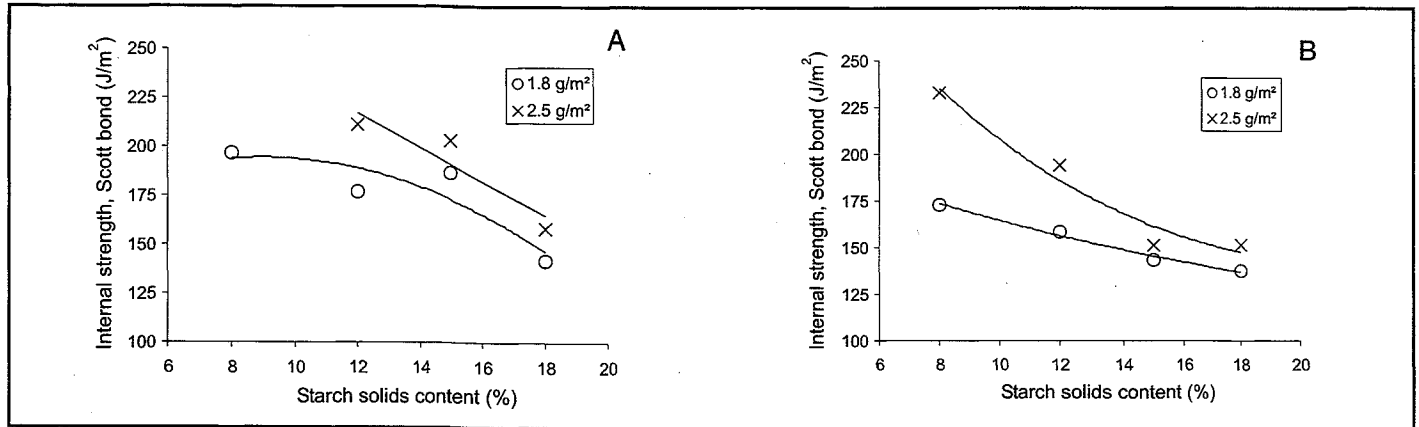

Fig. 10. Effect of solids content on internal strength (Scott Bond) as a function of the total amount of starch applied with (A) a low-viscosity starch A and (B) a high-viscosity starch B.
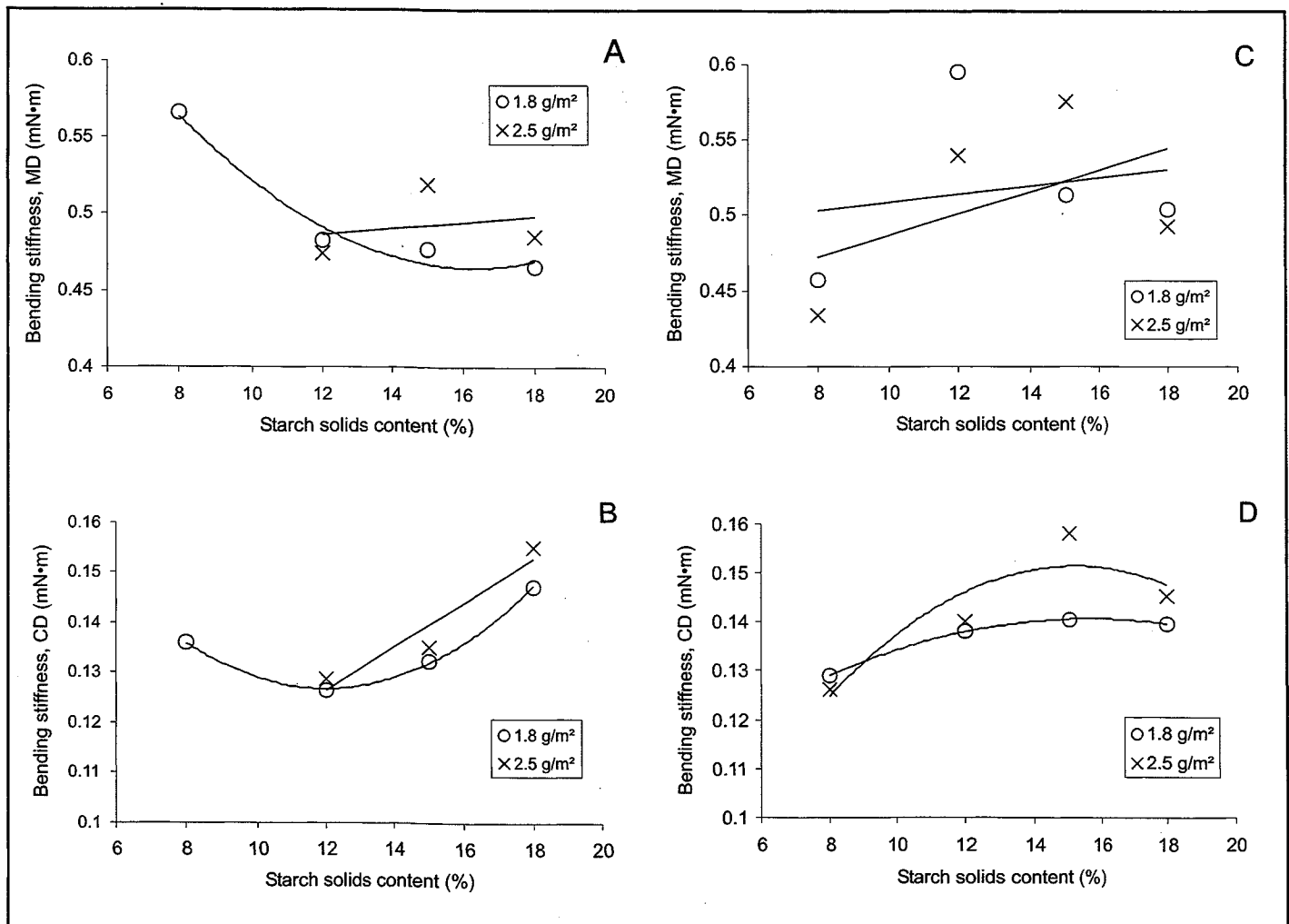

Fig. 11. Effect of solids content on MD (A,C) and CD (B,D) bending stiffness as a function of the total amount of starch applied for starch A (A,B) and starch B (C,D).

capacity in comparison to MSP coating. This is explained in Table IV as a difference in the required evaporation capacity.

Table IV indicates that it is possible to utilize the same afterdrying capacity for coating and surface sizing when the size solids content is increased from 8 to 18%. Table IV also presents the basic requirements for high solids surface sizing, where only a very thin starch solution film is required to achieve the desired dry starch amount.

By increasing the surface size solids content and keeping the applied starch amount constant, there is also a considerable reduction in the number of web breaks due to the higher web dryness after the MSP unit (i.e. more than 80% instead of 65–70%). According to Brecht and Erfurt [21], the wet breaking load of the sheet can increase up to 200% (i.e. from 400 to 1200 g/cm) as sheet dryness is increased from 65 to 80%, since the interdependence of wet strength and sheet dryness can be characterized as exponential. Web breaks at the surface sizing unit are induced mainly by the wetting of the sheet, and an increased solids content in the starch solution can be expected to improve paper machine efficiency by up to 2%. In addition, the ability to use smooth rods and softer roll covers (compared to surface sizing) may allow using the same application and afterdrying

concept for both the MSP coating and surface sizing process, as presented by Lipponen et al. [22].

Based on the results reported in this paper, increased solids contents in the sizing solution decrease its penetration into the sheet. This decreased penetration can be explained by a decreased volume of liquid transferred to the sheet, as well as by the effect of the increased solids content on the viscous flow of the starch solution into the porous network of the sheet. A decreased penetration of starch improves such paper properties as surface strength and bending stiffness. Decreased sheet porosity can also be achieved, which can have a tremendous im-

pact on the properties of printed paper. These observations agree with those of Tehomaa et al. [12], who could retain starch on the surface of paper by using SDTA application compared to MSP technology. However, some reduction in internal strength can also be observed. All these results can be explained by decreased penetration at an increased starch solids content.

The question whether the internal strength of uncoated fine paper really should be increased through surface sizing still remains. Would it be more beneficial to produce the required internal strength at an earlier stage in the papermaking process by a further optimization of furnish components and the internal sizing

TABLE IV
EVAPORATION CAPACITY REQUIRED

	Solids Content (%)	Film Thickness (g/m²)	Dry Amount Applied/ Side (g/m²)	Water to be Evaporated/ Side (g/m²)
MSP coating	67	18.8	10	4.9
MSP surface sizing	8	13.1	1	11.5
MSP high solids surface sizing	18	5.9	1	4.5

Evaporation capacity required for MSP coating at a solids content of 67% compared to MSP sizing at a starch solution solids content of 8 and 18%. A transfer ratio of 0.80 was used for coating and 0.95 for surface sizing.
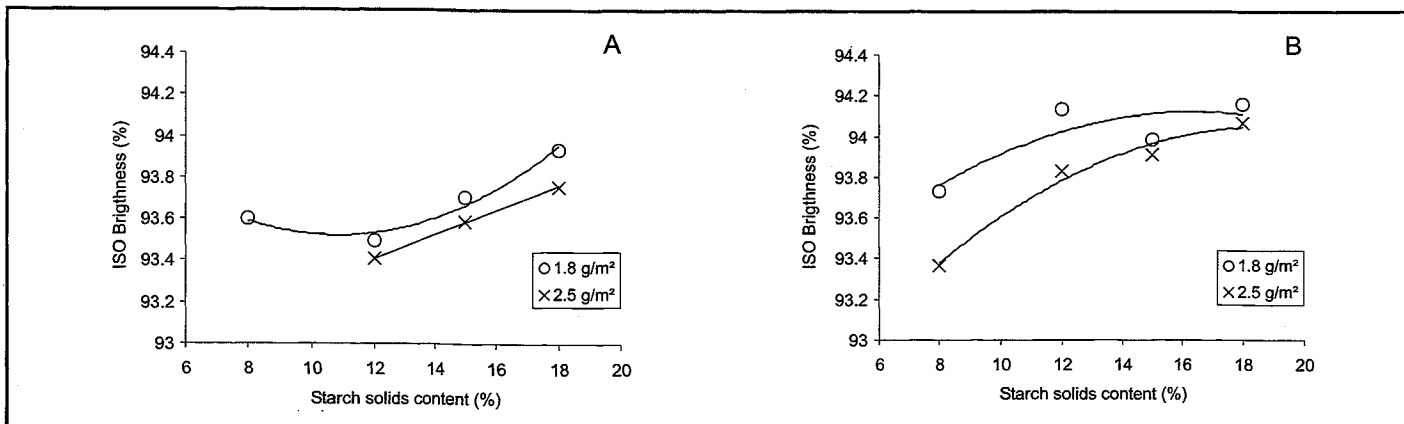

Fig. 12. Effect of solids content on ISO brightness as a function of the total amount of starch applied with (A) a low-viscosity starch A and (B) a high-viscosity starch B.
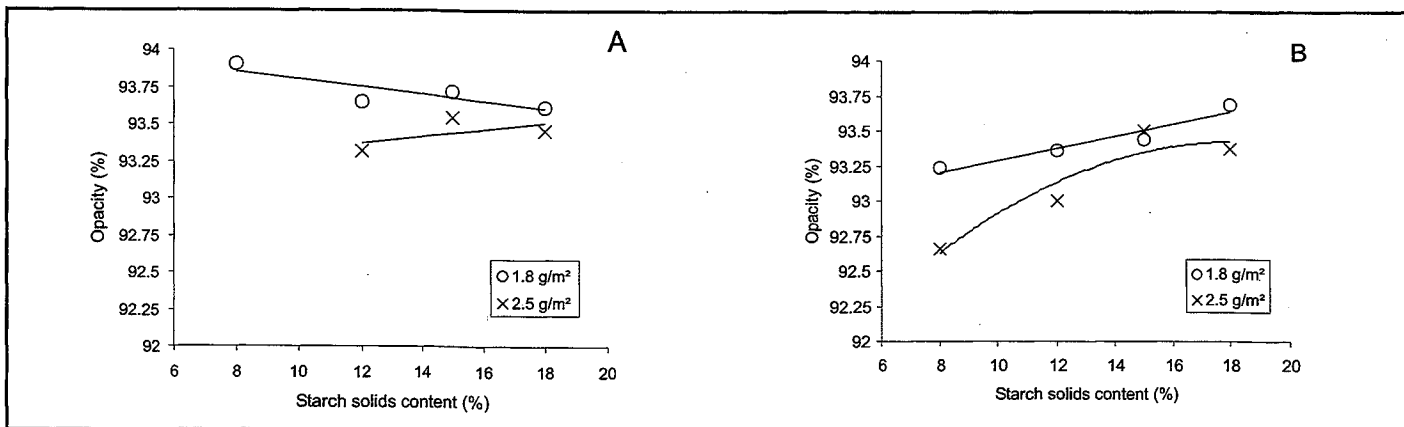

Fig. 13 . Effect of solids content on opacity as a function of the total amount of starch applied with (A) a low-viscosity starch A and (B) a high-viscosity starch B.

process? Compared to the current conventional sizing concepts, increased surface strength then could be produced through a more cost effective surface sizing operation. This will open opportunities to reduce raw material costs and increase the productivity of paper machines. An additional new and desirable paper property is the reduced porosity gained through reduced starch penetration, which is possible with a low starch amount at high solids contents in MSP application. A further objective underlying the maintenance of a low starch amount even at the highest solids content levels is preserving such optical properties of paper as brightness and opacity.

A greater effort needs now to be placed on optimizing the rheological properties of starch solutions when the solids content is considerably increased. Flow characteristics will have a large impact on the metering conditions, since metering will be based on hydrodynamic principles (i.e. smooth rods) instead of the current volumetric (i.e. grooved rods) approach.

CONCLUSIONS

When the solids content of the starch solution is increased from 8 to 18%, less starch penetrates into the sheet and more starch remains on the paper surface. The dry starch amount applied on the paper surfaces was ~2.0 g/m^2, and both starches penetrated through the paper at 8% and both remained on the surface at 18%. This has also been reported in a study by Bergh [2], where he found that a starch solution applied with a flooded nip size press at a 15% solids content penetrated far less than at 4%, despite equal viscosities of the solutions. He explained this result as more rapid closing of the pores at a higher solids content. In our study, the solids content of the starches also dominated the penetration behaviour, but the high viscosity level of starch B seemed to enhance slightly the concentration of starch on the paper surface. One of the objectives underlying the maintenance of a low starch amount, even at the highest solids content levels, is preserving such optical properties of paper as brightness and opacity. It was seen also that the increased solids content of up to 18%, or the increased viscosity, did not cause any web release problems. This was indicated by the low yield stress values of the starch solutions.

The findings show also that it is possible to use a wide variety of starch viscosities and molecular weights at increased starch solids content levels. Therefore, increasing the starch

solids content is not necessarily restricted only to highly degraded starches with lower binding power potential.

Surface sizing at high solids can create up to 50% savings in afterdrying capacity (assuming a solids content increase from 8 to 18%) or promote possibilities to increase the speed of paper machines restricted by their afterdrying capacity. Decreasing the wetting of the sheet will also increase paper machine efficiency as a result of a reduced number of web breaks. Here, the same afterdrying capacity can be used for both MSP coating and surface sizing at a size solids content of 18%.

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