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BEHAVIOUR OF DIFFERENT FURNISH MIXTURES IN MECHANICAL PRINTING PAPERS

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ABSTRACT

Mechanical printing papers consist of a mixture of mechanical pulp – groundwood or TMP − chemical reinforcing pulp and filler. They may also contain recycled fibre. The mixtures of different mechanical or chemical pulps are not used. A mixture of groundwood rich in fines and long-fibred TMP could be assumed to be an optimum mechanical pulp for high-quality mechanical printing papers, both regarding runnability and printability. The main objective of this thesis work was to research the validity of this hypothesis. The experimental part consisted of both lab trials and mill trials on modern paper machines.

The lab studies showed that a mixture of fine groundwood and well-bonding TMP can have synergy in SC paper. Synergy advantage was achieved especially in tear strength and to some extent also in fracture energy, tensile energy absorption and stretch while usually no synergy was found in tensile strength or Scott-Bond. Synergy advantage could also be achieved in light scattering coefficient and calendering response in density, air permeability and pore size distribution. All these synergies found in SC paper sheets were most probable at about a 30 % chemical pulp share of fibre. In LWC base paper sheets similar synergy was not found.

The mill studies also showed synergy advantage in the tear strength of SC paper but not in its tensile strength. Therefore the use of a mixture of groundwood and TMP and slightly more refined chemical pulp allowed a smaller than calculated chemical pulp share in paper, which reduces the furnish costs. In the mill trials synergy in printability was rare. In LWC paper no synergy was found. However, the use of groundwood could improve the printability of TMP-based LWC paper and the use of TMP in groundwood-based LWC paper allowed the reduction of the chemical pulp share.

Synergy was found in strength properties which depend on both fibre length and bonding but not in strength properties depending primarily on bonding. Synergy advantage in tear strength seems to be possible with any mixture of paper furnishes which have their bonding degrees on the opposite sides of the optimum, i.e. tear strength maximum, depending on fibre length. In highly filled SC paper with well-bonding pulps at about a 30 % chemical pulp share of fibre the bonding level vs. fibre length seems to be most suitable for synergy in strength properties with a mixture of groundwood and TMP. With the same mixture an optimum sheet structure for synergy in the light scattering coefficient and calendering response of SC paper could be achieved. In better bonded LWC base paper no similar synergy was found. Also differences in sheet density, drying shrinkage and surface chemistry, and passing the limiting state of fines content, which all affect bonding, can be partial reasons for these synergies.

This thesis showed valid the hypothesis of a mixture of groundwood and TMP being an optimum mechanical pulp for high-quality mechanical printing papers. The mixture was better than pure groundwood or TMP. However, both the lab and mill studies showed that the synergy advantages achieved with this mixture in SC paper are most sensitive both to the bonding ability and fibre length of pulps and to the need of bonding. Thus, e.g. the basis weight of paper and probably also the wood quality could affect the existence of synergy. The results of both the extensive lab studies and several mill trials were quite similar. Most of the lab testing of this research was done by an experienced laboratory assistant and the statistical reliability of most test results was checked. All this confirms the reliability of the results though the synergies found were often slight.

The exploitation of a mixture of groundwood and TMP in paper is feasible only in very few mills having existing production capacity of both pulps. Thus these results should be used in the development of fine mechanical pulps to achieve the advantages with one single pulp.

CONTENTS

PREFACE

Mechanical printing papers consist of a mixture of mechanical and chemical pulp and filler which is in paper furnish and/or coating. The mechanical pulp used is groundwood or TMP. At UPM-Kymmene Rauma paper mill high-quality mechanical printing papers, both SC and LWC papers, are made both based on groundwood and TMP. This experimental thesis work, which examines the behaviour of different furnish mixtures in SC and LWC papers, was initiated by UPM-Kymmene Rauma paper mill.

The financial support by the National Technology Agency of Finland in the early stages of this thesis is highly appreciated.

I express my gratitude to the supervisor of the thesis, professor Hannu Paulapuro, for his valuable advice during the course of this work. The topic for this post graduate thesis work was proposed by Yngve Lindström, former director of LWC production unit at Rauma paper mill. The former Rauma mill director Yrjö Olkinuora is especially acknowledged for the possibility of performing this study, to use the needed lab resources and to publish its results as a doctoral thesis. The positive development attitude of all the personnel of Rauma paper mill made this thesis including several mill trials possible. I am indebted especially to Anita Nygren-Konttinen, Kari Pasanen and Maria Alajääski. I express my sincere thanks for support to my superiors Päivi Miettinen, Jari Vainio and Jari Mäki-Petäys and all the persons who have contributed to this work. The lab work of Pirkko Myllymaa, who did alone practically all the lab work of this thesis at Rauma during the years 1995 – 2002, is acknowledged. Her especially careful work made the research of synergy phenomenon possible.

As a part of this thesis work two master's theses were completed: the first one by Kirsimarja Sipilä on synergy in LWC paper and the second one by Tuomo Laukkanen on the role of drying shrinkage in synergy. Their enthusiasm for their thesis works is acknowledged. All the lab work done at Rauma as part of both these theses was also done by Pirkko Myllymaa.

In the final stage of this work the simultaneous construction of a new house and the designing of its garden was time-consuming and occupied my mind a lot but also gave extra strength, both mental and physical, to finish this thesis.

My special thanks to my wife Kirsti for her unfailing support.

This thesis is dedicated to my late mother Lilja († 22.9.2000), who strongly encouraged me to do this thesis.

Rauma, November 2004

Jukka Honkasalo

AUTHOR`S CONTRIBUTION

Two master`s theses were made as a part of this study.

The master`s thesis of Kirsimarja Sipilä was instructed by the author. The results of that thesis are rediscussed by the author in chapters 5.2.2. and 6.3.

The master`s thesis of Tuomo Laukkanen was instructed by the author. The results of that thesis are totally rediscussed by the author in chapter 5.4.

All the rest of this doctoral thesis is totally contribution of the author.

LIST OF ABBREVIATIONS

AFM	Atomic force microscopy
Av.	Average
bs	Bottom side
cd	Counter direction
ch. p.	Chemical pulp
chem. pulp	Chemical pulp
CSF	Canadian standard freeness, ml
CTMP	Chemithermomechanical pulp
DD	Double disc (refiner) (both discs rotate)
Δ	Difference
ECF	Elementary chlorine free
ESA	Electrostatic assist of ink transfer (rotogravure printing)
ESCA	Electron spectroscopy for chemical analysis
fibre length	Length weighted average fibre length (abbreviation used for simplicity)
GW	Groundwood (atmospheric)
H_2O_2	Hydrogen peroxide
HUT	Helsinki University of Technology
KCL	Finnish Pulp and Paper Research Institute
l	Length weighted average fibre length, mm
LWC	Light weight coated
md	Machine direction
mech. pulp	Mechanical pulp
m.p.	Mechanical pulp
n.a.	Not analysed
PAM	Polyacrylamide
PGW	Pressure groundwood
PGW-S	Super pressure groundwood
PM	Paper machine
PPS10	Parker Print-Surf roughness at clamp pressure 980 kPa, µm
RBA	Relative bonded area, %
Ref.	Reference
RTS-TMP	Special commercial TMP process (Andritz)
SC	Supercalendered
SCO	Supercalendered offset
SCR	Supercalendered rotogravure
SD	Single disc (refiner) (only one disc rotates)
SEC	Specific energy consumption, MWh/t or kWh/t
SEL	Specific edge load, Ws/m
SEM	Scanning electron microscopy
T	Tear index of chemical pulp at certain tensile index (normally at 70 Nm/g), mNm^2/g
TCF	Totally chlorine free
TEA	Tensile energy absorption, J/kg
TMP	Thermomechanical pulp
ts	Top side
w	Coarseness, mg/m
WRV	Water retention value, g/g

1. INTRODUCTION

Mechanical printing papers comprise different newsprint, supercalendered magazine paper (SC paper) and coated paper grades. The most important of the coated grades is light weight coated paper (LWC paper). Mechanical printing papers are used in newspapers, magazines, inserts and catalogues, i.e. they are used in applications where the life cycle of the printed product is quite limited. Mechanical printing papers are based on mechanical pulp or recycled fibre originating primarily from the same paper grades.

Different functional properties are demanded from the mechanical printing papers like from most paper grades. Especially high-quality mechanical printing papers, such as SC and LWC papers, should have both good runnability and good printability. Also the image of paper, e.g. stable quality and environmental friendliness, is regarded as important. In addition, paper production should be profitable. To fulfil these often partially contradictory demands mechanical printing papers, like most paper grades, consist of a mixture of several different components. Mechanical printing papers usually consist of a mixture of mechanical pulp, chemical pulp and minerals which are used as filler in furnish or as coating. Mechanical printing papers also often contain recycled fibre. Mechanical pulp gives good printability and some strength to these paper grades. This strength alone can be enough in newsprint. However, extra strength is needed in papers with higher printability demands like SC and LWC papers, where the use of a large amount of filler or supercalendering and coating demand more strength from paper. Chemical pulp is used as reinforcing pulp to give the extra strength which is needed in paper and which misses from mechanical pulp. However, excessive use of chemical pulp is avoided as it deteriorates printability and it is usually the most expensive component of mechanical printing papers. Filler is used as it improves the printability of paper and moreover, normal filler is the cheapest component of paper. The use of filler is restricted by its strength deteriorating effect.

The profitability of papermaking demands low enough furnish costs. The production costs of the bleached mechanical pulps used in high-quality printing papers, excluding capital costs, are about € 250 – 280 /t. Normal filler costs about € 100 – 110 /t. However, special filler pigments can be significantly more expensive. Chemical pulp is the most expensive component of mechanical printing papers. Its price varies a lot, the average being about € 500 - 550 /t. As little as possible chemical pulp is used because of its high cost and printability deteriorating effect. Also the price of recycled fibre varies a lot. Still, recycled fibre is usually economical to use in mechanical printing papers. Different trends in mechanical printing papers such as the reduction of basis weight or the increase of the filler share or coating tend to increase the chemical pulp share needed in paper, which increases the furnish costs.

The effect of different furnish components on paper properties is well known. However, the behaviour of different furnish mixtures and especially the synergy phenomena sometimes found are fairly unclear. One reason for this is that in most articles only a few pulp mixtures are studied. Consequently the results of these studies are partially contradictory and the effect of quality variation within different pulps remains unclear.

Mechanical printing papers are normally produced based on groundwood pulps, i.e. atmospheric groundwood (GW) or pressurized groundwood (PGW)), or thermomechanical pulp (TMP) as mechanical pulp. Today newsprint is produced mostly from recycled fibre because of low furnish costs, but purely TMP-based newsprint is also produced. High-quality mechanical printing papers, i.e. SC and LWC papers, are produced as groundwood-based or TMP-based though they are quite different mechanical pulps. Groundwood rich in fines gives good printability to paper but it has low strength, which means high chemical pulp need in paper. On the other hand the longer fibred TMP has better strength and less chemical pulp is needed in paper. However, TMP can give poorer printability to paper. One further drawback of TMP as compared to groundwood is also its higher specific energy consumption (SEC). However, in spite of the differences in strength properties, in practice the difference in the chemical pulp share needed in groundwood and TMP-based magazine papers (SC, LWC) is often smaller than it could be concluded from additive strength calculations. Thus, the strength potential of TMP cannot be totally utilized. This indicates that

1. probably neither groundwood nor TMP is optimal mechanical pulp for SC and LWC paper
2. there must be some synergy behaviour in different SC and LWC paper furnishes.

Due to the different properties of groundwood and TMP their mixture could be an optimum mechanical pulp for high-quality mechanical printing papers. Groundwood rich in fines would give good printability and long-fibred TMP would give strength and allow the reduction of chemical pulp content in paper and thus improve printability. In addition, this mixture would have lower specific energy consumption than pure TMP. However, literature references about the use of a mixture of groundwood and TMP in mechanical printing papers are scarce. Today only some paper mills have the possibility to use a mixture of groundwood and TMP in SC or LWC paper. To our knowledge a few mills make use of this mixture in SC paper production, for different reasons.

In 1994 at UPM-Kymmene Rauma paper mill, in order to improve the printability of groundwood-based SC rotogravure paper, groundwood was made significantly finer than earlier. This made groundwood denser but also significantly decreased its long fibre fraction. Probably because of that the need of chemical pulp in paper clearly increased, which restrained the improvement of paper printability. In order to reduce the need of chemical pulp in paper some groundwood, about 10 %, was replaced with available TMP used in SC offset paper. Even this small TMP share allowed a clear reduction of chemical pulp content in paper and improved paper printability. These results indicate even synergy advantages with the mixture of fine groundwood and TMP.

Since the mill trial run at Rauma paper mill in 1994 10 – 25 % of groundwood was replaced with TMP on the paper machine producing groundwood-based SC rotogravure paper, although reasons for the synergies found were unknown. In addition, the synergy effect with the use of the mixture of groundwood and TMP was not always found. This increased confusion about the exploitation of synergy. In order to optimise paper furnish and the exploitation of synergy the quality effects of different furnish components and their interactions should be known.

2. HYPOTHESES, OBJECTIVES AND STRUCTURE OF THE THESIS

The results of the mill trial in 1994 referred to above and the long-term experiences after that gave an impulse to start this research about the behaviour of different furnish mixtures, especially the mixtures of groundwood and TMP, in mechanical printing papers.

In the beginning the following hypotheses were set for this study:

- The mixture of fine groundwood rich in fines and long-fibred TMP would be an optimum mechanical pulp, over pure groundwood or TMP, for high-quality mechanical printing papers. Groundwood rich in fines would give good printability and long-fibred TMP good runnability to the paper.
- The mixture of groundwood and TMP would give synergy advantages in high-quality mechanical printing papers. The synergies would have several possible reasons:

- Most paper properties depend on several factors such as fibre length and bonding or fines content. When mixing different pulps these properties change simultaneously and may have an optimum combination giving a synergy effect.
- The lack of enough fines deteriorates several paper properties dependent on bonding, and the existence of paper furnish in relation to the limiting state of fines content may cause synergy with pulp mixtures both in paper strength and structural properties.
- Differences in drying shrinkage or surface chemistry can also be partial reasons for synergy.

The main objective of this thesis was to clarify the behaviour of different furnish mixtures in high-quality mechanical printing papers and research the validity of the hypotheses in SC and LWC papers. If the hypotheses were valid also the reasons for the synergy phenomena and the optimization of the synergy exploitation would be studied.

In order to understand the synergy phenomena the behaviour of different furnish mixtures used in mechanical printing papers were investigated. Better knowledge of these phenomena would help the optimization of paper furnish components and allow better utilization of their quality potential in paper making.

This thesis is started with a product analysis of mechanical printing papers and the demands set to the quality of paper furnish components. After this the previous studies of the interactions of pulp fractions and the behaviour of different furnish mixtures are reviewed. The development trends of mechanical printing papers and their effects on paper furnish and possible synergy are also evaluated. This review is followed by an experimental part where the validity of the hypotheses is researched. The experimental part consists of both lab and mill studies. In the lab trials the behaviour of different furnish mixtures and the reasons for the synergies found were researched. The results of the lab studies were verified in mill trials. Also the practical exploitation of synergy with the mixtures of groundwood and TMP was researched in the mill trials.

3. BACKGROUND

3.1. Introduction

Mechanical printing papers usually consist of a mixture of one mechanical and one chemical pulp and filler. The filler is in the furnish and/or in the coating. Mechanical pulp is groundwood or TMP. Newsprint is often made from recycled fibre. Magazine papers, i.e. SC and LWC papers, also more and more often contain recycled fibre. Mixtures of different mechanical pulps or chemical pulps are usually not used because of process stability and simplicity.

Because of their properties a mixture of groundwood and TMP could be regarded as an optimal mechanical pulp for mechanical printing papers. TMP would supply the long fibres to the mixture and groundwood the fines lacking in TMP. Already in 1969 von Kilpper proposed that a mixture of fine groundwood and long-fibred refiner mechanical pulp could give an optimal combination of strength and printability /v. Kilpper 1969/. In the late 1980´s Gullichsen, when developing a low frequency refiner which produced long-fibred mechanical pulp, proposed the use of this pulp in mechanical printing papers in a mixture with groundwood rich in fines. The mixture would have had good strength and high light scattering coefficient and also clearly smaller specific energy consumption than normal TMP.

/Gullichsen 1989./ However, mixtures of different mechanical pulps are rarely utilized in paper production and only a few references to this subject can be found in literature. They are mostly from the early days of the TMP process /Dillen et al. 1975, Frazier et al. 1976, Vaarasalo et al. 1981, Tuovinen et al. 1993, Honkasalo 2001/. In some cases the use of this mixture has given a clear synergy advantage also utilized in paper production /Dillen et al. 1975, Honkasalo 2001/.

The chemical pulp used in mechanical printing papers is long-fibred, strong reinforcing pulp, which compensates the insufficient strength of mechanical pulp in paper. It is proposed that a mixture of different kind of chemical pulps could also give advantages to mechanical printing papers as it does to woodfree grades, where these mixtures are widely used and where they even have synergy advantages /Alava et al. 1997/.

Mixtures of different fillers are used to optimize different paper printability properties and filler costs. These mixtures are commonly used, even in high-quality mechanical printing papers, opposite to the mixtures of different mechanical pulps or chemical pulps.

It is generally assumed that mixtures of different pulps would behave additively in paper. However, this is often found not to be true with the mixtures of mechanical and chemical pulps; instead, some properties of their mixtures may behave in a synergistic way / Bovin et al. 1971, Mohlin et al. 1983, Retulainen 1992/. Yet, different kind of mechanical pulps are believed to behave similarly in a mixture with chemical pulp and filler /Mohlin et al. 1983, 1985/. This has made possible the optimization of mechanical pulps alone without needing to take into account their interactions with other components of paper. However, often the clearly better strength potential of TMP compared to groundwood cannot be totally utilized in magazine papers. Thus the properties of paper components have influence on their behaviour in the mixture, contrary to the literature /Mohlin et al. 1983, 1985/. This means that the quality potential of different pulps cannot be evaluated alone without considering their interactions with the other components of the paper furnish mixture. The behaviour of pulp mixtures and their possible synergy is not much studied systematically. Synergy is believed to depend on numerous factors /Retulainen 1992/ and as such it is difficult to utilize. However, if synergy is consistent, it could be utilized in the quality and composition of paper and this could reduce the furnish costs. Thus, knowledge about the behaviour of furnish mixtures and their synergy is important in developing mechanical printing papers and demands more thorough studies.

3.1.1. Definition of synergy

In the dictionary synergy is defined as "the combined effect of two or more things, processes etc. that exceed the sum of their individual effects" /Crother 1995/. Thus, synergy can give extra advantages. Synergy is also defined to mean "the behavior of whole systems unpredicted by the behavior of their parts taken separately". This definition emphasizes the unpredictable nature of the synergy phenomenon. Synergy is well known for instance in chemistry and metallurgy. /Fuller et al. 1975./

Synergy is often regarded as accidental or at least an unpredictable phenomenon. This rather shows that synergy is an unknown phenomenon. Still, some synergy effects are well known and systematical in paper making, and they are exploited in paper production. The behaviour of the mixtures of separately refined softwood and hardwood chemical pulps is such. These mixtures have better strength properties than additively calculated and consequently they are exploited in fine paper production.

Synergy effect is the deviation from additive value with a mixture. Synergy is divided into synergism and antagonism, i.e. deviation upwards and downwards from additivity, respectively. This definition can be deceptive as both these phenomena can be beneficial or detrimental depending on the property in question. In this thesis the main interest was on beneficial synergy, which for simplicity is called synergy advantage.

3.2. Product analysis of mechanical printing papers

Mechanical printing papers comprise various newsprint and magazine papers. Magazine papers are divided into uncoated SC papers and coated papers, of which the most important is LWC paper.

Several requirements are set to mechanical printing papers by their processing and printing. The paper must have good runnability, which means trouble-free running with low frequency of web breaks or any other running problems. This is demanded from the paper web at paper mill on paper machine, on/off-machine coating and post machine treatments, such as supercalendering and winding. Good runnability is also demanded in the printing house both in printing itself and in the handling of the paper web or printed products. The paper must also have good printability, which means success in the printing event and good-quality printing. The profitability of paper in printing is also demanded, including e.g. low rate of spoilage and small demand of printing inks. In addition to these functional properties the paper should have good reliability and image, e.g. have good, stable quality and be environmentally friendly. However, the concept of environmental friendliness of paper has not been clearly defined. The relative importance of the properties demanded from paper depend on the processes in both the paper mill and printing house, paper grade and its basis weight, final product, printer, publisher and market area. Good runnability is vital and without it the other properties have no importance. If runnability is good, also printability becomes important.

3.2.1. Runnability

The runnability of the wet web on the paper machine demands good enough drainage properties of paper furnish. The wet web should also have high enough initial strength at about 45 – 53 % dryness level, which corresponds the level of first open draw on modern paper machines.

The runnability of the dry paper web both in the processing and printing sets similar requirements to paper. In coating a lot of water is brought to the dry paper web which together with the coating blade sets especially tight demands on runnability.

Good runnability particularly means low frequency of web breaks. A break of the paper web is caused by its excessively high momentary load and/or too low local strength (fig. 1) /Niskanen 1993, Kärenlampi 1996a/. A reason for high load can be too big tension of the web or fluctuation in it caused by its control or e.g. non-round paper rolls in printing. A too low local strength may be caused by macroscopic defects as holes, cuts or wrinkles /Roisum 1990, Uesaka et al. 1999/. The paper web should have the ability to resist fracture when these small defects exist. Good runnability of paper can be characterized with two properties:

1. paper web has only small and very few defects /Niskanen 1993/, or a small variation of strength /Kärenlampi 1996a/
2. paper has good fracture toughness /Niskanen 1993, Kärenlampi 1996a/.

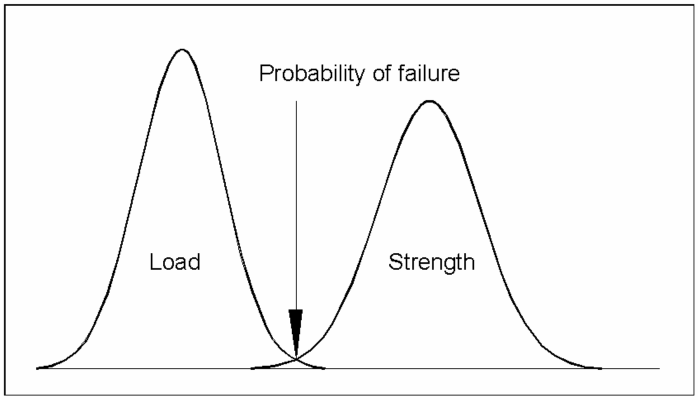

Figure 1. Probability of web failure depending on the distributions of the load and strength of paper /Kärenlampi 1996a/.

The mechanism in paper fracture is the break of fibre bonds or fibres. In mechanical pulp sheets fracture is primarily the fracture of fibre bonds /Shallhorn et al. 1979, Retulainen et al. 1985/. In this case strength can be improved by increasing bonding area or bonding strength in paper. Also the increase of fibre length or width or the decrease of fibre coarseness improve strength (fig. 2 - 3) /Shallhorn et al. 1979, Retulainen 1996a/. In good-quality mechanical pulps with high fibre length and good bonding ability, the increase of bonding may turn tear strength to a decrease, as the breaking of fibres becomes significant in sheet fracture /Shallhorn et al. 1979/. The longer the fibres are, the less bonding is needed for maximum tear strength (fig. 3) / Parsons 1969, Shallhorn et al. 1979, Seth et al. 1987, Mohlin 1989, Kärenlampi 1996b/. Also other strength properties reach their maximum when fibres start to break. After tear strength this point is next reached in fracture energy and only at a very high bonding degree in tensile strength /Retulainen et al. 1985, Shallhorn 1994, Kärenlampi 1996a, Kazi et al. 1996/. When fibres start to break, fibre strength becomes important and the role of fibre length decreases /Shallhorn et al. 1979, Retulainen 1996a/.

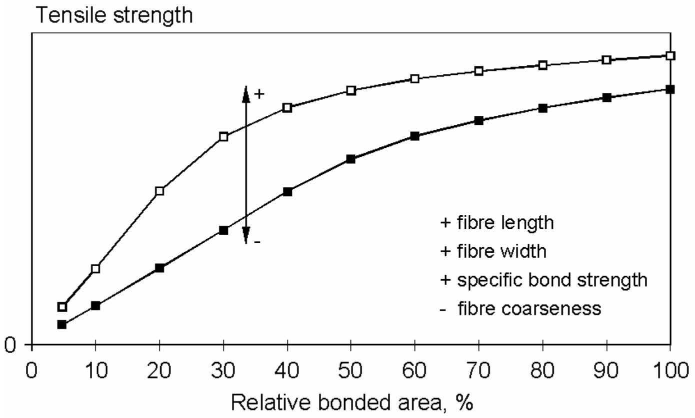

Figure 2. Effect of relative bonded area and some basic properties of fibres on the tensile strength of paper /Retulainen 1996a/, based on the modified Shallhorn-Karnis model /Shallhorn et al. 1979/.

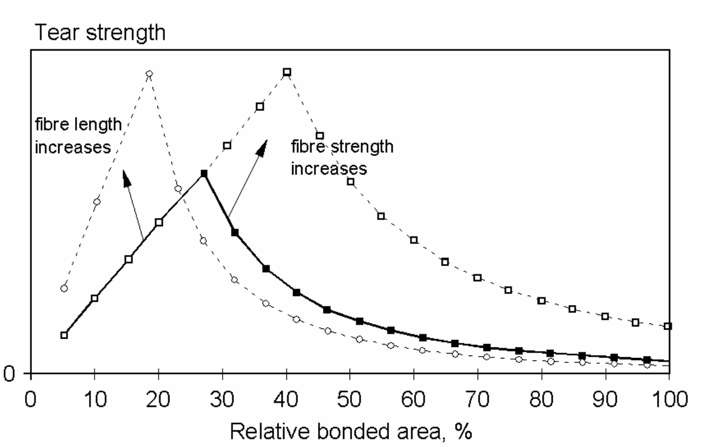

Figure 3. Effect of bonding degree and fibre length and strength on the tear strength of paper /Retulainen 1996a/ based on the modified Shallhorn-Karnis model /Shallhorn et al. 1979/.

In paper mills the runnability of paper is usually characterized by tensile strength and possibly also stretch in machine direction and/or tear strength in counter direction. The importance of these strength properties depends on e.g. paper grade and its basis weight, the mechanical pulp used or chemical pulp content in paper, the construction of paper machine and the possible coating.

The strength level of paper, i.e. the maximal loadability, is characterized by tensile strength. However, this average value has little to do with runnability as usually the paper web breaks at a clearly lower tension /Niskanen 1993, Kärenlampi 1996a/. The probability of low tensile strengths, i.e. the weakness of paper, would better characterize the loadability of paper (figure 1). Thus good runnability demands a good tensile strength level and its small variation. /Kärenlampi 1996a./ The stretch of paper increases with increasing fibre length, which spreads the fracture to a wider area, and with better bonding /Algar 1965, Lobben 1978, Seth 1990/. At a high refining degree the stretch may pass its maximum /Algar 1965, Retulainen et al. 1985/.

The ability of paper web to withstand defects is normally characterized by tear strength. However, this out-of-plane tear strength is difficult to connect with runnability though possible on a particular paper machine /Niskanen 1993/. Consequently, especially since the 1990´s tear strength is proposed to be replaced by fracture energy, which is tested in the real fracture mode of paper web. Fracture energy characterizes the work needed to propagate a crack existing in paper. There is not yet full agreement on how to measure fracture energy. However, the different measures are believed to rank the papers of a given grade in the same order, but their sensitivity to various changes on fibre level may not be the same /Niskanen 1993, Kärenlampi et al. 1996c/. Even finding a correlation between fracture energy and the very rare paper breaks in printing houses has been laborious demanding months of data /Page et al. 1982, Moilanen et al 1996/. Thus, tear strength is still rarely replaced by fracture energy in mills.

A defect in paper is regarded as the most common reason for a web break in printing /Fellers et al. 1999/. Also blade coating demands paper particularly free of defects /Koskinen et al. 2001/. A high fracture energy helps the paper to withstand defects /Fellers et al. 1999/. Lately

Uesaka et al. have criticized the use of fracture energy as a measure of paper runnability in printing. They claim that only very few web breaks in printing are associated with clear defects in paper and only large defects (> 40 mm) are detrimental. According to their large study on newsprint and directory papers the strength uniformity of paper is the most important factor influencing break frequency. Other important factors are elastic stretch and tensile strength. A decrease in these properties causes statistically significant increase in break frequency. /Uesaka et al 2001./

In addition to sufficient strength and the lack of defects the paper web must be stable in processing without too much fluttering. This demands good stiffness and bulk and even profiles of basis weight and moisture content both in the machine and counter directions. In printing good runnability demands also good-quality paper rolls. The paper must be easy to handle, which means good enough stiffness and folding strength and suitable friction and electrical properties to avoid troubles in post treatments in printing.

3.2.2. Printability

The printability of paper means both a successful printing event and high quality of the printed products. The lowest printability requirements of mechanical printing papers are set by newsprint and the strictest by LWC paper. These requirements show in the composition of these paper grades, the quality of their furnish components and surface treatments such as coating and supercalendering. Being uncoated high-quality SC paper sets strict requirements to its surface properties and so to its components and surface treatment, i.e. supercalendering. In addition, rotogravure and offset printing methods set their own special requirements to printability.

Good printing quality means high printing gloss, large tone area and small print-through requiring high surface density of paper characterized with low oil absorption and air permeability, good smoothness and high gloss, brightness and opacity of paper. Good printing smoothness, i.e. good smoothness and compressibility of paper surface, are especially important in rotogravure printing to assure that there are no missing dots in printing. Good printing also means uniform printing and equal printing on both sides of the paper. Uniform printability demands good formation of paper and small variation of quality in both machine and counter directions. To get equal printing on both sides the paper should have small two-sidedness of surface and absorption properties. This is affected by e.g. z-direction distributions of filler and fibre fines, which are influenced by both paper furnish and forming.

In coating and offset printing paper gets into interaction with water and subject to forces which tend to cause surface roughening, the break of paper surface, linting and paper splitting. To avoid problems related to wetting the paper should have good dimension stability and also be well bonded having good surface and bond strengths.

3.3 Demands set to the components of mechanical printing papers

Mechanical pulp gives good printability to mechanical printing papers and also a large share of the strength needed. In SC and LWC papers, contrary to newsprint, mechanical pulp alone cannot give enough strength, but also strong chemical pulp is needed. The only task of the chemical reinforcing pulp is to give the extra strength to paper, especially tear strength, which is missing from mechanical pulp. Excessive use of chemical pulp is avoided because it deteriorates printability and it is clearly the most expensive paper component. Filler is used to improve printability and also because it is usually the cheapest component of paper. However, filler deteriorates all the strength properties of paper.

3.3.1. Demands set to mechanical pulp

Good wet web runnability on paper machine demands good initial strength and that demands good drainage of paper furnish. Good drainage is best achieved with coarse, high freeness pulps. The demanded good initial strength at a certain dryness level is achieved with a furnish of well fibrillated fibres and high fines content having a high specific surface area. This requirement is in contradiction with good drainage. The drainage of TMP-based paper furnish is believed to be more difficult than that of groundwood-based, especially as it usually contains less chemical pulp. Good strength of paper demands good strength of pulps. Good tensile strength and stretch demand well-bonding mechanical pulp with high fines content, i.e. pulp with low freeness. Good tear strength demands long-fibred, suitably bonding mechanical pulp. Too low freeness may decrease fibre length and deteriorate tear strength. Fracture energy sets quite similar demands as tear strength but emphasizes bonding more. TMP has the best and groundwood the poorest strength properties of mechanical pulp, the relative difference being biggest in tear strength.

Troublefree running of paper web demands good stiffness of paper. To achieve good stiffness of uncalendered paper mechanical pulp should be bulky, long-fibred and relatively little refined. In calendered sheets more refined mechanical pulp has given better stiffness, because of increased elasticity irrespective of the decrease of bulk /Kakko 1996/. TMP-based furnish probably gives better stiffness to paper than groundwood-based furnish because of the bigger long fibre content and better bulk of mechanical pulp and lower chemical pulp percentage needed in paper.

Good optical properties of mechanical printing papers are achieved with mechanical pulp and filler. Groundwood has the highest brightness of mechanical pulps and TMP the lowest. Normally this difference in brightness is only about 2 - 3 percentage. Even this difference may have importance in grades with the highest brightness targets, as a difference in maximum brightness or bleaching costs. A good opacity of paper demands high light scattering coefficient of mechanical pulp, which is achieved with low freeness pulp rich in fines. In this respect groundwood is better than TMP.

Good printability of SC rotogravure paper, i.e. good smoothness, high opacity and gloss and low air permeability, is achieved with well-refined, low freeness mechanical pulp, which has flexible fibres and plenty of fines. With an effective refining of long fibre fraction TMP can give paper lower permeability than groundwood. Still, groundwood gives more easily good opacity and smoothness to paper than TMP. Good offset printability requires particularly well-bonding pulp with well-bonding long fibre fraction.

Most quality demands set by mechanical printing papers, especially good printability, are reached with a well-refined mechanical pulp, which has flexible, well-bonding fibres and which is rich in fines, i.e. pulp with low freeness. The decrease of the freeness is restricted by poorer drainage on the paper machine and the increase of specific energy consumption in mechanical pulping. A further restricting factor is the possible decrease of tear strength, which can increase the chemical pulp need in paper.

Today the finest mechanical pulp is used in high-quality SC rotogravure paper, which must meet its strict quality demands on surface properties to achieve good printability without coating. If the target is not top quality paper, the freeness level may be slightly higher. In SC offset grade the demands set on paper smoothness are not equally strict and the mechanical pulp can have higher freeness. In LWC paper the freeness of mechanical pulp is the same or slightly higher than in SC rotogravure paper. In newsprint mechanical pulp is clearly coarser than in SC or LWC papers.

3.3.2. Demands set to chemical pulp

Chemical pulp is used in mechanical printing papers only to make up the inadequate strength of mechanical pulp. Chemical pulp is added to paper furnish as weight percentages, but its reinforcing ability depends on the number of long fibres. Chemical pulp increases the average fibre length and total fibre strength, which both improve paper strength. Yet, in mechanical printing papers the relatively slightly refined fibres of chemical pulp bond less than additively calculated and their activity in loading is quite poor. Therefore chemical pulp hardly improves the bonding strength of SC or LWC papers /Retulainen 1992/.

The quality demands set to chemical reinforcing pulp depend mainly on the chemical pulp share in paper, which is affected by e.g. the mechanical pulp used, paper grade and its basis weight. The properties of the chemical pulp used can be influenced by both the pulp choice and its suitable refining.

At a share less than 30 % of fibre furnish in paper, i.e. in newsprint or SC paper, a unified chemical pulp fibre network does not yet show in paper properties /Alava et al. 1997/. Then the reinforcing ability of chemical pulp is characterized with the ratio (l/w) of fibre length (l) and coarseness (w) /Levlin 1990/. This means that the chemical pulp fibres should be long to be able to bond with as many fibres as possible, and thin to have many fibres in a certain amount of pulp. The fibres should also be flexible and thin walled to flatten and bond easily.

When the chemical pulp covers over about 30 % of the fibre furnish in paper, i.e. in LWC paper, a unified chemical pulp network is formed in paper. Though this is believed to happen already earlier, it shows in paper properties totally only at over a 30 % share of chemical pulp /Alava et al. 1997/. Now the behaviour of the strength properties changes and the tear strength of chemical pulp itself starts to affect the tear strength of paper. The reinforcing ability of chemical pulp is characterized with T*(l/w). /Mohlin et al. 1983, Levlin 1990./ So the previous index characterizing the strength potential of reinforcing pulp is multiplied by the tear index of the pulp (T) at a certain tensile index, normally 70 Nm/g or on a level corresponding to that used in the certain paper grade. Now the ratio l/w cannot be maximized any more but it has to be optimized. Hence the chemical pulp should have both long and strong fibres. /Levlin 1990./

Good reinforcing pulp is easy to refine. This means good development of bonding without too much deteriorating drainage and moderate specific energy consumption. As chemical pulp is used solely as reinforcing pulp in mechanical printing papers, it is refined relatively little not to cut fibres. So it has long fibres and it is poor in fines.

Newsprint based on TMP or recycled fibre can be made without any chemical pulp, but newsprint based on groundwood pulps can contain up to 20 % chemical pulp. In high-quality SC paper containing plenty of filler 8 – 25 % chemical pulp is needed. In the light weight base paper of LWC paper 25 – 50 % chemical pulp is usually needed.

3.3.3. Filler

Filler improves the printability of paper by increasing brightness and gloss and decreasing air permeability and roughness. Filler addition can, however, deteriorate the opacity of calendered paper. /Lorusso et al. 1999./ The clear increase of filler content in paper during the last 15 - 20 years, in spite of the decrease in basis weight, has been made possible by the improvement of pulps, especially mechanical pulp. The increase of filler content is regarded as the most important factor in improving the printability of SC paper. This is said to have been even more important than the improvement of mechanical pulp quality or the development of stock preparation technology, wire and press sections of paper machine and supercalendering. /Weigl et al. 1995./ On the other hand the development of paper machine technology, primarily water removal and the control of profiles, has made it possible to use finer mechanical pulp and these together have allowed the increasing of filler content.

Filler replaces fibres and so it deteriorates paper strength. It does not only fill empty voids between fibres but also spreads on fibre surfaces in the forming stage in paper making /Breunig 1981/. Filler is especially associated with fibre fines and fibrillation /Bown 1997/. Thus, when in the wet pressing and drying fibres get near each another, the filler particles reduce fibre contacts and prevent the formation of hydrogen bonds between fibres, the more the bigger the content or the smaller the particle size of filler is /Weigl et al. 1995, Tanaka et al. 200l/. Because of that strength properties sensitive to bonding deteriorate most /Breunig 1981, Mohlin et al. 1985, Weigl et al. 1995, Bown 1997/. The decreasing bonding has to be compensated with better bonding pulps or sizing.

The share of filler and its particle size and form affect different paper properties in different ways. Tear strength is primarily affected by the filler content and less by the particle size or form /Bown 1983/. Filler increases paper density, though less than if it would just fill voids between fibres, and decreases fibre density /Mohlin et al. 1985/. The decreasing particle size of filler improves the optical properties and most printability properties of SC rotogravure paper /Bown 1983, Weigl et al. 1995/. In uncalendered paper coarser filler decreases paper volume more, but in calendering this effect disappears /Bown 1983/. The optimal particle size of filler is reported to depend on mechanical pulp properties. Finer groundwood would give the best printability, expressed as least missing dots, with slightly coarser filler /Breunig 1981/. The particle form, surface chemistry and polarity of filler also affect paper properties /Weigl et al. 1995, Bown 1997/. The particle form has little effect on bonding, but it may have a bigger effect on printability than particle size has. Plate-like filler gives highest gloss and the best calendering properties and printability /Bown 1983, Weigl et al. 1995/.

Newsprint contains up to 15 % filler measured as ash, especially if it is based on recycled fibre. High-quality SC paper contains 25 – 35 % filler as ash to get good printability and LWC base paper contains about 6 – 12 % filler, which comes mostly from coated broke.

3.4. Fractions of pulps and their interactions

The fraction composition of different pulps essentially affects the pulp properties and their interactions in paper. Both the share and properties of different fractions have importance. This is why this topic is considered extensively.

3.4.1. Fractions of mechanical pulps

Heterogeneous mechanical pulps are usually divided into long fibre, middle and fines fractions. The non-desired coarse wood-like shives and fibre bundles are today practically non-existing in final pulps used on paper machines. Long fibre fraction is usually defined as fraction remaining on 28 mesh wire in screening (+28 fraction). Fines fraction is the fraction passing 200 mesh screen (-200 fraction). Middle fraction is the rest of pulp.

Long fibre fraction

Mechanical pulps used in SC and LWC papers contain about 5 – 30 % long fibres. This fraction is smallest in groundwood, in low freeness pulp for SC rotogravure paper only about 5 - 10 %, second smallest in pressurized groundwood and biggest in TMP, about 25 – 30 %.

The long fibres of groundwoods are well fibrillated while in TMP they are typically stiffer and less fibrillated /Laamanen 1983/. Mechanical pulps for newsprint have more long fibres. Long fibres typically have small specific surface area, which means quite poor bonding ability and light scattering coefficient.

Long fibre fraction gives strength to mechanical pulp by spreading load to a larger area /Retulainen 1992/. Increasing this fraction, i.e. increasing fibre length, improves the tear and tensile strengths and fracture energy /Mohlin 1979/. However, too big long fibre fraction deteriorates the bonding, light scattering and smoothness of mechanical pulp sheet /Mohlin 1979/. Because of their relatively poor bonding ability the fibre length and strength potential of long fibres cannot be totally utilized alone, but also extra bonding is needed. Tear strength maximum requires least bonding, fracture energy more and tensile strength requires most bonding. The importance of fibre length decreases in the same order. To totally utilize the fibre length of long fibres, their own bonding ability has to be improved or well-bonding middle and especially fines fractions are needed. This increases the bonding area between long fibres, the more the poorer bonding the fibres are. When loading paper, fines fraction lowers local maximum stresses by spreading tension to the whole bonded area. /Htun et al. 1978, Paavilainen 1990, Retulainen 1992./ This means that long fibre fraction and well-bonding fines fraction help each other in getting strength and ability to withstand defects in paper. Both these fractions are needed to achieve the required runnability /Retulainen 1992/. It is even typical to mechanical pulps, especially to TMP, that the tear strength of whole pulp can be clearly better than that of any individual fraction. Thus there is synergy between the fractions of mechanical pulps /Mohlin 1979, Honkasalo et al. 1981/.

Making the long fibres of mechanical pulps acceptable for SC and LWC papers demands extra treatment. The fibres should be made more flexible, fibrillated, better bonding fibres by mechanical non-cutting refining, where also chemicals can be used. Refining increases the density and bonding area of fibre network and improves all strength properties. /Corson et al. 1993, Corson 1996./ If fibre fraction is well-bonding, the tear strength of mechanical pulp may even turn to a decrease (fig. 4) /Corson et al. 1993/. The refining of long fibres improves paper printability by decreasing the air permeability, print through and roughness of paper and by increasing opacity /Mohlin 1979, 1980/. As refining increases the bonding area and decreases open pore volume between fibres available for fines fraction, the need of fines decreases. Extra fines would improve light scattering. The drawback of the treatment of long fibres in refining is the high specific energy consumption and in chemical treatment the deteriorated light scattering coefficient. /Corson et al. 1993, Corson 1996./

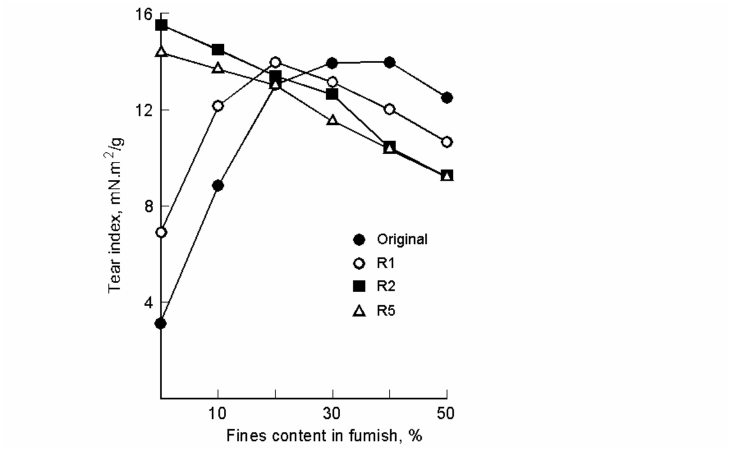

Figure 4. Effect of the refining of long fibre fraction of TMP on tear index as a function of the fines content of furnish, the number of the refining stages of long fibre fraction as parameter /Corson et. al. 1993/.

Middle fraction

The middle fraction of mechanical pulps has properties in between those of long fibre and fines fractions. It can contain well-bonding ribbons and fibrillar particles as well as poorly-bonding cutted fibres and pieces of fibre wall /Forgacs 1963, Mohlin 1980, 1987/. The properties of middle fraction depend on the ratio of these well and poorly-bonding particles /Forgacs 1963, Mohlin 1980/.

Middle fraction is often regarded as useless / Law et al. 1976, Corson 1980, Lindholm 1983a/ or even as detrimental in good-quality TMP with well-bonding long fibre fraction /Corson 1980/. On the other hand, middle fraction is found to be useful, at least to certain paper properties /Mohlin 1979, Corson 1980, Kakko 1996, Vanninen 1996/. In poor-quality TMP middle fraction can increase the density of fibre network and so also the bonding area. Even in good quality TMP middle fraction with stiff fibres has improved paper stiffness at low basis weight. /Corson 1980./ In TMP the middle fraction can be even more important than long fibre fraction to give stiffness to noncalendered newsprint /Kakko 1996/. A partial substitution of the long fibres of mechanical pulp with middle fraction has increased the density, smoothness, stretch, tensile energy absorption and tensile and z-strengths but deteriorated the tear strength and stiffness of LWC base paper sheets. This change in the fibre length distribution of mechanical pulp would improve the printability of LWC paper and deteriorate its stiffness and runnability. /Vanninen 1996/. According to Mohlin well-refined middle fraction improves the tensile and z-strengths, light scattering and smoothness of a sheet and can be as important as fines fraction in mechanical pulp. However, middle fraction deteriorates tear strength. /Mohlin 1979./

In a case where the fibre fraction of groundwood is a mixture of long and short fibres, initial strength has been found to be better than with either fraction alone. This change is believed to be caused by the denser packing of the mixture, which increases friction forces between fibres. Simultaneously also bonding area increases and this decreases the need of fines. /Brecht et al. 1953./ This packing phenomenon is known from powder studies, where a mixture of larger and smaller particles, at about 25 % proportion of the latter, has bigger density than powder with only smaller or larger particles /Fedors et al. 1979/. Also the difficulty of the increasing of fines content in TMP emphasizes the role of good-quality middle fraction as partial substitute of fines.

Lindholm /Lindholm 1983a/ believes that the importance given to middle fraction e.g. by Mohlin /Mohlin 1979/ could be caused by misleading trial plan. When one fraction at a time is added to the basic TMP, the advantage of simultaneous addition of long fibre and fines fractions does not appear.

Fines fraction

The low freeness mechanical pulps used in SC and LWC papers have high fines content, from about 30 % in TMP up to 35 - 45 % in groundwood. The fines fraction contains fibrils, bundles of fibrils, lamellae, parenchyma cells, fibre pores, short cut fibres and particles of middle lamellae /Gavelin 1976, Giertz 1977, Mohlin 1987, Retulainen et al. 1993/. Still finer is the colloidal fines fraction covering a few percent of pulp /Rundlöf 1996/.

As early as in 1939 Brecht and Holl divided the fines fraction of mechanical pulp, i.e. groundwood, in good quality fibrillar fines (Schleimstoff) and poor-quality flake-like fines (Mehlstoff) containing cut fibre fragments /Brecht et al. 1939/. In practice, the properties of the fines fractions would be between these two extremes.

The fines of mechanical pulps are often divided according to their formation stage in the pulping process into primary and secondary fines. The primary fines are formed at the fiberizing stage, in grinding or refining. In groundwood they originate quite randomly from different layers of fibre and their lignin content, 31 – 32 %, is practically the same as that of spruce wood on average (30 %). The primary fines of TMP originate more from middle lamella and so their lignin content is higher, about 35 – 37 % /Marton 1964, Kolman et al. 1975, Heikkurinen et al. 1993/. The primary fines are mostly flake-like, resembling mehlstoff. They have high light scattering coefficient but relatively poor bonding ability. /Luukko et al. 1998/. The secondary fines are formed in the refining of fibres. The particles of secondary fines are more fibrillar resembling schleimstoff and their particle length increases and lignin content decreases with refining. This improves the bonding ability of the fines and deteriorates their light scattering /Brecht et al. 1939, Honkasalo et al. 1981, Corson 1989, Heikkurinen et al. 1993, Luukko et al. 1998/. Thus, the quality of fines fraction depends on its proportion of fibrillar particles /Luukko et al. 1997a, 1998/.

Within paper structure the fines particles of mechanical pulp have three different functions. First, fines form bridges between fibres pulling them closer to each other thus increasing the density of fibre network and the probability of fibre bonds. Second, fines block between fibres also at points where fibres would have bonded even without it and so fibre bonds do not increase. Instead, the fibre density of the sheet starts to decrease. Third, fines in a sheet have a voids filling function. This does neither increase the fibre-fibre bonds nor affect fibre density, but increases sheet density as bridging and blocking also do. These three functions occur at least partially simultaneously. /Görres et al. 1996a./

Brecht and Holl found that fines quality affects the tensile strength of pulps. The best bonding was achieved with kraft pulp fines and the poorest with the fines of coarse groundwood. /Brecht et al. 1939./ Later Retulainen has found that the addition of TMP fines to different relatively stiff long fibre fractions improves tensile strength slightly and light scattering clearly. On the contrary, kraft pulp fines clearly improve tensile strength but impair light scattering. With a suitable mixture of these two different fines fractions the ratio of tensile strength and light scattering could be controlled over a wide range (fig. 5). Scanning electron microscopy (SEM) confirmed these findings. Mechanical pulp fines formed filaments between fibres while chemical pulp fines densely covered fibres and formed membrane-like structures. /Retulainen et al. 1993, Retulainen 1996a./

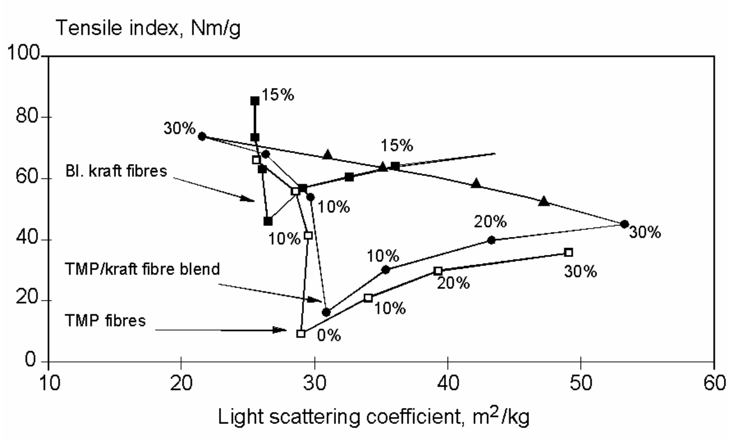

Figure 5. Effect of the fines fraction addition of kraft pulp (left) and TMP (right) to different long fibre fractions (slightly refined kraft pulp, TMP and a mixture of these two with ratio 45/55) on tensile index and light scattering coefficient /Retulainen et al. 1993/.

All fines particles with their large specific surface area strongly interact with water and fibres and respond to surface tension forces, often called the Campbell forces which pull fibres together. The fines particles deteriorate drainage, increase sheet density and decrease porosity /Corson 1996, Görres et al. 1996a, Sirviö et al. 2003a/. The flexible fibrillar fines particles of both mechanical and chemical pulps with their large specific surface area efficiently compact sheet structure and thus promote fibre-fibre bonding but can decrease light scattering. On the other hand, the flake-like fines particles of mechanical pulps have large specific surface area but relatively rigid structure rich in lignin and low polarity. So the flake-like fines particles can resist the Campbell forces and surface forces between water and the fines particles. The flake-like fines particles may block fibre-fibre bonding and give more open sheet structure with better light scattering but poorer bonding. /Brecht et al. 1943, Retulainen 1993, Heikkurinen et al. 1993, Luukko et al. 1997a, 1997b, 1998, Retulainen et al. 2001, Sirviö et al. 2003./ The fines having highest fibrillar content, i.e. kraft pulp fines, have the greatest sheet compacting effect and mechanical pulp fines with least fibrillar nature have the smallest compacting effect (fig 6) /Sirviö et al. 2003a/. The sheet compacting effect of fines may arise during drainage, pressing and drying shrinkage. /Sirviö et al. 2003b./

As a consequence of their properties the fines particles of mechanical pulp deteriorate drainage less and promote light scattering more and bonding less than those of chemical pulp. The stiffer fines particles of mechanical pulps also fill voids in between fibres more efficiently thus decreasing the air permeability and improving the smoothness of paper /Luukko et al. 1997a/. Due to these effects the fines fraction of mechanical pulp gives good printability to paper. Even the colloidal fines of mechanical pulps can improve the bonding of unbleached pulps but in peroxide bleached pulp the extractives in colloidal fines can deposit on fibre surfaces deteriorating bonding /Rundlöf 1996/.

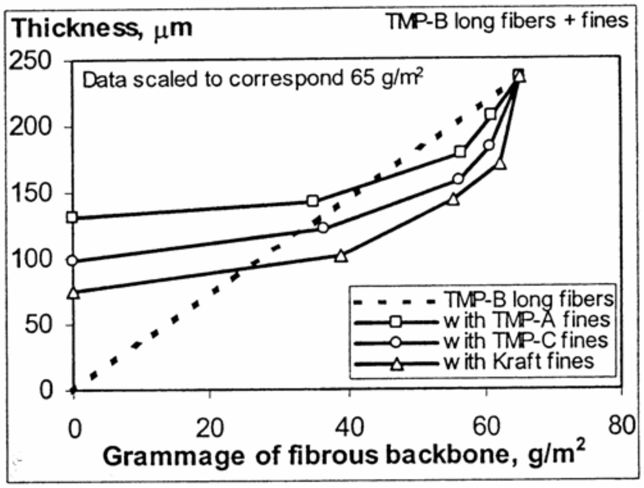

Figure 6. Apparent sheet thickness as a function of fibre fraction grammage in mixture sheets containing mechanical pulp long fibres and varying amounts of distinct fines. The fibrillar nature of fines increases in order TMP-A < TMP-C < kraft /Sirviö et al. 2003b/.

Importance of fibre length distribution in mechanical pulp

During the past well over 20 years several scientists have shown that the fibre length distribution of mechanical pulp for printing papers should be "u-shaped" containing a lot of long fibres and enough fines, but no middle fraction, which would be useless /Law et al. 1976, Corson 1980, Lindholm 1983a/. This kind of pulp would have good strength; especially tear strength, because of its high fibre length. Fines fraction would give the needed bonding, good smoothness and opacity and low air permeability. In these studies the optimal fraction composition of pulp is usually studied just by mixing different fractions without striving to affect the quality of these fractions, as is done in mills.

Brecht and Klemm showed in the 1950´s that in an optimal groundwood sheet all voids between fibres should be exactly filled with fines. Then the contact area in the sheet would be big, and maximum initial strength would be achieved and fibres would still form a unified network. Extra fines would separate fibres from each other thus starting to break their unified network. This would decrease initial strength. They called this optimum fines content "the limiting state". /Brecht et al. 1953/. At this state the increase of tensile strength also slowed down, or even turned to a decrease as the limiting state was passed and the increase of sheet density and the decrease of air permeability practically stopped /Lindholm 1983a/. As the fines content passes a saturation point, probably corresponding to the limiting state of Brecht and Klemm, sheet thickness starts to increase /Corson 1996/. At this point blocking increases over bridging and fibre density turns to a decrease /Görres et al. 1996a/. Görres has developed a model to determine the effects of fines amount and fibre quality on the fibre density of a mixture sheet of mechanical and chemical pulps /Görres et al. 1996a/. Lindholm has developed a model for the dependence of bulk and the limiting state of a sheet on the fractional composition of mechanical pulp and some properties of its fractions /Lindholm 1978/. The limiting state is a function of sheet density and chemical pulp share /Retulainen 1991/. Thus the limiting state of fines content should probably be regarded rather as a point of optimal bonding.

Corson has shown that increasing the average fibre length and refining the long fibre fraction would improve the quality of TMP, except light scattering /Corson 1980/. The fines amount needed in mechanical pulp depends essentially on the sheet fibre density and the quality of both long fibre and fines fractions /Brecht et al. 1953, Corson et al. 1993, Görres et al. 1996a/. To achieve good strength the missing bonding ability of fibres has to be offset by some other bonding material. If the fines fraction is small or fibres are only slightly fibrillated, good fines retention is especially important. In this respect TMP is more critical than groundwood. /Mohlin 1977./ Refining or chemical treatment, which make fibres more flexible, decrease the need of fines /Brecht et al. 1953, Lindholm et al. 1983b, Corson et al. 1993, Corson 1996/. As the refining of fibres decreases the need of fines and also produces some fines, well-refined TMP has enough fines for good bonding /Corson 1980/. As earlier shown in this review good quality middle fraction may also have a function in mechanical pulp /Mohlin 1979, Corson 1980, Kakko 1996, Vanninen 1996/.

Several studies have shown that mechanical pulps should have a certain minimum amount of fines, at least about 25 - 30 %, for optimal properties /Mohlin 1977, 1979/. However, the maximum of tear and folding strengths, depending mostly on the amount and properties of long fibre fraction, may be reached already before this at about 15 – 30 % fines content, especially in well-bonding pulps /Brecht et al.1953, Mohlin 1979, Lindholm 1983a/. The extra fines of over 25 – 30 % would improve only some printability properties such as light scattering, smoothness and air permeability at the cost of tear strength /Brecht et al. 1953, Corson 1980, Lindholm 1980/.

In studies where u-shaped fibre length distribution is regarded as optimal for mechanical pulps, the importance of tear strength is emphasized, often at the cost of light scattering. The reason for this may be the great influence of tear strength on the chemical pulp dosage on paper machines affecting the furnish costs of paper essentially. In addition, tear strength cannot usually be improved by additives, such as sizers. If in future the out-of-plane tear strength measurement is replaced by fracture energy in paper production, the bonding ability of pulps may be emphasized more than today.

In literature the optimizing of the fibre length distribution of mechanical pulp is usually done in pure mechanical pulp /Law et al. 1976, Mohlin 1979, Corson 1980/ instead of considering the properties of the other paper components, i.e. chemical pulp and filler. This is of course possible in newsprint containing only mechanical pulp. This has been regarded as possible also in other cases because all mechanical pulps are believed to behave in the same way in a mixture of mechanical and chemical pulps and filler /Mohlin et al. 1983, 1985/. However, this is not always true /Retulainen 1992/ as shown later in this review.

Making mechanical pulp finer into lower freeness, i.e. using more energy in pulping both in groundwood and TMP processes, improves the bonding ability of all fractions /Brecht et al. 1939, Honkasalo et al. 1981, Corson 1989, Heikkurinen et al. 1993/. Fibre cutting /Corson 1989/ or fractionation and the different treatments of fractions can change this trend. The lower freeness of pulp improves the light scattering of long fibre fraction but can deteriorate that of fines fraction /Corson et al. 1993, Heikkurinen et al. 1993/. However, both the light scattering coefficient of mechanical pulp and properties depending on bonding ability normally improve as the pulp is made finer.

3.4.2. Fractions of chemical pulps

Chemical pulps are usually divided only into fibre fraction (+200 fraction) and fines fraction (-200 fraction). The fines fraction of chemical pulp consists of primary fines originally existing in pulp and secondary fines generated in refining.

In unrefined chemical softwood pulp the share of fibre fraction is 95 – 100 %. The fibre fraction consists mostly of intact fibres with different lengths. It contains both stiff summerwood fibres with good fibre strength but poor bonding ability and more flexible, weaker, and better bonding springwood fibres. In refining the former cut more easily and form more fines with larger particles while the latter fibrillate more easily /Paavilainen 1990/.

The primary fines of chemical pulp, about 0 – 5 % of the pulp, consist of parenchyma cells, fibre pores and short cut fibres /Paavilainen 1990, Waterhouse et al. 1993/. In primary fines the content of lignin, ash and extractives is higher than in secondary fines or the whole pulp and its specific surface area is relatively small. Thus the bonding ability of primary fines is quite poor but still the fines improve the bonding of long fibre fraction.

Secondary fines are formed in refining. The total fines content increases to 2 – 10 % in slightly refined chemical pulps used in mechanical printing papers, being still clearly less than in mechanical pulps. The secondary fines of chemical pulp consist of flexible fibrils, fibre wall fragments and short cut fibres and their chemical composition is similar to fibre fraction /Paavilainen 1990/. Secondary fines have a high water retention value (WRV) /Giertz 1980/, which deteriorates drainage on the paper machine /Weise et al. 1996/. The WRV of fines decreases in drying but still the secondary fines of dried chemical pulp are found to have good water bonding ability /Waterhouse et al. 1993, Weise et al. 1996/. Secondary fines have bigger effect on the bonding of chemical pulp fibres than their external fibrillation has /Giertz 1980, Paavilainen 1990/ and double effect on that of primary fines. /Retulainen et al. 1993/.

The fines particles of chemical pulp and TMP have about the same size / Retulainen et al. 2001/. In chemical pulp fines the chemical composition has a minor importance, contrary to mechanical pulp, where the lignin content of fines has a great effect /Heikkurinen et al. 1993, Nieminen et al. 1994/. Being poor in lignin, more fibrillated and having a larger specific surface area the secondary fines particles of chemical pulp respond easily to Campbell forces and bond better. The bonding ability of fines also improves as the specific surface area increases /Nieminen et al. 1994/. The specific surface area of the primary fines of chemical pulp is about 4 - 5 m^2/g and that of secondary fines 10 - 20 m^2/g while the specific surface area of mechanical pulp fines is about 7 - 8 m^2/g /Nieminen et al. 1994/. Because of a better bonding ability the secondary fines of chemical pulp have poorer light scattering coefficient than mechanical pulp fines /Retulainen et al. 1993/.

Importance of fibre length distribution in chemical pulp

As in mechanical pulps, also in the slightly refined chemical pulps used in mechanical printing papers the long fibre fraction contains relatively stiff fibres which need fines for bonding with each other. However, chemical pulp contains only a small amount of fines.

The strength properties of chemical pulp, both tensile and tear strengths, both with springwood and summerwood fibres, improve linearly with increasing fibre length. Yet, Paavilainen regards fibre wall thickness as even more important for the papermaking potential of chemical pulp than fibre length. /Paavilainen 1990./

In sheet forming the efficiently water-retaining fines fraction deteriorates drainage /Retulainen et al. 1993, Seth 2003/, clearly increases the Campbell forces between fibres by conforming easily to fibre network and makes a denser, better bonding sheet structure /Htun et al. 1978, Giertz 1980/. In drying, if shrinkage is not totally prevented, an increase in bonding area made possible by fines fraction promotes the forming of micro-compressions. This activates fibre segments in paper loading /Paavilainen 1990, Retulainen et al. 1993/. When loading paper the fines on fibre-fibre bonds help to lower tension peaks by spreading tension to the whole bond area and by shrinking the sheet / Htun et al. 1978, Paavilainen 1990, Seth 2003/. Fines fraction makes paper more homogeneous and improves strength. It activates fibre network from the very beginning of elongation to load carrying and pushes the start of the breaking of bonds forward. Due to their good bonding ability chemical pulp fines decrease light scattering, opposite to mechanical pulp fines. /Retulainen et al. 1993./ Even the small fines amount is found to have a distinct increasing effect on the density and bonding area of chemical pulp. This is seen as an increase in tensile stiffness and tensile strength /Htun et al. 1978, Giertz 1980, Nieminen et al. 1994, Suur-Hamari 1994/ and decrease in the tear strength of refined softwood kraft pulp /Nieminen et al. 1994, Suur-Hamari 1994/. Fines also increase the stretch /Lobben 1978/ and initial strength of kraft pulp.

The importance of fines fraction in chemical pulp depends essentially on the properties of fibre fraction. The well-bonding secondary fines are particularly important in bonding thick-walled, stiffer summerwood fibres, which respond less to the Campbell forces than springwood fibres. Both with summerwood and springwood fibres the fines increasing Campbell forces increase sheet density and decrease light scattering coefficient. With summerwood fibres fines fraction improves tensile strength more than with springwood fibres. Summerwood fibres determine the tear strength of chemical pulp, but totally without fines they are unsuitable as reinforcing pulp, opposite to springwood fibres. /Paavilainen 1990./ With a lot of fines a chemical pulp behaves as if it were highly refined /Seth 2003/.

It is proposed that also in chemical pulp, like in mechanical pulp, u-shaped fibre length distribution with a reasonable amount of fines, no middle fraction and a large amount of long fibres would be optimal /Nieminen et al. 1994/.

3.5. Behaviour of different furnish mixtures

The behaviour of a mixture of two different pulps differs from that of one pulp. The components of a mixture may have different bonding degrees, load carrying between them has to be taken into account and their stretch to break may change /Alava et al. 1997, Retulainen 1991/.

3.5.1. Mixtures of different mechanical pulps

In literature only a few studies can be found concerning the use of the mixtures of different mechanical pulps in papermaking /Dillen et al. 1975, Frazier et al. 1976, Vaarasalo et al. 1981, Tuovinen et al. 1993, Honkasalo 2001/. In the study of Dillen et al. a mixture of groundwood and TMP has given a clear synergistic advantage in the initial tensile strength and tear strength of paper. When replacing 2/3 of groundwood with TMP the strength advantage of TMP was practically obtained. As a result the chemical pulp percentage needed in paper was smaller than calculated and the negative effects of TMP on optical properties were avoided. These advantages were found in newsprint both in lab sheet trials and in mill scale trials on paper machine. Because of insufficient information about the pulps used in the trials the reasons for this synergy are difficult to evaluate. The Swedish paper mill where that study was made was reported to have achieved significant economic benefit with this mixture in newsprint production. /Dillen et al. 1975./ A similar synergy benefit with a mixture of groundwood and TMP was found in SC paper in the author's own study /Honkasalo 2001/. In addition to strength the mixture gave synergy advantage also in printability.

3.5.2. Mixtures of different chemical pulps

Several properties of the mixtures of separately refined chemical softwood and hardwood pulps behave non-linearly as a function of their mixing ratio. The tensile, tear and folding strengths, light scattering and opacity of the mixture can be higher and air permeability lower than linearly calculated /Bovin et al. 1971, Clark d'A 1985 p. 299, Sepke at al. 1992, Colley et al. 1973/. Usually the bulk, breaking length and the stretch of the mixture behave linearly /Colley et al 1973/. The length weighted average fibre length of this mixture is, just according to the formula, even 0.15 – 0.20 mm lower than linearly calculated /Sepke et al. 1992/. Bovin and Teder have found synergistic advantage in the tear strength of the mixtures of any different chemical pulps if their tensile strengths are on different sides of the tear strength maximum on their tensile-tear strength curves /Bovin et al. 1971/. Thus, the normal inhomogeneous refining action could even be an advantage. The mixtures of separately refined softwood and hardwood chemical pulps are commonly used and their synergy advantage is utilized in woodfree printing papers. The mixtures of different chemical pulps are not used in mechanical printing papers, though they are proposed to be possibly advantageous in simultaneously achieving good elastic strength and energy properties to paper /Alava et al. 1997/.

Corte found that a mixture of chemical pulps refined to different degrees or a mixture of two unrefined pulps with different coarsenesses gives a bimodal pore size distribution. The frequency of both pore size maximums depended on the mixing ratio of the pulps. He concluded that the different pulps behaved as if they formed two separate networks in the sheet, each contributing to its own pore size distribution. /Corte 1982/.

3.5.3. Mixtures of mechanical and chemical pulps

Chemical pulp is used in mechanical printing papers solely to give the paper the strength missing from mechanical pulp. Reaching the strength targets together with acceptable drainage on the paper machine determines the dosage and refining of chemical pulp. Its reinforcing effect in mechanical papers originates from the increases in the average fibre length of furnish, the number of long fibres and so the number of load carrying segments and fibre strength/gram of pulp /Retulainen 1991, 1992/.

The strength properties of mechanical pulps can be quite different. Groundwood with its short fibres could be assumed to utilize the strength of long-fibred chemical pulp more efficiently than TMP. However, this is found to be true only in the initial strength. In other properties all mechanical pulps in a mixture with chemical pulp behave similarly, independent of their fibre length distribution or bonding ability. Thus, mechanical pulps can be developed without needing to take the interactions between meachanical pulp and chemical pulp in the mixture into account. /Mohlin et al. 1983./ Yet, later Mohlin has found that the evaluation of the reinforcing ability of chemical pulp cannot be based on 100 % chemical pulp sheets, but mixture sheets with mechanical pulp are needed. This evaluation should be based on the fracture mechanics instead of traditional testing. /Fellers et al. 1999./

Despite the similar behaviour of different mechanical pulps with chemical pulp the properties of the mixture cannot be calculated linearly from the properties of the components. Mohlin has found that the tensile strength of this mixture is poorer and tear strength better than additively calculated (fig. 7 and 8). /Mohlin et al. 1983./ Similar non-linear behaviour is also found in some other studies /Bovin et al. 1971, Retulainen 1997/. Also the density, tensile stiffness, z-direction tensile strength, tensile energy absorption and shrinkage stress of this mixture are found to be smaller and light scattering coefficient bigger than calculated /Retulainen 1997/.

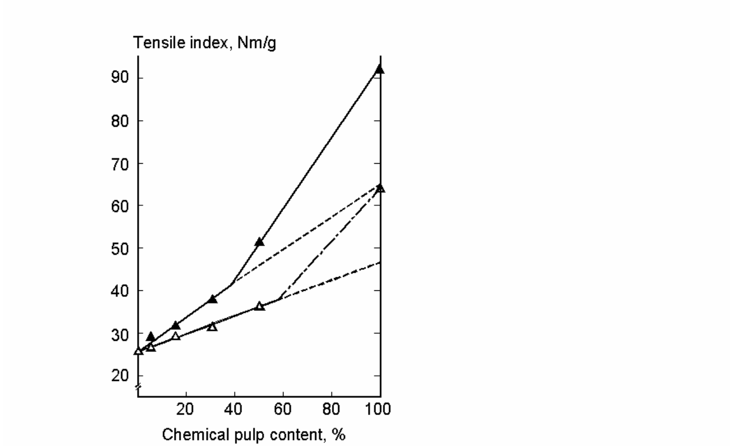

Figure 7. Tensile index of a mixture of groundwood and chemical pulp as a function of the chemical pulp share, chemical pulp at two different refining levels (open triangles: slightly refined (CSF 610 ml) and closed triangles: more refined (CSF 330 ml)) /Mohlin et al. 1983/.

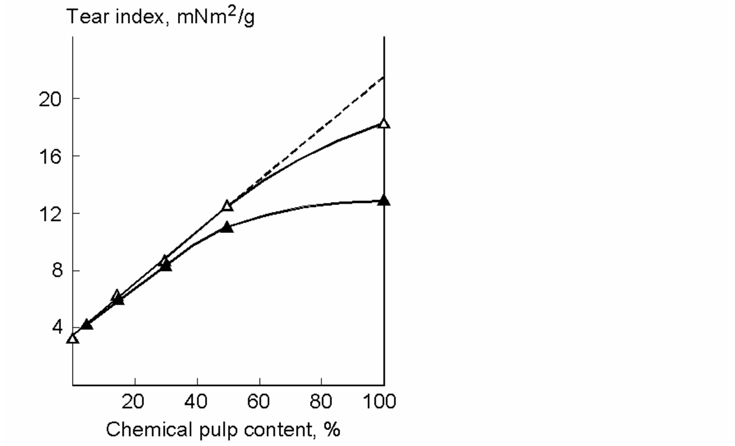

Figure 8. Tear index of a mixture of groundwood and chemical pulp as a function of the chemical pulp share, chemical pulp at two different refining levels (open triangles: slightly refined (CSF 610 ml) and closed triangles: more refined (CSF 330 ml)) /Mohlin et al. 1983/.

According to Zhang the fracture energy of a pulp mixture behaves linearly if the bonding potential of the components of the mixture can be fully utilized /Zhang et al. 2002/. However, it seems that the mixtures of mechanical and chemical pulps behave as if only a part of the bonding potential of chemical pulp could be utilized. This is the clearer the more flexible the chemical pulp fibres are, like springwood fibres vs. summerwood fibres /Retulainen 1991/. This phenomenon is explained by the stiff mechanical pulp fibres forming a bulky fibre network which partially prevents the bonding of more conformable chemical pulp fibres /Mohlin et al. 1983, Retulainen 1992, Alava et al.1997/. Consequently, the relative bonded area (RBA) between chemical pulp fibres first increases less than additively as a function of mixing ratio (fig. 9) and the synergistic behaviour of the mixture is most natural /Alava et al.

1997/. Also Gates showed that with suitable pulps the RBA changes unlinearly as a function of their mixing ratio and synergy is probable. Especially a mixture of pulp and fines behaves this way /Gates et al. 2002/.

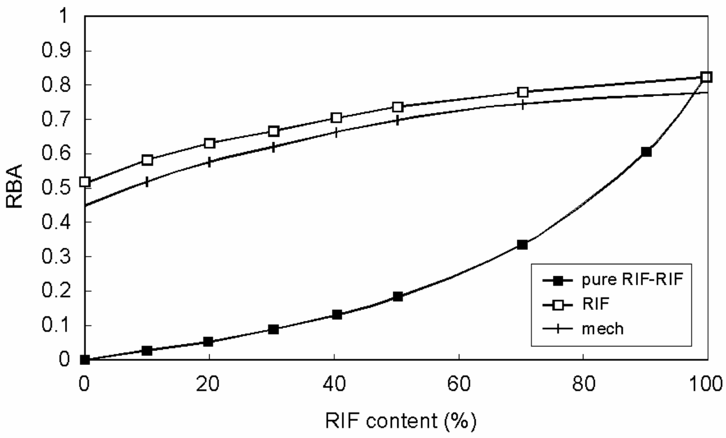

Figure 9. Relative bonded area of groundwood (mech) and chemical pulp (RIF) fibres to any fibre type and between chemical pulp fibres (RIF-RIF) as a function of chemical pulp share /Alava et al. 1997/, curves calculated by PAKKA-model /Niskanen et al. 1997/.

At a small share, 0 – 10 %, chemical pulp fibres are at least partially separated not yet forming a unified fibre network in mechanical printing paper /Mohlin et al. 1983, Alava et al. 1997/. Because of that the stress distribution in loaded paper is more uneven than with pure mechanical pulp and the chemical pulp may have even a negative effect on paper strength /Alava et al. 1997/. A decrease is found in z-strength /Mohlin et al. 1983, Retulainen 1992/, tensile strength /Retulainen 1992/ and fracture energy /Mohlin 1989/ when mixing a small amount of chemical pulp fibres with mechanical pulp fibres. Retulainen has found a slight increase in light scattering coefficient /Retulainen 1992/, against the results of Mohlin and Kazi /Mohlin et al. 1983, Kazi et al. 1996/.

Because of the decrease found in strength properties at a small chemical pulp share Mohlin has regarded bonds between mechanical and chemical pulps as even weaker than the bonds between mechanical pulp fibres. She assumed that these pulps would behave as their own fibre networks in the mixture. /Mohlin et al. 1983./ The bimodal pore size distribution of a sheet of a mixture of two different pulps found by Corte is compatible with the idea of separate fibre networks /Corte 1982/. The idea of separate fibre networks is criticized widely /e.g. Retulainen 1992, Görres et al. 1996b, Kazi et al. 1996, Alava et al. 1997/. Kazi did not believe in the existence of independent fibre networks, but assumed that bonds between mechanical and chemical pulps are very weak, probably because of the difference in drying shrinkage /Kazi et al. 1996/. Retulainen bases his criticism on the finding that the bonds between mechanical and chemical pulp fibres are stronger than the bonds between mechanical pulp fibres, though weaker than the bonds between chemical pulp fibres /Retulainen 1992/. Also the uniform distribution of mechanical pulp fines makes pure chemical pulp bonds rare thus preventing the formation of separate networks /Alava et al. 1997/. The decrease in strength properties with a small addition of chemical pulp has not been found in all studies; on the contrary, even a clear increase has been observed /Fellers et al. 1999/.

In a mixture of mechanical pulp and chemical pulp, the chemical pulp fibres do not totally carry load and activate at the beginning of the loading because of their clearly bigger stretch to break, which is caused by their greater number of curls, crimps and dislocations /Retulainen 1997/. As a result a mixture of mechanical and chemical pulps has tensile strength poorer than additively calculated /Retulainen 1992/**.** This may also be caused by the difference in the chemical composition of fibre surfaces or in drying shrinkage and twist, which can weaken the already formed bonds in drying /Mohlin et al. 1983, Mohlin 1989/.

According to the percolation theory, in a two-dimensional sheet already a 10 % share of chemical pulp forms a unified fibre network /Ritala et al. 1989/. However, this may show in paper properties totally only at a share of 30 % or even higher. Thus in SC paper, where the share of chemical pulp is about 20 - 30 % of fibres, its reinforcing ability is mainly a result of its bonds with mechanical pulp fibres. When the share of chemical pulp is still bigger, above about 30 %, as in LWC base paper, it forms a unified network behaving as chemical pulp. In this case chemical pulp fibres break in the tear fracture of paper. /Levlin 1990, Alava et al. 1997./

On the other hand a small amount well-bonding mechanical pulp rich in fines added to slightly refined chemical pulp can improve tensile strength, even if the strength of mechanical pulp is clearly poorer than that of chemical pulp /Kärenlampi 1996a/.

In various studies the strength properties of the mixtures of mechanical and chemical pulps have not behaved consistently. Bovin and Mohlin have found that the tensile strength of the mixtures of mechanical pulp and refined chemical pulp is poorer and tear strength better than additively calculated /Bovin et al. 1971, Mohlin et al. 1983/. The tensile strength of a pulp mixture is found to be possibly poorer than additively calculated especially, if the stronger pulp has smaller elastic modulus /Kärenlampi 1996a/. Thus, the addition of reinforcing chemical pulp has a relatively small improving effect on the tensile strength of paper. Totally opposite to these results Riddell found positive synergy in tensile strength, stretch and tensile energy absorption but not in the tear strength of a mixture of kraft pulp and TMP (CSF 125 ml). This synergy found provided that chemical pulp was unrefined or only slightly refined and handsheets were rich in fines, made with white water circulation. /Riddell et al. 2001./ Smook also found positive synergy in tensile and burst strengths but also in out-of-plane and in-plane tear strengths in the mixtures of newsprint grade groundwood rich in fines and unrefined, dried chemical pulp /Smook 1979/. Retulainen has found a negative synergy in tensile stiffness /Retulainen 1991/. According to Retulainen a mixture of mechanical and chemical pulps can have either a positive or negative synergy in tensile strength, depending on the properties of the components. Positive synergy is probable if mechanical pulp is well-bonding. /Retulainen 1992./ Praast has found only slight, less than 10 – 12 %, deviations from additivity in any strength properties of the mixtures of SC grade groundwood and chemical pulp /Praast et al. 1998/. The contradictory results can be caused by the low number of pulps used in most of the studies.

Shallhorn has observed positive synergy in the fracture energy of a mixture of groundwood and softwood kraft pulp, but not in that of a mixture of groundwood and hardwood kraft or sulphite chemical pulp. He explains this by more flexible, lower coarseness softwood kraft fibres bonding more with each other than with groundwood fibres or groundwood fibres with each other /Shallhorn 1994/. Also Hiltunen, Kazi and Zhang have found positive synergy in the fracture toughness or fracture energy of a mixture of TMP and softwood kraft pulp, when the latter is unrefined or only slightly refined /Kazi et al. 1996, Hiltunen et al. 1999, Zhang et al. 2002/. Only at over a 60 % proportion of chemical pulp refining improved the fracture energy of this mixture and it changed to linear. The authors believed that also too high refining would change the behaviour of fracture energy non-linear. /Zhang et al. 2002./

Independently of the mixing ratio of mechanical and chemical pulp at constant fibre length Parsons observed maximum tear strength of the mixture at a certain bonding degree characterized by Scott-Bond. Because of this the tear strength of mixtures where one of the components was poorly bonding and the other well bonding, was better than that of either component. /Parsons 1969./ The behaviour of a mixture of mechanical pulp long fibre and fines fractions is analogous to this result /Mohlin 1979, Honkasalo et al. 1981/. Positive synergy in tear strength or fracture energy is found to be typical in mixtures where one component is well-bonding pulp, rich in fines, and the other one long-fibred, poorly-bonding pulp. Such are e.g. mixtures of fine mechanical pulp and slightly refined chemical pulp /Retulainen 1992, Zhang et al. 2002/. Even when mixing refined chemical pulp and poorly-bonding long viscose fibres the in-plane tear strength and fracture energy of the mixture behave in the same way having a maximum, though this mixture has lower than calculated density, tensile strength, tensile energy absorption and Scott-Bond /Yu et al. 1999/.

Brecht has found that if the properties of two pulps differ considerably, their mixing curve is unlinear and if the difference is small, their mixing curve is almost always linear. Typically the mixtures of softwood and hardwood chemical pulps or softwood chemical pulp and groundwood can have synergy. The air permeability and brightness of the mixture would be lower than additive value and in tear strength, stiffness and opasity positive synergy is achieved. Density and tensile strength would behave additively. /Brecht 1963/. Görres agrees on Brecht´s idea of the synergy behaviour of the mixtures of different pulps. Synergy is achieved when mixing pulps with different coarseness and some other property such as fiber flexibility. Especially at a small share of low-coarseness chemical pulp, 0 – 10 %, added to higher-coarseness pulp, synergy is found in density because of fibre collapse. He regarded complex interactions between fibres and the changes of average fibre properties as reasons for synergy. /Görres et al. 1996b./ Most properties of mechanical and chemical pulps, e.g. the chemical composition, fibre length distribution and properties of fractions differ from each other. Because of this, and as several mechanisms impact simultaneously in their mixture (table 1), Retulainen has regarded the non-linear behaviour of this pulp mixture as most natural. /Retulainen 1992, 1997./ Fernandez has assumed that the collapse of chemical pulp fibres is a reason for the non-additive behaviour of the density and tear strength of mechanical and chemical pulp mixtures As a result of the collapse the increase of bonding area starts significantly only at over a 50 % chemical pulp share. /Fernandez et al. 1994./ Retulainen has regarded this rather as an effect of lacking interaction between the fibres of these pulps, which leads to poor activity of chemical pulp at its small proportion /Retulainen 1997/. Görres has regarded fibre collapse only as a secondary contributor to nonlinearity /Görres et al. 1996b/.

Table 1. Factors affecting the strength properties of the mixtures of mechanical and chemical pulps /Retulainen 1997/.

Factor	**Effect of kraft pulp addition**
Number of long fibres	++
Average fibre length	++
Fibre strength/mass unit	+
Bonded area/fibre length	-+
Specific bonding strength	+
Fines/fibre ratio	-
Activity of material in loading	-

++ strong increase
-- strong decrease
-+ weak effect, positive or negative

Bovin found that the strength of different mixtures of mechanical and chemical pulps deviated most from the calculated value at equal proportions of the components (50/50) /Bovin et al. 1971/. Sepke and Selder found with the mixtures of different chemical pulps that a maximum deviation from additivity was possible also at other mixing ratios /Sepke et al. 1992/. According to d´A Clark the mixtures of long-fibred, poorly-bonding pulp and short-fibred, well-bonding pulp can have maximum synergy advantage in strength properties at a 25 % proportion of the latter because of improved bonding. This synergy disappears at a 50 % proportion because of decreased fibre length. /Clark d'A 1985 p. 686./

It is proposed that the behaviour of the mixtures of mechanical and chemical pulps should be studied as a function of volume proportions instead of normal weight proportions. This was supported by the finding that with this mixture the bonding area and as a result of that also the strength properties behave more linearly as a function of volume proportions. /Tristram et al. 2000./

Brecht and Klemm and later Retulainen have applied the idea of the limiting state of fines content to the mixtures of mechanical pulp and unrefined or slightly refined chemical pulp /Brecht et al. 1953, Retulainen 1992/. This was regarded as possible as the fibres of slightly refined chemical pulps used in mechanical printing papers are relatively stiff, not much differing from mechanical pulp fibres /Retulainen 1992/, and as they also need fines to bond properly /Paavilainen 1990, Retulainen 1992/. The addition of chemical pulp to mechanical pulp clearly decreases the ratio of fines to long fibres /Retulainen 1992/. Thus, when mixing chemical pulp with mechanical pulp rich in fines the initial strength first increased until the limiting state of the mixture was reached. After that the fines of the mixture could no more fill voids between fibres /Brecht et al. 1953/ and if the proportion of chemical pulp in the mixture is relatively small, its fibres can not compensate this decrease in bonding area caused by the lack of fines /Retulainen 1992/. Hence the initial strength turned to a decrease /Brecht et al. 1953/. Other properties depending on fines content and bonding could also turn to a decrease /Retulainen 1992/. According to this the mixture of groundwood and chemical pulp can have synergy at the optimum fines content of the mixture. Thus, the fines content of the mechanical pulp used in paper has to be big enough to tolerate the addition of chemical pulp poor in fines without going below the limiting state of the furnish mixture /Retulainen 1992/. This means the demand of extra fines in mechanical pulp. Thus, when optimizing the mechanical pulp the properties of all the components of paper furnish should be taken into account. The adequate fines content of a pulp mixture, the limiting state, depends on e.g. paper density and fibre properties such as the share of chemical pulp fibres /Retulainen 1991, Görres et al. 1996a/ and probably also on the filler quality and amount in paper. As at the limiting state voids between fibres are exactly filled with fines, that point would also be a turning point in the calendering behaviour of paper /Retulainen et al. 1993/.

Fibre properties affect the fibre density in a sheet and the fines amount needed in it. Mechanical pulp usually contains a high amount of fines and the fines are partially flake-like. Therefore though fines first increase fibre density in pure mechanical pulps, the whole fines fraction can decrease fibre density /Luukko et al. 1997b, Görres et al. 2001/. When in a pulp mixture the share of chemical pulp is 0 - 25 % and the mechanical pulp used is TMP, the maximum fibre density is achieved at about a 20 % fines content in the mixture sheet. At a 50 % share of chemical pulp the fibre density decreases as a function of fines content from the very beginning opening the fibrous sheet structure. /Görres et al. 1996a./ Pure chemical pulp has so little fines, mostly fibrillar, that its fines fraction increases fibre density /Görres et al. 2001/. However, extra fines would probably decrease fibre density. The fines of all pulps tend to compact the paper sheet. The effect increases with a bigger fibrillar content of the fines, i.e.

the compacting effect is biggest with chemical pulp fines and smallest with coarse mechanical pulp fines. The compacting effect of fines is biggest with long fibre fraction which has lowest density. /Sirviö et al. 2003a/. In addition to fines content and quality also wet pressing and drying affect sheet density and thereby the behaviour of the mixture of mechanical pulp (TMP) and chemical pulp /Eriksson et al. 1999/.

If the aim is to improve the strength of mechanical printing paper, an improvement in mechanical pulp has a much bigger effect on it and the needed chemical pulp percentage in paper than equivalent change in chemical pulp /Mohlin et al. 1985/. This also means that the quality evenness of mechanical pulp is important. Even a big change in the refining degree of chemical pulp has only a small impact on the tear strength of paper, when the share of chemical pulp in the mixture is less than 30 % /Mohlin et al. 1983/.

In order to obtain good strength properties to the mixture of mechanical and chemical pulps the bonding area and fibre length of both components should be maximized. To achieve a large bonding area, pulps having small coarseness and large fibre width, both mechanical and chemical pulp, are advantageous. However, the coarseness of chemical pulp fibres should not be too low to increase flexibility thus too much decreasing the activity of fibres in loading. The refining of chemical pulp increases the bonding area in paper. The bonding strength of the component with poorer value, i.e. mechanical pulp, should be improved. Mechanical pulp should have enough fines to keep the fines content of the mixture above the limiting state and its fibres should have high strength and their number of defects should be minimized. To make the fibres of both pulps well activated in loading the chemical pulp should have lower fracture elongation, i.e. its fibres should have fewer kinks and microcompressions, and the stretch of mechanical pulp should be increased to the level of chemical pulp to get both pulps active in loading. /Retulainen 1992, 1997, Alava et al. 1997./

3.5.4. Effect of filler addition on different furnishes

Filler addition deteriorates all strength properties of a mixture of mechanical and chemical pulps. When the share of chemical pulp is 15 - 50 %, the relative deterioration of strength is found to be quite independent on chemical pulp content and its refining degree or mechanical pulp quality. Tensile stiffness and tear strength are least sensitive and tensile energy absorption and burst strength most sensitive to filler addition. /Mohlin et al. 1985./ The tear strength of a well-bonding furnish may first even increase with a small filler addition turning to a decrease at higher filler loading /Gullichsen et al. 1999/.

Filler reduces the bonding of the fibre network. This shows clearly as decreased fibre density. /Tanaka et al. 2001/. Because filler reduces bonding area, its amount and particle size presumably impact the optimum bonding and fibre fines content in paper furnish. Due to the results of Mohlin and Bown /Mohlin et al. 1985, Bown 1985/ and the theory of the limiting state of fines /Brecht et al. 1953/ it could be assumed that with mechanical pulp containing more fines the decrease of bonding area and the deterioration of strength when adding filler would be smaller. In mechanical pulp, where fines particles do not tend to bond as tightly on fibre surfaces as in chemical pulp, the effect of filler addition on the increase of light scattering may also be smaller /Retulainen 1992/. Filler addition to more refined chemical pulp being more fibrillated and richer in fines has increased the light scattering of paper more by preventing fibre fines from bonding firmly on fibre surfaces in drying. The increased fibrillation and fines content has also decreased the strength weakening with filler addition. /Bown 1985./ Actually chemical pulp refining has the opposite effect from filler addition to all in-plane mechanical properties except elastic stiffness which is less affected by filler addition. The out-of-plane properties are less sensitive to filler addition than refining. These effects are similar in mixture sheets with TMP to pure kraft sheets. /Tanaka et al. 2001./ To reach the maximum tear strength and fracture toughness of filler containing paper chemical pulp should be refined to lower freeness /Parsons 1969, Nordström et al. 1992/.

3.5.6. Refining of chemical pulp in mechanical printing papers

In the production of mechanical printing papers target values are set to the machine direction tensile strength and/or counter direction tear strength of paper to secure good runnability. The importance of these strength properties depends on several factors such as paper grade and its basis weight and paper machine construction. The tear strength and fracture energy of mechanical printing papers are controlled with chemical pulp share /Fellers et al. 1999, Eriksson et al. 1999/. However, chemical pulp share only slightly affects the tensile strength of paper. Bonding and tensile strength are affected with chemical pulp refining. The refining degree of chemical pulp affects also the printability of paper, though printability is primarily made by mechanical pulp. Refining is limited by acceptable drainage on the paper machine. The needed refining degree of chemical pulp is affected by several factors such as paper furnish.

Refining improves the bonding of chemical pulp by fibrillating its fibres, making them more flexible and by producing fines. This improves initial strength at a certain dry content and strength properties such as tensile, z-direction and surface strengths. Tear strength deteriorates because of both increasing bonding and cutting and fibre damages. The refining of chemical pulp also densifies paper.

When the share of chemical pulp in paper is less than 20 - 30 % of fibres, as in newsprint or SC paper, chemical pulp can be refined clearly over its maximum tear strength to improve the tensile strength of chemical pulp and paper. This does not deteriorate the tear strength or fracture toughness of paper /Mohlin et al. 1983, Mohlin 1989, Levlin 1990/. According to Seth in mechanical printing papers chemical pulp should be refined to good tensile strength at acceptable drainage to maximize its reinforcing ability. In this case the paper will also have good stretch, elasticity and fracture energy and the decrease of tear strength can be left without consideration. /Seth 1996./ It is also proposed that in paper grades containing a high amount of filler, chemical pulp should be refined clearly over its maximum tear strength to increase the fracture energy of paper /Nordström et al. 1992/.

With a higher than 30 % share of fibres, as in LWC paper, the impact of deteriorating the tear strength of chemical pulp by refining clearly shows in paper properties and it has to be refined less /Mohlin et al. 1983, Levlin 1990, Alava et al. 1997/. At a share of over 40 % chemical pulp, independent of mechanical pulp (groundwood or TMP) in the mixture, the refining of chemical pulp decreases, or possibly first slightly increases, the tear strength of both chemical pulp and the mixture /Parsons 1969, Hiltunen et al. 1999/. The fracture energy of a mixture of mechanical and chemical pulps decreases from the very beginning /Hiltunen et al. 1999/ or slightly improves /Åström et al. 1993/ with refining. The fracture energy of pure chemical pulp first increases turning later to a decrease /Hiltunen et al. 1999/.

It can be asked, if the mechanical pulp used in paper and as a result of that the different paper furnish should also affect the refining degree of chemical pulp. Should chemical pulp be refined more or less if mechanical pulp is TMP instead of groundwood? According to Levlin the smaller the proportion of chemical pulp in paper is, the more it should be refined /Levlin 1990/. This means that the chemical pulp of TMP-based paper should be refined more than that of groundwood-based. However, a pulp with longer fibres demands less bonding to its maximum tear strength than a pulp with shorter fibres (fig. 3) /Parsons 1969, Shallhorn et al. 1979/. Although TMP with longer fibres than groundwood allows smaller chemical pulp dosage, the average fibre length of TMP-based paper is still usually higher. Thus, the chemical pulp of TMP-based paper should be refined less than that of groundwood-based paper. In TMP-based sheets the refining degree of chemical pulp is found to have a bigger effect on the apparent tensile strength than the chemical pulp share in the paper furnish and in groundwood-based sheets the order is reverse /Koskinen et al. 2001/.

3.6. Development trends of mechanical printing papers affecting their furnish

Today the development of mechanical printing papers concentrates on improving the printability but also decreasing the furnish and mailing costs and improving the environmental image. All these trends affect paper furnish.

During the last few decades the use of stronger reinforcing chemical pulps and stronger mechanical pulps (PGW, TMP) have allowed the decreasing of chemical pulp dosage in paper, which has cut furnish costs /Breunig 1981/. In order to improve the printability of SC and LWC papers an effort is made to increase the fines content and bonding ability of mechanical pulps, i.e. mechanical pulps are made finer, to lower freeness. This has allowed the increasing of the filler content of paper to further improve printability and to reduce furnish costs. All these changes together with the developments in the technologies of paper machines and supercalendering have improved paper printability. /Breunig 1981, Weigl et al. 1995, Veness et al. 1999/.

In addition to the increased filler content of paper also finer and brighter fillers, e.g. calsium-carbonate, are used to improve the printability and to increase the brightness of paper. However, filler deteriorates paper strength more than in proportion to the fibres replaced and may also decrease bulk and deteriorate runnability. /Bovin et al. 1971, Breunig 1981, Lorusso et al. 1999, Carter 1999, Wurster et al. 1999./ The brightness of paper is improved also by bleaching mechanical pulp to higher brightness than earlier.

The basis weight of paper is gradually reduced, because of raw material costs and environmental reasons. However, this tends to deteriorate most paper properties such as strength, stiffness and opacity in ratio to the reduction of basis weight or even faster. /Seth et al. 1989, Skowronski 1991, Mohlin 1992, Retulainen 1996a/. These changes are still reasonable until the basis weight area 30 - 35 g/m^2 /Seth et al. 1989/.

Elementar chlorine free (ECF) or even totally chlorine free (TCF) bleached chemical pulps are used for environmental reasons in mechanical printing papers. The TCF bleaching may cause damages to fibres, which can show in refined pulp as poorer strength properties than in traditionally bleached pulps. The poorer strength tends to increase the chemical pulp percentage needed in paper. However, as TCF bleaching is still in a development stage, improvements in pulp quality are expected. /Ebeling et al. 1994./

Lately the use of recycled fibre has been increased in paper furnish because of its environmental image and lower cost than that of virgin pulps. Newsprint is made from 100 % recycled fibre, but in SC and LWC papers the maximum use of recycled fibre is smaller because of stricter quality demands. The possible drawbacks of recycled fibre can be reduced e.g. by the choice of waste paper and its processing.

Several of these development trends tend to deteriorate paper strength. This deterioration could be compensated by increasing the chemical pulp dosage, but this is avoided as it deteriorates printability and increases furnish costs. The decrease of tensile strength could theoretically be prevented by improving specific bonding strength and reducing relative bonding area (RBA) not to deteriorate opacity or by increasing total surface area and keeping RBA constant /Retulainen 1996a, 1997/.

The bonding strength in paper can be improved with a sizer. Sizer clearly improves the tensile strength of slightly refined chemical pulp and CTMP, but only slightly improves bonding between stiff mechanical pulp fibres because it does not increase bonding area. Sizer slightly deteriorates the light scattering coefficient. /Retulainen et al. 1996b, Retulainen 1997./ Usually sizer deteriorates tear and folding strengths, but even tear strength could have been slightly improved with certain sizers, such as a hydrocolloid, together with a network former. Sizer deteriorates the compressibility and opacity of paper, which can deteriorate paper printability. /Breunig 1981, Weigl et al. 1994./ The use of sizers may also cause some problems in the wet end of the paper machine. /Breunig 1981/.

Both the bonding ability and light scattering could be improved and widely controlled with the addition of a suitable mixture of the fines of chemical pulp and TMP, and a sizer. The fines addition would also improve the smoothness of paper. The effects of fines fraction and sizer are nearly additive as they improve strength in a different way. The sizer improves specific bonding strength and its effect shows in the plastic area of deformation while fines mainly increase bonding area and affect both in the elastic and plastic areas. This combination would also allow the reduction of the basis weight of paper without deteriorating tensile strength or opacity. However, tear strength would still deteriorate. Maintaining tear strength would demand the increasing of the strength and length of fibres. Maintaining stiffness would be difficult and would demand lighter calendering. This would, however, deteriorate smoothness and air permeability. To avoid these drawbacks fibres with low coarseness and furnish with high fines content are preferable. /Retulainen et al. 1993, 1996a, 1996b./ The production and handling of a separate fines fraction could be difficult because of the extreme nature of this fraction.

The new multilayering technique can improve the printability of mechanical printing papers and affect paper furnishes and their behaviour /Tubek-Lindblom et al. 2003/. Depending on the objectives and the way of multilayering furnish components, a chemical pulp fibre network can probably form at a lower share, which reduces the chemical pulp amount needed in paper and affects synergy behaviour.

3.7. Conclusions

Most mechanical printing papers consist of a mixture of different components: mechanical and chemical pulp and filler in furnish and/or coating. It is often assumed that different furnish mixtures would behave additively in paper. However, this is found to be untrue with the mixtures of mechanical and chemical pulps. As the mixing ratio of the paper components is changed, several factors affect simultaneously and some of them change non-linearly. Also most paper properties depend on several factors and may have e.g. optimum bonding degree and fines content depending on fibre length. Thus it is most natural that pulp mixtures may behave in a synergistic way in paper. Synergy is typically found in a mixture where bonding ability and fines are mainly concentrated on one component and where fibre length is concentrated on the other component. This could be e.g. a mixture of fine mechanical pulp and unrefined or slightly refined chemical pulp. Neither of the components may have good strength alone, but as a mixture they can. Also a mixture of fine groundwood and long-fibred TMP could result in some advantages and behave synergistically in paper. Even changes in fines content around the limiting state and differences in drying shrinkage or surface chemistry are possible reasons for synergy.

The behaviour of different pulp mixtures and especially their possible synergy has not been studied widely. Thus the knowledge of the synergy behaviour of furnish mixtures in paper and its reasons still seem to be quite limited and partially contradictory. Reasons for this can be the numerous factors affecting synergy behaviour making its study difficult and also differences in the pulps and testing methods used. Thus, too small a number of pulps and mixtures tested may cause misleading assumptions. Also testing errors, which are not always considered, can cause apparent synergy behaviour.

If the synergy of paper furnishes would be consistent, the quality potential of paper components, as strength, could be utilized more efficiently than today. This could reduce paper furnish costs as a smaller chemical pulp percentage in paper and also improve paper printability. Therefore better knowledge about the behaviour of pulp mixtures and their synergy in paper would be needed. Also the characterizing of paper runnability should be studied further.

4. EXPERIMENTAL

4.1. Experimental approach

At the beginning of this research the behaviour of a mixture of groundwood and TMP in mechanical printing papers was quite poorly known and little consistent information about the topic could be found in literature. At Rauma only a short mill trial had been run prior to this study using a mixture of groundwood and TMP in SC paper (1. Introduction) and that trial indicated synergy advantage in paper strength. Yet, the reasons and predictability of this synergy were unknown. Similarly it was unknown if synergy could also exist in other paper grades and other paper properties. The question remained, if this synergy of the mixture of groundwood and TMP could intentionally be exploited in paper and what kind the different components of paper should be to achieve biggest synergy advantages.

It is most successful and economical to start the study of a relatively unknown phenomenon which can be caused by several partially unknown factors affecting simultaneously, on a lab scale with handsheet trials of simple pulp mixtures. On a lab scale the control of different parameters and the study of their effects are easier.

However, real papermaking on modern paper machines differs a lot from lab sheet making in forming, pressing and drying. These dissimilarities cause several differences in paper, the most important being differences in formation, fibre orientation and the z-distribution of fines and filler /Heikkurinen et al. 1991, Mohlin 1999./ Thus, handsheet studies are considered only indicative about the strength properties of paper and they are regarded as non-valid to characterize paper structure, optical properties or printability /Levlin et al. 1983/. Lab sheet trials are even regarded as useless to characterize paper quality /Mohlin 1999/. In order to check the validity of the results of lab studies and especially if the synergy behaviour can also be exploited in practice in real paper production, the results should be verified on a modern paper machine.

Most available pilot paper machines are constructed primarily to study the effects of different machine parameters or chemical additives. On these pilot machines the exact control of the mixing ratio of paper furnish components may be difficult. The relatively small pulp and water volumes on pilot machines make the runs short not allowing the stabilization of white water or pulp systems. On the contrary, Rauma paper mill with both fine groundwood and TMP production, modern high speed SC and LWC paper machines and the possibility to mix the pulps to a certain degree offered a good environment for mill trials. Relatively short mixing trials are possible without too much disturbing paper production. Therefore the lab studies were verified with several mill scale trials at UPM-Kymmene Rauma paper mill.

4.2. Lab studies

4.2.1. Objectives of lab studies

The objective of the lab studies was to clarify whether the use of a mixture of groundwood and TMP would be beneficial in SC paper and LWC base paper. Benefits could be achieved, on one hand, in strength properties and as a result of that in the chemical pulp need and paper furnish costs and on the other hand, in paper printability. A special interest was, if the mixture of groundwood and TMP behaves synergistically, in which paper properties, under which circumstances and which are its reasons.

4.2.2. Lab studies

The vague knowledge of the behaviour of pulp mixtures and especially their synergy in mechanical printing papers affected the trial plan of the lab studies. The lab studies consisted mostly of several different trials with their partially different objectives. The trial plan was gradually modified on the basis of the results achieved.

In the lab studies handsheets with different furnishes consisting of mechanical pulp, which was groundwood, TMP or their mixture, and chemical pulp and filler clay were made. The main interest was in SC paper and LWC base paper furnishes.

The lab studies were started by investigating if a mixture of groundwood and TMP can really behave synergistically in SC paper or LWC base paper. These studies were made with two different combinations of groundwood and TMP. These were pulps typically used in the production of SC paper. The chemical pulp used in these trials was ECF bleached softwood kraft reinforcing pulp refined in a pilot plant with a small mill scale Metso JC-01 conical refiner. The chemical pulp was refined in three passes, specific edge load (SEL) was 2.1 Ws/m and refining consistency was 4.0 %. Some of the handsheets were also supercalendered. At this stage the studies of LWC base paper were limited.

As a result of the positive results of the studies with SC paper the behaviour of the mixture of groundwood and TMP was studied more thoroughly also in LWC base paper. A master's thesis /Sipilä 1999/, instructed by the author, was completed on this subject and its results are rediscussed in this thesis. The lab trials were made with one combination of LWC grade groundwood and TMP. The chemical pulp was ECF bleached softwood kraft reinforcing pulp, which was refined at Finnish Pulp and Paper Research Institute (KCL) with a Voith-Sulzer conical lab refiner to two different freeness levels, i.e. 645 and 505 ml. The specific edge load in refining was 2.5 Ws/m.

The research was continued to better find the conditions and reasons for the synergy phenomena found in SC paper and LWC base paper. The effect of sheet density, i.e. bonding, was studied by affecting bonding with the wet pressing of sheets or the addition of certain fractions or starch to sheet furnish. The effect of the quality of groundwood and TMP and the quality and refining degree of chemical pulp were studied. The effects of mechanical pulp qualities, filler content and chemical pulp dosage, the refining degree of chemical pulp and the basis weight of paper were studied in an interval typical to SC and LWC papers. Several different groundwood, TMP and chemical pulp samples were chosen for these studies. The chemical pulps were mill refined with three Metso JC-04 conical refiners in series. The reasons for the effect of chemical pulp share and sheet basis weight were also studied.

The results achieved did not, however, totally clarify the synergy behaviour of the mixtures of groundwood and TMP in SC and LWC papers. In order to better understand the synergy

phenomena found the behaviour of different furnish mixtures used in mechanical printing papers was also studied. The studied basic mixtures were
- different pulps used in furnishes: groundwoods, TMPs, chemical pulps
- mixtures of different groundwoods and TMPs
- mixtures of different mechanical and chemical pulps
- filler addition to different pulps and pulp mixtures
- different SC paper furnish mixtures

In these studies a special interest was in
- the effect of the quality of furnish components
- the effect of bonding degree
- the effect of furnish mixing ratios, i.e. the TMP share of mechanical pulp, chemical pulp dosage, ash content

Several new groundwood, TMP and chemical pulp samples were chosen for these studies. The chemical pulps were mill refined with three Metso JC-04 conical refiners in series.

The results indicated that differences in drying shrinkage or surface chemistry could have a role in synergy. These results gave an impetus to study also the importance of these factors. The importance of drying shrinkage on the synergy of different furnish mixtures was studied in a master's thesis /Laukkanen 2002/, instructed by the author, the results of which are totally rediscussed in this thesis. The mixtures of SC rotogravure grade groundwood and TMP in combination with two different chemical pulps were studied. The chemical pulps were refined with Voith-Sulzer lab refiner to low freeness, about 400 ml. The importance of surface chemistry was studied by comparing the chemical properties of the pulps of paper furnishes where synergy was both found and not found.

The trial plan of the lab studies could have been more explicit, if different pulp fractions had been mixed with each other. This could also have allowed larger changes in paper furnishes. However, this was regarded as too laborious in the scope of this thesis. This could also have given irrelevant or misleading results in the form of mixtures which are impossible in practice. Fractionation could also have caused the losing of some fines.

The lab studies were started in January 1995 and ended in November 2002. Some supplementary testing was done still until November 2003.

4.2.3. Methods

The testing methods used in the lab studies are listed in appendix 1. Primarily ISO and SCAN methods were used.

In order to minimize differences compared to the results of the mill studies all the handsheets, except the sheets with pure chemical pulps or different fractions, were made with white water circulation. Retention aid, 260 mg/kg polyacrylamide (PAM), was used in furnishes containing filler. Handsheets were wet pressed with normal pressure or different pressing levels. Handsheets with different pressing levels were dried on a drum and handsheets with normal wet pressing were drum-dried or plate-dried.

The right furnish composition of the handsheets was utmost important as any deviations from the target could have caused misleading conclusions. To check the right composition the fibre length distribution was measured both in sheet furnishes and in one wet sheet. These values were compared to the value calculated from the fibre lengths of the components and their target shares in mixture sheets. Note that length weighted average fibre lengths are not linearly additive! Usually the fines content in the sheets was slightly lower than in furnish. The ash content of the final sheets was measured. If sheet basis weight, average fibre length or ash content significantly deviated from the calculated or target value, the sheets of that trial point were made again. This happened only a few times.

In some cases the drum-dried handsheets were supercalendered after conditioning in a tropics cabinet to a high, 8 – 12 %, moisture content. The Gradek lab calender used has a single nip with one steel roll and one paper roll. The diameters of the rolls are 180 and 250 mm, respectively. Normal calendaring speed is 12 m/min. In supercalendering the target was to achieve the density level of mill made SC rotogravure paper, i.e. about 1200 kg/m^3. The supercalendering conditions were: pressure 80 bar, temperature 80 ^{o}C, nips 5 + 5, top side of sheets first against steel roll.

In the drying shrinkage study free drying shrinkage was measured with image analysis from normal handsheets dried between propylene filters. The controlled uniaxial drying of handsheets at different shrinkage or straining levels was done at Helsinki University of Technology (HUT) with equipment described by Zhang /Zhang 2004/.

In the study of handsheet fracture zones 2 % mechanical pulp fibres dyed with toluid blue and 1 % chemical pulp fibres dyed with congo red were added to the furnish of handsheets. The cut and intact dyed fibres in fracture zone were counted under light microscope.

4.2.4. Raw materials

Different kind of final pulp samples from mill processes were chosen for all the lab trials in order to minimize differences in the results of the lab and mill trials. A few mechanical pulps were also taken from different stages of the mechanical pulping mill or pilot processes.

The mechanical pulps were mostly unbleached pulps. Most of them were made for SC or LWC paper but a few also for newsprint. Most of the pulp samples used in the lab studies were taken from Rauma paper mill but also a few samples from other mills were used. Groundwood samples were taken from four mill and one pilot process and TMP samples from four mill processes. The raw material of all the mechanical pulps was 100 % spruce (Norway spruce, *Picea abies*). In the TMP processes most chips were made from logs but in some cases a minor part of chips was sawmill chips.

The chemical pulps were Finnish ECF and TCF bleached softwood kraft reinforcing mill pulps taken from two different chemical pulp mills. Chemical pulp samples were dried or undried pulps. They were made from a mixture of 40 – 60 % spruce (Norway spruce, *Picea abies*) and 40 - 60 % pine (Scots pine, *Pinus silvestris*). They were refined on a lab, pilot or mill scale.

Because of the long interval of the experimental and samples taken from different mills the quality of wood raw material naturally varies somewhat and that may have affected mechanical pulp quality. However, this was not regarded as a drawback in this study, where the behaviour of different furnish mixtures was researched. Any changes in pulp qualities would merely be desirable to confirm the application area of the hypothesis.

The filler was kaolin, a mixture consisting of 75 % M and 25 % CCL kaolin, used in SC paper production. The filler was dispersed in a paper mill process.

In some cases different pulp fractions were also added to the pulps to affect their fibre length distribution. Altogether 27 different combinations of groundwood, TMP and chemical pulp and 18 different combinations of groundwood and TMP were investigated.

4.3. Mill studies

4.3.1. Objectives of mill studies

Lab studies with handsheets are criticized as improper to characterize modern paper making /Levlin et al. 1983, Mohlin 1999/. Thus, the objective of the mill studies was to verify the synergy results of the lab studies on a mill scale on modern, high speed paper machines producing SC and LWC papers.

4.3.2. Mill trials

The early mill trial performed in 1994 and the results of the lab studies done affected the trial plans of mill trials. The mill trials of this thesis were started on Rauma paper machine number two (PM2) with groundwood and TMP from the same mill processes as in the early mill trial. In mill trials on PM2 up to 50 % of the mechanical pulp of groundwood-based SC rotogravure paper (SCR paper) was replaced with TMP. This mixture of groundwood and TMP was also tried later on TMP-based SC paper to study the interval from 100 % to 50 % TMP share of mechanical pulp in the mixture. In that trial on PM3 up to 50 % of the mechanical pulp of TMP-based SC offset paper (SCO paper) was replaced with groundwood.

The idea of using a mixture of groundwood and TMP in mechanical printing papers was also tested in LWC paper though in that paper grade practically no synergy was found in the lab studies. In the mill trial on Rauma PM1 up to 50 % of the mechanical pulp of groundwood-based LWC paper was replaced with TMP. In the second mill trial in LWC paper on Rauma PM4, the mechanical pulp of normally TMP-based LWC paper was totally replaced with groundwood.

Several mill trials were done on PM2 producing groundwood-based SC rotogravure paper and the first two of them are reported in this work. Later trials completed on PM2 and not reported here had fewer test points and less special testing. These later trials confirmed the results of the first trials. On the other paper machines one trial on each was run and they are reported in this thesis.

In most of the mill trials pulp pumps set the upper limits to the mixing of mechanical pulps. All the mixing trials were possible only for a few days' periods and they demanded a stop or an opposite change in the furnish of the paper machine normally using that mixing mechanical pulp. An important factor making these trials possible and worthwhile doing was that both groundwood and TMP are produced at Rauma paper mill both for SC and LWC papers.

All the mill trials were carried out completely on the terms of production. Because of the relatively short trial runs process parameters were kept as constant as possible when making furnish changes, in order to make sure that paper orders were fulfilled and paper machine runnability was maintained. No changes were made in supercalendering and only changes unavoidable to operate the process, such as controlling paper machine draws, were made. At the time of the mill trials it was not yet known what kind the mechanical pulps should be for the mixtures of groundwood and TMP in different paper grades. This together with the relatively short trials made the optimization of pulps impossible. However, the refining degree of chemical pulp was controlled, if needed, as this immediately affected the papermaking.

The mill trials were run on each paper machine of Rauma paper mill. They are all modern, large, high speed paper machines producing high-quality SC and LWC papers. The mill trials were run between January 1996 and January 2001.

4.3.3. Methods

The testing methods used in the mill studies are listed in appendix 1. In addition to the normal pulp and paper testing also some special testing of pulps, furnishes and paper and printing trials were done in most mill trials.

4.3.4. Raw materials

The wood raw material of the mechanical pulps used in the mill trials was 100 % spruce (Norway spruce, *Picea abies*). In the TMP processes most chips were made from logs but a minor share, 0 – 10 %, could be sawmill chips. The mechanical pulps were bleached with dithionite or hydrogen peroxide (H_2O_2). The chemical pulps were dried ECF and TCF bleached softwood kraft reinforcing pulps from two different chemical pulp mills. They were made from a mixture of 40 – 60 % spruce (Norway spruce, *Picea abies*) and 40 - 60 % pine (Scots pine, *Pinus silvestris*).

Because of the mills trials were run between 1996 and 2001 wood quality has naturally varied somewhat and that has affected pulp quality.

4.3.5. Process equipment in mill trials

At UPM-Kymmene Rauma paper mill there are four paper machines. PM 2 produces groundwood-based SC rotogravure paper and PM 3 TMP-based SC offset paper. PM 1 produces groundwood-based and PM 4 TMP-based LWC offset and rotogravure papers. Originally the mechanical pulp of PM1 and PM2 was groundwood and the mechanical pulp of PM3 and PM4 was TMP.

Mechanical pulping

SC grade groundwood is produced with atmospheric Tampella 1815 grinders, which were originally started in 1971. The groundwood mill was modernized in the 1990´s. During this research all grinders were equipped with water sharpening. The groundwood mill has pressure screens with narrow wedge wire slots, cleaners and high consistency reject refining. The pulp is bleached with dithionite.

SC grade TMP was produced for SC offset paper on TMP1 and TMP2 lines, which both were started in 1980. TMP1 is equipped with pressurized SD60 main refiners in two stages. Its screening and reject refining were later totally rebuilt with pressure screens with wedge wire slots and pressurized high-consistency reject refining. The TMP1 was refiner bleached with dithionite in first stage refiners. TMP2 was actually a PRMP line, i.e. TMP without preheating, equipped with pressurized SD60 main refiners in two stages. That TMP line had less modern screening and reject refining than TMP1 line and its pulp quality was poorer. Today TMP2 line is already closed down and replaced with a new TMP line.

The LWC grade groundwood is produced with practically similar equipment to SC grade ground-wood. This line was started in 1969. During this research all grinders were equipped with water sharpening. Today the line has pressure screening with narrow wedge wire slots, cleaning and high-consistency reject refining. This LWC grade groundwood is bleached with peroxide in high-consistency and the pulp is washed before and after bleaching.

The LWC grade TMP is produced on TMP4 line, which was started in 1997. This line is equipped with SD65 main refiners in two stages, multi-stage pressure screening with wedge wire slots and extensive high-consistency reject refining. All refiners are pressurized. The pulp is peroxide bleached in high-consistency and washed before and after bleaching.

Paper machines

PM1 was started originally in 1969. It was rebuilt in 1988 and 1996 by Valmet to produce LWC paper. At the time of the trial run it had a SpeedFormer HHS, a SymPress II + 4th press and two OptiCoat on-line coating stations. The machine width is 8.15 m and it had a speed of 1.130 – 1.200 m/min during the trial.

PM2 was started originally in 1971 but it was totally rebuilt in 1990 by Valmet. At the time of the trials it had a SymFormer and a SymPress II + 4th press. The trimmed width of the machine is 8.30 m and its normal speed during the trials was about 1.250 m/min.

PM3 is made by Valmet and it started in 1980. It has a SymFormer and a SymPress II. The trimmed width of the machine is 8.35 m. Its normal speed at the time of the trial run was about 1.250 m/min.

PM4 is made by Valmet and it started in 1998. It has a SpeedFormer HS, a SymPress B press section and two OptiBlade on-line coating stations. The machine width is 9.20 m and it had a production speed of about 1.630 m/min at the time of the trial.

5. RESULTS OF LAB STUDIES

The lab studies consisted of several different trials. In the first trial typical SC grade pulps were used. Different pulp samples were intentionally chosen for the later trials. The discussion of the results of each trial was started with the properties of the furnish components. These were regarded as a prerequisite and an explaining factor for the behaviour of paper properties, together with paper composition.

5.1. Behaviour of the mixtures of groundwood and TMP

5.1.1. SC paper

The lab studies were started by checking if the use of a mixture of SC grade groundwood and TMP could be beneficial and behave synergistically in SC paper handsheets. It was also interesting to see in which paper properties synergy would be found. If these mixtures of groundwood and TMP would behave synergistically in SC paper handsheets, the reasons for the synergy phenomena would be searched more thoroughly.

The behaviour of the mixtures of groundwood and TMP in SC paper was studied with two different combinations of pulps typically used in SC papers (table 2). The samples of the first combination were taken from the same groundwood and TMP processes which had given synergy in the early mill trial in 1994 on Rauma PM2. Groundwood was normal SCR grade atmospheric groundwood and TMP was somewhat coarser SCO grade TMP. In the second combination groundwood was SCR grade PGW from mill A and TMP was SCR grade pulp from mill B. In both these trial series chemical pulp was ECF bleached softwood kraft reinforcing pulp used at that time at Rauma. It was refined to freeness 500 ml and its share in SC paper handsheets was 20 or 30 % of fibre. Filler content target in handsheets was mostly 32 % as ash, which is typical to SC rotogravure paper. The results were studied as a function of the TMP share of mechanical pulp at constant chemical pulp content of paper.

The mechanical pulps of the first combination were shorter fibred and had more flexible fibres than the corresponding pulps of the second combination (table 2). Still the pulps of the second combination had better bonding long and medium fibre fractions and more fines. In the first combination TMP was bulkier mechanical pulp and in the second one groundwood.

The gradual change from groundwood to TMP as mechanical pulp naturally clearly changed the fibre length distribution of SC paper sheets. At a constant chemical pulp content their average fibre length increased from about 1.1 – 1.2 mm to 1.5 – 1.7 mm and their fines content clearly decreased (fig. 10).

Table 2. Properties of mechanical and chemical pulps used in the first SC paper handsheets.

	First combination of GW and TMP		**Second combination of GW and TMP**		**Chemical pulp**
	GW1	**TMP1**	**GW2**	**TMP2**	
Freeness, ml	35	55	39	39	500
Fibre length, mm*	0,72	1,33	0,84	1,47	2,03
Median fibre stiffness** (+28 fraction), 10^{-12} Nm^2	12,1	13,8	19,8	18,8	n.a. ***
Bauer-McNett					
28 %	9,8	22,7	14,3	25,2	60,2
-200 %	36,1	28,8	38,5	31,6	8,5
Density, kg/m^3	465	431	431	447	562
Tensile index, Nm/g	38,2	38,4	38,4	43,7	55,8
Tear index, mNm^2/g	3,38	5,99	3,48	6,26	16,7
Scott-Bond, J/m^2	378	328	425	322	222
Light scattering coefficient, m^2/kg	69,9	58,1	70,5	60,9	31,1
Tensile index of fractions					
+28, Nm/g	11,2	9,2	12,7	12	n.a.
48/200, Nm/g	33,7	45,7	36,8	56,3	n.a.

* length weighted average fibre length (FS-200)

** TamDoo & Kerekes method /TamDoo, Kerekes 1981/

*** not analysed

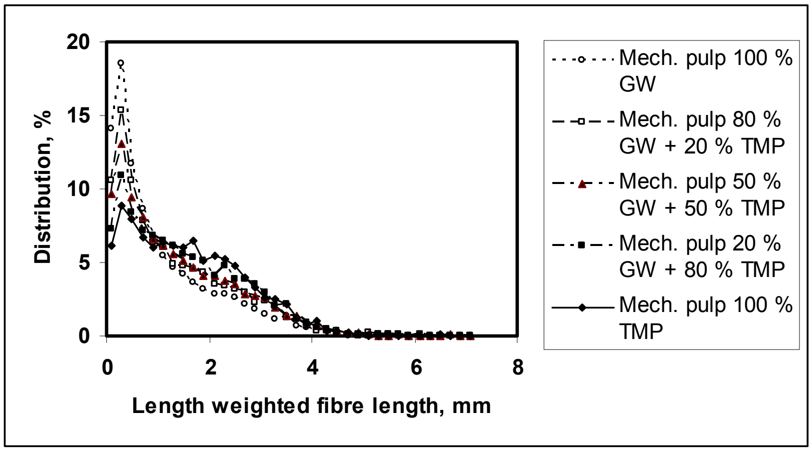

Figure 10. Length weighted fibre length distribution of SC paper sheets, according to Kajaani FS-200, with the first combination of groundwood and TMP at different TMP shares of mechanical pulp, chemical pulp share 30 % of fibre.

The difference in the densities of groundwood and TMP (table 2) showed in the density and air permeability of SC paper sheets (fig. 11 - 12). Their density changed relatively linearly as a function of the TMP share of mechanical pulp, which indicates linear change of bonding. Paper stiffness or rigidity, which depends primarily on sheet thickness and tensile modulus, i.e. bonding, is well characterized with Edana stiffness. High TMP share of mechanical pulp could decrease Edana stiffness of SC paper sheets (fig. 13). The tensile strength of SC paper handsheets with both combinations of groundwood and TMP behaved relatively linearly as a function of TMP share (fig. 14), quite similarly to density. With both combinations Scott-Bond decreased with increasing TMP share and decreasing fines content (fig. 15). In stretch, tensile energy absorption and fracture energy (fig. 16) the mixture of groundwood and TMP could result in some synergy advantage. In SC paper sheets with both mixtures of groundwood and TMP a clear synergy advantage was achieved in tear strength at a 50 – 80 % TMP share of mechanical pulp at a 30 % chemical pulp share of fibre (fig. 17). At a higher TMP share tear strength turned to a decrease. At a smaller, 20 % chemical pulp share, only some synergy could be found in strength properties (fig. 14 – 17). At a 30 % chemical pulp share of fibre only slightly lower light scattering coefficient was achieved in SC paper sheets with TMP than with groundwood (fig. 18) though the light scattering coefficient of pure TMP was clearly lower than that of groundwood. With a 20 – 50 % TMP share of mechanical pulp even a maximum was reached in the light scattering coefficient of SC paper sheets. At a lower, 20 % chemical pulp share of fibre, the light scattering coefficient of SC paper sheets was higher and decreased with an increasing TMP share from the very beginning, as anticipated.

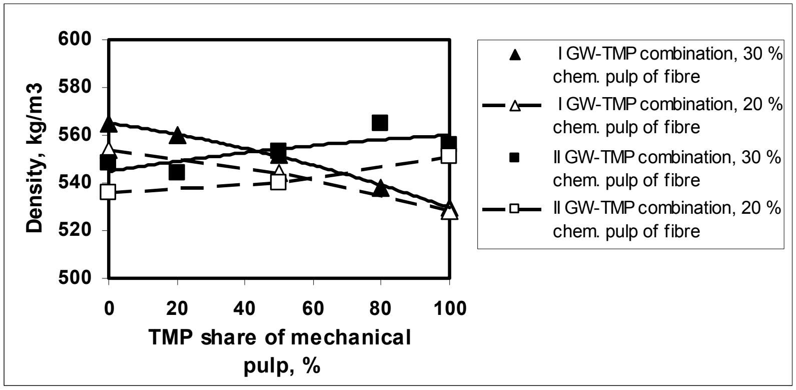

Figure 11. Density of SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of density: 95 % +/-8 and 90 % +/-6 kg/m^3.

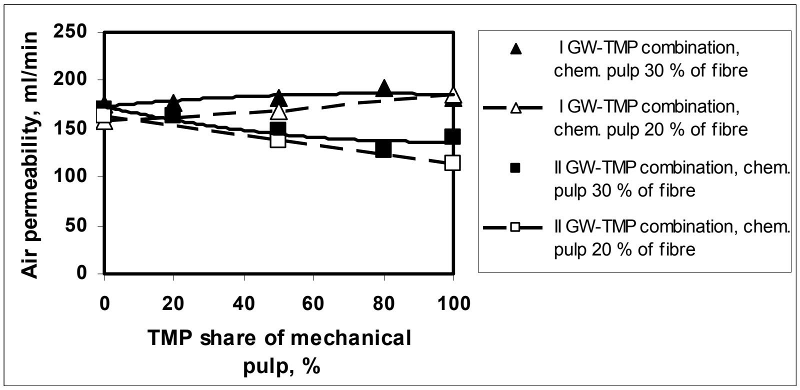

Figure 12. Air permeability of SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of air permeability: 95 % +/-15 and 90 % +/-10 ml/min.

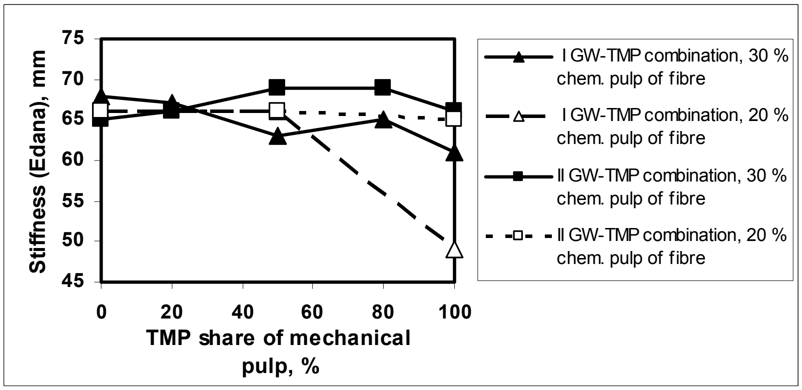

Figure 13. Edana stiffness of SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of stiffness: 95 % +/-6 and 90 % +/-5 mm.

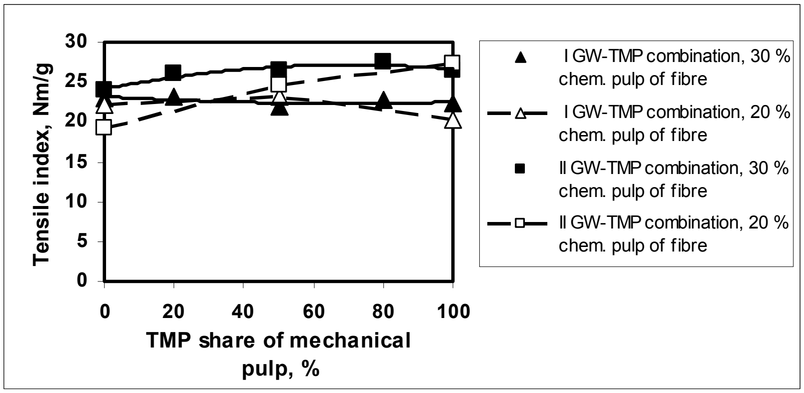

Figure 14. Tensile index of SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of tensile index: 95 % +/-1.3 and 90 % +/-0.9 Nm/g.

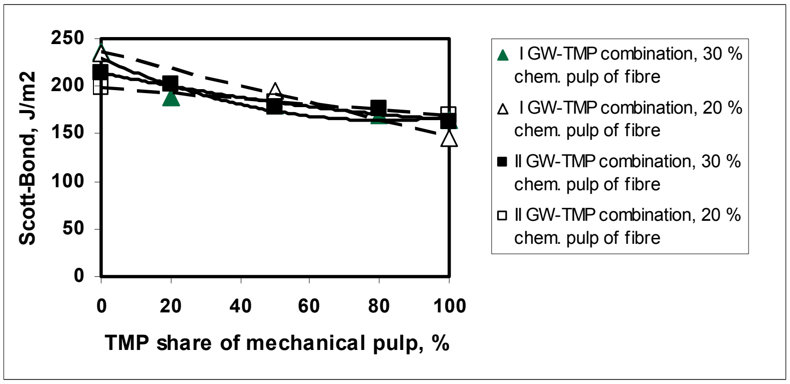

Figure 15. Scott-Bond of SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of tensile index: 95 % +/-37 and 90 % +/-25 J/m^2.

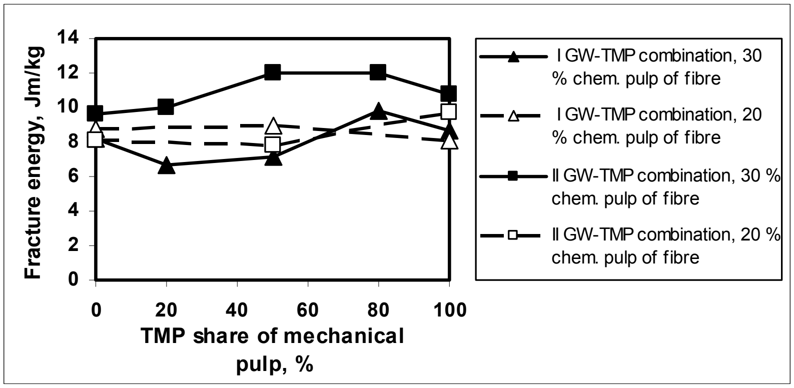

Figure 16. Fracture energy of SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of fracture energy: 95 % +/-5.58 and 90 % +/-3.79 Jm/kg.

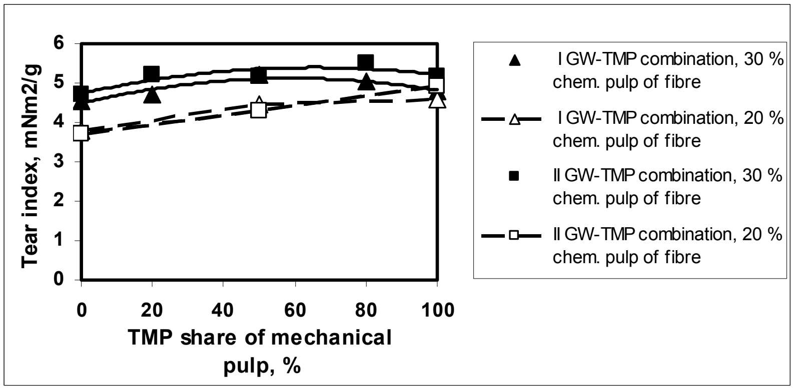

Figure 17. Tear index of SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of tear index: 95 % +/-0.54 and 90 % +/-0.37 mNm^2/g.

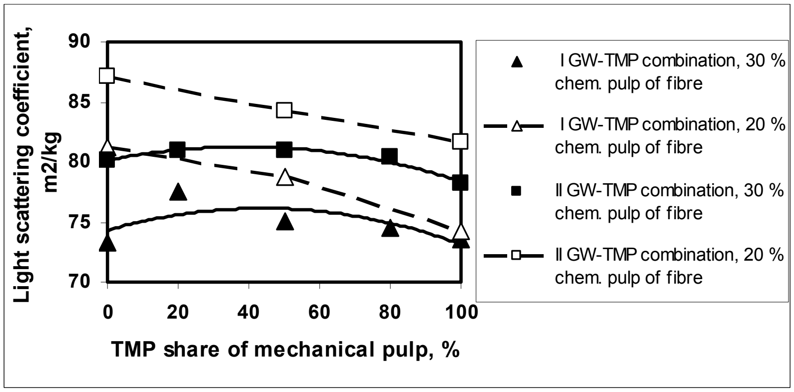

Figure 18. Light scattering coefficient of SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of light scattering coefficient: 95 % +/-2.9 and 90 % +/-2.0 m^2/kg.

The drum-dried SC paper handsheets were also supercalendered to see the effect of paper furnish on printability. Before calendering the handsheets were conditioned to about a 9 – 10 % moisture content. In supercalendered SC paper sheets with both combinations of groundwood and TMP their mixture gave higher than additive density (fig. 19) and lower air permeability (fig. 20) at a 30 % chemical pulp share of fibre, though they behaved linearly in uncalendered sheets. At a lower, 20 %, chemical pulp share the density and air permeability of supercalendered sheets behaved nearly linearly. In all cases the originally bulkier sheets, groundwood vs. TMP-based sheets, had higher density after supercalendering. With the second mixture the pore size distribution of SC paper sheets was measured with Coulter oil porosimeter at KCL. In supercalendered sheets the smallest average pore size was achieved with a mixture of groundwood and TMP though not in uncalendered sheets (table 3). The PPS roughness of supercalendered SC paper sheets increased linearly as a function of the TMP share of mechanical pulp. Also according to optical roughness profile (UBM) measurements, tested at KCL, with increasing TMP share the roughness increased on the whole wave length area (fig. 21). This was probably caused by the higher fibre length and lower fines content of TMP compared to groundwood. Supercalendering slightly improved the tensile strength of SC paper sheets, decreased stretch and clearly decreased tear strength. Supercalendering also decreased the light scattering coefficient of SC paper sheets. As a result of this the synergy in the strength properties and light scattering coefficient of supercalendered SC paper sheets with a mixture of groundwood and TMP decreased. Different supercalendering could have preserved these synergies.

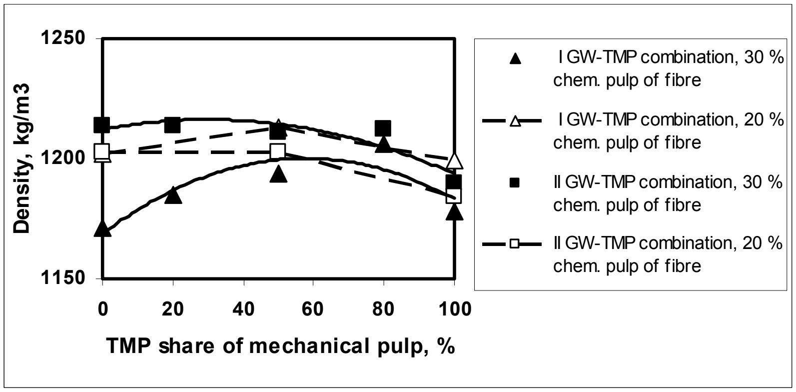

Figure 19. Density of supercalendered SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of density: 95 % +/-2 and 90 % +/-1 kg/m^3.

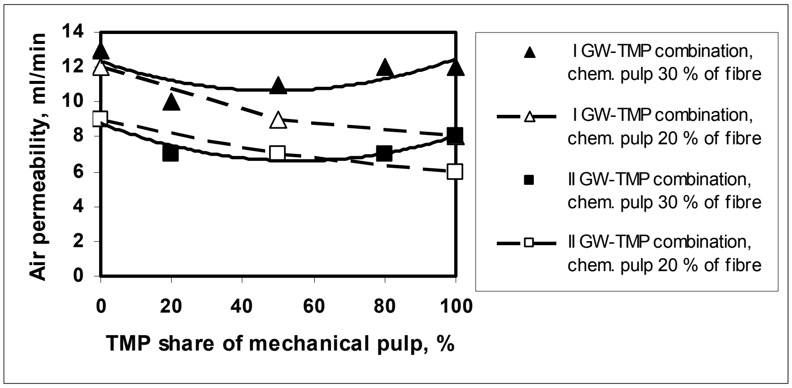

Figure 20. Air permeability of supercalendered SC paper handsheets with two different combinations of groundwood and TMP, 32 % filler as ash. The confidence interval of air permeability: 95 % +/-3 and 90 % +/-2 ml/min.

Table 3. Average pore size of non-pressed, normally pressed and supercalendered SC paper handsheets with the second combination of groundwood and TMP, tested with Coulter oil porosimeter at KCL. The differences of two parallel measurements are included. Chemical pulp 30 % of fibre, 32 % filler as ash.

TMP share of mechanical pulp %	**Non-pressed sheets**		**Normally pressed sheets**		**Supercalendered sheets**	
	Average pore size µm	**Difference** µm	**Average pore size** µm	**Difference** µm	**Average pore size** µm	**Difference** µm
0	2,249	0,229	0,686	0,030	0,213	0,012
50	1,853	0,070	0,690	0,037	0,199	0,010
100	1,572	0,000	0,742	0,023	0,213	0,003

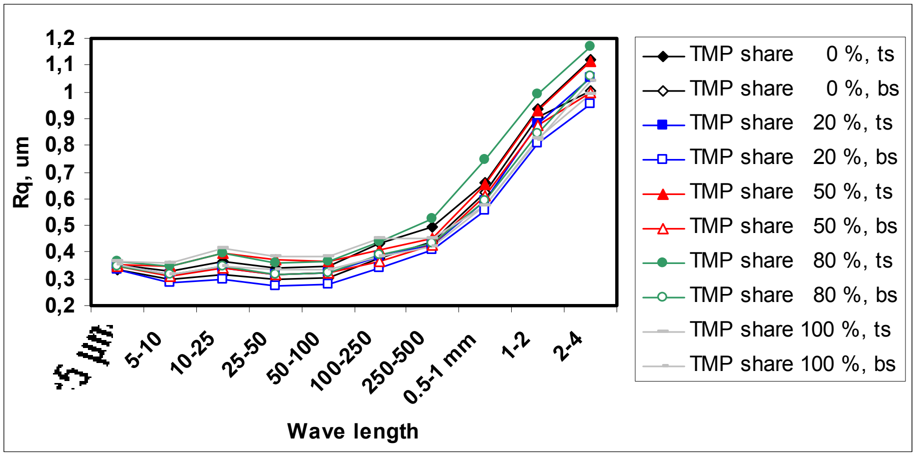

Figure 21. Optical roughness profile (UBM) of supercalendered SC paper sheets tested at KCL, top side (ts) and bottom side (bs), with the first mixture of groundwood and TMP at different TMP shares of mechanical pulp, chemical pulp share 30 % of fibre and 32 % filler as ash.

The synergy advantages found with the mixtures of groundwood and TMP in the tear strength and stretch of uncalendered SC paper handsheets and in the density of supercalendered SC paper handsheets at a 30 % chemical pulp share of fibre were statistically at least almost significant.

5.1.2. LWC base paper

Together with the SC paper trials a few test points were also made with typical LWC base paper furnish. No noteworthy synergy was found with these SC grade pulps in LWC base paper handsheets. However, the only three TMP share levels of mechanical pulp could possibly cause the non-appearance of synergy.

5.1.3. Discussion and conclusions

The results of these first lab trials showed that the use of a mixture of groundwood and TMP can be beneficial in SC paper and synergy advantages can be achieved both in some strength properties and printability. Synergy advantage was clearly found in tear strength and some synergy also in fracture energy, stretch and tensile energy absorption whereas no synergy was found in tensile strength or Scott-Bond. Clear synergy was also found in light scattering coefficient and calendering response in properties such as density, air permeability and pore size distribution but not in the roughness of calendered sheets. Maximum synergy was achieved in different paper properties at different TMP shares. In light scattering coefficient the maximum was achieved at about a 20 – 50 %, in calendering response at about a 50 % and in tear strength at about a 50 – 80 % TMP share of mechanical pulp. All synergies were most clearly found in SC paper sheets containing 32 % filler as ash at a 30 % chemical pulp share of fibre which corresponds to a 20 % share of paper. This is a typical level of groundwood-based SC paper. Less synergy was found at a 20 % chemical pulp share of fibre, which corresponds to a 13 % share of paper. This is a typical level of TMP-based SC paper. Only some synergy was found in LWC base paper sheets.

The reasons for the synergies found remained unclear. However, some hypotheses could be made on the basis of both the results and earlier knowledge.

When groundwood is replaced with TMP as mechanical pulp in paper, the fines content of paper decreases. Consequently, the approaching and passing of the limiting state of fines content towards the lower side /Brecht et al. 1953, Retulainen 1991/ could be a possible reason for some synergies found in SC paper handsheets at a higher, 30 %, chemical pulp share with less fines in paper furnish. At a lower, 20 %, chemical pulp share with more mechanical pulp fines synergy was more improbable. In LWC base paper sheets with low ash content and more chemical pulp probably less fines were needed. The limiting state concerns paper properties, such as tensile strength and air permeability which depend significantly on fines content and bonding. However, in tensile strength no synergy was found. Tear strength, which depends mostly on fibre length is known to have its maximum well below the limiting state of fines content /Brecht et al. 1953/. Thus, passing the limiting state of fines content hardly affected the tear strength synergy behaviour but could affect synergy in some other paper properties.

At a 30 % chemical pulp share of fibre purely groundwood-based SC paper sheet contains plenty of both mechanical pulp fines and well-bonding fibrillar chemical pulp fines. In that case a SC paper sheet can be even too well bonded for maximum light scattering coefficient, which can be lower than calculated. A small TMP share with less fines and more stiff mechanical pulp long fibres added to groundwood decreases bonding, characterized with Scott-Bond, and can make the sheet more porous, which can improve the light scattering coefficient. The well bonded groundwood-based SC paper sheet can also be difficult to restructure in calendering and maximum calendering response on density and air permeability is not achieved. On the other hand, a TMP-based SC paper sheet is less bonded and may have too porous a structure for maximum calendering response. In this case with a mixture of groundwood and TMP as mechanical pulp the best properties of calendered SC paper sheet can be achieved. The denser the pure groundwood was compared to TMP the bigger TMP share was needed for maximum density of supercalendered SC paper sheets. At a lower, 20 %, chemical pulp share the sheets contained less particularly well-bonding fibrillar chemical pulp fines and more mechanical pulp fines. In this case the light scattering coefficient of groundwood-based SC paper sheets was higher and synergy in light scattering coefficient no more existed and synergy in calendering response was smaller. Thus, the synergies in light scattering coefficient and calendering response could relate to the limiting state of fines content, as stated by Retulainen /Retulainen et al. 1993/. Accordingly, a certain mixture of groundwood rich in fines and TMP poorer in fines can give an optimum structure to paper for good light scattering coefficient and calendering properties.

The synergies found at a 30 % chemical pulp share of fibre may also be connected to the formation of unified chemical pulp network, which is believed to happen around this 30 %

chemical pulp share /Levlin 1990/. The formation of chemical pulp fibre network may start at a slightly different chemical pulp share depending on the fibre length of mechanical pulp.

If the tear strength of paper is decisive in controlling the chemical pulp dosage on paper machine, the synergy advantage found in tear strength allows a smaller than calculated chemical pulp share when using the mixtures of groundwood and TMP in SC paper. This can reduce paper furnish costs. The use of the mixture can also improve paper printability both via synergy in light scattering coefficient and calendering properties and by reduced chemical pulp share needed in paper.

5.2. Reasons for the synergies found

Possible reasons for the synergy phenomena found in SC paper handsheets with a mixture of groundwood and TMP were studied next.

5.2.1. SC paper

Effect of bonding on synergy

The groundwood-based and TMP-based SC paper sheets used in the studies had different densities and possibly because of that also different bonding degrees. This could be a partial reason for the synergies found. In order to check the importance of bonding with the second combination of groundwood and TMP used, SC paper handsheets were made at a 30 % chemical pulp share of fibre with three new wet pressing levels, which would allow the interpolation of the results to constant density. These new sheets were not calendered.

The increasing of wet pressing naturally made the sheets denser and consequently improved their bonding and decreased air permeability. As a result of the lower thickness sheet stiffness decreased, independent of the mechanical pulp used. The increase of bonding improved tensile strength, tensile energy absorption and Scott-Bond (fig. 22). Changes in all these properties were practically independent of the TMP share of mechanical pulp. Heavier wet pressing turned stretch to a decrease except with pure TMP as mechanical pulp. The increasing of wet pressing did practically not affect the tear strength of groundwood-based SC paper sheets. However, when the TMP share was over 50 % of mechanical pulp, the increasing of wet pressing turned tear strength to a decrease (fig. 23). The effect on tear strength was similar both as a function of density and Scott-Bond. This showed that SC paper sheets containing plenty of TMP, instead of groundwood, could be even too well bonded for maximum tear strength. Thus a mixture of fine groundwood and well-bonding TMP could result in a synergy advantage in the tear strength of SC paper sheets. Shallhorn and Retulainen have shown this kind of turn of tear strength to a decrease when bonding degree increases, the earlier the higher the fibre length is /Shallhorn et al. 1979, Retulainen 1996a/. The increase of wet pressing decreased light scattering coefficient but interestingly wet pressing usually first slightly increased it (fig. 24). Possibly non-pressed sheets had too big a pore size for good light scattering coefficient. Wet pressing first decreased especially the light scattering coefficient of groundwood-based sheets (fig. 25). This could result in synergy with a mixture of groundwood and TMP in the light scattering coefficient of SC paper sheets. Obviously groundwood-based sheet rich in fines became too dense and/or too well bonded for light scattering.

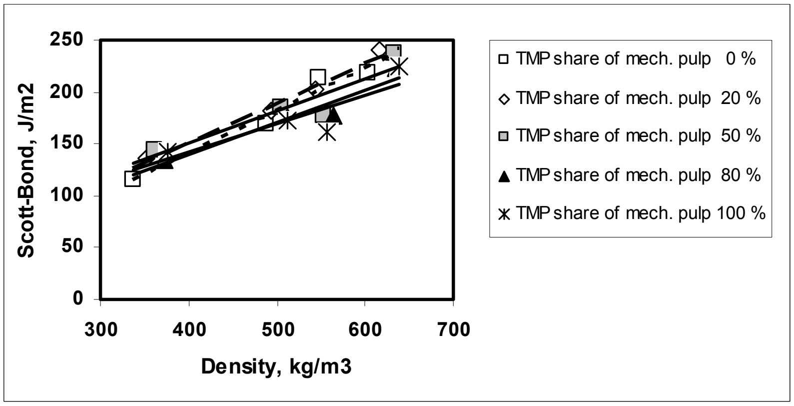

Figure 22. Effect of density, which was increased with wet pressing, on the Scott-Bond of SC paper sheets at different TMP shares of mechanical pulp, chemical pulp share 30 % of fibre, 32 % filler as ash.

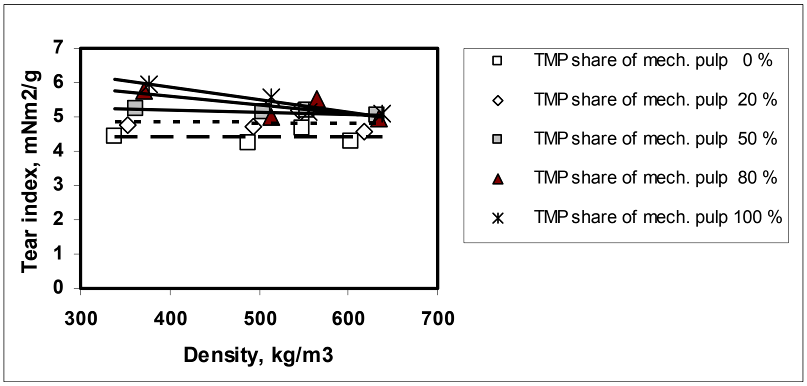

Figure 23. Effect of density, increased with wet pressing, on the tear index of SC paper sheets at different TMP shares of mechanical pulp, chemical pulp share 30 % of fibre, 32 % filler as ash.

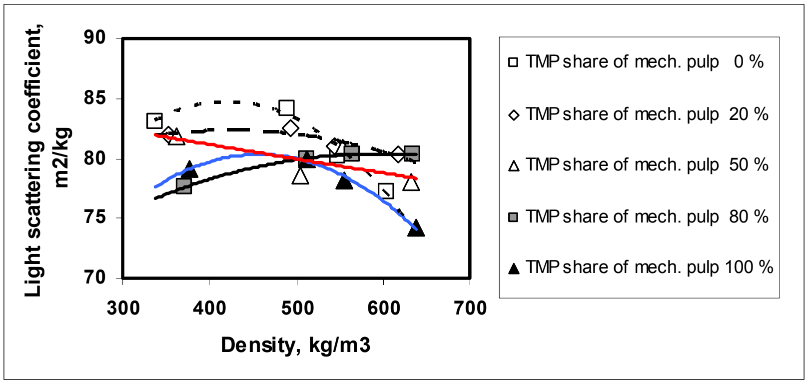

Figure 24. Effect of density, increased with wet pressing, on the light scattering coefficient of SC paper sheets at different TMP shares of mechanical pulp, chemical pulp share 30 % of fibre, 32 % filler as ash.

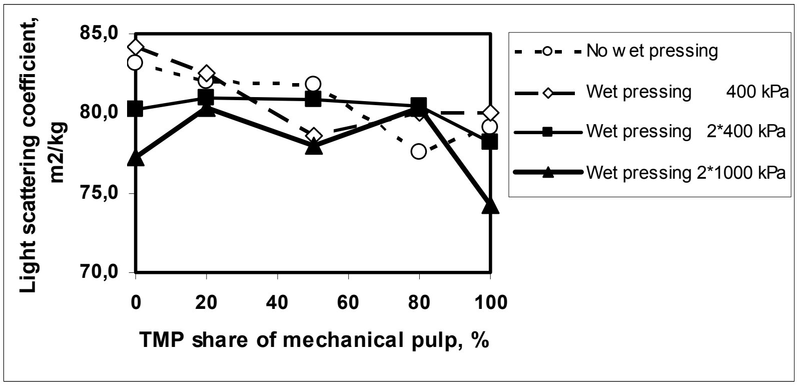

Figure 25. Effect of wet pressing on the light scattering coefficient of SC paper sheets as a function of the TMP share of mechanical pulp, chemical pulp share 30 % of fibre, 32 % filler as ash.

Mechanical pulp fractions are also found to have a maximum in light scattering coefficient at the same density level, about 500 kg/m³ /Mörseburg/, as SC paper handsheets had here (fig 24). Nesbakk has found calendering to have similar bigger decreasing effect on the light scattering coefficient of groundwood than TMP, because of the loss of more scattering interfaces /Nesbakk et al. 2002/, as wet pressing had here (fig. 25).

When the results of different wet pressing levels were interpolated to constant density, the synergy found in tear strength still existed, especially at a high density level. Consequently, the difference in density was not a reason for the synergy found in SC paper handsheets. The different wet pressing levels showed to be an interesting way to affect the bonding in handsheets and to study the reasons for synergy phenomena.

Effect of mechanical pulp quality on synergy

In order to investigate if the passing of the limiting state of fines content would be a reason for synergy in SC paper handsheets, groundwood was gradually replaced with well-bonding flexible or poorly-bonding stiff TMP long fibres, i.e. Bauer-McNett +28 fraction.

Already a 20 % replacement of groundwood with TMP long fibre fraction made the fibre length distribution of SC paper sheets quite similar to that of purely TMP-based SC paper and clearly reduced sheet fines content (table 4). The original groundwood-based SC paper sheets contained 27.8 % fines, i.e. Bauer-McNett -200 fraction, of fibre furnish. At 10 % TMP long fibre fraction addition the fines content was 25.3 %, at 20 % addition 22.7 % and at 30 % addition 20.3 %.

Both well and poorly-bonding TMP long fibre fractions had quite similar effects on SC paper sheet properties (table 4). Until a 10 % share of mechanical pulp both TMP long fibre fractions had a small effect on the density of SC paper sheets, but after that they both decreased density. After a 20 % share of mechanical pulp TMP long fibre fractions turned the tensile strength of SC paper sheets to a decrease. This could be caused by the passing of the limiting state of fines content. Both the well-bonding and poorly-bonding TMP long fibre fractions similarly improved the tear strength of mechanical pulp though they had quite different tear indexes, 7.82 and 3.28 mNm^2/g, respectively. The latter had even poorer tear strength than groundwood. Obviously, in accordance with Mohlin, Honkasalo and Corson /Mohlin 1979, Honkasalo et al. 1981, Corson et al. 1993/, when a component or fraction has high fibre length but poor bonding ability, mixing it together with a well-bonding component gives synergy advantage and makes the exploitation of fibre length possible. This shows a positive synergy effect of different fractions. However, neither well-bonding nor poorly-bonding TMP long fibre fraction improved the tear strength of SC paper sheets in spite of the clearly higher fibre length. First until a 5 % share of TMP long fibre fraction the light scattering coefficient of mechanical pulp stayed constant though the light scattering coefficient of TMP long fibres was clearly lower than that of pure groundwood, i.e. 27.7 – 26.7 vs. 69.9 m^2/kg. This 5 % share of both TMP long fibre fractions increased the light scattering coefficient of SC paper and until a 20 % share light scattering coefficient was above the original level. Also according to this both fine groundwood and SC paper handsheets based on it could be even too well bonded for light scattering, as assumed earlier. The bonding ability of TMP long fibres had a relatively small effect on these SC paper properties.

Table 4. Effect of replacing 20 % of groundwood with flexible or stiff fibred TMP long fibre fraction (Bauer-McNett +28 fraction) on the properties of mechanical pulp and SC paper handsheets, chemical pulp 30 % of fibre, 32 % filler as ash.

	Mechanical pulp		
	100 % GW	80 % GW + 20 % flexible TMP long fibres	80 % GW + 20 % stiff TMP long fibres
Mechanical pulp			
Fibre length, mm	0,72	1,05	1,02
Density, kg/m^3	465	447	419
Tensile index, Nm/g	38,2	42,0	38,8
Tear index, mNm^2/g	3,38	5,21	5,10
Light scattering coefficient, m^2/kg	69,9	63,0	61,6
SC paper sheets			
Bauer-McNett			
28 %	24,9	37,6	37,6
-200 %	27,8	22,7	22,7
Fibre length, mm	1,07	1,41	1,40
Density, kg/m^3	565	553	538
Tensile index, Nm/g	23,0	23,4	21,6
Tear index, mNm^2/g	4,55	4,77	4,56
Light scattering coefficient, m^2/kg	73,3	73,3	73,9

The effect of mechanical pulp quality on the synergy in SC paper handsheets was studied with several new combinations of groundwood and TMP. TMP samples with different fibre length, fines content and bonding ability were chosen (table 5). The groundwoods were slightly better bonding than in the first studies (table 2 in chapter 5.1.). Wet pressing increased the density and Scott-Bond and decreased the tear strength of most of these pulps. Only the Scott-Bond and tear strength of the coarsest TMP stayed constant. It was targeted that in these series ground-wood and TMP-based SC paper sheets, both on the opposite sides and the same side of the limiting state, would be achieved (table 6). In groundwood-based SC paper sheets the calculated fines content was about the same as in the first studies in chapter 5.1. and in TMP-based sheets around that. The results would show if the passing of the limiting state of fines contents would explain the synergies found in SC paper. The bonding of TMP-based SC paper sheets was also affected with the addition of different fines and long fibre fractions to the furnish.

Table 5. Furnish components of SC paper handsheets.

	GW + TMP + chem. pulp 1					GW + TMP + chem. pulp 2 or 3					
	GW	**TMP**			**Chem.**	**GW**	**TMP**			**Chem. pulp**	
	3	**3**	**4**	**5**	**pulp 1**	**4**	**6**	**7**	**8**	**2**	**3**
Freeness, ml	34	57	41	37	500	30	113	46	53	550	315
Fibre length, mm*	0,77	1,30	1,45	1,46	2,03	0,78	1,78	1,43	1,54	1,99	1,77
Fibre stiffness (+28), 10^{-12} Nm^2**	14,7	32,1	29,8	14,0	n.a.	18,6	34,5	21,7	18,9	1,0	0,8
Bauer-McNett											
28 %	12,9	18,2	30,7	30,3	60,2	10,7	36,4	22,4	32,9	60,3	59,3
-200 %	37,9	38,8	28,7	26,4	8,5	39,1	29,3	29,8	26,4	2,9	7,7
Density, kg/m^3	453	423	437	473	562	456	383	446	457	551	615
Tensile index, Nm/g	39,7	36,5	43,8	54,8	55,8	39,2	41,3	45,9	42,8	53,7	66,1
Tear index, mNm^2/g	3,25	5,46	6,53	6,51	16,7	3,38	7,24	6,09	6,54	18,4	15,2
Scott-Bond, J/m^2	371	295	303	323	222	460	130	330	350	150	315
Light scattering _coefficient, m^2/kg	70,2	64,4	58	50,9	31,1	77,8	52	57,9	54,1	30,3	27,9

* Length weighted average fibre length (FS-200)

** Median fibre stiffness

Table 6. Calculated fines (Bauer-McNett -200 fraction) content of the fibre furnishes of SC paper handsheets with the mechanical pulps in the earlier studies (table 2 in chapter 5.1.) and with the pulps (table 5), the chemical pulp share in sheets 30 % of fibre.

Mechanical pulp	**Chemical pulp 1**	**2**	**3**
	Earlier studies (5.1.)		
GW1	27,8		
TMP1	22,7		
GW2	29,5		
TMP2	24,7		
	New studies (5.2.)		
GW3	29,1		
TMP3	29,7		
TMP4	22,6		
TMP5	21,1		
GW4		28,2	29,7
TMP6		21,4	22,8
TMP7		21,7	23,2
TMP8		20,8	20,8

Synergy similar to that found earlier in this research in different strength properties and light scattering coefficient of SC paper sheets was now achieved with only one of these new combinations of groundwood and TMP. The combination of GW4 and TMP7 together with coarse chemical pulp 2 (table 5), had some synergy in the stretch, tensile energy absorption, tear strength (fig. 26) and light scattering coefficient of SC paper sheets. With this mixture a maximum value was also achieved in the density and gloss and a minimum value in the air permeability and roughness of supercalendered SC paper sheets. This furnish mixture was most similar to those in the studies of chapter 5.1.1. (table 2) where synergy was clearly achieved. The finding that synergy was achieved with only one of these new combinations indicates that even relatively small changes in pulp qualities, in either direction, can cause the disappearance of synergy. Obviously the limiting state of fines content could not be the main reason for the synergies found in tear strength.

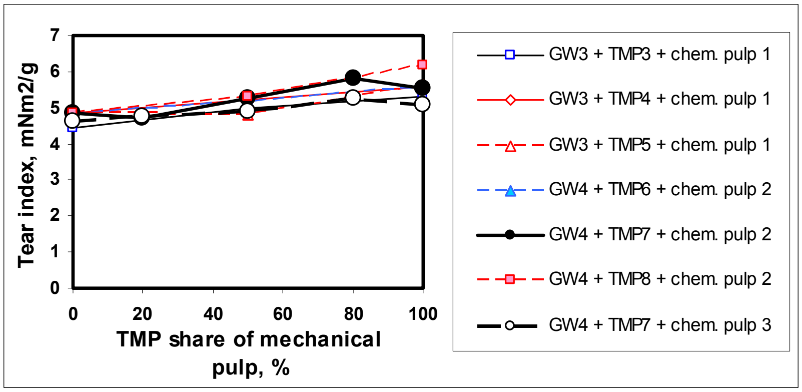

Figure 26. Tear index of SC paper handsheets as a function of TMP share of mechanical pulp with different fibre furnishes, chemical pulp 30 % of fibre and filler 32 % as ash.

The replacing of GW with poorest bonding TMP (TMP6) or average bonding TMP (TMP7) first increased the light scattering coefficient of SC paper sheets when chemical pulp was less refined, though the light scattering coefficient of those TMPs was clearly smaller than that of groundwood. With more refined chemical pulp the increase in light scattering coefficient was not found. With a mixture of groundwood and TMP7, at a 50 % share of TMP, the maximum density and gloss and minimum air permeability and roughness of calendered SC paper sheets were achieved.

The slight synergies found were clearer with less refined chemical pulp, freeness 550 vs. 315 ml. The synergies found in strength properties, light scattering coefficient and calendering properties were most apparent at a 30 % chemical pulp share of fibre, smaller at a lower 20 % and not found at a higher 38 % share.

These results were compared with the earlier clear synergy results of chapter 5.1. to see the importance of the bonding ability of the pulps. The use of better bonding groundwood or the increasing of the wet pressing usually affected the tear strength of groundwood-based SC paper sheets relatively little in either direction. In SC paper handsheets based on poorly-bonding TMP (TMP6 in table 5) with stiff fibres the increasing of bonding, either caused by increased wet pressing (A → B) or better bonding TMP (TMP7) (A → C) clearly improved tear strength (fig. 27). When TMP-based SC paper sheet is well-bonding enough, the increasing of bonding either way can turn the tear strength of SC paper sheets to a decrease (D → F or E → F). It seems that a well bonded TMP-based SC paper sheet (TMP2 in table 2) can be even too well bonded for maximum tear strength. Probably if a sheet is long-fibred enough, as TMP-based sheet, this can happen. In this case with a mixture of groundwood and TMP the best tear strength and clearest synergy advantage in it is achieved. This also shows that highest fibre length does not necessarily give best tear strength if bonding is too poor or too good. In furnish mixtures the importance of the bonding ability of groundwood was smaller than that of TMP. The decrease of the out-of-plane Elmendorf tear strength with wet pressing could, in addition to the increase of bonding, be caused by decreased bulk /Brecht et al. 1933/.

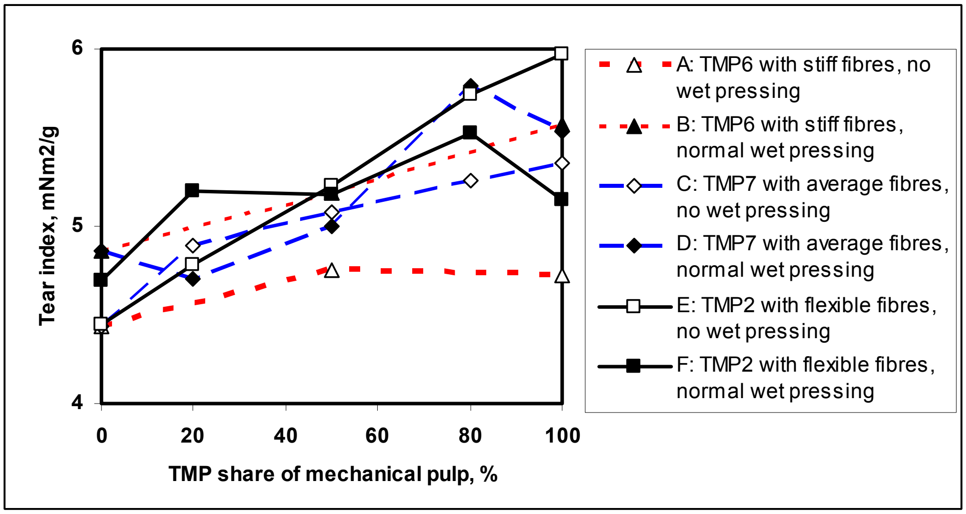

Figure 27. Tear index of SC paper handsheets as a function of the TMP share of mechanical pulp, with different TMPs and wet pressing levels, chemical pulp share 30 % of fibre and filler content 32 % as ash. TMP6 and TMP7 refer to tables 5 and 6 and TMP2 to tables 2 and 6. Confidence interval of tear index: 95 % +/-0.23 and 90 % +/-0.18 mNm^2/g.

TMP	TMP6	TMP7	TMP2
Median stiffness of TMP long fibres (+28), $*10^{-12}$ Nm^2	34,5	21,7	18,8
Fibre length of TMP , mm	1,78	1,43	1,47
Scott-Bond of GW/TMP-based sheets, J/m²			
unpressed	110/50	110/90	115/145
normally pressed	195/95	195/150	215/160

The results of figure 27 show that the better bonded the TMP is and the more flexible fibres it has the more probable synergy in SC paper sheets with a mixture of groundwood and TMP is. All groundwoods were practically similar. However, if furnish mixtures studied so far are compared, it seems that in order to achieve synergy in the tear strength of SC paper sheets the TMP fibres should have a suitable stiffness (table 7). The fibres of TMP should definitely be flexible. However, this does not ascertain synergy, because in some cases the other paper components may prevent the existence of synergy. Correlation between any other fibre properties measured, i.e. fibre length distribution, the coarseness of long fibres, the specific filtration resistance of middle fraction or the specific sedimentation volume or turbidity of fines and synergy was not found.

Table 7. The TMPs of the studies (tables 2 and 5) classified according to synergy in the tear strength of SC paper sheets, and the median stiffness of TMP long fibres (+28), $*10^{-12}$ Nm^2, measured with the TamDoo & Kerekes method /TamDoo, Kerekes 1981/.

Clear synergy		**Some synergy**		**No synergy**	
TMP	**Stiffness**	**TMP**	**Stiffness**	**TMP**	**Stiffness**
TMP1	13,8	TMP7	21,7	TMP3	32,1
TMP2	18,8			TMP4	29,8
				TMP5	14
				TMP6	34,5
				TMP7	18,9

The fracture mechanism of SC paper sheets in cases with synergy and no synergy with a mixture of groundwood and TMP were studied by adding a small amount of dyed long fibres, both mechanical and chemical pulp fibres, into SC paper sheets and examining the share of broken dyed fibres, both mechanical and chemical fibres. This addition of long fibres increased tear index by 0.3 mNm^2/g but had no effect on other strength properties. In tensile fracture the TMP share of mechanical pulp had no effect on either the share of broken mechanical or chemical pulp fibres. In tear fracture in case of synergy with an increasing TMP share the number of broken chemical and especially mechanical pulp fibres increased (fig. 28). In case of no synergy the number of broken fibres decreased with an increasing TMP share. This also indicates that synergy is achieved around the optimum bonding degree for tear strength, i.e. when fibres start to break in the fracture of TMP-based sheets. In all trial points on wire side richer in fines and better bonding both in tensile and tear fracture both mechanical and chemical pulp fibres broke more. In this series with a small addition of dyed long fibres synergy in tear strength with the mixtures of groundwood and TMP was found with more refined chemical pulp, freeness 315 vs. 550 ml, instead of the less refined pulp earlier in normal sheets.

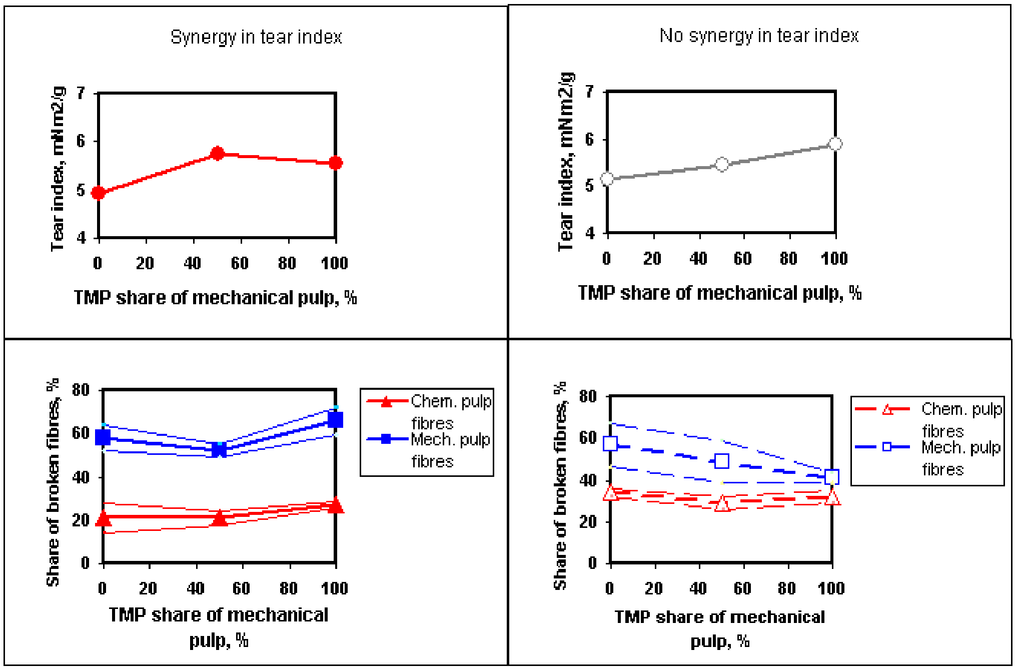

Figure 28. Tear index and the share of broken mechanical and chemical pulp fibres in the tear fracture of SC paper handsheets in the case of synergy (left) and no synergy (right) in tear strength at chemical pulp share 30 % of fibre and filler content 32 % as ash. The curves of 90 % confidence intervals are included.

In order to create synergy the fines content and bonding of the SC paper handsheets of a furnish mixture without any synergy, i.e. a mixture of GW2, TMP4 and chemical pulp 1 in table 5, were affected with the additions of 2 – 10 % different fines and long fibre fractions or starch. Although the sheets were made with white water circulation, a 10 % addition of all different fines fractions, i.e. the fines of PGW, refined TMP rejects or well refined chemical pulp, to the TMP-based SC paper handsheets was needed to affect significantly sheet properties. This fines addition increased sheet density, tensile strength, tensile energy absorption, stretch and Scott-Bond and decreased air permeability. Especially chemical pulp fines improved bonding (fig. 29). Both mechanical pulp fines increased light scattering coefficient by about 4 – 5 m^2/kg while chemical pulp fines slightly decreased it. The improved bonding caused by all these different fines fraction additions clearly decreased the tear strength of TMP-based SC paper sheets (fig. 30) and made synergy possible. The reduction of average fibre length probably had a minor effect as the measured fibre length of SC paper handsheets decreased only with a 10 % chemical pulp fines addition, then only by 0.06 mm.

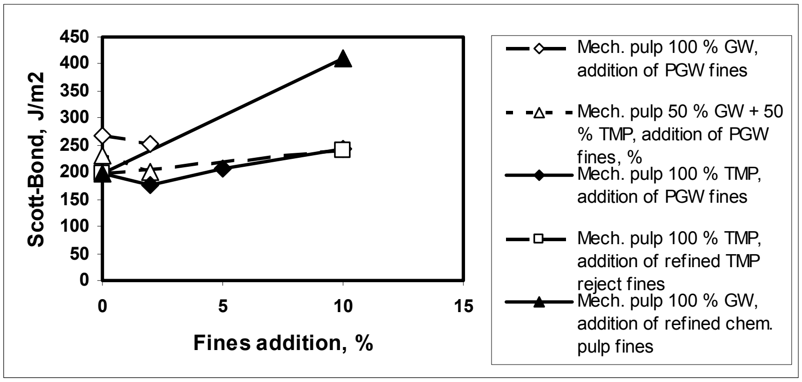

Figure 29. Effect of different fines fractions on the Scott-Bond of TMP-based SC paper handsheets, chemical pulp share 30 % of fibre, 32 % filler as ash.

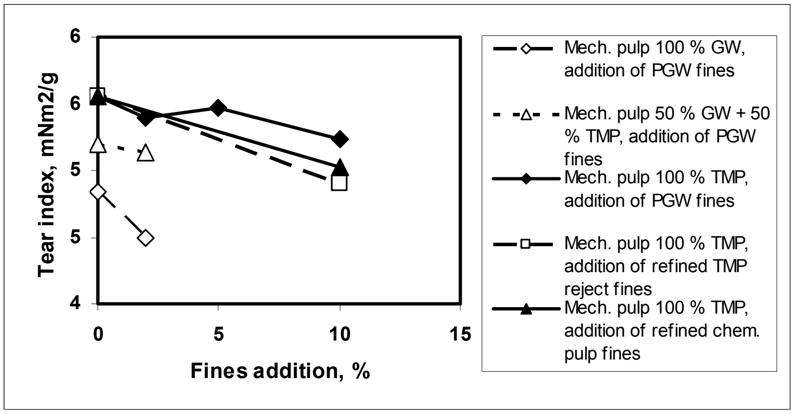

Figure 30. Effect of different fines fractions on the tear index of TMP-based SC paper handsheets, chemical pulp share 30 % of fibre, 32 % filler as ash.

The effects of different fines fractions on bonding and light scattering coefficient were consistent with the earlier results of Retulainen /Retulainen et al. 1993/.

The bonding of SC paper sheets was also improved with starch which does not affect sheet density or bonding area but improves bonding strength and increases the stiffness of bond areas /Retulainen et al. 1996b/. Starch addition slightly increased the tear strength of TMP containing SC paper sheets but their wet pressing could already turn the tear strength of TMP-based (TMP7) SC paper sheets to a slight decrease (table 8).

Table 8. Effect of starch dosage and wet pressing on the density and strength properties of SC paper sheets, chemical pulp 30 % of fibre, 32 % filler as ash.

TMP share of mechanical pulp %	**Starch content** %	**Wet pressing** kPa	**Density** kg/m³	**Scott-Bond** J/m²	**Tear index** mNm2/g
0	0,00	0	360	110	4,44
50	0,00	0	363	100	5,08
100	0,00	0	376	90	5,36
0	0,00	2*400	570	195	4,86
50	0,00	2*400	561	175	5,24
100	0,00	2*400	570	150	5,53
0	0,66	0	357	125	4,12
50	0,59	0	358	110	5,37
100	0,70	0	352	100	5,95
0	0,66	2*400	578	260	4,41
50	0,59	2*400	579	225	5,48
100	0,70	2*400	565	200	5,9

The improvement of bonding, either with the addition of fines or starch or with wet pressing, could turn the tear strength of TMP-based SC paper handsheets to a decrease which made synergy in tear strength possible.

The 10 % addition of different long fibres into TMP-based SC paper handsheets naturally increased their average fibre length, 0.07 mm with stiff, poorly-bonding and 0.13 mm with flexible well-bonding TMP fibres and decreased bonding and light scattering coefficient. The addition of 10 % well-bonding long fibres of refined TMP reject screen accept clearly increased the tear strength of non-pressed SC paper sheets but wet pressing decreased it (fig. 31). The effect of the addition of poorly-bonding long fibres of TMP main line screen accept did not affect the tear strength of SC paper sheets, but wet pressing increased it. According to the effects of wet pressing in these cases the tear strengths of SC paper sheets were on the opposite sides of its maximum value. The effects of long fibre additions were partially opposite to fines addition because of a different effect on bonding.

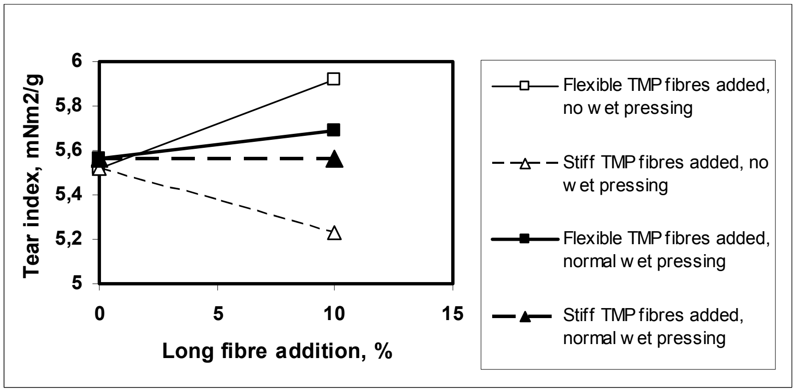

Figure 31. Effect of different long fibre fractions on the tear index of TMP-based SC paper handsheets, chemical pulp share 30 % of fibre, 32 % filler as ash.

Both the results with different combinations of groundwood and TMP in SC paper handsheets and the addition of different fines or long fibre fractions or starch into TMP-based SC paper handsheets showed that synergy in tear strength with a suitable mixture of groundwood and TMP is possible in SC paper handsheets.

Effect of sheet basis weight and chemical pulp refining degree on synergy

The effect of sheet basis weight and chemical pulp refining degree on synergy with the mixtures of groundwood and TMP was investigated with two different refining degrees of chemical pulp, i.e. freeness levels 565 and 350 ml, with 56 and 45 g/m^2 SC paper handsheets. Mechanical pulp and refined chemical pulp samples were all taken directly from mill processes. Accidentally all these pulp samples, especially the chemical pulps, were exceptionally rich in fines. They all contained lots of mechanical pulp fines and filler originating from mill white waters. This affected the furnishes and properties of SC paper sheets. The calculated fines content (Bauer-McNett -200 fraction) in all SC paper handsheets was 3.4 – 4.4 percentage units bigger than in earlier trial series. Probably because of this both the density and Scott-Bond of SC paper handsheets were higher (table 9, cf. figures 11 and 15) than in earlier trials, i.e. the SC paper sheets were better bonded. In all trial points the increasing of wet pressing decreased the tear strength of SC paper sheets. Thus, these SC paper sheets, even the groundwood-based ones, were too well bonded for maximum tear strength and mostly no synergy in tear strength or any other property was achieved with a mixture of groundwood and TMP. However, at lower 45 g/m^2 basis weight, especially with coarser chemical pulp, a mixture of groundwood and TMP had some synergy advantage in the stretch, tensile energy absorption and tear strength of SC paper sheets (fig. 32). Obviously in this case the sheets were less bonded and possibly because of lower basis weight more bonding was needed. Thus, at lower basis weight the conditions seemed to be more favourable for synergy with these pulps rich in fines.

Table 9. Density and Scott-Bond of SC paper handsheets at different basis weights and chemical pulp freeness levels, the TMP share of mechanical pulp was 0 – 100 % and filler content 32 % as ash.

Basis weight g/m²	**Chemical pulp CSF** ml	**Density** kg/m³	**Scott-Bond** J/m²
56	565	562 - 589	200 - 236
56	350	560 - 575	200 - 266
45	565	541 - 556	187 - 221
45	350	529 - 538	213 - 232

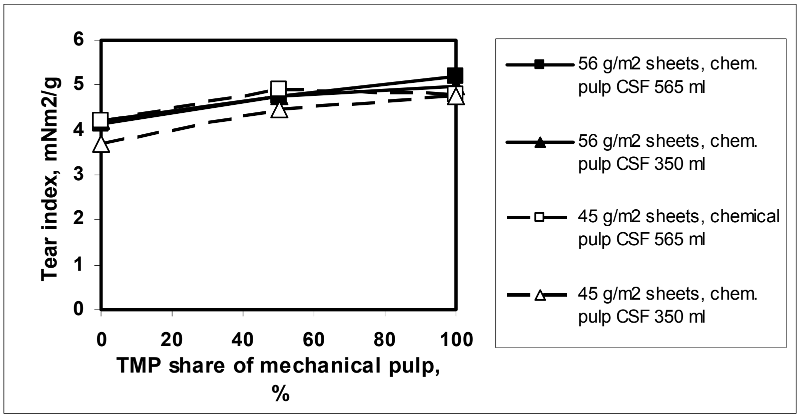

Figure 32. Effect of basis weight and chemical pulp refining degree on the tear index of SC paper handsheets as function of the TMP share of mechanical pulp, chemical pulp 30 % of fibre, 32 % filler as ash. The confidence interval of tear index: 95 % +/-0.64 and 90 % +/-0.32.

5.2.2. LWC base paper

Encouraged by the synergy results in SC paper sheets, it was decided that the behaviour of the mixtures of groundwood and TMP in LWC base paper would still be clarified.

The lab studies of LWC base paper were done with one mixture of groundwood and TMP. Both pulps were final peroxide bleached mill pulps used in LWC paper production. One ECF bleached chemical kraft pulp refined in lab into two different refining degrees, i.e. CSF 645 and 505 ml, was used. The trials were made at two different basis weights, 40 and 56 g/m^2, two different chemical pulp shares of paper, 35 and 50 %, and five TMP shares of mechanical pulp, 0, 20, 50, 80 and 100 %. The filler content target in handsheets was 10 % measured as ash. Altogether this LWC base paper study included 40 lab sheet trial points.

The TMP and chemical pulp samples used in these trials were (table 10) quite similar compared to the pulps used in the earlier SC paper studies. However, the LWC grade groundwood had clearly higher freeness and lower bonding ability than the earlier groundwoods. Thus, the TMP sample used in these LWC base paper trials was clearly finer than the groundwood sample, freenesses respectively 28 vs. 55 ml.

Table 10. Quality of pulps used in LWC base paper handsheet trials.

	Mechanical pulps		**Chemical pulps**	
	GW	**TMP**	**Pulp1**	**Pulp2**
Freeness, ml	55	28	645	505
Fibre length, mm	0,79	1,43	2,19	2,18
Density, kg/m^3	460	510	614	665
Air permeability, ml/min	142	37	1869	891
Tensile index, Nm/g	35,9	51,6	62,6	82,2
Stretch, %	1,9	2,3	3,4	3,6
TEA index, J/kg	475	828	1455	2001
Tear index, mNm^2/g	3,46	6,18	19,3	14,2
Fracture energy, Jm/kg	3,7	7,2	25,1	23,5
Scott-Bond, J/m^2	275	290	173	322
Light scattering coefficient, m^2/kg	73,7	63,2	27,3	23,5

The replacement of groundwood with TMP in LWC base paper sheets increased the fibre length of paper furnish by about 0.3 – 0.4 mm. The increasing of chemical pulp content from 35 to 50 % increased fibre length by about 0.2 mm and the refining of chemical pulp from freeness 645 to 505 ml, decreased fibre length by about 0.1 mm. In 56 g/m^2 sheets the increased TMP share increased drainage time but this was not seen in lighter 40 g/m^2 sheets.

The replacement of groundwood with finer TMP quite linearly increased the density of LWC base paper handsheets and the increase was bigger at higher basis weight. The bigger dosage and lower freeness of chemical pulp had only a minor increasing effect on density. Replacing groundwood with finer TMP decreased the air permeability of LWC base paper sheets. Also smaller chemical pulp dosage and its lower freeness decreased air permeability.

Until a 50 % TMP share of mechanical pulp the initial tensile strength of all furnishes was practically the same. At a bigger TMP share, smaller chemical pulp dosage and its lower freeness gave better initial tensile strength. With coarser chemical pulp the maximum of initial tensile strength was achieved with a 50 % TMP share of mechanical pulp. Initial stretch was almost constant independent of paper furnish.

The internal bond strength, characterized with Scott-Bond, depended mostly on chemical pulp content and its freeness. The increasing of chemical pulp share decreased Scott-Bond and its lower freeness improved bonding. Scott-Bond behaved oddly as a function of the TMP share of mechanical pulp. In the 40 g/m^2 sheets the general shape of the curve was convex and in the heavier 56 g/m^2 sheets concave.

The tensile strength of LWC base paper sheets was most improved by the increasing of the TMP share of mechanical pulp. Also lower freeness of chemical pulp increased tensile strength. In the heavier 56 g/m^2 sheets a mixture of groundwood and TMP gave higher tensile strength than could be estimated on the basis of the tensile strength of purely groundwood or TMP-based sheets. This was not found in the lighter 40 g/m^2 sheets. The apparent tensile strength behaved similarly as tensile strength and they were the only sheet properties that were not significantly affected by chemical pulp content. The stretch of 40 g/m^2 LWC base paper sheets had a maximum at a 20 – 50 % TMP share of mechanical pulp but this was not found in heavier sheets. Also tensile energy absorption in the lighter sheets at a 20 – 50 % TMP share was often better than calculated.

Differences in the tear strength of LWC base paper sheets could be best explained by differences in chemical pulp content. The more refined chemical pulp gave better tear strength to the heavier 56 g/m^2 sheets though that pulp as such had lower tear strength. The tear strength of LWC base paper sheets slightly increased as a function of the TMP share of mechanical pulp. Some positive synergy was found in tear strength with a mixture of groundwood and TMP with more refined chemical pulp. Also in fracture energy most of the variation could be best explained by chemical pulp content. Furnishes with lower chemical pulp freeness had bigger fracture energy. Fracture energy increased with the increase of the TMP share of mechanical pulp. Synergy in fracture energy with a mixture of groundwood and TMP was found in 56 g/m^2 sheets with less refined chemical pulp and in 40 g/m^2 sheets with more refined chemical pulp (fig. 33). The maximum of fracture energy was achieved at a 50 to 80 % TMP share, especially with less refined chemical pulp at its 50 % content.

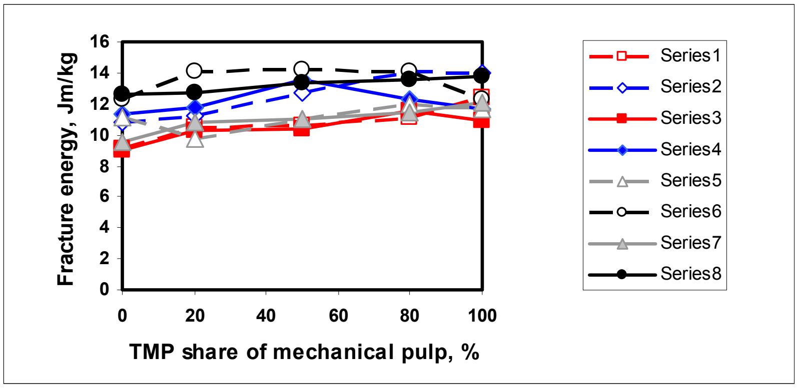

Figure 33. Fracture energy of LWC base paper sheets as a function of the TMP share of mechanical pulp, filler content target 10 % as ash.

Series	Basis weight g/m²	Chemical pulp share of fibre %	Chemical pulp freeness ml
1	40	35	645
2	40	50	645
3	56	35	645
4	56	50	645
5	40	35	505
6	40	50	505
7	56	35	505
8	56	50	505

The light scattering coefficient and opacity of handsheets were significantly deteriorated by the increasing of chemical pulp content. The increasing of the TMP share of mechanical pulp decreased the light scattering coefficient logically but in heavier sheets the changes were smaller than expected. In heavier sheets the increase of TMP share improved opacity. This could be caused by the lower brightness of TMP than groundwood.

The increasing of wet pressing naturally increased sheet density, decreased air permeability and light scattering coefficient and improved strength properties. Wet pressing improved even tear strength against earlier results with SC paper.

Statistically significant synergy advantage in LWC base paper sheets with the mixture of groundwood and TMP was found only in heavier, 56 g/m^2, sheets in fracture energy, apparent tensile strength and air permeability.

5.2.3. Discussion and conclusions

The very first results of this research showed that the mixtures of groundwood and TMP can behave synergistically in SC paper but in LWC base paper synergy is more unlikely. Possible reasons for the synergies both in SC paper and LWC base paper were investigated.

The effect of bonding degree on synergy in SC paper sheets was studied with different wet pressing levels. Heavier wet pressing naturally increased sheet density and bonding. This improved most strength properties and decreased the light scattering coefficient and air permeability of SC paper handsheets, independent of mechanical pulp. The tear strength of groundwood-based SC paper sheets remained practically constant. At a high TMP share of mechanical pulp tear strength first increased but, however, later turned to a decrease. Wet pressing always first increased the stretch of SC paper sheets but later turned it to a decrease independent of mechanical pulp. Usually the increase of bonding made synergy more probable.

Most strength properties of paper depend on both fibre length and bonding. Tear strength first improves with the increase of bonding and at that stage bond breakage is the main fracture mechanism. Tear strength has an optimum bonding degree at a certain fibre length, after which it turns to a decrease. At this stage the tensile fracture of fibres becomes significant. The optimum bonding degree decreases with the increase of fibre length (fig. 3). /Shallhorn et al. 1979, Retulainen 1996a./ The results of this thesis show that with well-bonding SC grade pulps TMP-based SC paper handsheets can be excessively well bonded for high tear strength. In this case the high fibre length of TMP can no more be totally exploited and the tear strength of paper is poorer than it could be. As a result, a certain mixture of groundwood and TMP can have an optimum bonding degree vs. fibre length for the tear strength of SC paper sheets and synergy advantage is achieved with that mixture. Some synergy was also found in fracture energy, tensile energy absorption and stretch, which all depend on both fibre length and bonding. Stretch increases with the increase of fibre length and fines content or bonding but this increase stops at a high bonding degree /Seth 1990/. This can explain the synergy found in stretch with a mixture of groundwood and TMP but not the effect of wet pressing on stretch. Synergy was not found in tensile strength or Scott-Bond which primarily depend on bonding.

Some synergy with a mixture of groundwood and TMP was also found in the light scattering coefficient of SC paper handsheets. This synergy was mostly achieved when synergy existed in tear strength. Groundwood-based SC paper sheets had biggest Scott-Bond and normal wet pressing had biggest decreasing effect on the light scattering coefficient of groundwood-based SC paper sheets. This indicated that groundwood-based sheets can be so dense and/or well bonded that mixing groundwood with TMP can first increase the light scattering coefficient of SC paper sheets. On the other hand, TMP-based sheets are too porous and contain too little fines for maximum light scattering coefficient. This could also be a reason for synergy in calendering response.

The synergies found with a mixture of groundwood and TMP in SC paper were most sensitive both to the bonding ability of the pulp components and to the need of bonding which seemed to depend on sheet basis weight. When either of these changes in paper, the probability of synergy easily varies.

The synergy in LWC base paper with a mixture of groundwood and TMP was less probable. This synergy was obviously different from the synergy found in SC paper and it looked more random. Because of this the synergy in LWC base paper was no more investigated on a lab scale.

In the lab studies some reasons for the synergy phenomena with the mixtures of groundwood and TMP in SC paper handsheets were found. However, the reasons still remained partially unknown. Unknown was for instance
- the role of chemical pulp share in synergy
- the effect of filler content in synergy
- the role of chemical pulp properties in synergy
- reasons for synergy in light scattering and calendering properties

5.3. Behaviour of different furnish mixtures in mechanical printing papers

The effect of different furnish components on paper properties has been studied a lot. However, the interactions of the components and especially the possible synergy behaviour of their mixtures have been studied less. Neither is the effect of the properties of the components on synergy known. In order to understand the synergy mechanisms this research was continued by studying more thoroughly different basic furnish mixtures existing in mechanical printing papers. The study was started from the different components of mechanical printing papers, continued by the study of their simple mixtures and was concluded by studying the furnish of SC paper.

The properties of the pulps used in these trials are shown in appendix 2.

5.3.1. Different pulps

The bonding of pulp lab sheets, characterized with Scott-Bond, was increased with wet pressing. This naturally increased also sheet density. The increasing of bonding improved tensile strength and tensile energy absorption, and decreased air permeability and light scattering coefficient. As a function of density the Scott-Bond of all pulps, both mechanical and chemical pulps, increased quite similarly (fig. 34). However, the Scott-Bond of unrefined or slightly refined chemical pulp increased less and that of most refined chemical pulp increased most. At a constant density groundwood had the best Scott-Bond, second best TMP and chemical pulp had the lowest Scott-Bond.

The effect of density or bonding on stretch and tear strength was somewhat more complex. Stretch usually first increased with wet pressing but often later, at a density level of about 400 – 430 kg/m^3, turned to a decrease. The tear strength of most well-bonding SC grade pulps, groundwood, TMP and chemical pulp, decreased with the increasing of wet pressing (fig. 35). However, wet pressing could, at least first, improve the tear strength of slightly refined, poorly-bonding chemical pulp having Scott-Bond below about 150 - 200 J/m^2. In earlier trials, in chapter 5.2.1., wet pressing could also slightly increase the tear strength of relatively coarse newsprint grade TMP (csf 113 ml) with stiffest fibres. Wet pressing always slightly deteriorated the tear strength of groundwood, independent of its density or Scott-Bond. Consequently, it seems that if a pulp is poorly-bonding and long-fibred enough, the increase of bonding can first increase its tear strength but turns it later to a decrease. Wet pressing decreased the light scattering coefficient of all SC or LWC grade groundwoods, TMPs and chemical pulps by about the same amount, but less that of coarser mechanical pulps.

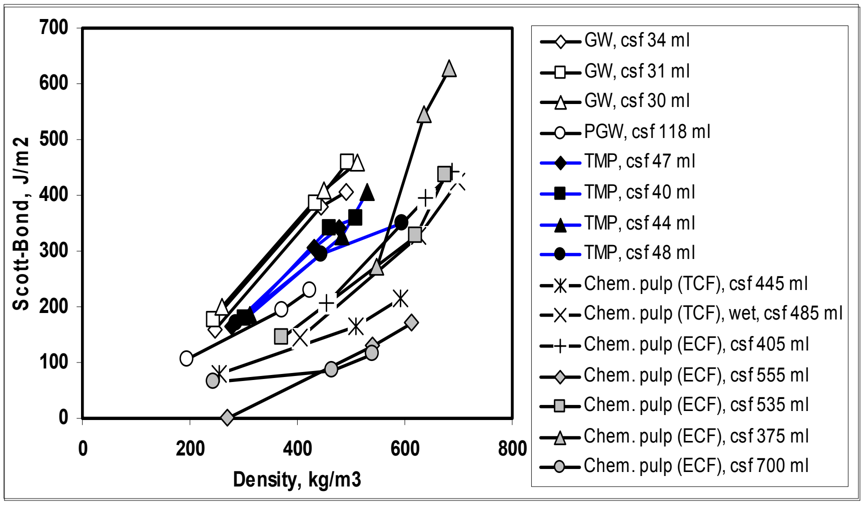

Figure 34. Effect of sheet density, affected by wet pressing, on the Scott-Bond of different pulps.

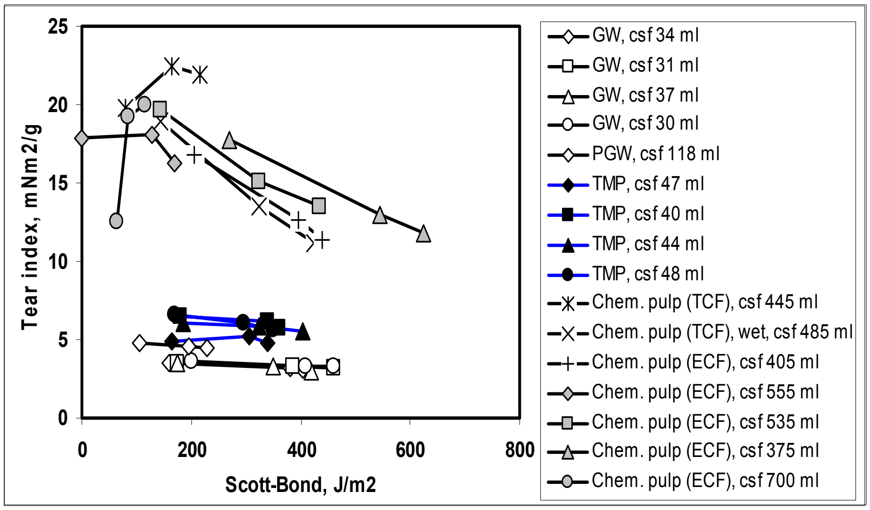

Figure 35. Effect of bonding, characterized with Scott-Bond and affected with the wet pressing of handsheets, on the tear index of different pulps.

5.3.2. Mixtures of groundwood and TMP

The mixture of different mechanical pulps, such as SC grade groundwood and TMP, could be assumed to behave additively as a function of the mixing ratio of the pulps, because their properties are relatively similar, except fibre length distribution. The density as well as light scattering coefficient of the mixture behaved additively. However, the properties of this mixture depending on both bonding and fibre length distribution could have some synergy advantage. This was found in tensile energy absorption (fig. 36) and sometimes also in tensile strength, stretch and tear strength. Surprisingly the mixture of groundwood and TMP could have a minimum Scott-Bond at about an 80 % TMP share. Filler addition into the mixture of groundwood and TMP maintained the synergy.

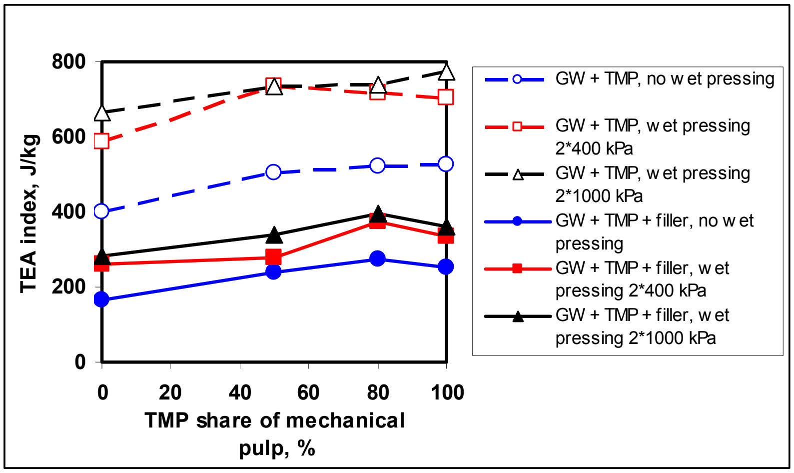

Figure 36: TEA index of a mixture of groundwood and TMP, the effect of wet pressing and filler addition, 32 % as ash, pulps of trial series 6 in appendix 2.

5.3.3. Mixtures of mechanical and chemical pulps

In order to clarify the behaviour of the mixtures of mechanical and chemical pulps different chemical pulp samples were taken and the effect of the shares in the mixture with mechanical pulp was investigated. 0 – 100 % of mechanical pulp, which was groundwood, TMP or their mixture, was replaced with

- dried TCF bleached kraft pulp, refined to freeness 445 ml, or
- dried ECF bleached kraft pulp, unrefined, freeness 700 ml, or refined to freeness level 535 ml or 375 ml.

The replacement of SC grade groundwood, TMP or their mixture, with unrefined ECF bleached chemical pulp, freeness 700 ml, only at a high share slightly increased sheet density (fig. 37, because of clarity only TMP as mechanical pulp in figures 37 - 39 and 41). Refined ECF bleached chemical pulp, freeness 535 or 375 ml, increased sheet density, the more the more refined the chemical pulp was. The type of mechanical pulp had a small effect on density. In spite of the slight density increase unrefined chemical pulp first less than additively increased the air permeability of the mixture and at over a 70 – 85 % share the increase was clear. Even the most refined chemical pulp first slightly increased air permeability but at over a 70 – 85 % share turned it to a decrease.

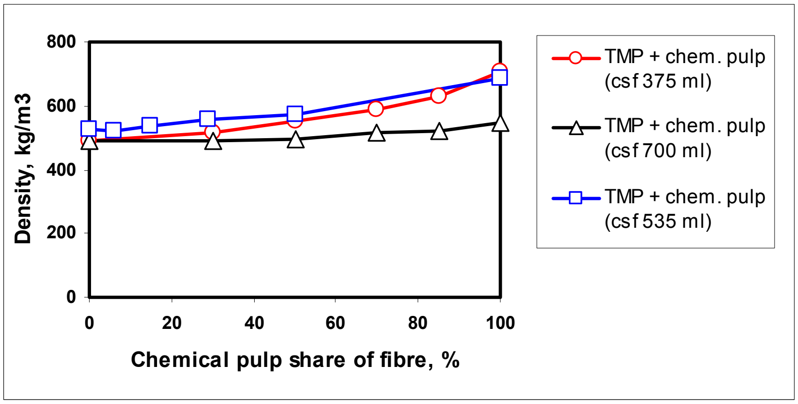

Figure 37. Density of a mixture of TMP and chemical pulp refined to different freeness levels, plate-dried sheets.

The changes in sheet density were well reflected in tensile strength, tensile energy absorption and Scott-Bond (fig. 38 and 39) which depend significantly on bonding. Heavier wet pressing naturally increased sheet density and bonding. However, changes in these strength properties were clearer than in density. Unrefined chemical pulp decreased tensile strength and Scott-Bond (fig. 38 and 39). Slightly refined chemical pulp could first slightly decrease Scott-Bond and it had a minimum value at about a 70 % share, after which it turned to a clear increase. With well refined chemical pulp both tensile strength and Scott-Bond increased from the very beginning but turned to a clearer increase at over a 70 – 85 % share. With unrefined chemical pulp stretch first increased and turned to a decrease at about a 50 – 70 % chemical pulp share. With refined chemical pulp stretch increased with the increase of the chemical pulp share. The increasing of the chemical pulp share clearly increased tear strength until a 70 – 85 % share, after which it turned to a decrease in well bonded high density sheets, especially plate dried sheets, with well refined chemical pulp or heavy wet pressing (fig. 40 and 41). In poorer bonded lower density sheets tear strength turned to a smaller decrease or could even increase linearly up to a 100 % chemical pulp share. The behaviour of the fracture energy of a mixture of mechanical and chemical pulps was different. With unrefined chemical pulp fracture energy turned to a decrease at a big chemical pulp share but with refined chemical pulp increased linearly (fig. 42). Similar results are also reported in literature /Zhang et al. 2002/. Chemical pulp decreased the light scattering coefficient of the mixture of mechanical and chemical pulps first slightly and later more steeply (fig. 43). TCF and ECF bleached chemical pulps had similar effects on SC paper sheet properties at the same refining degree.

The opposite mixing of well refined chemical pulp with even a small mechanical pulp share, e.g. 15 %, clearly decreased sheet density and properties which depend mainly on bonding, such as Scott-Bond and tensile strength. This small share of fine mechanical pulp made the sheet clearly bulkier and less bonded, and clearly increased light scattering coefficient. Unrefined chemical pulp and fine mechanical pulp had so similar a bonding ability that mechanical pulp addition had only a small effect on most strength properties (fig. 38 – 39). However, mechanical pulp could clearly improve tear strength (fig. 40).

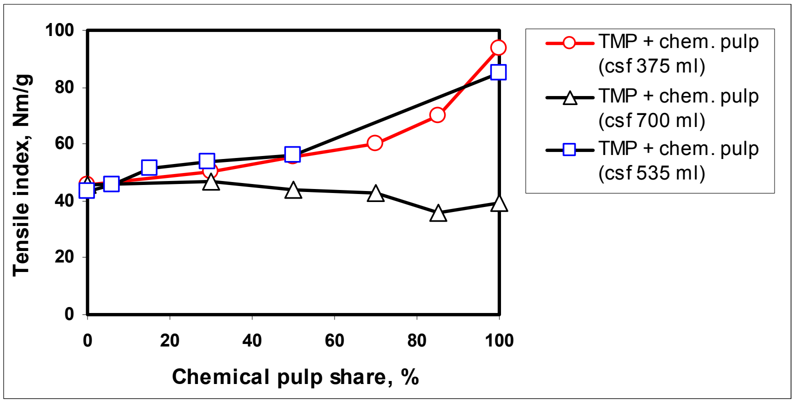

Figure 38. Tensile index of a mixture of TMP and chemical pulp refined to different freeness levels, plate-dried sheets.

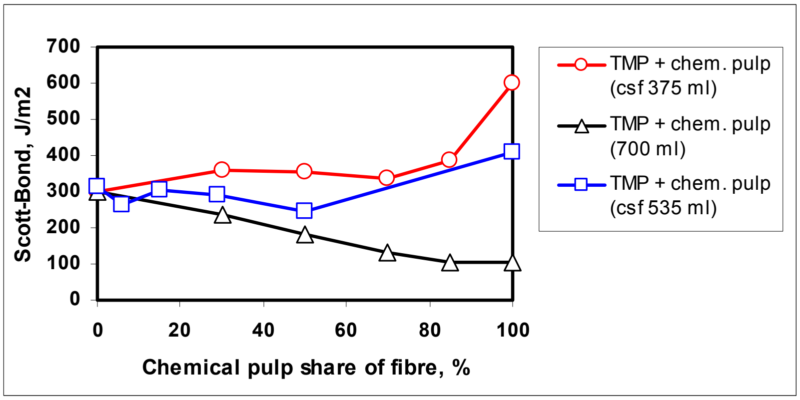

Figure 39. Scott-Bond of a mixture of TMP, and chemical pulp refined to different freeness levels, plate-dried sheets.

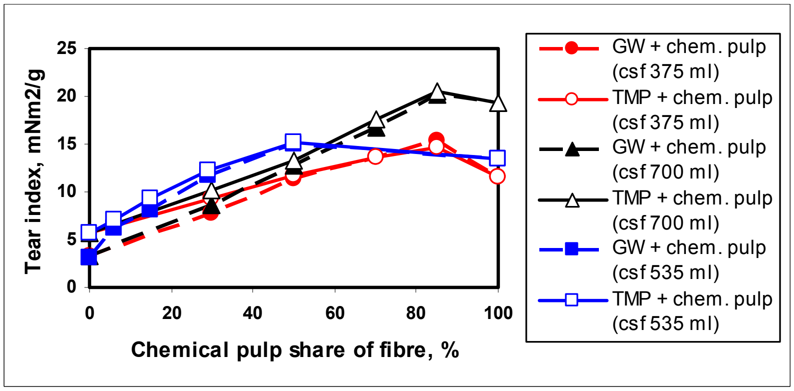

Figure 40. Tear index of a mixture of mechanical pulp, GW or TMP, and chemical pulp refined to different freeness levels, plate-dried sheets.

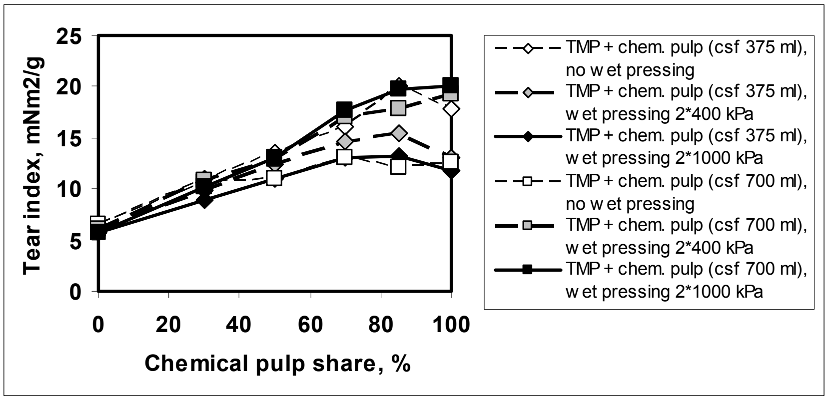

Figure 41. Effect of chemical pulp share, its refining degree and wet pressing on the tear index of a mixture of TMP and chemical pulps, drum-dried sheets.

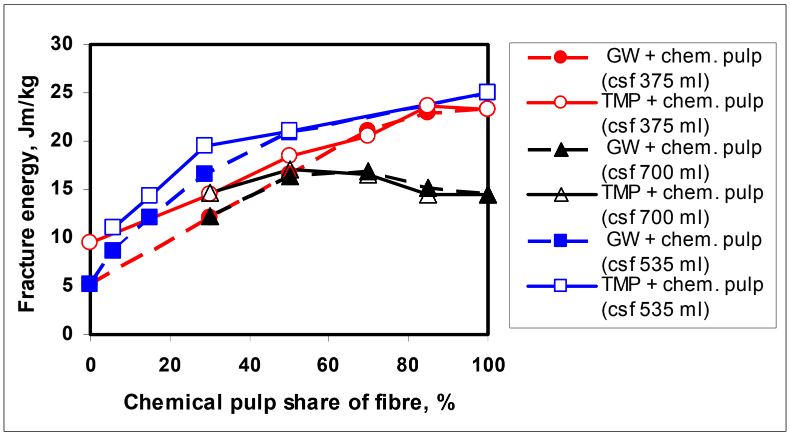

Figure 42. Fracture energy of a mixture of mechanical pulp, GW or TMP, and chemical pulp refined to different freeness levels, plate-dried sheets.

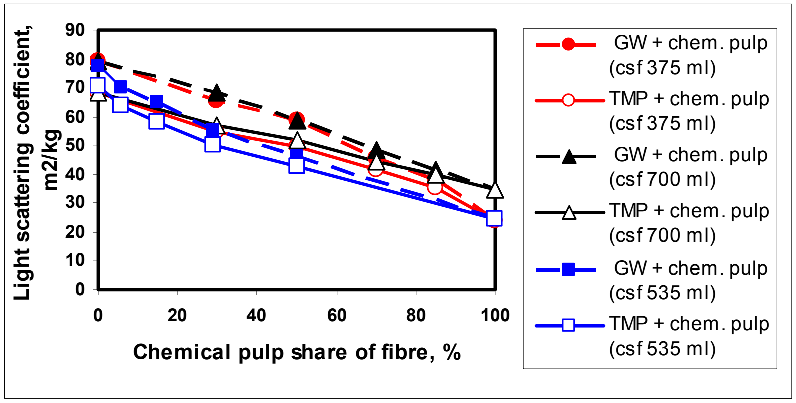

Figure 43. Light scattering coefficient of a mixture of mechanical pulp, GW or TMP, and chemical pulp refined to different freeness levels, plate-dried sheets.

The studied mixtures of mechanical and chemical pulps mainly behaved similarly and had similar synergies as found earlier by Mohlin /Mohlin at al. 1983/. In all these mixtures the mixture of groundwood and TMP behaved only slightly synergistically.

To evaluate different sheet properties at the constant relative bonded area (RBA) comparisons are often made in constant light scattering coefficient, density or Scott-Bond. When paper furnishes are different and contain mechanical pulp, light scattering coefficient is inapplicable to characterize the relative bonding area. In filler containing sheets density probably does not properly characterize changes in the bonding area.

The results discussed above showed that changes in sheet densities, i.e. in bonding, clearly showed in other properties of mixture sheets. Because of this the sheet properties of drum-dried handsheets made at three different wet pressing levels were interpolated to constant density.

At constant density the figures looked different. At density 500 kg/m^3 the Scott-Bond of mixtures with unrefined and slightly refined chemical pulps decreased quite linearly as a function of chemical pulp share while those with well refined chemical pulp first slightly increased and decreased later (fig. 44). With the increasing of chemical pulp share the tensile strength and tensile energy absorption of the mixtures of mechanical and chemical pulp increased nearly linearly with the share of well or slightly refined chemical pulps, freeness 375 and 535 ml, and with unrefined chemical pulp remained practically constant (fig. 45). Tear strength increased and light scattering coefficient decreased linearly with the increase of chemical pulp share independent of their refining degree (fig. 46 and 47). Stretch with well refined and slightly refined chemical pulp increased linearly while with unrefined chemical pulp at about a 70 % share it turned to a slight decrease. At constant density the differences between mechanical and chemical pulps remained but the synergies found with the mixtures of mechanical and chemical pulps mostly disappeared. It can be concluded that the synergies of the mixtures of mechanical and chemical pulps were mostly caused by differences in density.

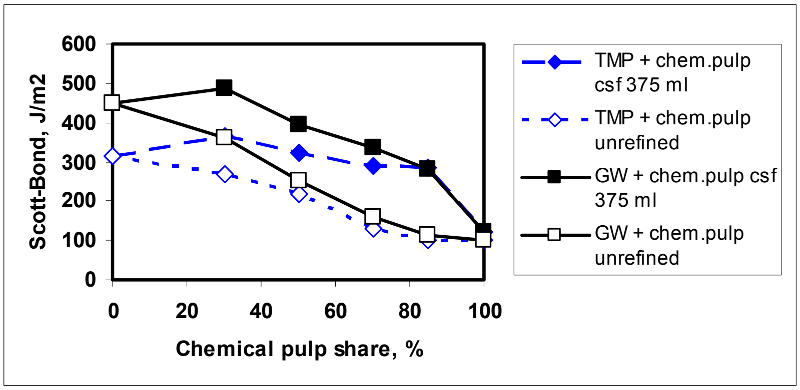

Figure 44. Scott-Bond of a mixture of mechanical pulp, GW or TMP, and chemical pulp refined to different freeness levels at constant density, 500 kg/m^3, drum-dried sheets.

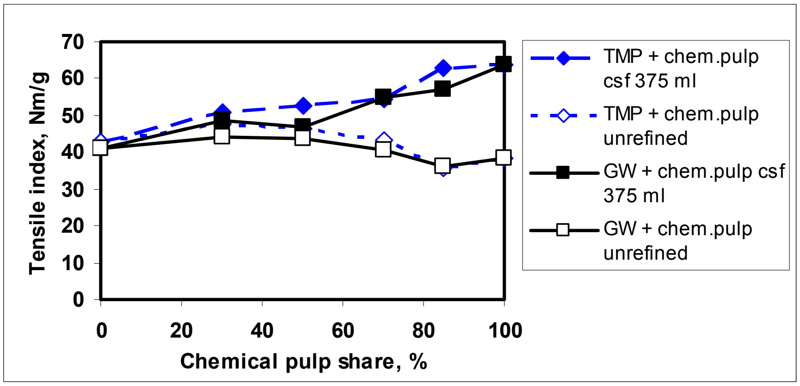

Figure 45. Tensile index of a mixture of mechanical pulp, GW or TMP, and chemical pulp refined to different freeness levels at constant density, 500 kg/m^3, drum-dried sheets.

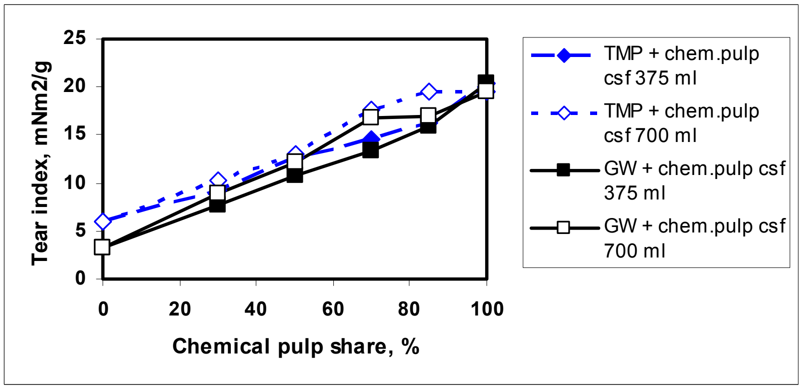

Figure 46. Tear index of a mixture of mechanical pulp, GW or TMP, and chemical pulp refined to different freeness levels at constant density, 500 kg/m^3, drum-dried sheets.

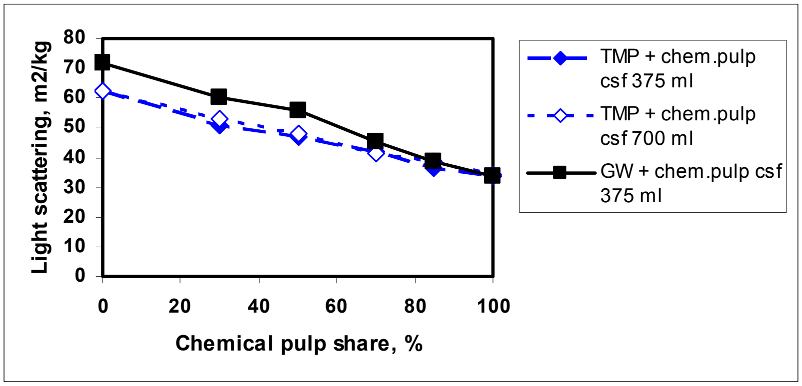

Figure 47. Light scattering coefficient of a mixture of mechanical pulp, GW or TMP, and chemical pulp refined to different freeness levels at constant density, 500 kg/m^3, drum dried sheets.

5.3.4. Filler addition

In paper forming filler settles on fibre surfaces, which prevents the bonding of that area. Consequently, filler also decreases fibre density in paper and fills pores between fibres. Actually in papermaking filler is not added into pulps but it replaces some pulp. Thus the basis weight of paper is kept constant but the basis weight of the fibre share decreases. The total effect of filler on the strength properties of paper is both the reduction of fibre share and the decreased bonding of fibres. The reduction of the bonding of well fibrillated fibres is believed to contribute 40 % of the apparent increase of light scattering coefficient with filler addition while with poor quality fibres the reduction of bonding has practically no importance. Still filler itself has the major contribution to light scattering coefficient. /Bown 1985./

Filler addition to different pulps

The 32 % filler share as ash, which is a normal level in SC paper, was added into both mechanical and chemical pulps. Further, the effect of filler was studied more thoroughly with 10, 20 and 32 % filler shares as ash added into fine groundwood, fine and coarse TMP and well refined chemical pulp. The filler used was clay. The properties of the pulps used in the study with constant 32 % filler share and those with 0 – 32 % filler share are shown in tables 1 and 2 of appendix 2, respectively.

The 32 % filler addition to different pulps increased the sheet density of mechanical pulps and unrefined chemical pulp (table 11). However, filler addition increased the density of refined chemical pulp less and could even decrease sheet density at a low bonding level, i.e. in non-pressed sheets. Also a small filler share could decrease sheet density (fig. 48). This was probably caused by lower bonding, which decreased the fibre density of sheets. Filler increased air permeability and light scattering coefficient.

Table 11. Effect of filler addition (32 % as ash) and wet pressing on the handsheet density of different pulps.

		Wet pressing								
		No wet pressing			**2*400 kPa**			**2*1000 kPa**		
		Pulp	**Pulp + filler**	**Δ**	**Pulp**	**Pulp + filler**	**Δ**	**Pulp**	**Pulp + filler**	**Δ**
Pulp	CSF ml	Density kg/m³			Density kg/m³			Density kg/m³		
GW	30	260	327	**67**	449	514	**65**	512	575	**63**
TMP	44	311	365	**54**	482	534	**52**	531	599	**68**
Chem. pulp	700	243	342	**99**	465	504	**39**	541	594	**53**
Chem. pulp	535	371	350	**-21**	620	622	**2**	675	687	**12**
Chem. pulp	375	548	477	**-71**	637	654	**17**	683	709	**26**

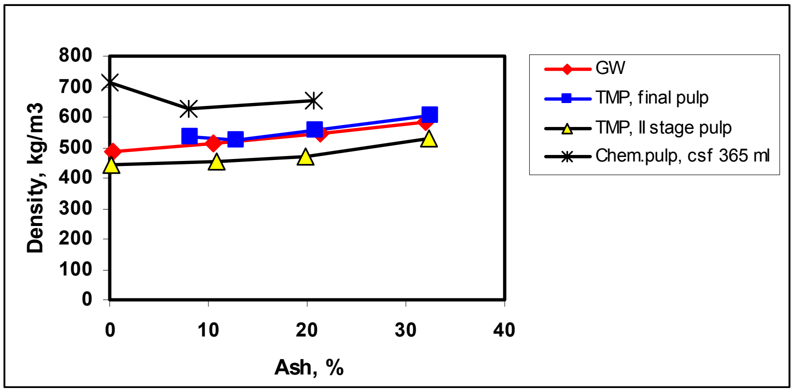

Figure 48. Effect of filler content, measured as ash, on the density of different pulps.

The addition of 32 % filler, as ash, decreased the bonding, characterized with Scott-Bond, the more the better bonded the pure pulp sheet was, either with well refined pulp or heavily wet pressed sheets (fig. 49). A small filler share deteriorated the bonding of well refined chemical pulp clearly more than that of other pulps (fig. 50 and 51). The replacement of well or slightly refined chemical pulp with 32 % filler as ash deteriorated tear strength most at a low bonding degree, i.e. at light wet pressing, but only slightly at higher bonding degree (fig. 52). A small filler share could even increase the tear strength of well bonded pulp (fig. 53). Obviously the bonding degree of that pulp was well beyond the tear strength maximum. The bonding increase of a mixture of well refined chemical pulp and 32 % filler with wet pressing could slightly decrease its tear strength. The 32 % filler share clearly deteriorated all strength properties of unrefined chemical pulp, especially at the heaviest wet pressing level. However, the bonding increase of poorly-bonding pulp or a mixture of chemical pulp and filler with wet pressing increased tear strength and stretch. In a mixture of TMP or groundwood with 32 % filler wet pressing maintained tear strength quite constant or decreased it slightly or clearly. A decrease in tear strength could be caused by either the increasing of bonding area or the reduction of bulk, which may deteriorate Elmendorf tear strength /Brecht et al. 1933/. Tensile strength increased but less with the increase of filler content when wet pressing was increased.

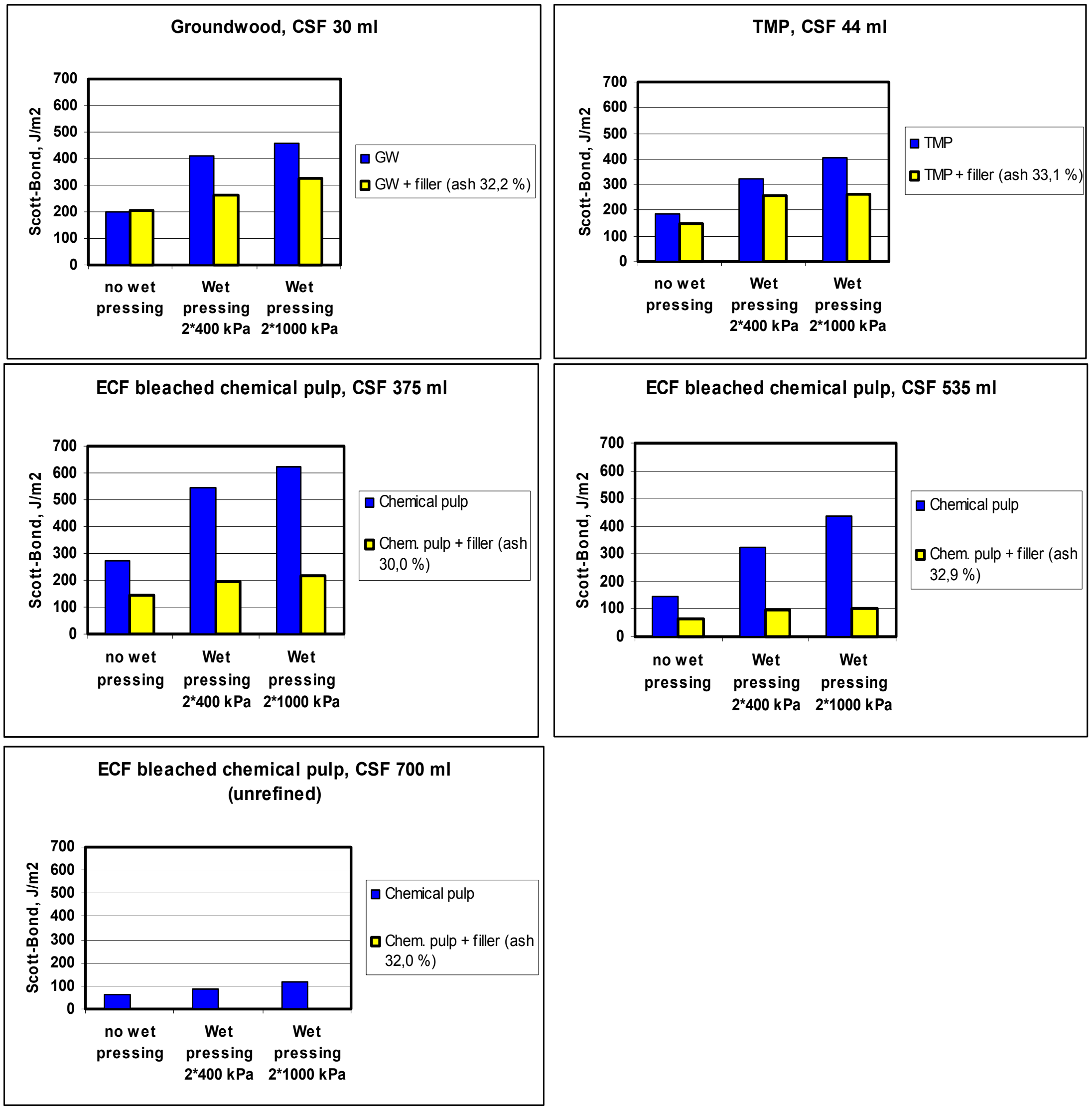

Figure 49. Effect of filler addition, about 32 % as ash, and wet pressing on the Scott-Bond of different pulps. The ash content of the original pulps was: GW 0.25 %, TMP 3.71 %, chemical pulp CSF 375 ml 0.16 %, 535 ml 5.57 % and 700 ml 0.12 %.

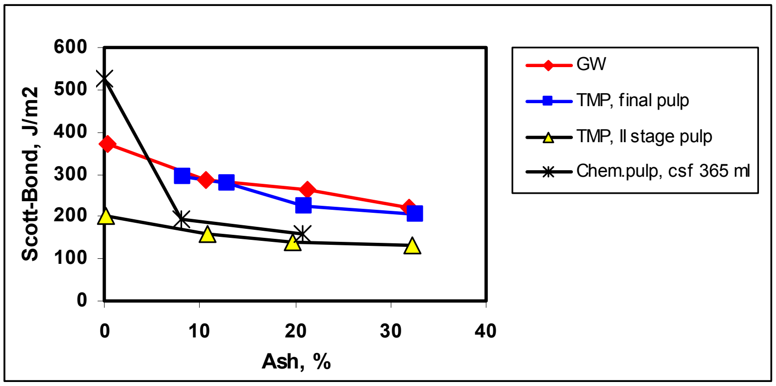

Figure 50. Effect of filler content, measured as ash, on the Scott-Bond of different pulps.

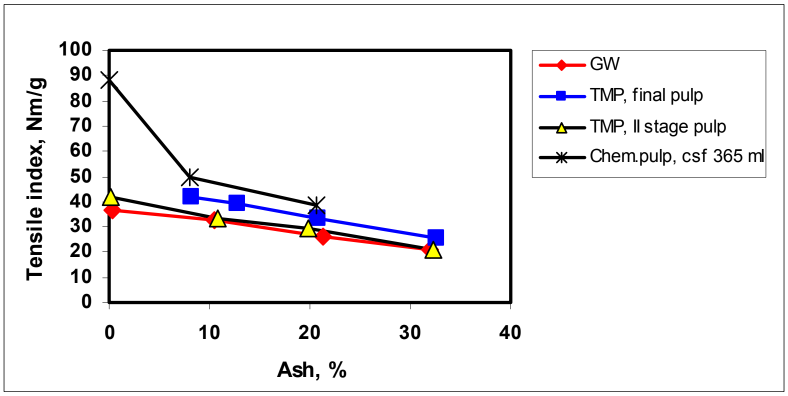

Figure 51. Effect of filler content, measured as ash, on the tensile index of different pulps.

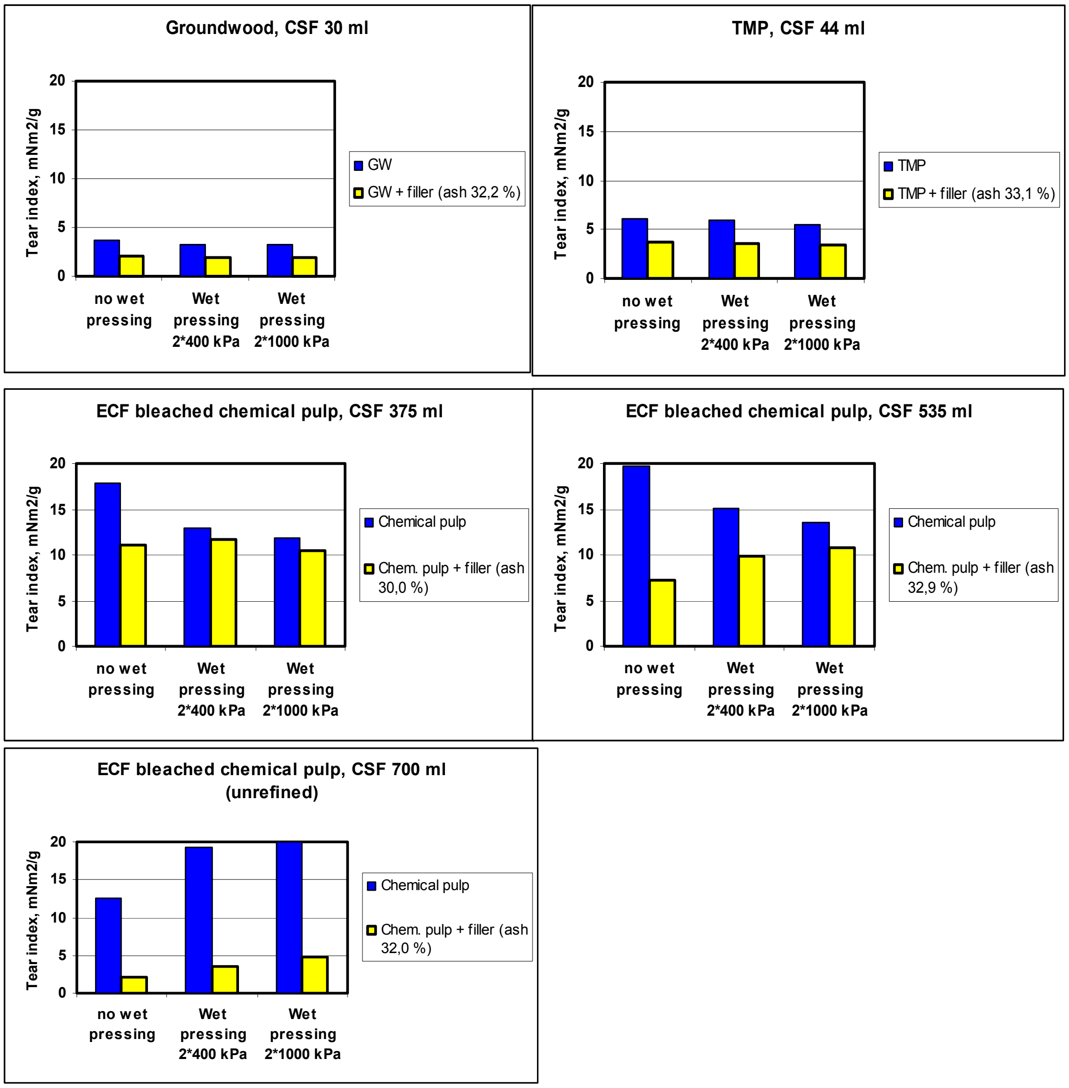

Figure 52. Effect of filler addition, about 32 % as ash, and wet pressing on the tear index of different pulps. The ash content of the original pulps was: GW 0.25 %, TMP 3.71 %, chemical pulps CSF 375 ml 0.16 %, 535 ml 5.57 % and 700 ml 0.12 %.

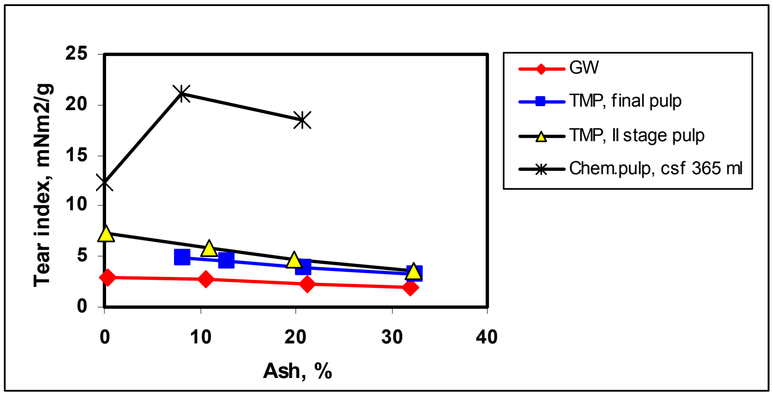

Figure 53. Effect of filler, measured as ash, on the tear index of different pulps.

Filler addition to a mixture of mechanical and chemical pulps

Filler shares of 0 – 32 % were added to the mixtures of mechanical and chemical pulps. A special case was the furnish of SC paper, i.e. about 32 % filler as ash in paper and about 20 – 30 % chemical pulp of fibre.

Filler addition, 0 – 32 % as ash, to a mixture of mechanical and chemical pulps, where the chemical pulp share of fibre was 30 %, linearly affected most sheet properties and the effect was similar in sheets based on SC grade groundwood or TMP. Filler increased the sheet density, air permeability and light scattering coefficient and quite similarly deteriorated all strength properties of this mixture (fig. 54). For instance 32 % filler as ash in groundwood-based sheets deteriorated Scott-Bond 39 %, tensile strength 46 %, tensile energy absorption 53 % and tear strength 41 % and increased sheet density 18 % and light scattering coefficient 35 %.

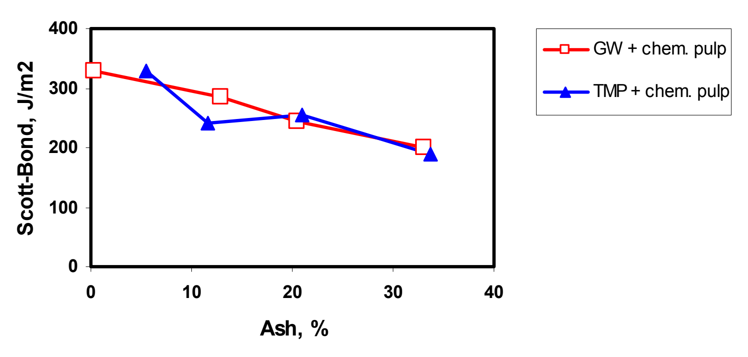

Figure 54. Effect of filler addition, measured as ash, to the Scott-Bond of a mixture of mechanical pulp, which is SC grade groundwood or TMP, and well refined chemical pulp, freeness 365 ml, plate dried sheets.

The 32 % filler share as ash, which is typical in SC paper, was added to a mixture of mechanical pulp, which was groundwood, TMP or their mixture, and chemical pulp, which was unrefined (CSF 700 ml), slightly refined (CSF 535 ml) or well refined (CSF 375 ml) ECF bleached softwood kraft pulp. The chemical pulp share was 0 – 100 % of fibre. This 32 % filler share somewhat increased the sheet density of different pulp mixtures (fig. 55) (because of clarity in figures 55 – 58 only the mixtures of TMP and chemical pulp are presented). Filler addition mostly increased the air permeability of SC paper sheets. Naturally filler clearly decreased bonding, the more the better bonded the sheet was, i.e. the bigger the share of well-refined chemical pulp was or the heavier wet pressing was (fig. 56 – 57). Filler addition could decrease the bonding of chemical pulp, characterized with Scott-Bond, to a lower level than the level of a mixture of mechanical pulp and filler. Filler decreased the stretch of unrefined chemical pulp more than that of refined chemical pulp or mechanical pulp or their mixture. Filler increased the light scattering coefficient of all pulps (fig. 58). Filler decreased usually the tear strength of highly wet pressed sheets most and the more the bigger the chemical pulp share was and the less refined it was (fig. 59). Consequently, filler containing mixtures with coarser chemical pulp had lower tear strength, opposite to mixtures without filler. Filler decreased the tear strength of mixture sheets containing TMP slightly more than that of sheets containing groundwood. Filler addition had quite a similar effect on the fracture energy and tear strength of a mixture of mechanical and chemical pulps (fig. 59 and 60).

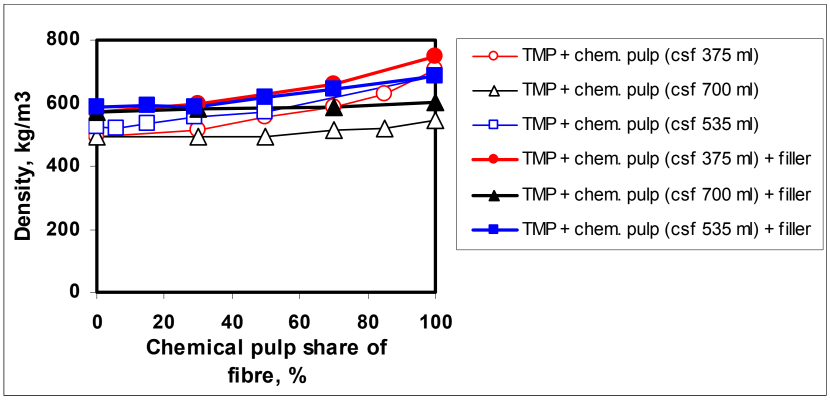

Figure 55. Density of the mixtures of TMP and chemical pulp refined to different freeness levels, pulp mixtures vs. SC paper, 32 % filler as ash, plate-dried sheets.

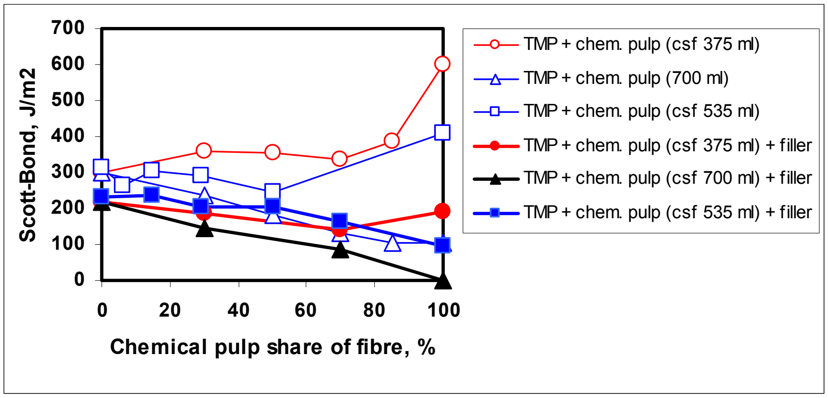

Figure 56. Scott-Bond of the mixtures of TMP and chemical pulp refined to different freeness levels, pulp mixtures vs. SC paper, 32 % filler as ash, plate-dried sheets.

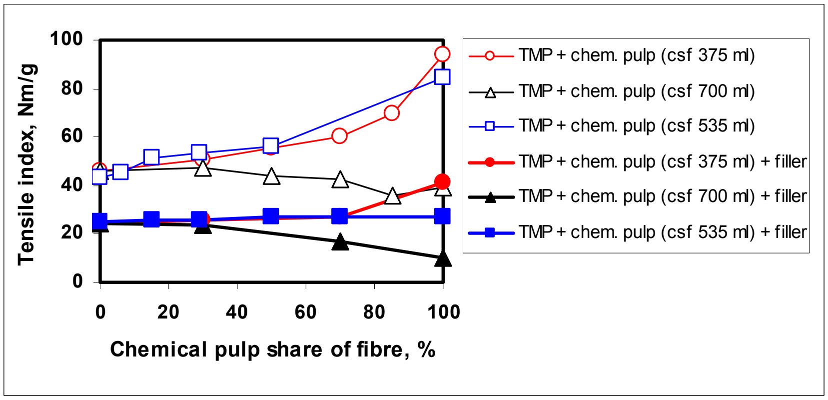

Figure 57. Tensile index of the mixtures of TMP and chemical pulp refined to different freeness levels, pulp mixtures vs. SC paper, 32 % filler as ash, plate-dried sheets.

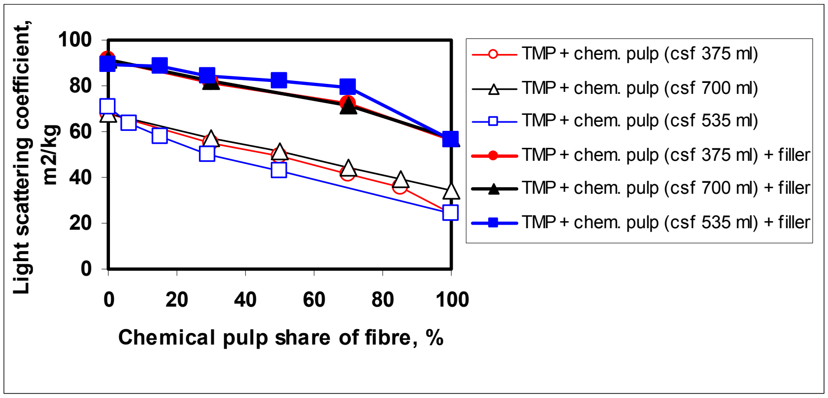

Figure 58. Light scattering coefficient of the mixtures of TMP and chemical pulp refined to different freeness levels, pulp mixtures vs. SC paper, 32 % filler as ash, plate-dried sheets.

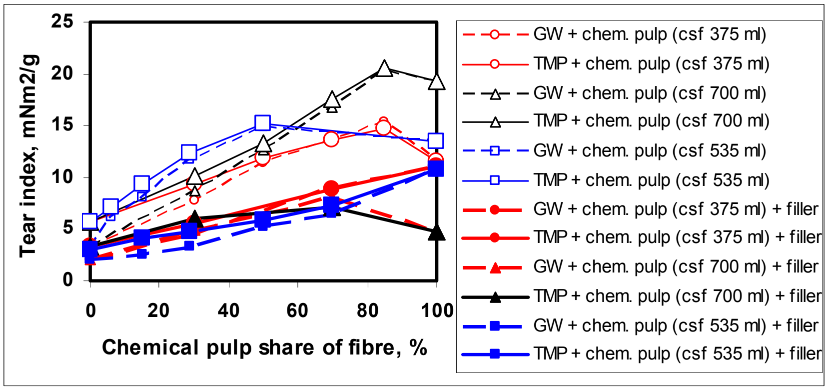

Figure 59. Tear index of the mixtures of mechanical pulp, groundwood or TMP, and chemical pulp refined to different freeness levels, pulp mixtures vs. SC paper, 32 % filler as ash, plate-dried sheets.

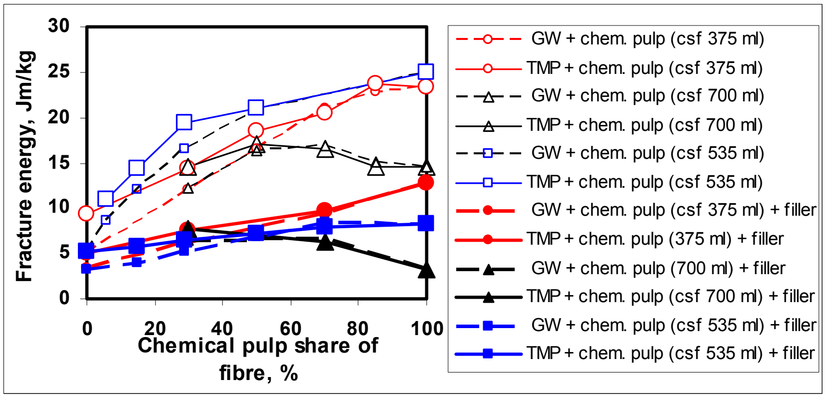

Figure 60. Fracture energy of the mixtures of mechanical pulp, groundwood or TMP, and chemical pulp refined to different freeness levels, pulp mixtures vs. SC paper, 32 % filler as ash, plate-dried sheets.

5.3.5. SC paper furnishes

Finally after the study of different furnish mixtures SC paper furnishes were studied again. In this context SC paper furnish widely means any mixture of mechanical and chemical pulps and filler. The chemical pulp share of fibre was 0 – 100 %. Filler content target was constant, 32 % as ash. However, the basic SC paper furnish mixtures studied contained a constant 30 % share chemical pulp of fibre. Now the reasons for synergy with the mixtures of groundwood and TMP were studied and discussed more thoroughly and the results were compared with the earlier results.

Mixtures of mechanical and chemical pulp in SC paper handsheets

In SC paper sheets the different properties of the mixtures of mechanical and chemical pulps mostly behaved linearly as a function of chemical pulp share, in opposite to the mixtures without filler, unless the chemical pulp was unrefined. The density (fig. 55) of SC paper sheets usually increased quite linearly as a function of their chemical pulp share, except with unrefined chemical pulp, in which case density stayed practically constant. However, also air permeability increased linearly with refined chemical pulp. With unrefined chemical pulp air permeability turned to a sharp increase at a high share. The increasing of chemical pulp share usually quite linearly decreased the Scott-Bond of SC paper sheets (fig. 56). However, with well refined chemical pulp Scott-Bond could turn to a slight increase at over a 70 % chemical pulp share. Tensile strength slightly decreased with unrefined chemical pulp, stayed practically constant with slightly refined chemical pulp and first slightly increased and turned to clearer increase at over a 70 % share of well refined chemical pulp (fig. 57). Stretch behaved similarly to tensile strength. Tear strength increased linearly with the increase of chemical pulp share but with well refined chemical pulp it turned to a decrease at about 70 % share (fig. 59). Fracture energy increased linearly with well refined chemical pulp and with slightly refined pulp increased until about a 50 % share of chemical pulp and after this remained constant. With unrefined chemical pulp fracture energy first increased and turned to a decrease at over a 50 % share (fig. 60). Light scattering coefficient decreased linearly with chemical pulp share independent of its refining degree (fig. 58).

In the interval of the chemical pulp share typical in mechanical printing papers the increase of chemical pulp share had only a marginal improving effect on the tensile strength of SC paper. In some cases the effect could even be negative even if the chemical pulp had clearly better strength than mechanical pulp. Chemical pulp clearly improved the tear strength and fracture energy of SC paper.

Wet pressing improved the bonding of SC paper sheets, characterized with Scott-Bond, especially at a low chemical pulp share and tensile strength and tensile energy absorption and stretch at a high share of chemical pulp. Wet pressing usually had a small effect on the tear strength of SC paper sheets. Wet pressing did not affect tear strength when chemical pulp was slightly or well refined but improved it at a high share of unrefined chemical pulp. Wet pressing made the behaviour of the tear strength of a mixture of mechanical and chemical pulps in SC paper sheets more linear.

SC paper sheets at constant density

The density difference of handsheets consisting of a mixture of 32 % filler as ash and pure chemical pulp or pure mechanical pulp, groundwood or TMP, was moderate, about 100 kg/m^3, if the chemical pulp was well or slightly refined. If the chemical pulp was unrefined there was practically no difference in densities. The density difference of groundwood and TMP-based mixture sheets was small compared to the difference of mechanical and chemical pulp based paper sheets. Still the sheet properties were linearly interpolated to constant density, 500 kg/m^3. This was done though constant density is probably not the best way to characterize filler containing sheets at constant bonding degree. Interpolation to constant density decreased the synergy of the mixtures of mechanical and chemical pulps in SC paper handsheets (fig. 61 – 64).

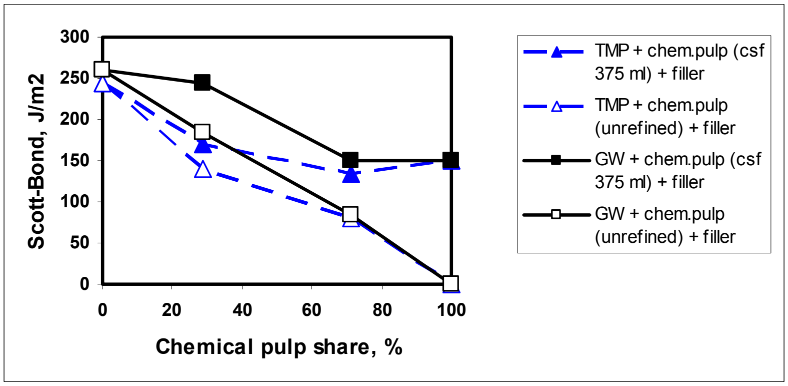

Figure 61. Scott-Bond of SC paper sheets, 32 % filler as ash, at constant density, 500 kg/m³, as a function of the chemical pulp share of fibre.

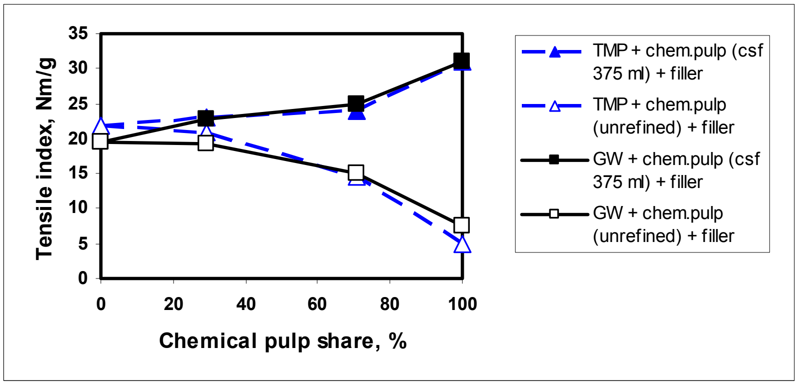

Figure 62. Tensile index of SC paper sheets, 32 % filler as ash, at constant density, 500 kg/m³, as a function of the chemical pulp share of fibre.

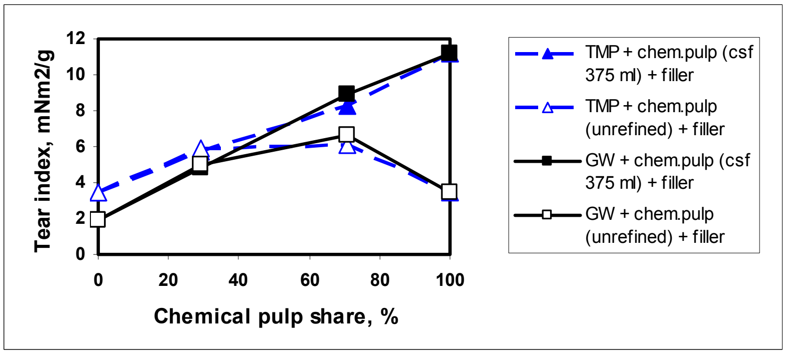

Figure 63. Tear index of SC paper sheets, 32 % filler as ash, at constant density, 500 kg/m³, as a function of the chemical pulp share of fibre.

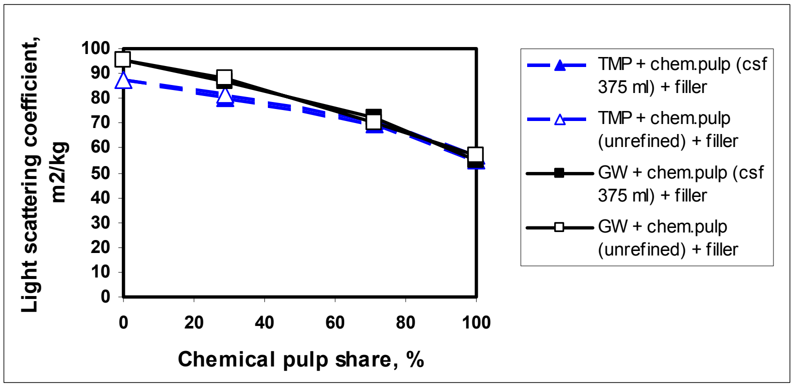

Figure 64. Light scattering coefficient of SC paper sheets, 32 % filler as ash, at constant density, 500 kg/m³, as a function of the chemical pulp share of fibre.

Altogether 11 further basic SC paper furnishes were studied, i.e. furnishes with a 30 % chemical pulp share of fibre and 32 % filler as ash, with different combinations of groundwood, TMP and chemical pulp were studied (appendix 2). The mechanical pulps, except one newsprint grade groundwood, were all SC or LWC grade pulps. The chemical pulps were ECF bleached (series 4 – 10) or TCF bleached (series 1 – 3, 11) softwood reinforcing kraft pulps refined to different freeness levels.

The behaviour of the mixtures of groundwood and TMP in SC paper sheets was similar to that in earlier trials. In about half of these SC paper furnishes a mixture of groundwood and TMP gave at least some positive synergy advantage in tear strength while the rest of the mixtures behaved more or less linearly, but never antagonistically (fig. 65 and 66). Light scattering coefficient sometimes behaved synergistically. Interestingly, though coarse groundwood (CSF 118 ml) had slightly bigger light scattering coefficient than fine TMP (71.8 vs. 68.1 m^2/kg), the replacing of that groundwood with TMP increased the light scattering coefficient of SC paper sheets.

Most of the mixtures of groundwood and TMP had at least some synergy in the tear strength of SC paper furnishes with ECF bleached chemical pulp except the last mixture (fig. 65). All the ECF bleached pulp samples originated from the same chemical pulp mill, but the last sample was taken after the renewal of that mill. Among the SC paper sheets containing TCF bleached pulp only the mixture containing the latest TCF bleached pulp sample had this synergy (fig. 66). Because of the novelty of the bleaching method TCF bleached pulp has been under development during this thesis. This could have caused the appearance of synergy in the latest series.

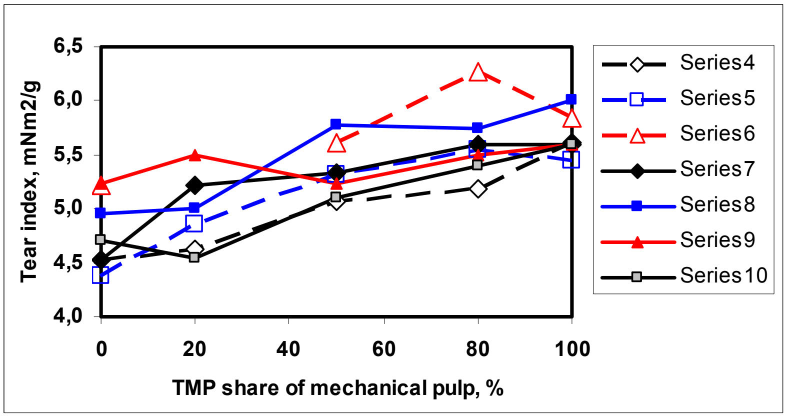

Figure 65. Tear index of plate-dried SC paper handsheets as a function of the TMP share of mechanical pulp, 30 % ECF bleached chemical pulp of fibre and 32 % filler as ash. Seven different combinations of groundwood, TMP and chemical pulp, pulp properties in appendix 2.
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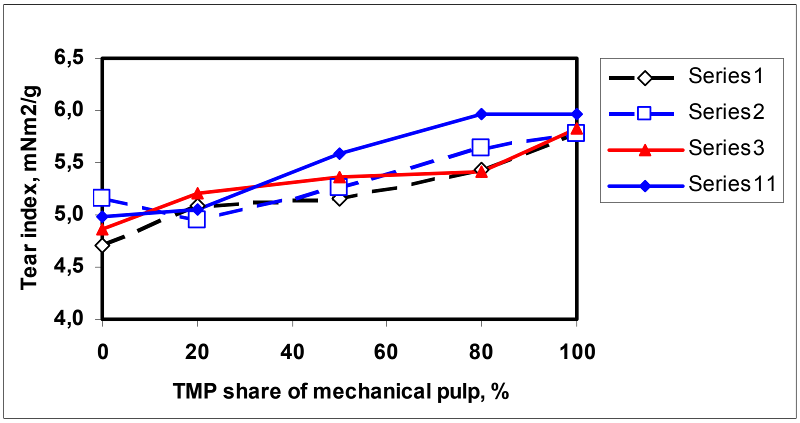

Figure 66. Tear index of plate-dried SC paper handsheets as a function of the TMP share of mechanical pulp, 30 % TCF bleached chemical pulp of fibre and 32 % filler as ash. Four different combinations of groundwood, TMP and chemical pulp, pulp properties in appendix 2.

In these SC paper furnishes and all the different paper furnishes made earlier in this thesis synergy in tear strength with a mixture of groundwood and TMP was achieved when the Scott-Bond of groundwood-based furnish was about 210 J/m^2 or more and that of TMP-based furnish was about 160 J/m^2. In spite of this lower value the TMP-based sheet was beyond tear strength maximum as it with higher fibre length demanded less bonding for maximum tear strength (see fig. 3). If the Scott-Bond interval was narrower, less synergy was found, perhaps because the bonding of TMP and groundwood-based sheets were not on the opposite sides of the tear strength maximum. Obviously the TMP-based sheet with clearly higher fibre length is easily too poorly or too well bonded, both giving poorer than maximum tear strength. In the latter case synergy is achieved with a mixture of groundwood and TMP in tear strength. In groundwood based sheets bonding degree has less importance.

Because groundwood-based and TMP-based SC paper sheets had nearly the same density, their interpolation to constant density had no effect on the synergy of the mixtures of groundwood and TMP in SC paper sheets.

In series 7, which had some synergy with a mixture of groundwood and TMP in the tear strength, stretch, TEA and light scattering coefficient of SC paper sheets, the shares of fibre, filler, pore and lumen in z-direction of the cut sheets was measured. This test was done at UPM-Kymmene Valkeakoski Research Center. The method is based on SEM figures and the image analysis of sheet cuttings. Altogether 30 parallel measurements were made at each trial point. According to the results the only noticeable difference between the trial points was that at an 80 % TMP share of mechanical pulp, i.e. at tear strength maximum, the pore share was clearly biggest (table 12). This could also indicate less bonding at that point and consequently better tear strength. The poorer bonding could be caused by different drying shrinkages of TMP and groundwood.

Table 12: Average fibre, filler, pore and lumen shares of SC paper sheets at different TMP shares of mechanical pulp.

TMP share of mechanical pulp, %	Fibres		Filler		Pore		Lumen		Solids	
	share	St. dev.	share	St. dev.	share	St. dev.	share	St. dev.	share	St. dev.
0	0,52	0,034	0,162	0,036	0,259	0,027	0,059	0,18	0,682	0,035
20	0,562	0,034	0,11	0,02	0,296	0,04	0,032	0,011	0,672	0,04
50	0,549	0,025	0,134	0,022	0,246	0,03	0,072	0,018	0,683	0,034
80	0,514	0,026	0,1	0,017	0,35	0,034	0,037	0,009	0,614	0,035
100	0,47	0,032	0,238	0,026	0,249	0,033	0,044	0,015	0,708	0,036

Importance of fibre properties

Fibre properties of some pulps of the basic SC paper study were tested (normal pulp properties in appendix 2, except TMP3, which was a new sample):
Chemical pulp 1: dried ECF bleached kraft pulp, freeness 375 ml
Chemical pulp 2: dried ECF bleached kraft pulp after renewal of the process, freeness 410 ml
Chemical pulp 3: wet TCF bleached kraft pulp, freeness 365 ml
Groundwood 1: fine SC grade groundwood, freeness 30 ml
TMP 1: fine SC grade TMP, freeness 31 ml
TMP 2: fine SC grade TMP, freeness 48 ml
TMP 3: coarser TMP, freeness 79 ml

The tested fibre properties were
- WRV
- fibril share of fines
- FS200 fibre length distribution

According to the basic SC paper results and pulp properties the furnish mixtures containing chemical pulps 1 or 3, groundwood 1 and TMP 2 or possibly TMP 1 would probably have synergy with a mixture of groundwood and TMP in SC paper sheets. No synergy would probably be achieved with furnishes containing chemical pulp 2 or TMP3. The fibre properties show that in the case of synergy in SC paper sheets, TMP had higher WRV, though not necessarily lower freeness (table 13). In the fibril share of fines fractions practically no difference was found but the ray cell share of fines was the smallest when synergy existed. In the fibre properties of chemical pulps no difference could be found between pulps favourable to synergy and pulps unfavourable to synergy. Both the correlation of synergy with low stiffness of TMP fibres found earlier in this research (chapter 5.2.1.) and now with high WRV of TMP indicate the importance of good bonding ability of TMP to synergy.

Table 13. Fibre properties of some pulps used in this study of basic SC paper furnishes

Pulp sample	CSF ml	FS-200 Fibre length mm	WRV g/g	Fibril share of fines %	Ray cells, share of fines %
Chem. pulp 1	350		1,19	29	20
Chem. pulp 2	410	2,17	1,16	27	17
Chem. pulp 3	365	2,36	1,18	30	21
GW	30	0,73	1,52	36	16
TMP-1	31	1,27	1,67	40	10
TMP-2	48	1,44	2,1	40	9
TMP-3	79	1,67	1,59	41	16

Effect of chemical pulp share on the synergy of the mixtures of groundwood and TMP in SC paper

Earlier in this research synergy in SC paper with a mixture of groundwood and TMP was found to be clearest at a 30 % chemical pulp share of fibre, some synergy existed at the lower, 20 %, share and no synergy at the higher, 38 %, share. In LWC base paper, with 8 % filler as ash, only some accidental synergy was found in the studied interval of 35 – 50 % chemical pulp share of fibre.

In further SC paper series the effect of the chemical pulp share of fibre on synergy with the mixtures of groundwood and TMP was investigated more thoroughly. SC paper handsheets were made at 0, 6, 15, 29 and 50 % shares of ECF bleached chemical pulp refined to freeness 535 ml. The TMP shares of mechanical pulp were 0, 50, 80 and 100 %. The pulp properties are shown in appendix 2, trial series 6. At a 50 - 80 % TMP share of mechanical pulp the Scott-Bond of these SC paper sheets had a minimum at all chemical pulp shares, i.e. those sheets were poorly bonded (fig. 67). Earlier (chapter 5.3.2.) a minimum was found in the Scott-Bond of a mixture of groundwood and TMP at an 80 % share of the latter. An opposite effect on Scott-Bond could be assumed as a result of the denser packing of different size particles when adding a small share of groundwood to TMP. The behaviour of both these mixtures could be caused e.g. by differences in drying shrinkage, which would cause bond breakage in drying. The minimum in Scott-Bond could be a partial reason for tear strength maximum at a 50 – 80 % TMP share of mechanical pulp in SC paper sheets (fig. 68).

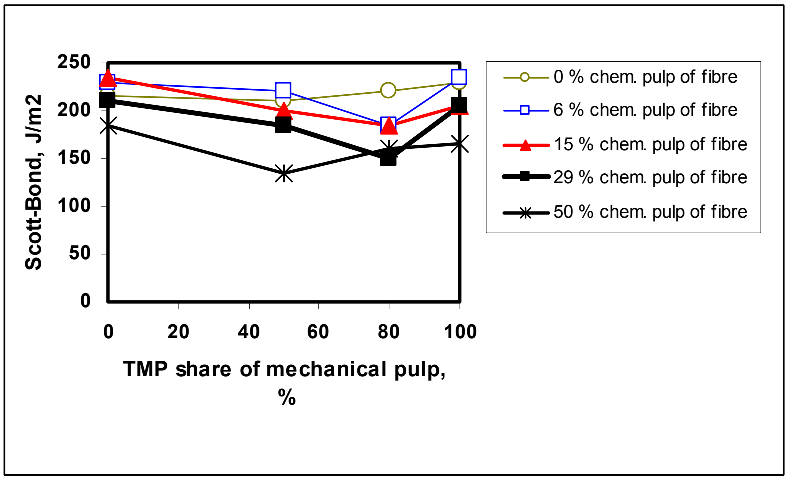

Figure 67. Scott-Bond of plate-dried SC paper handsheets as a function of the TMP share of mechanical pulp at different chemical pulp shares of mechanical pulp, 32 % filler as ash.

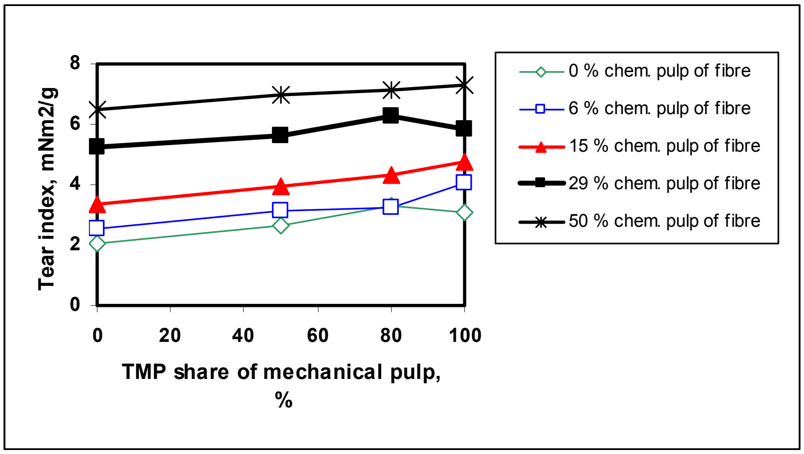

Figure 68. Tear index of plate-dried SC paper handsheets as a function of the TMP share of mechanical pulp at different chemical pulp shares of mechanical pulp, 32 % filler as ash.

Synergy in the tear strength of well bonded sheets, i.e. in plate-dried sheets or drum-dried sheets with heavy wet pressing (2*1000 kPa), was only found at a 29 % chemical pulp share of fibre but not at a lower or higher share (fig. 68). In less bonded low density sheets with no wet pressing synergy in tear strength was only found at a higher, 50 %, chemical pulp share.

On the basis of the earlier results the synergy behaviour of mechanical pulp mixtures depends, in addition to the bonding ability of the pulp components of paper, also on the basis weight of paper, which affects the need of bonding in paper. When conditions change, the optimum bonding degree can also change. Possibly in normal SC paper handsheets at only around a 30 % chemical pulp share of fibre the bonding of groundwood and TMP-based SC paper sheets vs. fibre length was on a suitable level for synergy in tear strength, i.e. Scott-Bond was about 160 – 210 J/m² (fig. 67).

It was found earlier that the increase of bonding could turn the tear strength of TMP-based SC paper sheets to a decrease while that of groundwood-based sheets stayed practically constant. This effect was found to be a reason for synergy in the tear strength of SC paper sheets. Now according to later results synergy is often clearer at a normal than at a higher wet pressing level. This is possibly caused by the excessively good bonding of high density sheets for tear strength even with groundwood.

5.3.6. Discussion and conclusions

The behaviour of different basic furnish mixtures was studied to better understand the synergy phenomena in mechanical printing papers.

Pulps

The increasing of bonding with wet pressing improved most strength properties and decreased light scattering of all pulps, both mechanical and chemical. The tear strength of poorly-bonding, long-fibred, coarse mechanical pulp and unrefined chemical pulp could first improve with the increase of wet pressing. However, the tear strength of most SC and LWC grade pulps was well beyond the maximum and thus tear strength decreased as bonding was improved. Tear strength maximum was achieved at Scott-Bond level 160 – 210 J/m^2.

Mixtures of mechanical and chemical pulps

The density of the mixture of mechanical pulp and unrefined chemical pulp behaved linearly. However, with well refined chemical pulp the mixture had lower than calculated sheet density which indicated poorer bonding. This showed often as negative synergy in Scott-Bond and tensile strength and positive synergy in tear strength and fracture energy. Pure mechanical pulps and refined chemical pulps had a great density difference. As interpolated to constant density, which characterizes constant bonding, the synergies in all strength properties disappeared but the differences between pure mechanical and chemical pulps remained. The mixtures of SC grade mechanical and chemical pulps, both with groundwood and TMP, had tear strength well beyond the maximum. Consequently, in these sheets a mixture of groundwood and TMP as mechanical pulp could have only a slight synergy.

Filler addition

With any pulp or pulp mixture filler usually increased sheet density but decreased bonding, which showed as poorer strength properties. A small amount of filler could improve the tear strength of well bonded pulps, i.e. pulps with tear strength beyond its maximum, but normally filler deteriorated also tear strength. In the mixtures of pulp and filler the increase of bonding with wet pressing could improve tear strength, especially with chemical pulps.

SC paper furnishes – the mixtures of mechanical and chemical pulps and filler

Highly filled SC paper furnishes are clearly less bonded than just the pure mixtures of mechanical and chemical pulps. Depending on bonding level SC paper furnish mixtures could have synergy both as a function of the chemical pulp share of fibre and the TMP share of mechanical pulp.

SC paper furnish could have positive synergy in tear strength and fracture energy as a function of chemical pulp share if chemical pulp was unrefined, i.e. poorly-bonding, but not with refined chemical pulp. With refined chemical pulp some negative synergy existed in tensile strength and Scott-Bond. The increasing of bonding had no big effect on these synergies.

The filler containing sheets had a small difference in density independent of their fibre furnish. Neither did their interpolation to constant density decrease the synergies found in SC paper sheets but rather increased them.

In SC paper with fine, well-bonding pulps and lots of filler the conditions are favourable for the synergies found in this thesis with the mixtures of groundwood and TMP. The synergy in SC paper demands well-bonding TMP with flexible fibres and high WRV. The chemical pulp should have a suitable bonding level. The quality of fine SC grade groundwood has less importance.

Synergy in the tear strength of SC paper with the mixtures of groundwood and TMP looked more probable with ECF bleached than with TCF bleached kraft pulp. However, the synergy sensitivity of the TCF bleached pulp seemed to be increasing. During this thesis the TCF bleaching process has been under development. This could have caused the appearance of synergy in the latest series. In the case of ECF bleached pulp with the latest sample no synergy was achieved. That pulp sample was taken soon after the renewal of the chemical pulp mill. Accordingly differences in the surface chemistry of the ECF and TCF bleached chemical pulps could affect the existence of synergy.

Different furnish mixtures

The synergy phenomena of all the different furnish mixtures studied seemed to be quite similar in principle, though the mixtures had e.g. different compositions, fibre lengths or bonding degrees. The results imply that synergy in the tear strength of paper depends mainly on optimum bonding degree vs. fibre length. Synergy is achieved with a combination of furnishes which have bonding degree on the opposite sides of tear strength maximum. In all furnishes the bonding, i.e. Scott-Bond, corresponding the tear strength maximum was on the level of 160 – 210 J/m². The exact level depended on fibre length and sheet basis weight. The bonding of highly-filled SC paper with well-bonding pulps was typically on this level. In SC paper this bonding level was most probably achieved at about a 30 % chemical pulp share of fibre. In this case synergy with a mixture of groundwood and TMP could be achieved. At a clearly lower or higher chemical pulp share the bonding level of both groundwood-based and TMP-based papers was on the same side of this optimum and synergy was less probable.

In the case of synergy with a mixture of groundwood and TMP in SC paper the long-fibred TMP-based sheet had a bonding degree beyond tear strength maximum, i.e. the TMP-based sheet was too well bonded for maximum tear strength. The shorter-fibred groundwood based SC paper sheet had a bonding degree below the optimum though it was better bonded.

In addition to tear strength, synergy was also found in fracture energy, stretch and tensile energy absorption, which all depend on both fibre length and bonding. The reasons for the synergies in these different strength properties probably are quite the same as those for tear strength because synergy in these properties was usually found only if synergy existed in tear strength.

The results indicate that synergy in strength properties has also other possible reasons. These can be difference in sheet density, surface chemistry or drying shrinkage or passing the limiting state of fines content, which all affect bonding. The importance of drying shrinkage and the surface chemistry of chemical pulps were still investigated.

5.4. Effect of differences in drying shrinkage

The different drying shrinkages of mechanical and chemical pulps are regarded as one possible reason for the synergy behaviour of their mixtures /Mohlin et al. 1983/. This difference could cause the breaking of already formed bonds in paper drying. Because of their low lignin content chemical pulps have bigger drying shrinkage than mechanical pulps. In addition to fibres and their lignin content also the fines strongly contribute to shrinkage /Lobben 1978/. Consequently, it could be assumed that in mechanical pulps the size of long fibre fraction, i.e. the TMP share of mechanical pulp, could affect the synergy phenomenon via drying shrinkage.

The shrinkage and straining of paper during drying affect its bonding and tensile properties essentially. In free drying the fibres bonded with each other shrink and their unbonded segments become winding. On the other hand straining during sheet drying breaks some fibre bonds and activates fibres by straightening them. Straining improves tensile strength and decreases stretch. The bonding can be characterized with elastic breaking strain or Scott-Bond and fibre activation with tensile stiffness.

The importance of the drying shrinkage difference of paper furnish components on synergy behaviour was studied with mixture sheets of different mechanical and chemical pulps. No filler was used in paper furnishes. The sheets were formed and wet pressed at Rauma. The wet pressing was lighter than normally in order to better study the drying shrinkage effects, according to an earlier study /Mäkinen 2000/. Water easily evaporates from wet sheets and too little moisture can cause inaccuracy in the drying shrinkage study. The mixture sheets were dried at Helsinki University of Technology (HUT) with four different controlled uniaxial drying shrinkages, i.e. free shrinkage, 2 % shrinkage, 0 % (restricted) and –2 % (strained). The equipment is described by Zhang /Zhang 2004/.

In this drying shrinkage study mechanical pulp was final mill groundwood or TMP (table 14). The TMP share of mechanical pulp was 0, 50 or 100 % and the chemical pulp share in the mixture sheets was 0, 20, 30, 50 or 100 %. Two different chemical reinforcing pulps (TABLE 14) with different drying shrinkages were used. They were dried ECF bleached softwood kraft pulp and wet TCF bleached softwood kraft pulp. These samples were taken in the pulp mills, from a bale and on the drying machine after press section, respectively. In addition to the sheets with different wet straining levels also normal plate-dried SC paper handsheets with filler were made from the same pulp samples in order to verify the existence of synergy.

The chemical pulps used in this drying shrinkage study naturally had clearly bigger free drying shrinkage than the mechanical pulps. The differences within a certain pulp type, i.e. mechanical or chemical pulps, were relatively small. Wet chemical pulp (pulp 2) had slightly bigger drying shrinkage than dried chemical pulp (pulp 1) and TMP had slightly bigger drying shrinkage than groundwood. (table 15). The other properties of the two chemical pulps used in these trials were quite similar though chemical pulp 2 had slightly better bonding ability characterized with Scott-Bond (table 14). TMP naturally had more long fibres than groundwood but the TMP sample had relatively low fibre length and tear strength for a TMP.

Table 14. Properties of the pulps used in the drying shrinkage studies.

	Groundwood	TMP	Chemical pulp 1	Chemical pulp 2
Freeness, ml	34	32	410	365
Fibre length, mm	0,70	1,27	2,17	2,36
Density, kg/m³	495	533	709	713
Air permeability, ml/min	76	35	169	194
Tensile index, Mm/g	38,6	42,8	89,2	88,2
Stretch, %	2,1	2,0	3,8	3,8
TEA index, J/kg	530	557	2167	2200
Tensile stiffness, MNm/kg	4,11	4,57	7,20	7,24
Scott-Bond, J/m²	370	295	455	525
Tear index, mNm^2/g	3,10	4,82	12,9	12,3
In-plane tear index, Jm/kg	4,80	7,38	25,6	27,8

Table 15. Free drying shrinkage of the pulps of table 14. The testing method based on image analysis is described by Mäkinen /Mäkinen 2000/

	Area	Length
Groundwood	4,82 %	2,54 %
TMP	5,43 %	2,70 %
Chem. pulp 1 (dried, ECF bleached)	6,41 %	3,22 %
Chem. pulp 2 (wet, TCF bleached)	7,14 %	3,52 %

The mixtures of mechanical and chemical pulps had practically additive free drying shrinkage; however at a 20 – 30 % chemical pulp share they surprisingly always had clearly higher than calculated free drying shrinkage (fig. 69). Then the absolute free drying shrinkage was even nearly the same as that of pure chemical pulp.

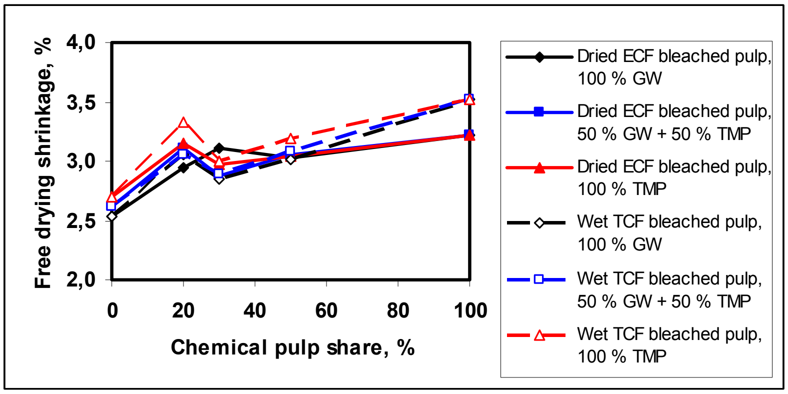

Figure 69. Free drying shrinkage of the mixture sheets of the different mixtures of chemical and mechanical pulps, as a function of chemical pulp share.

Because of light wet pressing the density of these mixture sheets was lower than normally. This affected all sheet properties. The increasing of drying strain from free drying to 2 % strain decreased the basis weight of the mixture sheets by about 3 – 4 g/m^2. Sheet straining during drying slightly decreased sheet density (fig 70) and increased air permeability. This was probably caused by some bond breaking in wet straining and decreased basis weight. The bond breaking in drying strain showed as a clear decrease in elastic breaking strain and Scott-Bond (fig. 71). At a 20 – 30 % chemical pulp share of fibre, which is typical to SC paper, bonding decreased slightly more with TMP than groundwood as mechanical pulp. Also stretch, tensile energy absorption and fracture energy decreased in drying strain and light scattering coefficient slightly increased. Drying strain usually had a slight increasing effect on tear strength, especially with TMP, but at a high share of dried chemical pulp drying strain slightly decreased tear strength. Drying strain increased fibre activation, which showed as a clear increase in tensile stiffness (fig. 72) and tensile strength. These effects on sheet properties, except on light scattering coefficient and tear strength, were biggest at a high chemical pulp share. The effects of drying strain were similar with mixtures containing both chemical pulps.

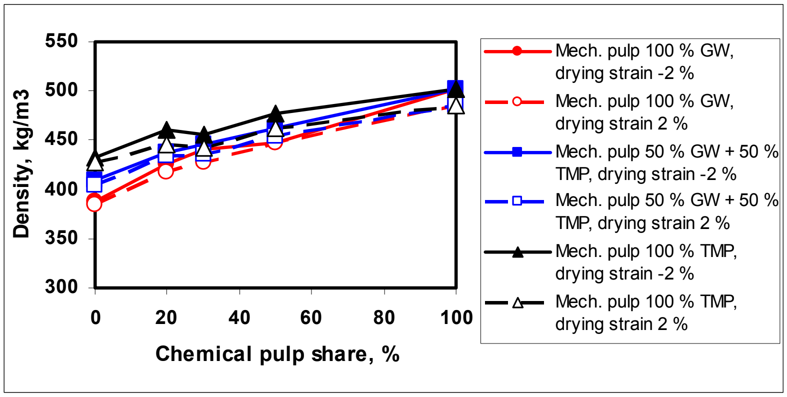

Figure 70. Effect of drying strain and chemical pulp share on the density of the mixture sheets of mechanical pulp and dried ECF bleached chemical pulp.

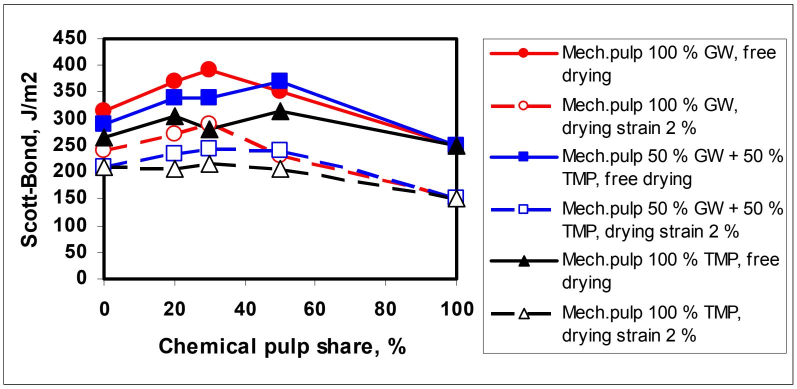

Figure 71. Effect of drying strain and chemical pulp share on the Scott-Bond of the mixture sheets of mechanical pulp and dried ECF bleached chemical pulp.

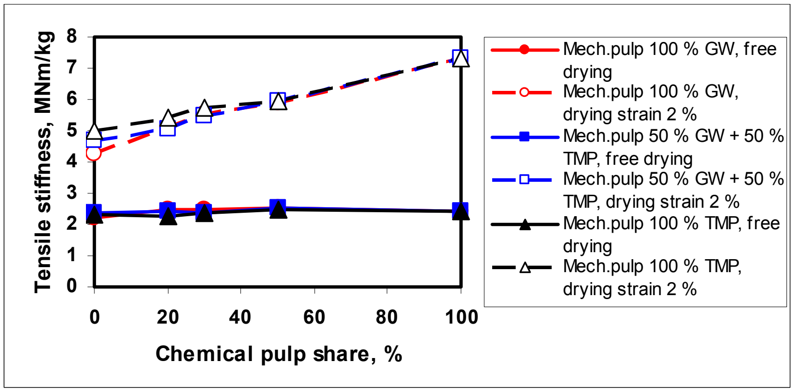

Figure 72. Effect of drying strain and chemical pulp share on the tensile stiffness of the mixture sheets of mechanical pulp and dried ECF bleached chemical pulp.

In this drying shrinkage study the mixtures of mechanical and chemical pulps usually had a slight positive synergy in sheet density, opposite to normal sheets. The positive synergy in density showed in most strength properties as a slight synergy advantage. This indicates that in these relatively bulky sheets the mixture sheets were better bonding than the pure pulp components. However, at constant drying strain only in Scott-Bond a clear synergy advantage was found (fig. 71). Scott-Bond had a maximum at a 20 – 50 % chemical pulp share. Interestingly this maximum bonding was clearest with groundwood as mechanical pulp. With groundwood the maximum bonding was achieved at a 20 – 30 % chemical pulp share and as the TMP share of mechanical pulp increased the maximum bonding moved to a 30 - 50 % chemical pulp share. Both the increase of the TMP share of mechanical pulp and drying strain decreased this synergy with the mixtures of mechanical and chemical pulps in Scott-Bond. With wet TCF bleached chemical pulp this synergy was smaller than with dried ECF bleached chemical pulp. Only tear strength was slightly poorer than calculated.

The synergies can be seen more clearly if the measured properties of the mixture sheets are compared to the values additively calculated from the properties of the components, i.e. groundwood, TMP and chemical pulp, and their shares in mixture.

Some synergy with the mixtures of groundwood and TMP could be seen in the drying shrinkage study. In the mixture sheets of mechanical and chemical pulps at about a 20 - 50 % share of dried ECF bleached chemical pulp or at a 20 – 30 % share of wet TCF bleached chemical pulp bonding and most measured strength properties were poorest with TMP and best with the mixture of groundwood and TMP or with pure groundwood (fig. 73 and 74). As a result of this a mixture of groundwood and TMP as mechanical pulp could give some synergy at free drying shrinkage or constant drying strain in these properties. These synergies were clearest at constant 2 % drying shrinkage and they decreased as sheets were strained during drying. These results show that the strength potential of TMP is least exploited in papermaking.

Relatively best bonding was achieved at above a 30 % share with dried chemical pulp. However, at a lower share with groundwood or a mixture of groundwood and TMP as mechanical pulp bonding could be relatively best exploited with wet chemical pulp (fig. 73).

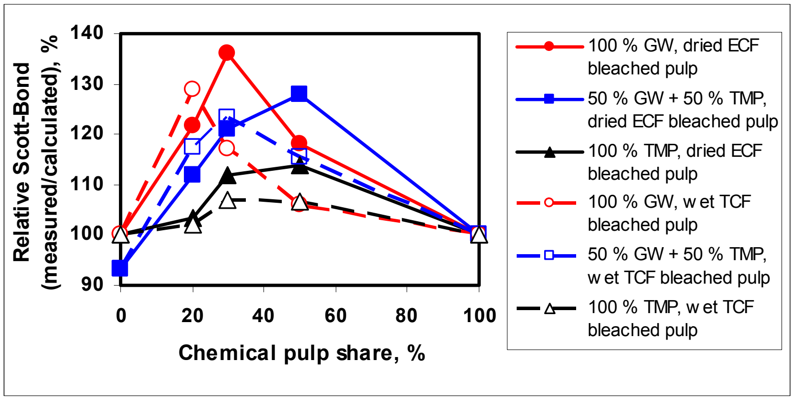

Figure 73. Relative Scott-Bond (measured/calculated) of a mixture of mechanical pulp and chemical pulp at 2 % drying strain.

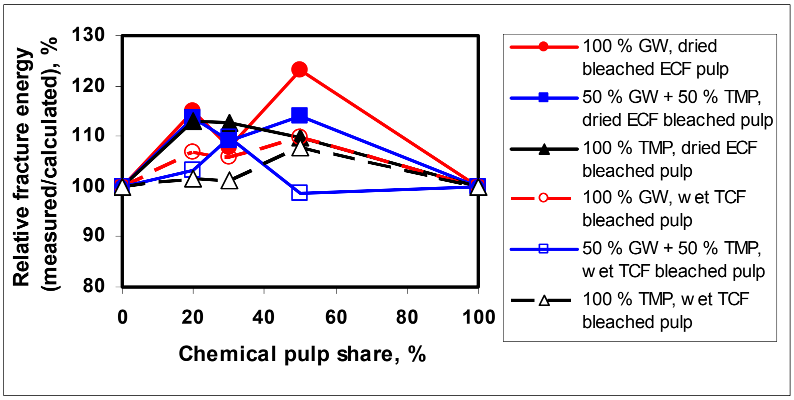

Figure 74. Relative fracture energy (measured/calculated) of a mixture of mechanical pulp chemical pulp at 2 % drying strain.

With the increase of the chemical pulp share, the effect of drying strain on tensile energy absorption, stretch and in-plane tear strength seems to be bigger with wet than dried chemical pulp while chemical pulp grade had no effect on the behaviour of tear and tensile strengths or Scott-Bond.

The pulps used in the mixture sheets naturally had also other differences than just drying shrinkage. These could also have affected the achieved differences in sheet properties.

5.4.1. Discussion and conclusions

The free drying shrinkage of mixture sheets was bigger than calculated at a 20 – 30 % chemical pulp share. Possibly this 20 – 30 % share of well-refined chemical pulp fibres could efficiently improve sheet bonding and as there still was plenty of mechanical pulp fines this showed as an increase in Scott-Bond. This improved bonding could possibly increase the free drying shrinkage of relatively poorly bonded mechanical pulp sheet. When the chemical pulp share still increased to over 20 – 30 %, less mechanical pulp fines existed and the limiting state of fines content was passed and the sheets had poorer Scott-Bond. This poorer bonding together with the still existing mechanical pulp fibres could perhaps prevent drying shrinkage effectively. This could also explain why with groundwood rich in fines the changes in free drying shrinkage were later and smaller than with TMP. The maximum free drying shrinkage found at a 20 – 30 % chemical pulp share could have been found even at a lower than 20 % share, since no trial points existed below the 20 % level.

The mixture sheets of the drying shrinkage study had light wet pressing and as a result of that lower than normal density and different synergy behaviour. At constant drying strain, at a 20 – 30 % chemical pulp share, most measured sheet properties compared to the calculated value were poorest when mechanical pulp was TMP and best with a mixture of groundwood and TMP. This indicates that the different drying shrinkages can be one reason for the synergy of the mixtures of groundwood and TMP at a chemical pulp share typical to SC paper. Drying strain deteriorated several paper properties. So the different need of drying strain with different furnishes can also affect the synergy behaviour.

5.5. Effect of surface chemistry on synergy

Some researchers have concluded that differences in surface chemistry could be one reason for the synergy behaviour of mechanical and chemical pulp mixtures /Mohlin et al. 1983, Mohlin 1989, Retulainen 1992, 1997/. The results of the studies discussed in chapter 5.3.5. have shown that for some reason there are differences in the probability of synergy with chemical pulps of different origin. In order to study the role of surface chemistry in synergy some properties of these chemical pulps possibly affecting the bonding of pulp mixtures were studied. The normal pulp properties of the samples are shown in appendix 2.

The chemical pulps tested were:

Chemical pulp 1:	dried ECF bleached kraft pulp, freeness 375 ml
Chemical pulp 2:	dried ECF bleached kraft pulp after the renewal of chemical pulp mill, freeness 410 ml
Chemical pulp 3:	wet TCF bleached kraft pulp, freeness 365 ml

SC paper sheets containing chemical pulps 1 or 3 but not 2 had synergy with a mixture of suitable groundwood and TMP.

The tested chemical properties were
- total extractives and lignin content
- share of extractives and lignin in fibre surfaces with electron microscopy for chemical analysis (ESCA), methods of KCL/HUT
- precipitated lignin with atomic force microscopy (AFM), method of HUT

The results show that the chemical pulp which gave no synergy had a higher total lignin content and surface lignin share than the other pulps (tables 16 and 17). According to AFM figures chemical pulps 1 and 3 contained no precipitated lignin, but chemical pulp 2 contained supposed traces of precipitated lignin, in two figures out of ten. These chemical tests showed that the chemical pulp with no synergy contained more lignin and especially on fibre surface, which can deteriorate the bonding of the fibres and so cause non-existence of synergy. The importance of surface chemistry was not studied more because the results indicated that surface chemistry affected the behaviour of furnish mixtures primarily via the effect on bonding.

Table 16. Total extractives and Klason lignin of chemical pulp samples.

	Total extractives mg/g	Klason lignin %
Chem. pulp 1 (ECF)	0,03	1,4
Chem. pulp 1 (ECF)	0,02	1,9
Chem. pulp 3 (TCF)	0,02	1,2

Table 17. Coverage of extractives and lignin in the fibre surfaces of chemical pulp samples, measured with ESCA.

	Extractives %	Lignin %
Chem. pulp 1 (ECF)	3,2	4,1
Chem. pulp 2 (ECF)	3,2	5,6
Chem. pulp 3 (TCF)	5,7	3,6

5.6. Reliability of the results of lab studies

The lab studies of this thesis were carried out in the years 1995 – 2002. In spite of this relatively long interval only one experienced laboratory assistant made all the lab sheets and the testing of the lab studies, except the printability testing and the special testing completed outside Rauma. This kept the effect of the human factor on the deviations of the testing results at a minimum.

The right composition of the mixture sheets was essential since the synergy was often so small that even relatively small deviations from the target composition could have given misleading results and caused false conclusions. The right composition of the handsheets was checked and if it deviated too significantly from the target, the trial point was made again.

The statistical reliability of most testing was checked. The presented confidence intervals of different handsheet properties are mostly based on repeated central test points and so they include the total test deviation from sheet making to sheet testing. In some figures the results of repeated testing are presented.

In the lab studies of this research altogether 12 groundwood samples, of which three were PGW, 16 TMP samples and 16 chemical pulp samples were used. The groundwood samples were from four mill processes and one from a pilot process. TMPs were from four mill processes and chemical pulps from two chemical pulp mills. Altogether 18 combinations of different groundwood and TMP and 27 combinations of different groundwood, TMP and chemical pulp were studied. The number of different pulp samples and furnish combinations studied was considerably large. This together with the repeatedly found similar synergy in SC paper handsheets confirms the reliability of the results. On the contrary, the synergy results of LWC base paper were random in nature and thus less reliable. Surely part of the non-systematic synergy found in the LWC base paper study was random variation or a result of testing error and as such this synergy is difficult or even impossible to exploit in LWC paper production.

5.7. Synergy mechanisms - discussion and conclusions

The main objective of the lab studies was to research the validity of the hypothesis that a mixture of groundwood rich in fines and long-fibred TMP would be an optimum mechanical pulp over pure groundwood or TMP in high-quality mechanical printing papers, i.e. SC and LWC papers. Another objective was to study, if the mixture of groundwood and TMP would have synergy in paper and if so, which are the reasons and optimum conditions for synergy. In order to understand these phenomena, in addition to normal SC and LWC paper furnishes also the behaviour of different furnish mixtures used in mechanical printing papers was investigated.

The results of the lab studies showed that with the use of a mixture of fine groundwood and well-bonding TMP synergy advantages can be achieved in several properties of SC paper. Synergy was found especially in tear strength but to some extent also in stretch, tensile energy absorption and fracture energy. Synergy was also found in light scattering coefficient and calendering response in density, air permeability and median pore size. However, no synergy was found in the tensile strength or Scott-Bond of SC paper. In LWC base paper synergy similar to that found in SC paper handsheets did not exist and on the whole no synergy was probable in LWC base paper.

The reasons for and the conditions of the synergies found were studied. Most paper properties depend on several factors which change simultaneously when the mixing ratio of paper furnish components is changed. Therefore the synergy behaviour of furnish mixtures is regarded as natural /Retulainen 1992, 1997/. Tear strength first improves if bonding degree increases and bond breakage is the principal mechanism in paper fracture. However, at high enough a bonding degree fibre breakage becomes significant in paper fracture, and tear strength turns to a decrease, the earlier the higher the fibre length is. In groundwood-based sheet the density, i.e. bonding degree, had small effect on tear strength while in TMP-based sheet the effect was more obvious. In long-fibred TMP based SC paper sheet the optimum bonding degree for tear strength is easily passed whereas it is less probable in shorter-fibred groundwood based SC paper sheet. Also fracture energy, stretch and tensile energy absorption, in which synergy was found, depend on both fibre length and bonding. Thus, a certain mixture of groundwood and TMP can have an optimum combination of fibre length and bonding for these strength properties and synergy advantage can be achieved. In the case of synergy the strength of purely TMP based paper is poorer than its fibre length would make possible. In tensile strength or Scott-Bond, depending mostly on bonding, no synergy exists in paper with a mixture of groundwood and TMP.

Most SC/LWC grade pulps, both mechanical and chemical, had a bonding degree beyond their tear strength maximum. However, the mixtures of SC/LWC grade mechanical and chemical pulps could have synergy advantage in tear strength. The synergy advantage in tear strength and disadvantage in tensile strength with a mixture of mechanical and chemical pulps is commonly reported in literature, e.g. by Mohlin /Mohlin et al. 1983/. It seems that the mixture behaves as if chemical pulp would bond less than additively. This could be caused by the bulky fibre network of mechanical pulp which decreases the bonding of chemical pulp fibres /Mohlin et al. 1983, Retulainen 1992, Alava et al. 1997/. In this study the density difference of mechanical and chemical pulps, which affects bonding, was found to be the main reason for the synergy of their mixtures. When the results were interpolated to constant density most synergies disappeared though differences between pure mechanical and chemical pulps still existed.

The mixtures of SC/LWC grade groundwood and TMP usually had no synergy in a mixture with chemical pulp in tear strength, probably because furnish mixtures based on both these mechanical pulps had tear strength clearly beyond the maximum and usually also their density difference was small. However, when a share of filler typical to SC paper was added to these furnish mixtures, the situation changed. The furnish mixtures based on groundwood or TMP could have their bonding degrees on the opposite sides of the tear strength maximum. Usually groundwood based paper had a bonding degree below and TMP based paper could have a bonding degree beyond the tear strength maximum. Consequently a mixture of groundwood and TMP could have synergy in SC paper. Thus in SC paper with this mixture of groundwood and TMP an optimum combination of fibre length and bonding for strength properties could be achieved. Still, groundwood-based paper had higher Scott-Bond, about 200 – 210 J/m^2, than TMP-based paper, about 160 J/m^2. If the groundwood-based and TMP-based SC papers had a bonding degree clearly on the same side of the tear strength maximum, no synergy existed.

In this research most furnish mixtures had their tear strength maximum at a Scott-Bond level of about 160 – 210 J/m^2. When different paper furnishes had bonding levels on the opposite sides of their tear strength maximums their mixture could have synergy advantage in tear strength. Synergy in fracture energy, stretch and tensile energy absorption was usually achieved when synergy existed in tear strength. Thus, it can be concluded that these synergies were caused by quite similar reasons as synergy in tear strength.

The strength synergies were clearest in SC paper at about a 30 % chemical pulp share of fibre when the Scott-Bond level was about 160 - 210 J/m^2. Less synergy was found at the lower 20 % chemical pulp share and no synergy at the higher 38 % share, where Scott-Bond was outside the 160 – 210 J/m^2 interval and fibre length differed from normal SC paper furnish. In LWC base paper, because of lower filler content, both groundwood-based and TMP-based furnishes had bonding degrees well beyond the tear strength maximum and similar synergy was not found.

In addition to the optimum bonding degree vs. fibre length and density difference some other factors were also found to affect the synergy in strength properties. These all affect bonding. A difference in drying shrinkage can cause a breakage of fibre bonds and affect synergy. In the case of synergy TMP had low fibre stiffness and high WRV, which both indicate good bonding ability. Higher lignin content, especially precipitated surface lignin, can deteriorate the bonding of chemical pulp fibres and so reduce the probability of synergy with a mixture of groundwood and TMP in SC paper.

The synergies found in light scattering coefficient and calendering response in density, air permeability and pore size distribution were mostly achieved with the same paper furnishes as synergy in tear strength. The results indicate that groundwood-based SC paper sheet rich in fines can be too dense and well bonded and TMP-based SC paper can be too poor in fines and too porous for light scattering coefficient and calendering response. Therefore a mixture of suitable groundwood and TMP can result in SC paper optimum fines content, bonding and sheet structure for high light scattering coefficient and calendering effect. This optimum can correspond the limiting state of fines content and maximum fibre density in paper sheet, as indicated by the results of Retulainen and Görres /Retulainen et al. 1993, Görres et al. 1996a, 2001/.

In SC paper in different sheet properties the optimum, i.e. the maximum synergy, was achieved at different TMP shares of mechanical pulp. Maximum in light scattering coefficient was achieved at the lowest TMP share, about 20 – 50 %, the biggest calendering effect at about a 50 % TMP share and tear strength maximum was achieved at a 50 – 80 % TMP share of mechanical pulp. This could be caused by the different need of fines and bonding.

The results showed that the synergies found are most sensitive, on one hand, to pulp qualities and their mixing ratios and, on the other hand, to the need of bonding. The need of bonding depends on the basis weight of paper. Any change in either the bonding degree vs. fibre length or the need of bonding can change the conditions favourable or unfavourable for synergy.

Usually the synergy of a mixture of groundwood and TMP in paper was clearest when the TMP was well-bonding and the chemical pulp was suitably bonding. The quality of low freeness groundwood seemed to have less importance. The need of bonding in paper depended on sheet basis weight.

The synergy results of the mixtures of groundwood and TMP are consistent with a few other studies. Bovin /Bovin et al. 1971/ found that synergy in tear strength exists when the paper components have bonding degree on different sides of their tear strength maximum. They regarded this as valid for mixtures of chemical pulps or one pulp refined to different degrees. The results of the current study show that Bovin's explanation can probably be applied to any furnish mixture having a suitable bonding level versus fibre length. The explanation can also be applied to other paper properties than just tear strength. Parsons /Parsons 1969/ found that the tear strength of a pulp or pulp mixture at certain fibre length has its maximum at a certain Scott-Bond level. This and the results of Shallhorn and Retulainen support the results of this study /Shallhorn et al. 1979, Retulainen 1996a/.

The lab studies showed that the using a mixture of groundwood rich in fines and long-fibred TMP can be beneficial in high-quality mechanical printing papers, at least in SC paper. With a suitable mixture of groundwood and TMP even some synergy advantages can be achieved in SC paper, but probably not in LWC paper. The strength synergy allows a smaller than calculated chemical pulp share in paper. This together with the synergies found in light scattering coefficient and calendering behaviour can improve paper printability. The lower need of chemical pulp would also decrease paper furnish costs.

6. RESULTS OF MILL STUDIES

Mill trials were run at Rauma paper mill on each four paper machines, both on SC and LWC paper, both on normally groundwood-based and TMP-based papers.

6.1. Mill trials on groundwood-based SC paper

Since 1994 Rauma PM2, which produces groundwood-based SC paper, had used about a 10 % TMP (TMP1) share in mechanical pulp. This TMP was made for SC offset paper. Thus, the TMP used on PM2 was not optimized for groundwood-based SC rotogravure paper and its freeness level was clearly higher than that of groundwood.

6.1.1. First trial

The first mill trial with a mixture of groundwood and TMP was run on PM2 on groundwood-based SC rotogravure paper in January 1996 and the trial lasted three days. The trial was started with that time normal 10 % TMP share of mechanical pulp. The target was to increase the TMP share of mechanical pulp in several stages up to 50 % (table 18). This was the maximum TMP dosage in practise, restricted by pumps. Several relatively short trial points, 7 to 16 hours, with different TMP shares of mechanical pulp were run as this was considered practical in order not to disturb the papermaking process too much with big changes and as the individual trial points were regarded as long enough. The changes in paper furnish from one trial point to another were made within a few hours. At the end of the trial the paper machine was run without any TMP dosage. During the trial the mechanical pulp mixture was bleached with dithionite and post refined together. The chemical pulp was ECF bleached kraft pulp.

The real TMP share of mechanical pulp, which calculated from the fibre lengths of the individual mechanical pulps and their mixture, was mostly somewhat smaller than the target (table 18).

Table 18. The accomplished test points with a mixture of groundwood and TMP and their schedule in the first mill trial on groundwood-based SC rotogravure paper.

Trial point	**TMP share of mechanical pulp**		**Duration**
	Target	**Calculated**	
1	10 %	7 %	16,5 h
2	20 %		7,5 h
3	36 %	29 %	14,0 h
4	50 %	42 %	9,5 h
5	10 %	14 %	12,0 h
6	0 %	0 %	9,0 h

The pulp and paper qualities were tested frequently according to their normal testing schemes in the process laboratory of the paper mill. In addition, in every trial point the mechanical and chemical pulps, broke and wet web samples from the press section of paper machine were tested. The web samples would show the real composition of paper furnish. Also some additional paper testing and a printing trial in a commercial rotogravure printing house were done.

Paper furnish and strength properties

During the first mill trial the length weighted average fibre length of TMP was 1.46 mm, which was about 0.15 mm bigger than normally in those days, that of groundwood 0.74 mm and that of the refined chemical pulp 1.93 – 1.99 mm, which was 0.10 mm lower than normally. The pulp qualities in the different trial points are shown in appendix 3. TMP dosage increased the long fibre fraction of mechanical pulp by four percentage points at the maximum and reduced fines content by an equal amount. The freeness of TMP was clearly higher than that of groundwood, 47 vs. 29 ml on average, respectively. The TMP dosage increased mechanical pulp freeness in the feed of post refiner up to 42 – 44 ml. As a result the freeness drop in post refining became too big to achieve good printability. The use of TMP increased the freeness of mechanical pulp mixture in dosage from 30 – 32 ml to 35 ml. The TMP dosage did not affect the density or air permeability, tensile strength or tensile energy absorption of mechanical pulp. TMP clearly increased the tear strength and decreased Scott-Bond and light scattering coefficient of mechanical pulp. In spite of the big difference in the fibre lengths of groundwood and TMP, the biggest TMP dosage increased the fibre length of machine chest pulp only by about 0.10 mm. This was caused by the decreased chemical pulp dosage. The fibre length of paper, measured from wet web coach trimmings sample, increased in the trial by 0.14 mm from 1.18 mm to 1.32 mm.

For the whole trial run the paper machine made 56 g/m^2 SC rotogravure paper. When the trial was started with the normal 10 % TMP share of mechanical pulp, for some reason the strength of paper deteriorated and that demanded the increasing of chemical pulp dosage up to 22 % (fig. 75). When the TMP share was increased the counter direction (cd) tear strength of machine paper improved but the machine direction (cd) tensile strength improved only slightly (table 19). As on this paper machine the strength targets are set to both cd tear strength and md tensile strength of machine paper the improved tear strength could not be exploited. Because of this during the biggest TMP dosage the freeness target of chemical pulp was lowered from 460 to 400 ml. Then the cd tear strength of machine paper was still above the target and also the md tensile strength of machine paper increased above the target. The chemical pulp dosage could be clearly reduced down to 18 %. Still both the strength properties of paper were above their targets, i.e. the chemical pulp dosage could have been reduced still slightly more. When the TMP share of mechanical pulp was returned back to the normal 10 %, the chemical pulp dosage had to be increased back to the original level, about 22 %.

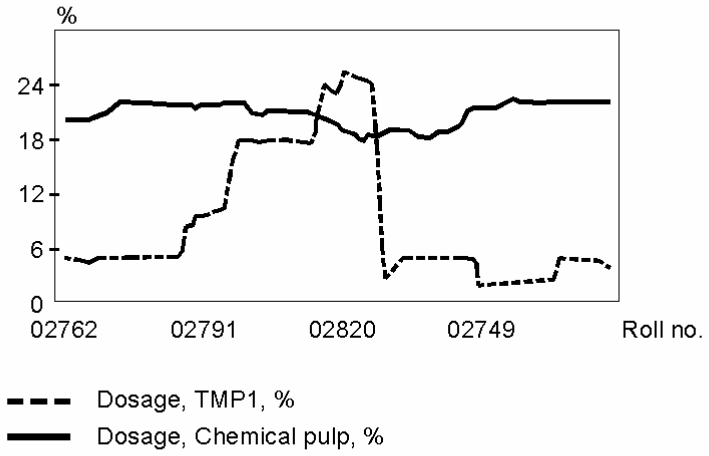

Figure 75. The TMP and chemical pulp dosages, i.e. percent of paper containing about 32 % filler as ash, on PM2 during the trial run.

Table 19: Average properties and their 95 % confidence interval of 56 g/m^2 SC rotogravure paper in different trial points. In each trial point 9 – 22 tests of machine paper and 4 -12 tests of different SC paper properties were done.

Trial point	1		2		3		4		5		6	
TMP share, %	**10**		**20**		**36**		**50**		**10**		**0**	
	Av.	± 95 %	Av.	± 95 %	Av.	± 95 %	Av.	± 95 %	Av.	± 95 %	Av.	± 95 %
Machine paper												
Tear strength cd, mN	279	20	285	20	291	23	288	13	274	13	277	23
Tensile strength md, kN/m	2,17	0,13	2,17	0,13	2,2	0,13	2,26	0,13	2,23	0,15	2,17	0,13
Stretch, %	0,9	0,3	0,9	0	0,9	0,3	0,9	0,3	0,9	0,3	0,8	0
Tensile strength ratio md/cd	2,63	0,23	2,62	0,18	2,67	0,3	2,68	0,15	2,63	0,15	2,59	0,15
Brightness, %	74,4	0,5	74,5	0,5	73,1	0,5	73,2	0,5	74	0,8	74,2	0,5
Opasity, %	94,8	0,8	94,7	0,3	95,6	0,5	95,6	0,5	94,9	0,8	95,1	0,5
Air permeability, ml/min	154	13	155	15	164	18	160	13	150	20	159	15
Formation (var. coeff.), %	6,5	0,8	6,6	0,5	6,5	0,5	6,5	0,5	6,1	0,3	6,1	0,8
SC paper												
Tear strength cd, mN	208	25	199	13	213	23	214	15	192	13	200	15
Tensile strength md, kN/m	2,24	0,2	2,31	0,28	2,36	0,28	2,38	0,33	2,29	0,18	2,26	0,23
Density, kg/m³	1196	53	1163	75	1205	45	1202	30	1200	25	1175	73
Air permeability, ml/min	14	3	14	3	15	3	13	3	14	3	15	3
Gloss ts, %	48,7	2,5	48,5	2,0	48,3	2,0	48,1	1,8	48,6	1,8	48,4	4,0
Gloss bs, %	49,3	3,0	49,3	3,0	49,3	2,3	49,3	1,8	49,5	2,3	49,1	3,0
PPS-10 ts, um	0,92	0,10	0,90	0,05	0,91	0,03	0,89	0,03	0,86	0,08	0,86	0,10
PPS-10 bs, um	0,91	0,05	0,93	0,08	0,95	0,08	0,93	0,05	0,92	0,05	0,90	0,10
Unger ts, g/m²	3,6	0,5	3,4	0,5	3,7	0,5	3,3	0,3	3,6	0,5	3,8	1,0
Unger bs, g/m²	3,9	0,3	3,8	0,8	4,0	0,8	3,8	0,3	4,0	0,5	4,3	0,8
Brightness, %	69,0	0,5	69,1	0,8	67,8	0,8	67,9	1,0	68,8	0,5	68,8	0,5
Opasity, %	91,1	0,8	90,9	1,5	92,4	1,3	92,1	0,8	91,7	0,5	91,8	1,0

Paper quality

When the TMP share of mechanical pulp was increased, the air permeability of machine paper tended to increase (table 19), probably as a result of the coarser mechanical pulp. However, when chemical pulp was refined more and its dosage was decreased, the air permeability of machine paper decreased to the original level. With the biggest TMP share the air permeability of finished paper had its lowest value, though calendering conditions were kept constant. This calendering response showed also in the pore size distribution of paper, measured with Coulter porosimeter at KCL. The TMP share had no effect on the pore size distribution of machine paper but in supercalendered paper the average pore size decreased when TMP share was increased (fig. 76). Also the K&N colour absorption was smallest with the biggest TMP share. With the increase of the TMP share the PPS roughness of paper tended to increase, especially on wire side, i.e. the two-sidedness of paper roughness increased. According to optical roughness profile measurement (UBM), made at KCL, the roughness of supercalendered paper increased with the increase of TMP share in wave length area above 0.5 mm, where the roughness is affected by fibre properties. The roughness decreased below about 250 µm area, where it is affected by the settling of fines and filler into paper structure (fig. 77). With the increase of TMP share paper gloss tended to decrease and black calendering to increase, probably because of the coarser TMP. During the biggest TMP dosage the opacity of paper was one percentage point higher because of lower brightness and the opacity/brightness ratio was slightly worse than with pure groundwood.

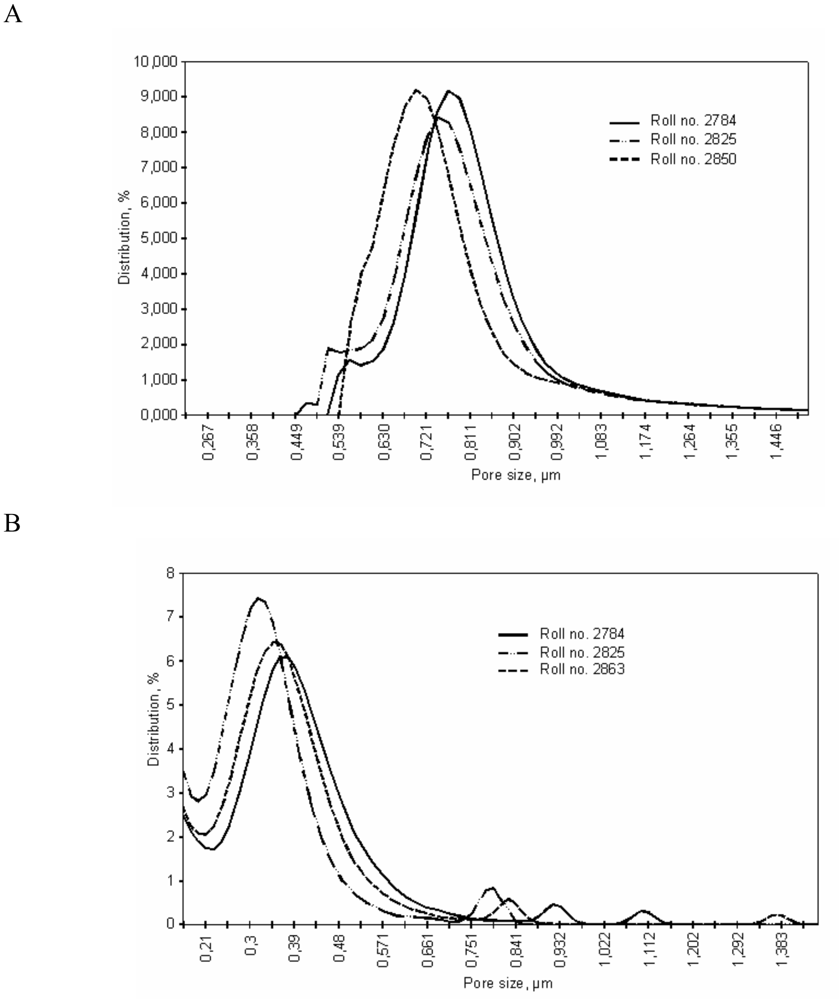

Figure 76. Coulter pore size distributions of the machine paper (A) and finished paper (B) of PM2 with different TMP shares of mechanical pulp.

Rolls no. 2850 and 2863:	TMP share 0 %
Roll no. 2784:	TMP share 10 %
Roll no. 2825:	TMP share 50 %

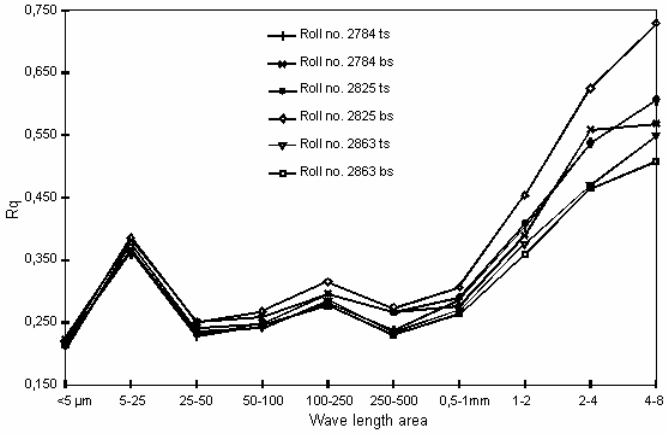

Figure 77. Optical roughness profile (UBM) of the finished paper of PM2, top side (ts) and bottom side (bs) in machine direction, with different TMP shares of mechanical pulp.

Roll no. 2863: TMP share 0 %
Roll no. 2784: TMP share 10 %
Roll no. 2825: TMP share 50 %

The changes in the air permeability of paper were probably caused by the differences in the fibre length distributions of groundwood and TMP and the higher freeness of TMP. Under constant circumstances the paper containing most TMP calendered best in respect of air permeability but not roughness. For air permeability this result was in agreement with the lab studies. In the mill trial also the decrease of chemical pulp dosage in paper and the decrease of its freeness may have affected the results.

In commercial printing the differences between trial points were negligible. The TMP share of mechanical pulp had a small deteriorating effect on the printability of SC rotogravure paper (table 20). The printing evenness was best without any TMP. The printed gloss and print-through were slightly better with no TMP than with 50 % TMP. With a 0 – 10 % TMP share there were less missing dots in printed paper than in paper containing a 50 % TMP share.

Table 20. Printing results of SC rotogravure paper (56 g/m^2) from a commercial printing house.

Machine roll	2863	2784	2794	2825
TMP share, %	**0**	**10**	**20**	**50**
Compact four colours				
Density, D ts	1,7	1,67	1,71	1,69
Density, D bs	1,7	1,69	1,67	1,69
Print-through D ts	0,058	0,053	0,056	0,056
Print-through D bs	0,06	0,066	0,063	0,058
Print-through, % ts	3,4	3,2	3,3	3,3
Print-through, % bs	3,5	3,9	3,8	3,4
Gloss, % ts	71,3	71,3	70,6	70,5
Gloss, % ws	69,4	68,2	69,1	68,3
Print evenness ts	2,33	2,32	2,28	2,45
Print evenness bs	2,99	3,01	2,94	3,01
Compact 1 colour black				
Density, D ts	1,38	1,39	1,38	1,37
Density, D bs	1,38	1,37	1,37	1,37
Print-through D ts	0,056	0,061	0,06	0,055
Print-through D bs	0,056	0,058	0,059	0,058
Print-through, % ts	4,1	4,4	4,4	4
Print-through, % bs	4,1	4,2	4,3	4,2
Gloss, % ts	54,2	49,4	50,9	50,1
Gloss, % ws	48,9	48,1	49,4	50
Print evenness ts	2,24	2,4	2,48	2,44
Print evenness bs	2,34	2,41	2,34	2,34
Missing dots	1	1	4	3
Ranking	**1**	**1**	**4**	**3**

When planning this first mill trial, the furnish changes were assumed to show in the headbox of the paper machine in less than an hour and in paper quality soon after that. The trial schedule with several relatively short trial points was planned on this assumption. However, in the whole trial run changes in the TMP share of mechanical pulp showed surprisingly slowly in the paper quality and the needed chemical pulp dosage. The furnish changes made showed totally in paper properties only after 6 to 14 hours. This slow change could be caused by the large white water system and the slow levelling of fines balance in it. Also the slow change of broke quality could be a partial reason for this phenomenon. Because of the slow change of paper quality after the changes of mechanical pulp the qualities of only a few last paper rolls of each trial point were compared. This concerns also the later trial runs. On the basis of this result longer and fewer trial points were run in the later mill trials.

The first mill trial showed that TMP addition to groundwood-based SC rotogravure paper tends to improve more the cd tear strength than md tensile strength of paper. After adjusting chemical pulp freeness both strength properties were above the target and this allowed a clear decrease in chemical pulp dosage because of synergy and made paper easier to calender to get low porosity. However, in this trial the clearly higher freeness of TMP compared to groundwood was probably the reason for the deteriorated surface properties and printability of SC rotogravure paper. A low freeness TMP with well refined long fibres would be an interesting component in the furnish of this paper machine, i.e. Rauma PM2.

6.1.2. Second trial

The second mill trial on PM2 was run in April 1998. It was planned based on the results and experiences of the earlier trials. Consequently, this trial run was clearly longer using only one TMP share level in order to find long term effects. For over a week's period between 27 April 1998 and 5 May 1998 a 20 - 25 % TMP share of mechanical pulp was used on Rauma PM2. This longer trial was made possible by the increased TMP capacity and some pulp changes between paper machines. The TMP used was well-bonding LWC grade pulp from a new line (TMP4). The freeness level of TMP4 was lower than that of TMP1 and so nearer that of the groundwood used on PM2, about 40, 45 and 32 ml, respectively. During the reference period in April before the start of this trial an 8 % share of SC offset grade TMP from the older line (TMP1) was used in the mechanical pulp of PM2. Earlier practical experiences had shown that even a 10 % TMP share decreases the need of chemical pulp in SC paper by 2 – 3 percentage points. The chemical pulp was ECF bleached kraft pulp.

The results of the second mill trial were followed only by the normal mill testing of pulps and paper quality.

Paper furnish and strength properties

In the second mill trial on groundwood-based SC rotogravure paper the increasing of the TMP share of mechanical pulp from 8 % TMP1 in reference point to 20 - 25 % TMP4 increased the length weighted average fibre length of mechanical pulp from 0.85 to 1.00 mm. During the trial the fibre length of chemical pulp was about 0.05 mm shorter than during the reference period. In the trial fibre length in the machine chest was 0.07 – 0.09 mm higher, at different basis weights of paper, than during the reference period, in spite of the smaller chemical pulp fibre length and its reduced dosage. During the trial the tensile strength of groundwood was clearly better and that of chemical pulp clearly worse than during the reference period.

The use of a 20 – 25 % share TMP4 in mechanical pulp instead of 8 % TMP1 allowed the decrease of chemical pulp dosage on paper machine by 5 percentage points on average (table 21).

Table 21. Chemical pulp dosage on PM2 during the 20 – 25 % TMP share and in reference situation with 8 % TMP share at different basis weights.

Basis	**Chemical pulp dosage**		
weight	**Reference**	**Trial**	**Change**
g/m²	**%**	**%**	**% units**
49	22,8	18,3	-4,5
52	20,9	16,0	-4,9
56	20,0	14,5	-5,5

Both during the trial and the reference period the md tensile strength of machine paper was clearly higher than the target (table 22). Cd tear strength was constant for both the trial and the reference period. With the increased TMP dosage the tensile ratio (md/cd) increased but otherwise the quality of paper, i.e. strength properties, air permeability, surface and optical properties, stayed constant. During the trial and also some time before it since 15 April the broke time on the paper machine was clearly lower than earlier. With the 20 – 25 % TMP share the chemical pulp dosage needed in paper was, because of synergy, nearer that of purely

TMP-based SC offset paper than that of purely groundwood-based SC rotogravure paper at the same basis weight.

Table 22. SC paper quality during the 20 – 25 % TMP share trial and reference of 8 %.

	49 g/m^2		52 g/m^2		56g/m^2	
	Trial	**Ref.**	**Trial**	**Ref.**	**Trial**	**Ref.**
Tensile strength, kN/m	2,34	2,3	2,33	2,28	2,46	2,46
Tear strength, mN	207	206	204	203	216	215
Density, kg/m^3	1156	1153	1197	1192	1237	1226
Air permeability, ml/min	20	18	16	16	13	13
Gloss ts, %	44,1	44,1	46	45,9	48,1	48,7
Gloss bs, %	44,8	44,7	46,8	47,4	49,5	49,8
PPS10, ts, um	1,01	1	0,97	0,95	0,93	0,91
PPS10, bs, um	1,01	1,09	0,95	0,99	0,92	0,92
Unger ts, g/m^2	4,1	3,9	3,8	3,8	3,5	3,5
Unger bs, g/m^2	4,4	4,2	4,1	4	3,7	3,9
Brightness, %	65	65,3	68	68	68,9	69,2
Opasity, %	91,4	91,6	90,5	90,4	91	91

6.2. Mill trial on TMP-based SC paper

A mill trial with a mixture of TMP and groundwood was run on TMP-based SC offset paper on PM3 in March 1996. The mechanical pulp used on this paper machine normally at the time of this trial was a mixture of TMP1 and TMP2. The share of TMP1 was refiner bleached with dithionite. On PM3 about 10 – 15 % of the mechanical pulp mixture was bleached with peroxide and after that all mechanical pulp further with dithionite.

In the trial on TMP-based SC offset paper in two stages up to 50 % of TMP was replaced with groundwood normally used in SC rotogravure paper. The freeness of this groundwood was clearly lower than that of the TMP. The mechanical pulp mixture went to normal bleaching and post refining on PM3. The chemical pulp was ECF bleached kraft pulp.

In addition to normal pulp and paper testing mechanical and chemical pulps, broke and wet web samples from press section were tested in every test point.

Paper furnish and strength properties

The mill trial on TMP-based SC offset paper lasted 36 hours and had only two relatively long trial points with different groundwood shares. Based on the fibre lengths of mechanical pulp mixture and individual mechanical pulps the calculated real groundwood shares of mechanical pulp were smaller than the target (table 23).

Table 23. Trial points run and their schedule.

	Groundwood share of mechanical pulp		
Trial point	**Target**	**Calculated**	**Duration**
1*	0 %	0 %	
2	25 %	13 %	16,0 h
3	50 %	43 %	20,0 h

* reference point before groundwood dosage

At the biggest groundwood share the length weighted average fibre length of mechanical pulp on PM3 decreased from original 1.42 mm to 1.11 mm. This decreased mechanical pulp long fibre fraction (Bauer-McNett +28 fraction) by 7 percentage points, but only slightly increased fines content. With the increased groundwood share the freeness of mechanical pulp decreased from 45 to 33 ml. So at the biggest groundwood share the quality of mechanical pulp differed significantly from the normal level on that paper machine. This mechanical pulp mixture was more porous and had poorer tear and tensile strengths but better light scattering coefficient than pure TMP. Pulp qualities in different trial points are shown in appendix 4.

The replacement of half of TMP with groundwood decreased the fibre length of machine chest pulp by about 0.20 mm and that of paper, measured from wet web coach trimmings from press section, by 0.25 mm from 1.58 to 1.33 mm, in spite of the increase of chemical pulp dosage.

For the whole trial run the paper machine made 56 g/m^2 SC offset paper. On PM3 the chemical pulp dosage is controlled using both the cd tear and md tensile strength of machine paper. At the beginning of the trial with a 0 % groundwood dosage the chemical pulp percentage in paper was 13.5 % (fig. 78). When the groundwood share of mechanical pulp was increased to 25 % both the md tensile and cd tear strength of machine paper tended to deteriorate slightly. However, the strength properties of finished SC paper stayed constant and the chemical pulp dosage could be kept practically constant. At a bigger, 50 %, groundwood share the chemical pulp dosage was increased up to 16.8 %, in which case the cd tear strength of paper was still only slightly poorer than originally but the md tensile strength was clearly worse. To achieve better tensile strength the chemical pulp was refined more to 50 ml lower freeness, to 400 ml. However, this did not give additional tensile strength to paper. At the end of the trial the groundwood share was decreased to 12 % and the chemical pulp dosage was decreased to 14.5 %. Then both the cd tear and especially md tensile strength of paper improved but remained lower than at the beginning of the trial. Thus, in the trial about 25 % of TMP could be replaced with groundwood without need to increase the chemical pulp dosage. At a bigger groundwood share the deterioration of the md tensile strength of paper could not be compensated with extra chemical pulp or by refining it more. Also this trial showed that in SC paper the mixture of groundwood and TMP could have synergy in tear strength but not in tensile strength.

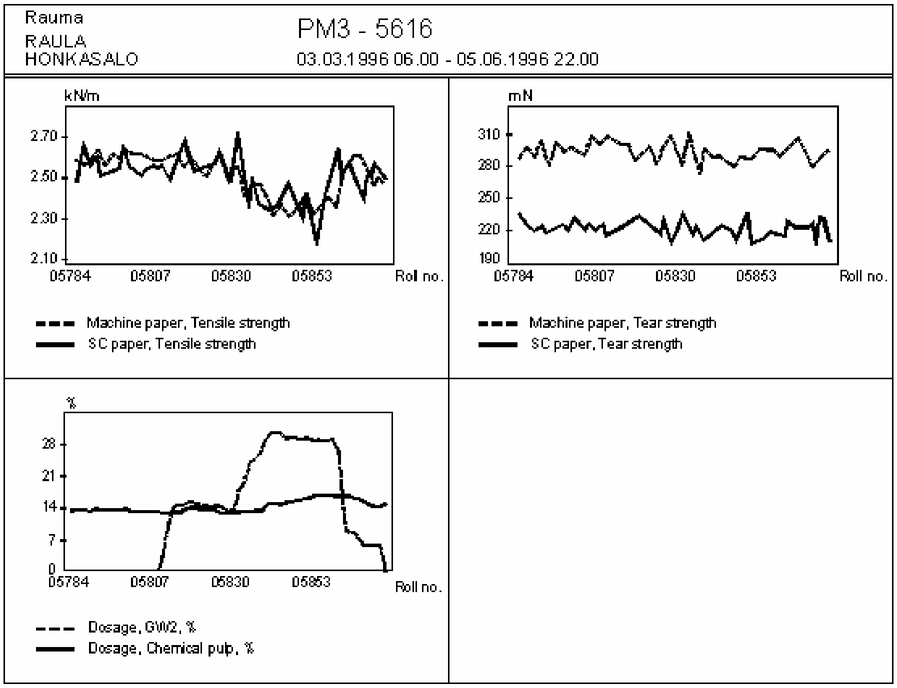

Figure 78. Pulp dosages and strength properties of machine paper and final 56 g/m² SC offset paper in the trial.

Paper quality

The partial replacing of TMP with fine groundwood in SC offset paper tended to increase the air permeability of machine paper but that of finished paper only at the very beginning of the trial (fig. 79). The PPS roughness, gloss and opacity of SC paper tended to improve slightly but brightness deteriorated.

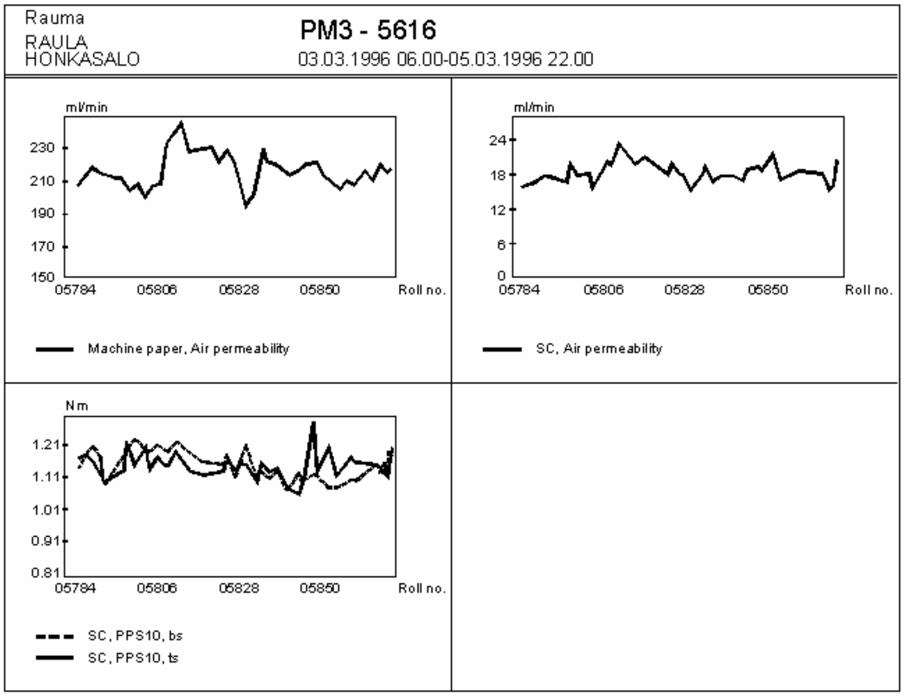

Figure 79. Air permeability of machine paper and SC paper and the PPS10 roughness of SC paper during the trial.

Also in this trial on TMP-based SC offset paper, like in earlier trials on groundwood-based SC rotogravure paper, even big changes in mechanical pulp showed very slowly in paper properties and the needed chemical pulp dosage, totally only after more than 10 hours.

6.3. Mill trial on TMP-based LWC paper

The first mill trial on LWC paper with the mixtures of TMP and groundwood was run to study the possibilities to improve the printability of purely TMP-based LWC offset and rotogravure papers. This mill trial was run in 1999. The mechanical pulp of TMP-based LWC paper was planned to be replaced totally with LWC grade groundwood in two stages. This demanded some new pipelines and pumps. The chemical pulp was ECF bleached kraft pulp. The test points with a mixture of groundwood and TMP and with pure groundwood each lasted approximately two days (table 24). The whole trial with reference points before and after groundwood dosage lasted one week. This trial run was possible during a stop on the other LWC paper machine, which uses groundwood as mechanical pulp.

Table 24. Trial points run and their schedule.

	Groundwood share of mechanical pulp		
Trial point	**Target**	**Calculated**	**Duration**
1*	0 %	0 %	
2	50 %	40 %	50 h
3	100 %	100 %	35 h
4*	0 %	0 %	

* reference points before and after groundwood dosage

During the trial fresh water had to be fed to the groundwood mill which was running at its maximum capacity, in order to keep process temperatures in the groundwood mill normal. The mechanical pulp of PM4 was totally peroxide bleached.

Quality monitoring

During the trial pulp and paper properties were monitored with routine process control laboratory testing, additional research laboratory testing, and on-line measurements. The mechanical pulps and their mixture, the chemical pulp, machine chest pulp and broke were also tested in each trial point.

Changes in the chemical balance at the wet end of papermaking process were expected as pulp components were changed. To avoid any problems a more extensive testing than normally was conducted at the wet end of the paper machine.

The runnability of paper was characterized with wet end chemistry as pH, charge, turbidity and the chemical residue contents of the pulps, water removal on paper machine and the breaking tendency and strength properties of paper.

Each paper machine roll and finished paper roll was tested at Rauma with PaperLab automatic paper tester for basic strength, surface, bulk and optical properties. In addition, moisture and ash content, surface strength, internal bond and ink absorption were tested manually. Base paper samples were taken in every test point. The fracture energy, apparent tensile strength, optical roughness profile and pore size distribution of base paper samples were tested at KCL.

One finished paper roll of each test point was trial printed at KCL´s heatset web offset pilot printing press. The printed samples were evaluated visually and tested in laboratory. All special testing and trial printing done outside the paper mill was completed from the end of each test point as the process was stabilized.

Furnish

When TMP (TMP4) was changed to groundwood, the length weighted average fibre length of mechanical pulp decreased from 1.51 mm with 100 % TMP first to about 1.15 mm with the mixture and finally to 0.79 mm with 100 % groundwood (fig. 80). In pure TMP the long fibre fraction (+28) was 26.9 % and 31.5 % in the reference points before and after the trial. This fraction decreased to 20.3 % in the mixture point and to as low as 10.7 % in pure groundwood. The fines content increased in mechanical pulp from 27.6 - 28.6 % to 30.6 % with the mixture and to 34.7 % with pure groundwood. The groundwood had clearly higher freeness than the TMP. Thus, replacing TMP with groundwood increased the freeness of mechanical pulp from 39 - 43 ml to 53 ml. This slightly decreased the density of mechanical pulp and clearly increased air permeability from 31 – 39 to 87 ml/min. Especially the tear strength, fracture energy, tensile energy absorption and initial tensile strength, but also the tensile strength of mechanical pulp decreased. TMP and groundwood had the same Scott-Bond but the mixture had the highest value. Groundwood had clearly bigger light scattering coefficient than TMP. Pulp qualities in different trial points are shown in appendix 5.

During groundwood dosage chemical pulp was refined slightly more than normally to about 560 ml freeness. Simultaneously with the increased groundwood share the long fibre fraction of chemical pulp increased from 52.6 % to 59.4 % though chemical pulp was refined more. During the trial run a relatively large amount of both uncoated and coated broke, 24.4 to 35.1 % in total, was dosaged into machine chest. This broke was first mainly TMP-based and so in the mixture point only about 40 % of mechanical pulp really was groundwood. At the end of the pure groundwood point the real TMP share of mechanical pulp was already nearly 100 %. The big change in mechanical pulp from pure TMP to pure groundwood showed only slightly in the fractions or average fibre length of machine chest pulp, which decreased from 1.80 – 1.87 mm to 1.62 mm (fig. 80). The freeness of machine chest pulp increased simultaneously from 153 – 162 ml to 180 ml.

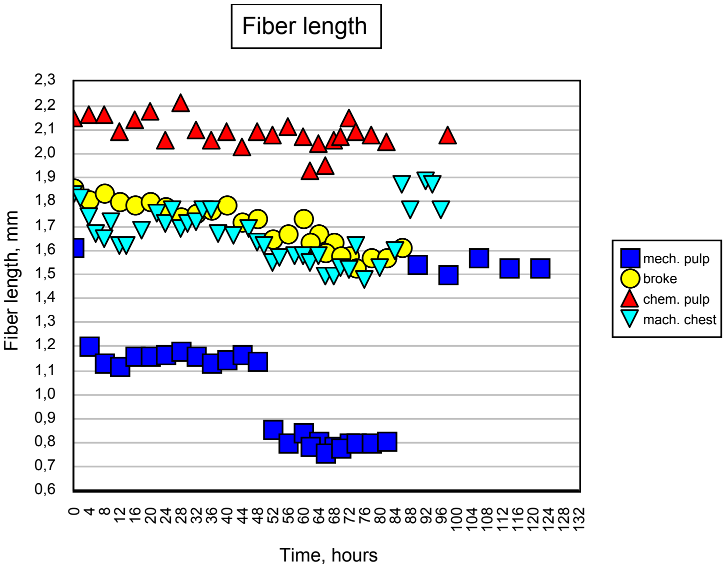

Figure 80. Average fibre length of different pulps during the paper machine trial. Time on the x-axis starts at the beginning of the mixture point, when the dosage of groundwood was started.

On PM4 chemical pulp dosage is controlled by the cd tear strength of machine paper. Because the trial points were relatively short, the chemical pulp dosage in different points was first set according to preliminary estimates. Thus, to get a reliable figure of the effect of mechanical pulp on paper making both the chemical pulp share and the strength properties of paper should be studied.

The total change from TMP to groundwood as mechanical pulp affected the quality of machine chest pulp less than expected. The increase of the share of the coarser groundwood increased the air permeability of machine chest pulp. Most strength properties of machine chest pulp remained quite constant, except Scott-Bond, which improved and had a maximum with the mixture. The replacing of TMP with groundwood improved the light scattering coefficient of machine chest pulp.

Paper properties

During the trial the paper machine made 54 to 60 g/m^2 LWC papers. The use of groundwood did not affect the break frequency on the paper machine and no difficulties in wet end chemistry were experienced. It was difficult to evaluate the effect of the mechanical pulp quality on the paper since at the same basis weight, in reference points before and after the groundwood dosage, the need of chemical pulp in paper was totally different. In 60 g/m^2 LWC paper 40 % chemical pulp was dosaged in the first reference point as well as with the mixture, with 100 % groundwood 43 % chemical pulp was needed and in the second reference point 45 % (fig. 81). However, at a certain chemical pulp content in 60 g/m^2 paper the best cd tear strength of machine paper was achieved in reference points (fig. 82). At other basis weights, 57 and 54 g/m^2 the situation was more volatile.

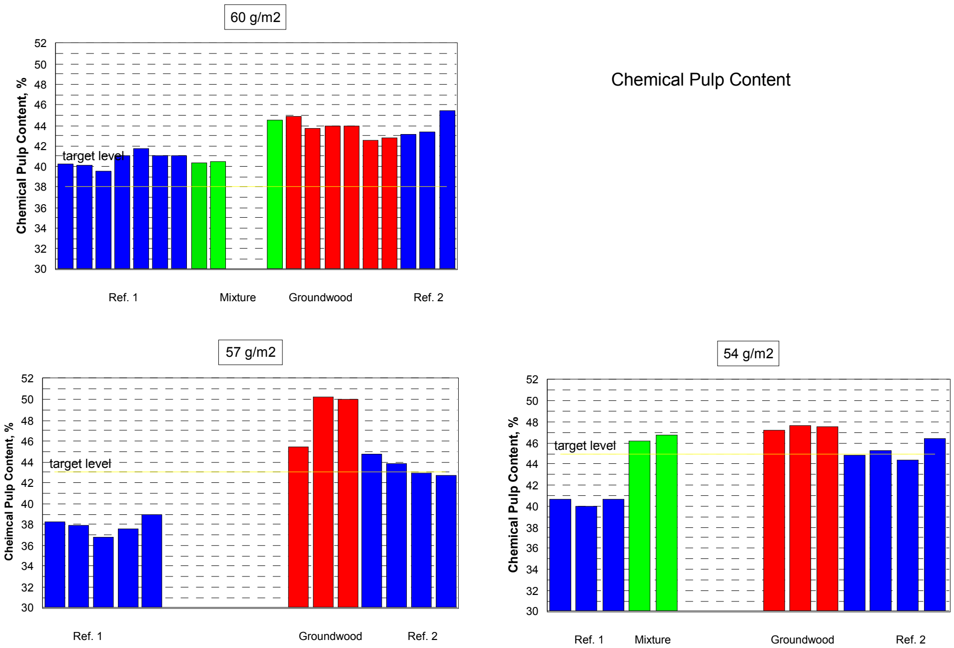

Figure 81. Chemical pulp content in paper at the end of each test point at different basis weights.

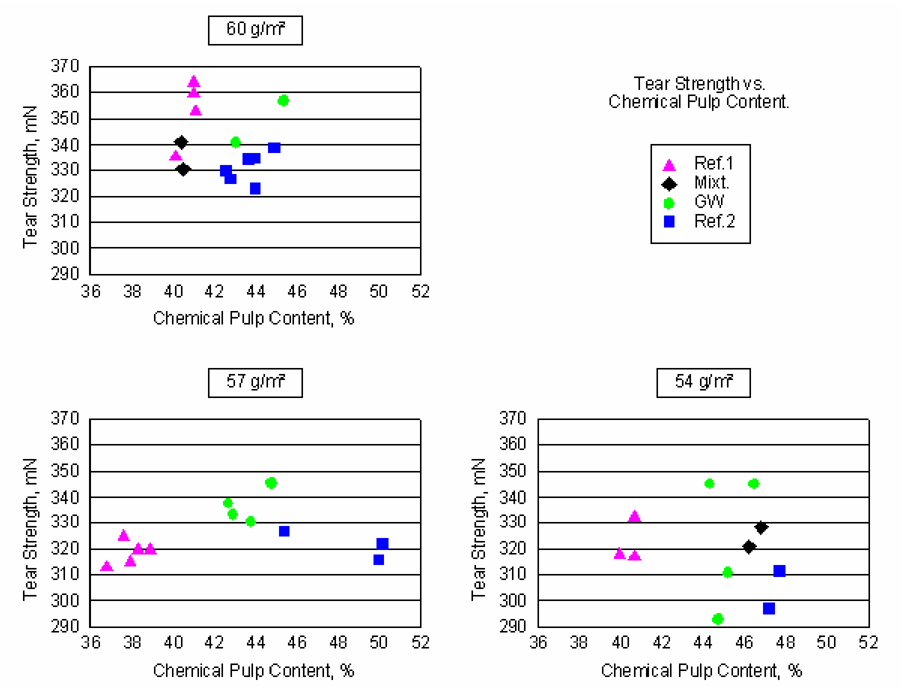

Figure 82. CD tear strength of machine paper vs. chemical pulp content at the end of each test point at different basis weights.

The tear strength of 60 g/m^2 paper was best in reference points (table 25). At lowest 54 g/m^2 basis weight tear strength was poorest with groundwood. Tensile strength was always best in the reference points. Best Scott-Bond was achieved in groundwood containing points though starch dosage was considerably lower, 34 % on average. Fracture energy and apparent tensile strength were measured from 40 g/m^2 base paper samples in each trial point. Fracture energy was clearly highest in the reference points and apparent tensile strength had a slight maximum value in the mixture point.

Table 25. Strength properties of LWC paper at the test points at different basis weights.

		Tear strength CD mN	**Tensile strength MD** kN/m	**Scott-Bond** J/m2	**Fracture energy MD** Jm/kg	**Fracture energy CD** Jm/kg	**Apparent tensile strength MD** kN/m	**Apparent tensile strength CD** kN/m
60 g/m2	**Ref. 1**	350	3,86	345				
LWC	**Mixture**	338	3,57	365				
	GW	332	3,59	352				
	Ref. 2	349	3,83	330				
57 g/m2	**Ref. 1**	319	3,66	338				
LWC	**Mixture**	324	3,45	363				
	GW	322	3,44	360				
	Ref. 2	337	3,56	328				
54 g/m2	**Ref. 1**	326	3,46	348				
LWC	**Mixture**	326	3,29	368				
	GW	305	3,12	355				
	Ref. 2	324	3,30	375				
40 g/m2 **Base**	**Ref.**				14,60	7,10	1,59	0,57
paper	**Mixture**				11,90	6,25	1,62	0,63
	GW				11,10	6,70	1,54	0,63

In machine paper mechanical pulp had no clear effect on density (table 26). In supercalendered finished paper purely groundwood-based paper had the highest density, but the differences were not significant. The roughness of machine paper was lowest with pure groundwood. However, the optical roughness profile was best with pure TMP and worst with the mixture. The more groundwood the base paper contained the smaller its medium pore size was and the narrower the pore size distribution was (fig. 83). Papers containing groundwood had the best optical formation. Purely groundwood-based paper had the highest light scattering coefficient but otherwise the groundwood share had no clear effect on optical properties.

Table 26. Surface and bulk properties of LWC paper.

		Density		**PPS10**		**Formation**	**index**
Basis weight	Trial point	Machine paper kg/m^3	Finished paper kg/m^3	Top side µm	Bottom side µm	Machine paper	Finished paper
60 g/m^2	**Ref. 1**	858	1191	1,31	1,10	103,1	97,7
LWC	**Mixture**	873	1189	1,31	1,08	106,2	101,2
	GW	877	1212	1,18	1,03	108,1	102,3
	Ref. 2	857	1175	1,14	1,05	105,2	97,0
57 g/m^2	**Ref. 1**	834	1159	1,24	1,07	104,1	102,8
LWC	**Mixture**	868	1155	1,32	1,10	106,1	103,4
	GW	878	1159	1,12	1,08	103,4	102,5
	Ref. 2	871	1180	1,16	1,18	104,8	96,5
54 g/m^2	**Ref. 1**	835	1146	1,24	1,11	96,1	88,8
LWC	**Mixture**	847	1159	1,30	1,10	98,8	95,0
	GW	884	1170	1,27	1,06		102
	Ref. 2	855	1170	1,25	1,10	94,6	85,5

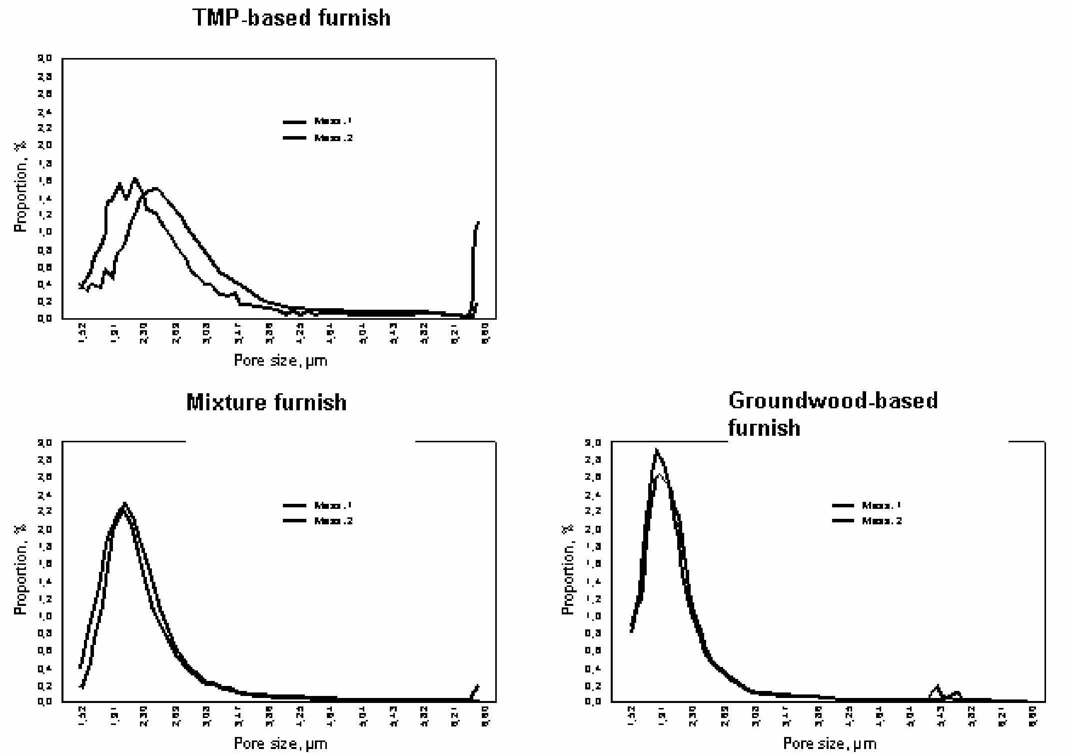

Figure 83. Pore size distributions of LWC base paper samples at different trial points, two parallel measurements.

Paper rolls were test printed on the heatset web offset pilot printing press of KCL. Printability testing showed no big differences between the trial points (table 27). Purely groundwood-based paper had the smallest printed PPS roughness. Visual evaluation made by three experienced laboratorians ranked the test point with pure groundwood the best (table 28). Otherwise the results were not consistent.

Table 27. Properties of printed LWC paper samples.

Sample	**Ref. 1**	**Mixt.**	**GW**	**Ref. 2**	**Ref. 1**	**Mixt.**	**GW**	**Ref. 2**	**Ref. 1**	**Mixt.**	**GW**
Basis weight, g/m2	54	54	54	54	57	57	57	57	60	60	60
Compact four colours											
Density, D ts	1,9	1,91	1,92	1,92	1,91	1,91	1,93	1,93	1,93	1,93	1,93
Density, D bs	1,87	1,88	1,9	1,88	1,87	1,88	1,89	1,89	1,86	1,9	1,89
Print-through D ts	0,050	0,060	0,070	0,060	0,060	0,060	0,050	0,070	0,060	0,060	0,050
Print-through D bs	0,050	0,050	0,060	0,060	0,050	0,050	0,040	0,060	0,050	0,050	0,050
Print-through, % ts	3,1	3,4	3,7	3,5	3,3	3,3	2,8	3,9	3,4	3,3	2,9
Print-through, % bs	2,8	3,0	3,4	3,3	2,9	2,9	2,5	3,3	3,2	3,0	2,9
Gloss, % ts	85	87,3	82,2	81,1	86,1	83	85,9	85,4	83,8	83,6	85,2
Gloss, % ws	81,3	79,3	80,1	76,9	80,1	79,3	82,2	80,1	79,3	80,9	82,3
Two colours (green)											
PPS10, µm ts	1,56	1,62	1,55	1,66	1,63	1,80	1,55	1,78	1,64	1,70	1,49
PPS10, µm ws	1,59	1,56	1,49	1,50	1,40	1,58	1,51	1,69	1,48	1,49	1,39
Compact 1 colour black											
Density, D ts	1,54	1,56	1,5	1,5	1,51	1,51	1,54	1,5	1,54	1,54	1,54
Density, D bs	1,5	1,48	1,46	1,41	1,44	1,45	1,47	1,44	1,44	1,51	1,49
Print-through D ts	0,056	0,059	0,072	0,065	0,064	0,062	0,053	0,071	0,067	0,061	0,059
Print-through D bs	0,05	0,057	0,062	0,06	0,055	0,052	0,049	0,061	0,057	0,054	0,055
Print-through, % ts	3,6	3,9	4,8	4,4	4,2	4,1	3,4	4,7	4,4	4,0	3,8
Print-through, % bs	3,4	3,8	4,3	4,3	3,8	3,6	3,3	4,2	4,0	3,6	3,7
Gloss, % ts	74,7	78,3	73,2	71,1	76,7	73,2	82,9	73,8	75,9	76,3	77,8
Gloss, % ws	70,0	67,8	63,3	63,0	67,5	65,0	70,0	65,7	67,6	68,9	70,2
Paper properties											
Gloss, % ts	54,4	58	52	50,4	55,6	55,8	60,5	56,4	55	57,3	57
Gloss, % bs	52,2	51,8	49,6	48,6	51,9	50	53,8	50,2	53	53,4	57,8
PPS10, µm ts	1,39	1,28	1,46	1,55	1,42	1,55	1,24	1,53	1,43	1,44	1,37
PPS10, µm ws	1,32	1,36	1,33	1,44	1,27	1,44	1,24	1,45	1,3	1,34	1,26

Table 28. Placement of the samples in the visual evaluation of the printed samples.

Basis weight	Side	Ref. 1	Mixt.	GW	Ref. 2
60 g/m^2	**Top side**	3	2	1	n.a.
	Bottom side	3	1	2	n.a.
57 g/m^2	**Top side**	2	4	1	3
	Bottom side	2	4	1	2
54 g/m^2	**Top side**	4	2	1	2
	Bottom side	4	2	1	2

Also this trial run showed that it takes some time before furnish change becomes visible in paper quality.

6.4. Mill trial on groundwood-based LWC paper

The target of the trial on groundwood-based LWC paper was to study how much the chemical pulp dosage could be decreased with the use of some TMP. The use of TMP could reduce the furnish costs even if there was no synergy with a mixture of groundwood and TMP. This trial on PM1 was run in January 2001. Up to 50 % of groundwood was replaced with LWC grade TMP (TMP4) in two stages (table 29). The quality of the TMP was not affected in this trial run. The TMP used was peroxide bleached together with groundwood. The chemical pulp was TCF bleached kraft pulp.

During the trial pulp and paper qualities were frequently tested in a mill process laboratory according to their normal schemes. In addition to this mechanical and chemical pulps, machine chest pulp and broke were tested in every trial point. Also the fibre length distribution of wet web samples at the end of each trial point was tested to get a figure of the real composition of paper furnish. The changes in the wet end chemistry were followed by temperature, pH and charge. Also some additional paper testing and a printing trial in a commercial rotogravure printing house were made.

This mill trial on groundwood based LWC paper lasted without a reference point about two and a half days. The test points 2 and 3 were relatively long (table 29).

Table 29. Trial points run and their schedule.

Trial point	TMP share of mechanical pulp	Duration
1*	0 %	
2	30 %	23 h
3	50 %	33 h
4	30 %	8 h

* reference point before TMP dosage

Furnish

About three hours before TMP dosage was started the chemical pulp used on the paper machine was changed from ECF bleached to TCF bleached softwood kraft pulp. This change decreased the length weighted average fibre length of chemical pulp by 0.1 mm. During the trial groundwood was slightly finer than before it. When replacing groundwood with TMP the freeness of mechanical pulp stayed quite constant though TMP was clearly finer than groundwood, ca. 37 ml vs. 55 ml. The long fibre fraction (+28 fraction) of mechanical pulp increased clearly from 9.6 % to 19.7 % and fines fraction (-200 fraction) decreased slightly from 34.1 % to 32.2 % with 50 % TMP. Fibre length increased from ca. 0.8 mm to 1.0 mm with 30 % TMP and to 1.1 mm with 50 % TMP. TMP dosage slightly increased the WRV of mechanical pulp. The use of TMP clearly improved the tensile and tear strengths and slightly improved the Scott-Bond of mechanical pulp. TMP increased the density and clearly decreased air permeability and light scattering coefficient of mechanical pulp. Pulp qualities in different trial points are shown in appendix 6.

During the trial run the dosage of broke was mostly relatively constant, 22 – 23 % of paper furnish. The 50 % replacing of groundwood with TMP increased the length weighted average fibre length of machine chest pulp by only about 0.1 mm. The increased fibre length was expected to improve runnability. The 10 ml drop of the freeness of machine chest pulp from 90 ml to 80 ml was probably caused by the lower chemical pulp dosage.

Wet end chemistry

On PM1 mechanical pulp is bleached with hydrogen peroxide. An effort was made to keep the bleaching conditions of mechanical pulp constant during the trial. TMP was slightly bleached, 0.10 – 0.56 % dosage, with dithionite on the TMP line. However, this did not show in the final brightness of peroxide bleached mechanical pulp on paper machine. Instead the use of TMP somewhat increased the hydrogen peroxide consumption. When replacing up to 50 % of groundwood with TMP the wet end chemistry on the paper machine did not change and the charge stayed constant. During the trial less groundwood was needed and its production was smaller than usually. As a result of that less heat was formed in the groundwood mill and less heat came from the groundwood mill to the paper machine. Because of the experimental arrangement enough heat did come neither with TMP. Because of that the temperature of groundwood decreased by 8^{o}C and that of wire water and headbox decreased by 5^{o}C. The lower temperature deteriorated drainage on the paper machine and could have caused problems in a longer trial. In a continuous run this kind of temperature decrease would naturally be prevented.

Paper making

During the trial the paper machine mostly made 70 g/m^2 LWC rotogravure paper. In spite of the decrease of machine chest pulp freeness and headbox temperature the paper machine speed could be kept constant during TMP dosage. However, at that time steam consumption in drying was at the maximum. In the reference point with pure groundwood as mechanical pulp the paper machine could have run faster. Before the trial with ECF pulp the chemical pulp dosage in base paper of 70 g/m^2 coated paper was 34 % and with TCF pulp just before the start of TMP dosage 35 %. With a 30 % TMP share of mechanical pulp the chemical pulp dosage could be decreased to 32 % and with 50 % TMP at minimum to 29 %.

Paper quality

The md tensile strength and cd tear strength of the base paper were nearly the same in all the trial points. The increasing of TMP share increased the tensile strength ratio (md/cd) of the base paper (table 30). The use of TMP improved the fracture energy and apparent tensile strength of the base paper. TMP dosage slightly increased the bulk and decreased the air permeability of the base paper but had no effect on the formation, roughness, roughness profile, oil absorption or pore size distribution of base paper. TMP slightly deteriorated the brightness and improved the opacity of the base paper.

Table 30. LWC base paper quality in the trial run with different TMP shares of mechanical pulp.

Machine roll **TMP share, %**	283 **0**	313 **30**	357 **50**
Basis weight, g/m2	41,9	41,7	41,1
Ash, %	4,6	6,7	7,3
Thickness, µm	65,1	66,2	65,6
Density, kg/m3	644	629	626
Tensile strength md, kN/m	3,15	3,32	3,26
Tensile strength cd, kN/m	0,81	0,79	0,79
Tensile strength ratio md/cd	3,93	4,25	4,16
Tear strength cd, mN	314	328	313
Fracture energy md, J/m	0,401	0,439	0,43
Fracture energy cd, J/m	0,235	0,236	0,22
Apparent tensile strength md, kN/m	1,44	1,48	1,48
Apparent tensile strength cd, kN/m	0,56	0,55	0,56
Scott-Bond HR, J/m2	315	320	300
Bendtsen roughness ts, ml/min	265	237	243
Bendtsen roughness bs, ml/min	340	320	315
PPS10 ts, µm	4,96	4,94	4,95
PPS10 bs, µm	5,44	5,48	5,47
Air permeability, ml/min	124	113	116
Unger ts, g/m2	10,7	10,5	10,6
Unger bs, g/m2	13,3	12,7	12,5
Brightness, %	78,0	79,0	73,3
Luminance, %	81,3	81,8	78,9
Opasity, %	80,9	81,6	82,2
Dominant wave length, nm	569,9	569,2	574,2
Excitation purity, %	3,08	2,69	4,83
Formation (beta, Ambertec)	3,4	3,4	3,5
Variation coefficient	8	8,3	8,5
Formation index (optical)	75,6	77,6	76,7

For the whole trial the cd tear strength of coated machine paper was in target and md tensile strength even slightly exceeded the target. Tensile strength ratio (md/cd) remained constant at about 4.20. The PPS roughness of the finished paper stayed constant as well as gloss, optical properties, and Heliotest. Even in the roughness profiles or pore size distributions of the base papers of different test points no differences could be found.

Printing trial

Printing trials were made in two different commercial printing houses. In the first one practically no difference was found in the printability of the reference point and the point with 50 % TMP share. In another commercial printing house with an increasing share of TMP the PPS roughness, gloss and printed gloss of paper deteriorated and print-through and missing dots increased (table 31). Thus, in this printing trial the printability of LWC paper deteriorated with increasing TMP share.

Table 31. Results of commercial printing trial with different TMP shares of mechanical pulp in LWC paper (70 g/m^2).

TMP share, %	**0** ESA	**30** ESA	**50** ESA
Compact four colours			
Density, D ts	1,95	1,96	1,97
Density, D bs	1,96	1,96	1,97
Print-through D ts	0,035	0,043	0,040
Print-through D bs	0,037	0,039	0,041
Print-through, % ts	1,8	2,2	2,0
Print-through, % bs	1,9	2,0	2,1
Gloss, % ts	82,4	81,5	80,3
Gloss, % ws	85,4	84,1	81,7
PPS10, µm ts	0,89	0,96	1,01
PPS10, µm ws	0,83	0,88	0,93
Compact 1 colour black			
Density, D ts	1,44	1,43	1,45
Density, D bs	1,41	1,42	1,43
Print-through D ts	0,035	0,044	0,038
Print-through D bs	0,039	0,043	0,039
Print-through, % ts	2,4	3,1	2,6
Print-through, % bs	2,7	3,0	2,8
Gloss, % ts	73,0	70,1	71,8
Gloss, % ws	72,6	69,6	70,2
PPS10, µm ts	0,69	0,77	0,77
PPS10, µm ws	0,66	0,81	0,71
Middle density			
Missing dots, n:o/cm^2 ts	2	1	9
Missing dots, n:o/cm^2 ts	1	13	8
Paper properties			
Gloss, % ts	75,9	73,2	70,4
Gloss, % bs	77,5	74,6	68,5
PPS10, µm ts	0,58	0,63	0,74
PPS10, µm ws	0,61	0,66	0,67

The mill trial on groundwood-based LWC paper showed that the use of TMP does not give any synergy advantages. Nevertheless, the use of TMP can appreciably decrease the need of chemical pulp and so reduce the furnish costs of LWC paper based on groundwood.

6.5. Reliability of the results of mill studies

Most of the mill trials done in this thesis were relatively short. As a result of this and because the optimum properties of the furnish components for the mixture were not known the pulps could not be optimized. Only the refining degree of chemical pulp was affected. Neither the running conditions on the paper machines could be optimized but only the draws were affected.

Often the quality of broke did not have enough time to change totally. During the trials pulp components normally not used on that paper machine could cause changes to pulp temperatures and their fines contents. Possibly because of these reasons even distinctive changes in mechanical pulp quality showed totally in paper quality surprisingly first after 6 to 14 hours. In the paper making process there is always some instability, which makes drawing reliable conclusions from the trial results difficult. All this makes short trial points useless and the optimization of the process after furnish changes time-consuming.

However, the quite uniform results of several mill trials and their similarities to the lab studies confirm the results achieved.

6.6. Discussion and conclusions of mill studies

Mill trials were done on each paper machine of UPM-Kymmene Rauma paper mill to verify the results of the lab studies. The mill trials discussed in this thesis were:

Groundwood-based SC rotogravure paper, Rauma PM2
    trial 1: 0 – 50 % of groundwood replaced with TMP
    trial 2: 25 % of groundwood replaced with TMP
TMP-based SC offset paper, Rauma PM3
    trial 1: 0 – 50 % of TMP replaced with groundwood
TMP-based LWC paper, Rauma PM4
    trial 1: 0 – 100 % of TMP replaced with groundwood
Groundwood-based LWC paper, Rauma PM1
    trial 1: 0 – 50 % of groundwood replaced with TMP

Though in most trials only about 50 % of mechanical pulp, groundwood or TMP, could be replaced with the other pulp, in both SC and LWC paper the whole interval from pure groundwood to pure TMP-based paper could be studied.

The results of the mill trials showed that the use of a mixture of groundwood and TMP can be beneficial both in originally groundwood-based and TMP-based papers, both in SC and LWC papers. In the mill trials on groundwood-based SC paper mixing groundwood with TMP first synergistically improved the cd tear strength of machine paper but did not affect the md tensile strength. The improved strength could first be exploited as a clearly smaller than calculated chemical pulp content in paper, which reduces furnish costs. In TMP-based SC paper mixing TMP with groundwood did not first increase the need of chemical pulp because of synergy in tear strength and the printability could improve. Both in groundwood-based and TMP-based SC papers at a high mixing share the synergy advantage decreased. In LWC paper no synergy in strength properties was found with the use of a mixture of groundwood and TMP. However, the use of this mixture in LWC paper could be beneficial because of the reduced chemical pulp need and decreased furnish costs of groundwood-based paper or better printability of TMP-based paper.

In the mill studies the mixture of groundwood and TMP did not give synergy advantage in light scattering coefficient. In supercalendering the air permeability and average pore size of SC rotogravure paper decreased more with a mixture of groundwood and TMP as mechanical pulp than with pure groundwood. No corresponding effect was found in roughness or roughness profile. The better calendering response with a mixture of groundwood and TMP similar to that found in lab sheet trials could be caused, in addition to the mechanical pulp mixture, also by the reduced chemical pulp content. In lab studies the calendering response was studied at a constant chemical pulp share.

In mill trials no synergy could be found in printability with a mixture of groundwood and TMP. Instead, usually the use of TMP slightly deteriorated printability and groundwood improved it. In SC paper trials the TMP used was coarser than groundwood and that was a partial reason for poorer printability. To avoid the deterioration of printability with TMP would probably demand heavy treatment of its long fibres.

In all the mill trials even big changes in paper furnish showed totally in paper quality and in the needed chemical pulp dosage surprisingly slowly, only after about 6 to 14 hours. Because of the pulp volumes in tanks the changes should have shown in paper in only a few hours. According to the lab studies with the mixtures of groundwood and TMP the strength properties of paper are most sensitive to the bonding level and fines content. The slow change of paper quality may be caused by the large water systems on paper machines and the slow levelling of the fines balance. Also the slow change of the quality of broke can be a reason for this phenomenon. The slow changes in paper quality show that in mill trials with different furnishes test points should be long. This may be difficult to arrange on pilot paper machines, though their pulp and water volumes are smaller than on a mill scale.

The mixture of groundwood and TMP has already been used continuously for several years in the production of originally groundwood-based SC rotogravure paper at Rauma paper mill. Experiences are mainly in accordance with the early mill trials. The mixture of groundwood and TMP behaves synergistically in SC paper production most of the time, but not always. Even quality fluctuations of the furnish components possibly sometimes cause the disappearing of synergy. This shows that synergy is most sensitive to the bonding abilities of the different components of the mixture and/or process conditions. In addition, often some groundwood is used in the furnish of TMP-based SC paper on one paper machine in order to improve paper printability.

The use of a mixture of groundwood and TMP was also started later in the production of groundwood-based LWC paper to reduce the chemical pulp need in paper. Though no synergy is found, the use of the mixture has reduced the furnish costs of paper.

7. COMPARISON OF SYNERGY BEHAVIOUR IN LAB AND MILL STUDIES

The papermaking process in lab studies with handsheets, despite the use of mill pulps and white water circulation in sheet mold, is different compared to modern paper machines. As a result of this e.g. the z-distribution of fines and filler, fibre orientation, fibre activation and formation in papers are different.

In spite of the differences the synergy behaviour of the mixtures of groundwood and TMP in mechanical printing papers was quite similar in handsheets and mill made paper. Synergy was found in both the lab and mill studies in SC paper but was not found in either of these studies in LWC base paper. Similar synergy behaviour was found in SC paper in strength properties and calendering effects. In both studies in SC paper a clear synergy advantage was found in tear strength and some synergy in fracture energy, stretch and tensile energy absorption. Synergy was also found in both studies in calendering effect in air permeability and average pore size. No synergy was found either in the lab or mill studies in tensile strength or Scott-Bond or in the roughness of calendered paper.

The major differences between the results of the lab and mill studies were that in the lab studies synergy was also found in the light scattering coefficient of uncalendered SC paper sheets and the printability of SC paper sheets but never in mill studies. These differences in the synergy behaviour could be caused by differences in sheet structure and fines content and supercalendering.

In the lab studies the synergies found in SC paper were most sensitive to the bonding ability of furnish components and other paper properties such as basis weight. In the mill trials the particularly slow appearance of synergy after furnish changes showed the sensitivity of synergy to pulp qualities, such as fines content, and papermaking conditions.

Despite the differences in the papermaking process and paper structure the results of the lab and mill studies concerning synergy were surprisingly similar which confirms the reliability of the results.

On the basis of the results of the very first handsheet studies (fig. 17) a curve for the chemical pulp share needed in SC paper as a function of the TMP share of mechanical pulp at a constant strength level, i.e. constant tear strength, was calculated (fig. 84). The mill trials gave, in average, quite a similar result for the chemical pulp share needed in SC paper, which strengthens the reliability of the results. The curve based on lab results shows first that in purely TMP based SC paper chemical pulp is needed clearly more than the additive calculation shows. Secondly especially at small TMP shares of mechanical pulp a lower chemical pulp share is needed in paper than could be calculated additively or based on purely groundwood and TMP-based SC paper sheets. The furnish costs of paper calculated with the curve in figure 84 show that with a mixture of groundwood and TMP the furnish cost of SC paper can be even smaller than that of purely groundwood or TMP-based SC paper (fig. 85). The minimum point of the curve depends on the price ratio of electricity and chemical pulp and it moves to the direction of groundwood-based paper when the former becomes more expensive and towards TMP-based paper in the opposite case.

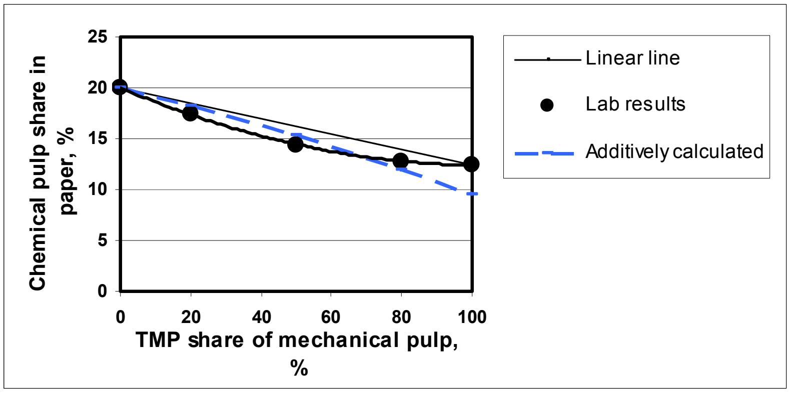

Figure 84. Chemical pulp share needed in SC paper handsheets as a function of the TMP share of mechanical pulp at constant strength level.

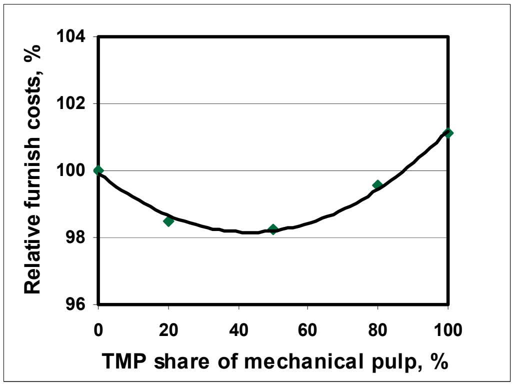

Figure 85. Relative furnish costs of SC paper as a function of the TMP share of mechanical pulp, filler content 32 % as ash, chemical pulp share according to the lab result curve in figure 84. Groundwood-based SC paper has cost level 100 %.

The results of this thesis show that lab trials with handsheets can still be useful in studies of the behaviour of different paper furnish mixtures, though opposite claims exist /Mohlin 1999/.

8. NEED OF FURTHER STUDIES

In the scope of this thesis work the behaviour of different furnish mixtures existing in mechanical printing papers, especially the mixtures of groundwood and TMP, and their synergies were investigated. The synergy behaviour of different pulp mixtures seem to depend on several, partially interrelated factors. This makes the understanding and exploitation of synergy difficult. However, the results of this thesis showed that the exploitation of the synergy of a mixture of groundwood and TMP can result both in economic and quality advantages in the production of mechanical printing papers. The exploitation of the total quality potential of pulps in different paper grades would demand more thorough studies and still better understanding of the synergy phenomena.

The synergy advantage achieved with a mixture of groundwood and TMP in mechanical printing papers shows that today neither groundwood nor TMP alone is an optimal mechanical pulp for high-quality mechanical printing papers. Neither the maximising of the fibre length of well-bonding TMP is necessarily optimal in high-quality mechanical printing papers, not even for tear strength or fracture energy. However, the use of a mixture of groundwood and TMP is possible only in a few mills and the investment on both systems is probably not feasible. On the basis of the results achieved an optimum mechanical pulp has good bonding ability, slightly lower fibre length and higher fines content than today's normal SC grade TMP has. In this research the optimum fibre length of mechanical pulp was 1.0 – 1.3 mm and fines content was about 33 %. This kind of mechanical pulp should be produced with one single mechanical pulping process. Probably this process would be possible by starting the development from a super pressure groundwood (PGW-S) pulp richer in fines than TMP and longer fibred than normal groundwood. This development could also be started from TMP made with double disc (DD) refiner or from RTS-TMP.

The use of the cd tear strength of paper as a criterion of paper runnability is criticized a lot. Fracture energy is commonly regarded as a better criterion, but it has not displaced tear strength in paper mills. The characterizing methods must be developed further. The methods used to characterize paper runnability also affect the exploitation of synergy.

9. DISCUSSION AND CONCLUSIONS

Mechanical printing papers usually consist of a mixture of mechanical pulp, chemical reinforcing pulp and filler in furnish and/or in coating. They may also contain recycled fibre. Mechanical pulp is groundwood or TMP though they have quite a different fibre length distribution. The use of the mixtures of different mechanical or chemical pulps is sometimes proposed to be beneficial. These mixtures could also have synergy. However, knowledge of the behaviour of different furnish mixtures and especially their possible synergy is poorly known. Synergy is even regarded as unpredictable. Therefore, the use of the mixtures of different mechanical or chemical pulps is avoided and synergy is usually not exploited in the practical papermaking process.

Good runnability of mechanical printing papers demands both high fibre length and good bonding. Similarly, light scattering demands a high fines content and large unbonded area and printability demands primarily a high fines content. Thus a mixture of groundwood rich in fines and long-fibred TMP could be assumed to be an optimum mechanical pulp for high-quality mechanical printing papers, i.e. SC and LWC papers. The main objective of this thesis was to research the validity of this hypothesis. The possible synergy behaviour of the mixture of groundwood and TMP was also researched. In order to understand synergy phenomena the behaviour of different furnish mixtures used in mechanical printing papers was investigated. This thesis consisted of both lab trials and several mill trials on modern, high speed SC and LWC paper machines.

The lab studies showed that with a mixture of suitable groundwood and TMP synergy advantage can be achieved in SC paper, especially in tear strength and often also in fracture energy, stretch and tensile energy absorption. However, no synergy was found in tensile strength or Scott-Bond. Synergy was even found in the light scattering coefficient of uncalendered SC paper sheets and in the calendering response of these SC paper handsheets. Synergy in calendering response appeared as a maximum in the density and minimum in the median pore size and air permeability of supercalendered handsheets. In LWC base paper handsheets no similar synergy was found.

In the mill trials on SC paper with the use of a mixture of groundwood and TMP synergy advantage was achieved in tear strength but not in tensile strength. Synergy was also found in calendering effect. No synergy was found in light scattering coefficient or printability. Best printability was usually achieved in purely groundwood-based SC paper rich in fines. In LWC paper no synergy was found. However, in TMP-based LWC paper the use of some groundwood could improve the printability and in groundwood-based LWC paper the use of some TMP allowed a clear reduction of the chemical pulp content.

The results of the lab and mill studies were mostly in accordance with each other. Both in the lab and mill trials synergy advantage with a mixture of groundwood and TMP was achieved in the tear strength but not in the tensile strength of SC paper. This synergy allows a smaller than calculated chemical pulp share in SC paper, which reduces the furnish costs of paper and can improve printability. Neither in the lab nor mill trials was synergy found in the strength properties of LWC base paper. However, the synergies found in the lab studies in the light scattering coefficient of uncalendered sheets and the printability of SC paper were not seen in the mill trials. This could be caused by differences in fines content, sheet structure and super-calendering. The mill studies showed that the use of a mixture of groundwood and TMP can be beneficial, in addition to SC paper, also in LWC paper, though no synergy was found in LWC base paper.

The reasons for the synergies found were investigated on a lab scale. The possible synergy mechanisms are discussed in more detail in the discussion and conclusions of the lab studies (chapter 5.7.). Synergy was found especially in tear strength, which depends on both fibre length and bonding degree. When bonding degree increases in paper, tear strength first improves and bond breakage is the main mechanism in paper fracture. If bonding still increases, at a certain stage fibre breakage becomes significant in paper fracture, the earlier the higher the fibre length is, and tear strength turns to a decrease. In this thesis the bonding of lab sheets was mainly affected with wet pressing or the selection of the pulp samples for tests. Accordingly, different pulp mixtures had synergy in tear strength if the papers based on the pulp components had their bonding degrees on the opposite sides of their tear strength maximum. When a mixture of groundwood and TMP had synergy in the tear strength of SC paper, groundwood-based paper had a bonding degree slightly below the tear strength maximum and TMP-based paper well beyond it. Thus a certain mixture of groundwood and TMP could have an optimum bonding degree vs. fibre length in SC paper. Some synergy was also found in fracture energy, stretch and tensile energy absorption, which all depend both on bonding degree and fibre length. Synergy in these strength properties was achieved with the same furnish mixtures as synergy in tear strength. Therefore the reasons for these synergies were probably quite similar. Synergy was not found in tensile strength or Scott-Bond which depend primarily on bonding. The synergies in strength properties, especially in tear strength, could also partially be caused by reduced bonding due to the differences in drying shrinkage or sheet density.

The maximum value in light scattering coefficient at a small TMP share could be caused by a too well bonded groundwood-based SC paper sheet rich in fines and, on the other hand, by a purely TMP-based sheet too poor in fines for high light scattering. A small TMP share added to groundwood-based paper made the sheet less bonded, which could increase light scattering. The reasons for synergy in calendering response seem to be similar to the reasons in light scattering coefficient. With a suitable mixture of groundwood and TMP in SC paper an optimum sheet structure, i.e. bonding degree, pore size distribution and fines content around the limiting state, for good light scattering and the restructuring of paper sheet in calendering can be achieved. A suitable mixture of groundwood and TMP can yield maximum fibre density and maximum bonding of fibres in an uncalendered SC paper sheet, though not maximum apparent density, because of lower fines content than in a purely groundwood-based sheet. This can result in maximum apparent density of a calendered sheet, which also shows as a minimum in median pore size and air permeability.

The synergy maximum in different SC paper properties was achieved at different TMP shares of mechanical pulp. In light scattering coefficient this maximum was at a 20 – 50 % TMP share, in calendering response at about a 50 % TMP share and in tear strength at a 50 – 80 % TMP share of mechanical pulp. This could be caused by the different need of fines and bonding.

The synergy found with a mixture of groundwood and TMP in tear strength seems to demand a suitable bonding level in paper. In this research this was Scott-Bond about 160 – 210 J/m². This bonding level was most probably achieved in highly filled SC paper with well-bonding SC grade pulps at about a 30 % chemical pulp share of fibre. Less synergy was found in SC paper at a lower, 20 %, share and no synergy at a higher, 38 %, share in poorer or better bonded SC paper sheets. Similar synergy was neither found in clearly better bonded LWC base paper sheets. Synergies in other paper properties demanded similar conditions.

In order to achieve synergy with a mixture of groundwood and TMP in SC paper TMP should be well-bonding pulp with flexible fibres and high WRV. Also to avoid the deterioration of printability long TMP fibres should be well refined. The quality of low freeness groundwood had less importance. Chemical pulp should be well-bonding enough, but usually not too well bonding. Low surface lignin content of chemical pulp, which affects its bonding, was advantageous for synergy.

Both the lab and mill studies have shown that synergy in strength properties is particularly sensitive to the bonding degree and fibre length in paper. If these properties of paper components change or, alternatively, the need of bonding in paper changes as a result of change in basis weight, the synergy may disappear. Even the quality variation of pulps may cause the disappearing of synergy. Thus also changes in wood species and quality or filler grade could affect the existence of synergy. The decrease of the basis weight made usually the conditions more probable for synergy

Similar synergy to the one found in this thesis with a mixture of groundwood and TMP is reported in one article /Dillen et al. 1975/. The synergy reported allowed the use of a smaller than calculated chemical pulp share in newsprint. However, the article does not explain the synergy phenomenon and provides only insufficient information on paper furnish components to evaluate the results. Possibly the furnish mixture of relatively coarse newsprint grade mechanical pulps and well-bonding sulphite chemical pulp with no filler has the same bonding level which was achieved in this thesis in highly filled SC paper with well-bonding pulps. In that case the reasons for synergy in tear strength in Dillen's study could be the same as in this thesis. Bovin has shown that a mixture of different chemical pulps has synergy advantage in tear strength if the tensile strengths of the pulps are on the opposite sides of their tear strength maximums /Bovin et al. 1971/. The present thesis has confirmed this explanation to be valid to different kind of furnish mixtures having a suitable bonding level.

The main objective of this thesis was to research the validity of the hypothesis that a mixture of groundwood rich in fines and long-fibred TMP would be an optimum mechanical pulp for mechanical printing papers. Secondly, it was hypothesized that a mixture of groundwood and TMP would behave synergistically in mechanical printing papers. The results of this thesis showed that a suitable mixture of groundwood and TMP can be a better mechanical pulp for SC paper than either of the components alone and that the mixture can have synergy in paper. Thus the results justified the hypotheses made at the beginning of this research. Reasons for the synergies were found in the lab studies.

Most of the lab testing in this thesis was done by one experienced laboratory assistant and the statistical reliability of most test results was checked. The results of both the extensive lab studies and several mill trials were quite similar. All this confirms the reliability of the results.

Today the mixture of groundwood and TMP is in use at Rauma paper mill in the production of both groundwood-based SC and LWC papers. However, the exploitation of the mixture of groundwood and TMP is possible only in a few paper mills having both existing groundwood and TMP production capacity. The advantages of the use of this mixture do not probably make the investment in a new type of mechanical pulping line feasible. Thus the results of this thesis should rather be used in the development of one single mechanical pulp which would give the advantages of a mixture of groundwood and TMP in SC paper.

LITERATURE

Alava M., Niskanen K.: Performance of reinforcement fibres in paper. The fundamentals of paper-making materials. Transaction of the 11th Fundamental Research Symposium, FRC, PIRA, Cambridge, UK, 21-26. September 1997, vol. 2, 1177-1213.

Algar W.: Effect of structure on the mechanical properties of paper. Consolidation of the paper web. Transactions of the symposium, BPBMA, Cambridge, September 1965, vol. 2, 814-819.

Bovin A., Teder A.: Some aspects of additivity. International Symposium on Paper Pulp Characterization 1971. STFI, SPCI, EUCEPA, Ronneby, May 24-26, 1971, 20s.

Bown R.: Die Einflüsse der Teilchengrösse und Teilchenform von Papierfüllstoffen auf die Papiereigenschaften. Wochenbl. Papierfabr. 111(1983)20, 737-740.

Bown R.: The relationship between strength and light scattering coefficient for filled papers. Papermaking raw materials. Transactions of the eighth Fundamental Research Symposium, FRC, Oxford, UK, September 1985, vol 2, 543-576.

Bown R.: A review of the influence of pigments on papermaking and coating. The fundamentals of papermaking materials. Transactions of the 11th Fundamental Research Symposium, FRC, PIRA, Cambridge, UK, 21-26. September 1997, vol. 1, 87-137.

Brecht W., Imset O.: Der Einreiss- und der Durchreisswiderstand von Papieren. Zellstoff Papier 13(1933)12, 564-567, 14(1934)1, 14-16.

Brecht W., Holl M.: Schaffung eines Normalverfahrens zur Gutebewertung von Holzschliffen. Papierfabr. 37(1939)10, 74-86.

Brecht W., Süttinger R.: Über die technologische Bedeutung des Formkarakters von Holzschliffen. Wochenbl. Papierfabr. 74(1943)1, 3-9, 74(1943)2, 21-27.

Brecht W., Klemm K.: The mixture of structures in a mechanical pulp as a key to the knowledge of its technological properties. PPMC 54(1953)1, 72-80.

Brecht W.: Das Mischen verschiedenartiger Halbstoffe in seinem Einfluss auf die physikalischen Eigenschaften der Papiere. Svensk Papperstid. 66(1963)5, 159-167.

Breunig A.: Wege zu höheren Füllstoffgehalten bei gleicher Festigkeit im Papier. Papier 35(1981)9, 407-416.

Carter D.: By using technology, improved SCA grades can target LWC. Pulp Paper 73(1999)11, 56-61.

Clark d'A J.: Pulp technology and treatment for paper. 2nd edition. San Francisco, Miller Freeman Publications, 1985, 878p.

Colley J.: Properties of blends of E. tetrodonta and P. radiate pulps. Appita 27(1973)1, 35-41.

Corson S.: Fibre and fines fractions influence strength of TMP. PPC 81(1980)5, 69-76.

Corson S.: Aspects of mechanical pulp fibre separation and development in a disc refiner. International Mechanical Pulping Conference 1989. EUCEPA, Helsinki, June 6-8, 1989, 309-319.

Corson S., Ekstam E.: Intensive refining of radiata pine fibre. International Mechanical Pulping Conference 1993. Proceedings, EUCEPA, Oslo, June 15-17, 1993, 86-94.

Corson S.: Development of TMP fibre and pulp quality. Appita 49(1996)5, 309-312,324.

Corte H.: The porosity of paper. Handbook of paper science: The structure and physical properties of paper, 1982, ed. H.F. Rance, Amsterdam, Elsevier Scientific Publishing Company, vol. 2, 1-70.

Crother J.: Oxford advanced learner's dictionary of current English. 5th ed. Oxford University Press, Oxford 1995.

Dillen S., Söderlund U.: Will TMP replace groundwood or chemical pulp in newsprint? International Mechanical Pulping Conference 1975. TAPPI-CPPA, San Francisco, June 16-20, 1975, 237-244.

Ebeling K., Hoppe J.: Einsatzerfahrungen von ECF- und TCF-Zellstoffen in der Papiererzeugung. Wochenbl. Papierfabr. 122(1994)18, 717-723.

Eriksson I., Edblom M., Gannå A., Pettersson L., Sandström P., Boman R., Westerling B.: Fracture mechanics as a tool to predict runnability in press rooms. 6th International conference on new available technologies. Stockholm, 1-4. June 1999, SPCI. p. 351-360.

Fellers C., Melander J., Mohlin U.-B.: Fracture mechanics – a tool for evaluating the effect of reinforcement pulps in mechanical pulps. TAPPI International Paper Physics Conference Proceedings. San Diego, California, USA, September 26.-30., 1999 TAPPI PRESS/PAPTAC 1999, 145–153.

Fedors R., Landel R.: An empirical method of estimating the void fraction of uniform particles of different size. Powder Technology 23(1979), 225-231.

Fernandez E., Young R.: An explanation for the deviation from linearity in properties of blends of mechanical and chemical pulps. Tappi 77(1994)3, 221-224.

Forgacs O.: The characterization of mechanical pulps. PPMC 64(1963)C, T89-T118.

Frazier W., Jackson M., Collicutt S.: Behavior of thermomechanical pulp in newsprint furnishes: a laboratory study. PPC 77(1976)2, 41-46.

Fuller R., Applewhite E.: Synergetics, exploration in the geometry of thinking. Macmillan Publishing Co. Inc. 1975, www.rwgrayprojects.com/synergetics/synergetics.html, 25.3.2003.

Gates D., Westcott M.: Formulae for the relative bonded area of paper made from blended pulps. Appita 55(2002)6, 468-470,479.

Gavelin G.: Thermo-mechanical pulp is different. PPI 18(1976)3, 70-73.

Giertz H.: Basic wood raw material properties and their significance in mechanical pulping. International Mechanical Pulping Conference 1977. EUCEPA, Helsinki, June 6-10, 1977, 1:1-15.

Giertz H.: Understanding the role of fines. International symposium of Fundamental Concepts of Refining. Appleton, September, 1980, 324-330.

Gullichsen J.: Low frequency refining - a new way to make mechanical pulp. International Mechanical Pulping Conference 1989. EUCEPA, Helsinki, June 6-8, 1989, Preprints, vol. 2, 320-342.

Gullichsen J., Paulapuro H., Neimo L.: Papermaking science and technology 4, Papermaking chemistry. Fapet Oy, Helsinki, Finland, 1999, 329 p.

Görres J., Amiri R., Wood J., Karnis A.:Mechanical pulp fines and sheet structure. JPPS 22(1996a)12, J491-496.

Görres J., Amiri R., Wood J., Karnis A.: The apparent density of sheets made from pulp blends. Tappi 79(1996b)1, 179-187.

Görres J., Amiri R., McDonald D.: The specific pore volume of multi-planar webs: the role of the short and long fibre fractions. 12th Fundamental Research Symposium, Oxford, September 2001, 1371-1383.

Heikkurinen A., Levlin J.-E., Paulapuro H.: Principles and methods in pulp characterization – basic fibre properties. Paperi Puu 73(1991)5, 412-417.

Heikkurinen A., Hattula T.: Mechanical pulp fines – characterization and implications for defibration mechanisms. International Mechanical Pulping Conference 1993, EUCEPA, Oslo, 15.-17. June 1993, Proceedings 294-308.

Hiltunen E., Kettunen H., Laine J., Paulapuro H.: Effect of softwood kraft refining on a mechanical-chemical mixture sheet. Tappi Papermakers Conference 1999, Proc., Vol 2, 741-749.

Honkasalo J., Ebeling K.: Comparative characterization of various mechanical pulps; GW, TMP, PGW. International Mechanical Pulping Conference 1981. EUCEPA, Oslo, June 16-19, 1981, 29p.

Honkasalo J.: Use of mixtures of groundwood and TMP in SC papers. International Mechanical Pulping Conference 2001, Helsinki, June 4.-8. 2001, Proceedings, vol 2, 219-228.

Htun M., deRuvo A.: The implication of the fines fraction for the properties of bleached kraft sheet. Sensk Papperstid. 81(1978)16, 507-510.

Kakko A.: Effect of TMP fractions on the stiffness of light weight newsprint. Licentiate´s thesis, HUT, Department of process engineering and material science. Espoo, Finland, 1996, 166p. (in finnish, only abstract in English).

Kazi S., Kortschot M.: The fracture behavior of TMP/kraft blends. Tappi 79(1996)5, 197-202.

Kilpper v. W.: Holzschliff und Füllstoff in ihrer Wirkung auf einige Eigenschaften von Druckpapieren. Papier 23(1969)7, 365-369.

Kolman M., Gavelin G.: Problem vid karakterisering av termomekanisk massa. Svensk Papperstid. 78(1975)3, 89-94.

Koskinen T., Kosonen M., Ebeling K.: The impact of paper defects on paper strength requirements. The science of papermaking. Transactions of the 12th Fundamental Research Symposium, Oxford, UK, 17-21 September 2001. FRS, Frecheville Court, 2001. Vol 2, 1441–1465.

Kärenlampi P.: Strength and toughness of paper: the effect of pulp fiber properties. Doctoral thesis, HUT, Laboratory of Paper Technology, reports, Series A4, Helsinki 1996a, 89p.

Kärenlampi P.: The effect of pulp fiber properties on the tearing work of paper. Tappi 79(1996b)7, 211-216.

Kärenlampi P., Cichoracki T., Pylkkö J., Paulapuro H.: A comparison of paper toughness testing methods: the effect of fiber properties and furnish design. Progress in Paper Physics - A Seminar. STFI. June 9-14. 1996c, Stockholm, 137-139.

Laamanen J.: Morphological fiber characteristics in mechanical pulps and their relation to paper properties. International Paper Physics Conference 1983. TAPPI, Harwichport, September 18-22, 1983, 11p.

Laukkanen T.: Relationship of the shrinkage to the synergy behaviour of pulp blends' properties. Master's thesis, LUT, Department of chemical technology, Lappeenranta, Finland, 2002, 132 p. (in finnish, only abstract in English).

Law K., Carceau J.: Optimum combinatios of groundwood fractions for higher sheet strength. PPC 77(1976)2, 63-68.

Levlin J.-E., Sundholm J.: Use of pilot equipment to evaluate raw materials for wood-containing printing papers. Appita 37th Annual Meeting 11.-13. April, 1983, Mt. Gambier. A13.1-13.12.

Levlin J.-E.: The role of softwood kraft pulps in printing and writing papers. 24th EUCEPA Conference 1990. Stockholm, May 8-11, 1990, 366-380.

Lindholm C.-A.: Modification of groundwood pulp through chemical treatment of the coarse fibre fraction. Paperi Puu 60(1978)4a, 219-231.

Lindholm C.-A.: Comparison of some papermaking properties of groundwood, pressure groundwood and thermomechanical pulp by means of artificial blends of pulp fractions. Part 2. The fines fractions. Paperi Puu 62(1980)12, 803-808.

Lindholm C.-A.: Determining optimum combinations of mechanical pulp fractions. Part 2. Optimisation of the composition of SGW, PGW and TMP pulps. Paperi Puu 65(1983a)6-7, 404-409.

Lindholm C.-A., Gummerus M.: Comparison of alkaline sulphite and ozone treatment of SGW, PGW and TMP fibres. Paperi Puu 65(1983b)8, 467-473.

Lobben T.: On the influence of the pulp components on the shrinkage and elongation of paper. Norsk Skogind. 32(1978)4, 80-84.

Lorusso M., Phipps J.: Filler options for uncoated groudwood paper. Wochenbl. Papierfabr. 127(1999)21, 1406-1410.

Luukko K., Kemppainen-Kajola P., Paulapuro H.: Characterization of mechanical pulp fines by image analysis. Appita 50(1997a)5, 387-392.

Luukko K., Paulapuro H.: Mechanical pulp fines: effect of particle size and shape. 1997 Engineering & Papermaking Conference, TAPPI, Nashville, October 6.-9. 1997b, Book 1, 131-136.

Luukko K., Paulapuro H.: Development of fines quality in the TMP process. CPPA Annual meeting. Montreal, January 20-30, 1998, Preprints, B23-B28.

Marton R.: Fibre structure and properties of different groundwoods. Tappi 47(1964)1, 205A-208A.

Mohlin U.-B.: Mechanical pulp properties - the importance of fines retention. Svensk Papperstid. 80(1977)3, 84-88.

Mohlin U.-B.: Properties of TMP fractions and their importance for the quality of printing papers. International Mechanical Pulping Conference 1979. CPPA-TAPPI, Toronto, June 11-14, 1979, 57-84.

Mohlin U.-B.: Properties of TMP fractions and their importance for the quality of printing papers. Part 1: Large variations in properties within fractions are observed. Svensk Papperstid. 83(1980)16, 461-466.

Mohlin U-B., Wennberg K.: Some aspects of the interaction between mechanical and chemical pulp. International Mechanical Pulping Conference 1983. TAPPI, Washington, June 13-17, 1983, 205-212.

Mohlin U.-B., Ölander K.: The influence of mechanical pulp quality on the properties of paper containing fillers. International Mechanical Pulping Conference 1985. SPCI, Stockholm, May 6-10, 1985, 231-241.

Mohlin U.-B.: Fibermorfologi och pappersegenskaper - mek. massa. Ekmandagarna 1987. STFI, 1987, 14p.

Mohlin U.-B.: Fibre bonding ability - a key pulp quality parameter for mechanical pulps to be used in printing papers. International Mechanical Pulping Conference 1989. EUCEPA, Helsinki, June 6-8, 1989, 49-57.

Mohlin U.-B.: Influence of grammage on sheet strength properties. Paper Physics Seminar 1992. KCL, SPIY, Otaniemi, June 8-11, 1992, Proceedings, p. 11.

Mohlin U.-B.: Pulp evaluation for modern papermaking. 6th International conference on new available technologies. SPCI. Stockholm, 1.-4. June 1999, p. 343-350.

Moilanen P., Lundqvist U.: Web defect inspection in the printing press - research under the Finnish technology program. Tappi 79(1996)9,88-94.

Mäkinen J.: Sellukuidun kutistumispotentiaalin yhteys paperin mekaanisiin ominaisuuksiin. Master's thesis, Helsinki University of Technology, Department of Forest Products, Laboratory of Paper Technology, Espoo, 2000, 127 p. (in finnish).

Mörseburg K.: Development and characterization of Norway spruce pressure groundwood pulp fibres. Dissertation, Åbo Akademi University, Faculty of Chemical Engineering, Laboratory of Pulping Technology, Turku, 1999, 150 p.

Nesbakk T., Helle T.: The influence of the pulp fibre properties on supercalendered mechanical pulp hand sheets. 88th Annual Meeting, PAPTAC, Montreal, January 28-31, 2002, 406-409.

Nieminen K., Retulainen E.: Effect of fibre properties on bonding and network structure of paper and its functional properties. Final report of VAIKKU project, HUT, Laboratory of Paper Technology, Espoo, Finland, 1994, 17p. (in Finnish).

Niskanen K.: Strength and fracture of paper. Products of papermaking. Transactions of the 10th Fundamental Research Symposium 1993. Oxford, UK, September 20-24, 1993, vol 2, 641-726.

Niskanen K., Nilsen N., Hellen E., Alava M.: KCL-PAKKA: simulation of the 3D structure of paper. The Fundamentals of Papermaking Materials. Transactions of the 11th Fundamental Research Symposium 1997. FRC, PIRA, Cambridge, UK, September 1997, vol 2, 1273-1291.

Nordström A., Fellers C.: Fracture toughness and tear strength of bleached papers - influence of filler content and beating. Paper Physics Seminar 1992. KCL, SPIY, Otaniemi, June 8-11, 1992, Proceedings, p. 21.

Paavilainen L.: Importance of particle size - fibre length and fines - for the characterization of softwood kraft pulp. Paperi Puu 72(1990)5, 516-526.

Page D., Seth R.: The problem pf pressroom runnability. Tappi 65(1982)8, 92-95.

Parsons S.: Effect of interfiber bonding on tearing strength. Tappi 52(1969)7, 1262-1266.

Praast H., Wohlbold J., Göttsching L.: Modellierung mechanischer Eigenschaften von Papier bei variation seiner Stoffzusammensetzung. Papier 52(1998)3, 111-118.

Retulainen E., Ebeling K.: Effect of paper on the load-elongation behaviour of fibre-to fibre bonds. Transactions of the eighth Fundamental Research Symposium 1985. FRC, Oxford, September 1985, vol 1, 229-263.

Retulainen E.: Properties of mechanical and chemical pulp blends. International Paper Physics Conference, 1991, Tappi, Kona, Hawaii, September 22.-26. 1991, 449–462.

Retulainen E.: Strength properties of mechanical and chemical pulp blends. Paperi Puu 74(1992)5, 419-426.

Retulainen E., Moss P., Nieminen K.: Effect of fines on the properties of fibre networks. Products of papermaking. Transactions of the 10th Fundamental Research Symposium 1993. PIRA, Oxford, UK, September 20-24, 1993, vol 2, 727-769.

Retulainen E.: Fibre properties as control variables in papermaking. Part 1. Fibre properties of key importance in the network. Paperi Puu 78(1996a)4, 187-194.

Retulainen E., Nieminen K.: Fibre properties as control variables in papermaking? Part 2. Strengthening interfibre bonds and reducing grammage. Paperi Puu 78(1996b)5, 305-312.

Retulainen E.: The role of fibre bonding in paper properties. Dissertation. Helsinki University of Technology, Laboratory of Paper Technology. Reports, Series A 7, 1997. 63 p.

Retulainen E., Luukko K., Nieminen K., Pere J., Laine J., Paulapuro H.: Papermaking quality of fines from different pulps – the effect of size, shape and chemical composition. 55th Appita Annual Conference, Hobart, 30. April – 2. May 2001, p. 309-314.

Riddell M., Kibblewhite R.: Kraft fibre and refining influences on the mechanical properties of low grammage kraft/TMP sheets. Appita 54(2001)2, 174–181.

Ritala R., Huiku M.: Scaling, percolation and network theories: new insights into papermaking? Fundamentals of papermaking. Transactions of the ninth Fundamental Research Symposium 1989. PIRA, Cambridge, September 1989, vol 1, 195-218.

Roisum D.: Runnability of paper. Part 2: troubleshooting web breaks. Tappi 73(1990)2, 101-106.

Rundlöf M.: Quality of fines of mechanical pulp. Licentiate's thesis, KTH, Department of Pulp and Paper Chemistry and Technology, Stockholm 1996, 20p.

Sepke P.-W., Selder H.: Grundlagenüberlegungen zur Auswahl und Behandlung von Zellstoffen fur die Druckpapierherstellung. Wochenbl. Papierfabr. 120(1992)10, 387-393.

Seth R., Page D.: Fibre properties and tearing resistance. International Paper Physics Conference 1987. PITA, TAPPI, CPPA, Mont Roland, Quebec, Canada, September 15.-18.1987, 16p.

Seth R., Jantunen J., Moss C.: The effect of grammage on sheet properties. Appita 42(1989)1, 42-48.

Seth R.: Fibre quality factors in papermaking - I, The importance of fibre length and strength. Materials Interactions Relevant to the Pulp, Paper, and Wood Industries. Caulfield D., Passeretti J., Sobczynski S (ed.), MRS Symposium Proceedings. Vol 197, Pittsburg 1990, 125-141.

Seth R.: Optimizing reinforcement pulps by fracture toughness. Tappi 79(1996)1, 170-178.

Seth R.: The measurement and significance of fines. PPC 104(2003)2, T47-T50.

Shallhorn P., Karnis A.: Tear and tensile strength of mechanical pulps. PPC 80(1979)12, TR92-TR99.

Shallhorn P.: Fracture resistance - theory and experiment. JPPS 20(1994)4, J119-J124.

Sipilä K.-M.: Behavior of pulp mixtures in LWC base paper. Master´s thesis, Helsinki University of Technology, Department of Forest Products Technology, Espoo, Finland 1999, 118p.

Sirviö J., Nurminen I.: Systematic changes in paper properties caused by fines. International Mechanical Pulping Conference 2003. PAPTAC, Quebec, Canada, June 2.-5. 2003a, 205-208.

Sirviö J., Nurminen I., Niskanen K.: A method for assessing the consolidating effect of fines on the structure of paper. International Paper Physics Conference 2003. PAPTAC, Victoria, September 7.-11. 2003b.

Skowronski J.: Fibre-to-fibre bonds in paper. Part II. Measurement of the breaking energy of fibre-to-fibre bonds. JPPS 17(1991)6, J217–J222.

Smook G.: The role of chemical pulp in newsprint manufacture. PPC 80(1979)4, 82-87.

Suur-Hamari H.: TCF-havupuusellun soveltuvuus LWC-paperin armeerausmassaksi. Master's thesis, Helsinki University of Technology, Department of Forest Products, Espoo, Finland 1994, 138p. (in finnish).

TamDoo P., Kerekes R.: A method to measure wet fibre flexibility. Tappi 64(1981)3, 113-116.

Tanaka A., Hiltunen E., Kettunen H., Niskanen K.: Inter-fiber bonding effects of beating, starch or filler. NPPRJ 16(2001)4, 306-312.

Tristram H., Weissenbach A.: Ausbewählte Aspekte der Herstellung von Streichrohpapieren für verschiedene Anwendungen. Wochenbl. für Papierfabr. 128(2000)9, 582-587.

Tubek-Lindblom A., Salmén L.: Wood containing multilayer paper for improved properties. International Mechanical Pulping Conference 2003. TAPPI, Quebec, June 2.-5. 2003, 43-47.

Tuovinen O., Liimatainen H.: Fibers, fibrils, and fractions - an analysis of various mechanical pulps. International Mechanical Pulping Conference 1993. EUCEPA, Oslo, June 15.-17. 1993, 324-339.

Uesaka T., Ferahi M.: Principal factors controlling press room breaks. International Paper Physics Conference. TAPPI, San Diego, September 26.-30. 1999, 229-245.

Uesaka T., Ferahi M., Hristopoulos D., Deng N., Moss C.: Factors controlling pressroom Runnability of paper. The science of papermaking. Transactions of the 12th Fundamental Research Symposium, Oxford, UK, 17-21 September 2001. FRS, Frecheville Court, 2001, vol 2, 1423-1440.

Vaarasalo J., Jokisalo H., Rahkila P., Levlin J.-E.: Stone groundwood, pressure groundwood and thermomechanical pulp as furnish components of newsprint. International Mechanical Pulping Conference 1981. EUCEPA, Oslo, June 16-19, 1981, 19p.

Vanninen M.-P.: The influence of quantity and quality of middle fraction and long fibre fraction of grinded pulps to prperties of LWC base paper..Master's thesis,HUT, Department of Forest products, Espoo, Finland, 1996, 90p. (in finnish, only abstract in english).

Veness J., Williams A.: The future of SC papers in LWC markets and others look bright. Pulp Paper 73(1999)9, 63-67.

Waterhouse J., Omori K.: The effects of recycling on the fines contribution to selected paper properties. Products of papermaking. Transactions of the 10th Fundamental Research Symposium 1993. PIRA, Oxford, UK, September 20-24, 1993, vol 2, 1261-1292.

Weigl J., Völker H.-G., Grenz R.: Erhöhung des Holzstoff- bzw. Füllstoffgehaltes von LLWC-streichrohpapier ohne Festigkeitsverlust. Wochenbl. Papierfabr. 122(1994)14, 562-569.

Weigl J., Ritter E.: Die Bedeutung der Teilchengrösse und -form von Füllstoffen sowie deren Verteilung bei der SC-papierherstellung. Wochenbl. Papierfabr. 123(1995)17, 739-747.

Weise U., Maloney T., Paulapuro H.: Quantification of water in different stages of interactions with wood pulp fibres. Cellulose 3(1996)4, 189-202.

Wurster K., Feichtmeier H.: Erfahrungen mit dem Einsatz von PCC in Pressendruckpapieren. Papier 53(1999)10A, V36-V41.

Yu Y., Kettunen H., Niskanen K.: Can viscose fibres reinforce paper? JPPS 25(1999)11, 398-402.

Zhang G., Laine J.E., Paulapuro H.: Characteristics of the strength properties of a mixture sheet under wet straining drying. Paperi Puu 84(2002)3, 169-173.

Zhang G.: Effect of drying on the in-plane tensile properties of paper. Dissertation. Helsinki University of Technology. Laboratory of Paper Technology. Reports, Series A21, 2004, 37 p.

Åström A., Nordström E., Rost T., Fellers C.: Fracture toughness as a pulp characterization method for runnability assessment of paper. Products of Papermaking. Transactions of the 10th Fundamental Research Symposium, PIRA, Oxford, UK, September 20-24, 1993, vol 2, 807-823.

LIST OF APPENDICES

Appendix 1. Testing methods, lab and mill studies

Pulps

Consistency	ISO 4119
Disintegration	SCAN-M10:77
Hot disintegration	SCAN-M1:64
Freeness	ISO 5267-1
Bauer-McNett	SCAN-M6:69 – except 14, 28, 48, 200 mesh wires
Fibre length	KCL 225-89 (Kajaani FS-200)
Drainage time	SCAN-M9:76 – sheet basis weight 56 g/m^2 as conditioned
Specific filtration resistance	KCL method
WRV	Tappi T256
Fibre stiffness	Hydrodynamic method according to TamDoo and Kerekes /TamDoo, Kerekes 1981/
Sedimentation volume of fines	KCL method
Turbidity of fines	KCL method
Total extractives	SCAN-CM49:93
Klason lignin	KCL 115b:82
AFM	HUT method
Handsheets	ISO 5269-1 - chemical pulp and fraction sheets without white water circulation - mechanical pulp sheets and mixture sheets with white water circulation - basis weight mainly 56 g/m^2 as conditioned
Testing of lab sheets	ISO 5270
Air conditioning	SCAN-P2:75
Ash content	SCAN-C6:62
Basis weight	SCAN-M8:76
Bulking thickness	SCAN-M8:76
Density	SCAN-M8:76
Initial tensile index	SCAN-M12:81
Initial stretch	SCAN-M121:81
Initial tensile energy absorption index	SCAN-M12:81
Tensile strength	SCAN-P38:80
Stretch	SCAN-P38:80
Tensile energy absorption	SCAN-P38:80
Tensile stiffness	SCAN-P38:80
Scott-Bond	Tappi T833
Tear strength	SCAN-P11:73
Fracture energy	characterized with the IPT (in-plane tear) method of HUT
Air permeability	ISO 5636-3
Roughness (PPS)	ISO 8791-4
Gloss	ISO 8254-1
Brightness	ISO 2470
Light scattering coefficient	ISO9416
Light absorption coefficient	ISO9416
Edana stiffness	/Kakko 1996/, the angle of inclined plane 21°, instead of 41.5°, because of short lab sheets
Image analysis of fines	/Luukko et al. 1997/
Starch content in paper	Fotometric method, UPM-Kymmene Rauma method
Optical roughness profile	UBM laser profile, KCL method

Pore size distribution	Coulter oil porosimeter, KCL method
Free drying shrinkage	Optidim, image analysis, KCL method /Mäkinen 2000/

Paper

Formation (beta)	Ambertech
Ash content, 900°C	ISO 2144
Basis weight, pulp and paper	ISO 536
Bulking thickness	ISO 534
Density	ISO 534
Tensile strength	ISO 1924-2
Tensile energy absorption	ISO 1924-2
Elongation (stretch)	ISO 1924-2
Tearing resistance	ISO 1974
Air permeability	ISO 5636-3
Roughness (PPS)	ISO 8791-4
Gloss	ISO 8254-1
Brightness, ISO	ISO 2470
Opacity	ISO 5631
Light scattering coefficient	ISO 9416
Light absorption coefficient	ISO 9416
Dominant wave length	UPM-Kymmene method
Excitation purity	UPM-Kymmene method
Printing quality, testing	UPM-Kymmene method
Printing quality, visual evaluation	UPM-Kymmene Rauma method

Appendix 2. Pulp qualities of SC paper handsheets (chapter 5.3.) Table 1/2

Trial series	**1**			**2**			**3**		
Pulp			**Chem.p.**			**Chem.p.**			**Chem.p.**
	GW	**TMP**	**TCFdry**	**GW**	**TMP**	**TCFdry**	**GW**	**TMP**	**TCFwet**
CSF, ml	34	47	445	34	33	445	31	40	485
Drainage time, s	62	38	6	62	49	6	51	44	5
Fibre length, mm	0,74	1,29	2,10	0,74	1,54	2,10	0,73	1,43	2,34
Fines <0,40mm, %	39,4	20,4	8,8	39,4	14,3	8,8	41,1	15,5	7,1
Fibre stiffness, 10-12Nm2									
Gloss plate dried sheets									
Ash, %	0,21	6,45	0,37	0,21	4,06	0,37	0,23	2,84	0,99
Density, kg/m3	494	507	657	494	515	657	487	514	699
Air permeability, ml/min	68	58	436	68	35	436	84	40	479
Tensile index, Nm/g	41,9	36,5	71,0	41,9	47,7	71,0	37,8	48,6	88,0
Stretch, %	2,0	2,1	3,7	2,0	2,1	3,7	1,9	2,2	3,4
TEA index, J/kg	660	530	1943	660	774	1943	479	720	2002
Tear index, mNm2/g	3,03	4,74	16,3	3,03	5,93	16,3	3,04	5,91	11,8
Scott-Bond, J/m2	345	330	390	345	265	390	360	340	380
Brightness, %	66,4	66,0	72,8	66,4	64,4	72,8	65,4	64,0	74,1
Light scatt. coefficient, m2/kg	82,4	70,1	25,5	82,4	66,6	25,5	79,7	62,8	19,4

Trial series	**4**			**5**			**6**		
Pulp			**Chem.p.**			**Chem.p.**			**Chem.p.**
	GW	**TMP**	**ECFdry**	**GW**	**TMP**	**ECFdry**	**GW**	**TMP**	**ECFdry**
CSF, ml	31	40	405	31	40	555	37	44	535
Drainage time, s	51	44	7	51	44	4	43	44	5
Fibre length, mm	0,73	1,43	2,16	0,73	1,43	2,17	0,70	1,46	2,05
Fines <0,40mm, %	41,1	15,5	8,1	41,1	15,5		40,2	15,9	8,8
Fibre stiffness, 10-12 Nm2							10,9	17,9	
Gloss plate dried sheets									
Ash, %	0,23	2,84	0,15	0,23	2,84	0,12	0,21	6,88	0,16
Density, kg/m3	487	514	700	487	514	611	501	524	685
Air permeability, ml/min	84	40	124	84	40	1529	102	46	384
Tensile index, Nm/g	37,8	48,6	98,3	37,8	48,6	64,4	37,7	43,1	84,7
Stretch, %	1,9	2,2	3,2	1,9	2,2	2,5	2,0	1,9	3,6
TEA index, J/kg	479	720	2049	479	720	1049	487	537	2003
Tear index, mNm2/g	3,04	5,91	12,5	3,04	5,91	19,8	3,10	5,64	13,5
Scott-Bond, J/m2	360	340	435	360	340	155	345	315	410
Brightness, %	65,4	64,0	77,4	65,4	64,0	78,5	66,5	64,8	79,4
Light scatt. coefficient, m2/kg	79,7	62,8	22,3	79,7	62,8	29,7	77,6	70,4	24,4

continues

Trial series	**7**			**8**			**9**		
Pulp	**GW**	**TMP**	**Chem.p. ECFdry**	**GW**	**TMP**	**Chem.p. ECFdry**	**GW**	**TMP**	**Chem.p. ECFdry**
CSF, ml	30	48	375	30	48	700	118	48	375
Drainage time, s	59	39	7	59	39	5	17	39	7
Fibre length, mm	0,73	1,44	1,97	0,73	1,44	2,23	1,08	1,44	1,97
Fines <0,40mm, %	41,3	14,9	9,8	41,3	14,9	8,4	29,3	14,9	9,8
Fibre stiffness, 10-12 Nm2	15,9	51,8		15,9	51,8		7,0	51,8	
Gloss plate dried sheets									
Ash, %	0,25	3,59	0,16	0,25	3,59	0,12	0,77	3,59	0,16
Density, kg/m3	502	491	708	502	491	547	427	491	708
Air permeability, ml/min	65	49	58	65	49	1716	226	49	58
Tensile index, Nm/g	39,2	45,8	93,8	39,2	45,8	39,3	33,4	45,8	93,8
Stretch, %	1,9	2,2	3,6	1,9	2,2	2,5	1,9	2,2	3,6
TEA index, J/kg	479	654	2214	479	654	667	405	654	2214
Tear index, mNm2/g	3,31	5,64	11,6	3,31	5,64	19,3	4,76	5,64	11,6
Scott-Bond, J/m2	335	300	600	335	300	105	215	300	600
Brightness, %	65,2	64,1	79,4	65,2	64,1	81,9	68,1	64,1	79,4
Light scatt. coefficient, m2/kg	79,0	68,1	24,0	79,0	68,1	34,6	71,8	68,1	24,0

Trial series	**10**			**11**		
Pulp	**GW**	**TMP**	**Chem.p. ECFdry**	**GW**	**TMP**	**Chem.p. ECFdry**
CSF, ml	34	31	410	34	31	365
Drainage time, s						
Fibre length, mm	0,70	1,27	2,17	0,70	1,27	2,36
Fines <0,40mm, %						
Fibre stiffness, 10-12 Nm2	11,4	5,6		11,4	5,6	
Gloss plate dried sheets						
Ash, %						
Density, kg/m3	497	533	709	497	533	713
Air permeability, ml/min	76	35	169	76	35	194
Tensile index, Nm/g	38,6	42,8	89,2	38,6	42,8	88,2
Stretch, %	2,1	2,0	3,8	2,1	2,0	3,8
TEA index, J/kg	530	557	2167	530	557	2200
Tear index, mNm2/g	3,1	4,82	12,9	3,1	4,82	12,3
Scott-Bond, J/m2	370	295	455	370	295	525
Brightness, %						
Light scatt. coefficient, m2/kg	78,1	70,1	21,8	78,1	70,1	18,7

Appendix 2. Pulp qualities of SC paper handsheets (chapter 5.3.) Table 2/2

Effect of filler addition (0 – 32 % filler clay as ash), pulp qualities

	GW **Final pulp**	**TMP** **Final pulp**	**TMP** **II stage refiner**	**Chem. pulp** **TCF wet**
Freeness, ml	34	31	100	365
Fibre length (FS-200), mm	0,70	1,27	1,60	2,36
Bauer-McNett				
28 %	10	17,6	33,5	n.a.
-200 %	34,9	38,0	25,8	n.a.
Density, kg/m³	495	533	442	713
Air permeability, ml/min	76	35	173	194
Tensile index, mNm2/g	38,6	42,8	41,6	88,2
Scott-Bond, J/m²	370	295	195	525
Light scattering coefficient, m²/kg	78,1	70,1	56,2	18,7
Tensile index of fractions				
28, Nm/g	16,9	17,6	10,7	n.a.
48/200, Nm/g	32,4	54,7	41,9	n.a.

Appendix 3. Pulp qualities in the 1st mill trial of groundwood-based SC paper (chapter 6.1.1.)

Pulp	**TMP share** %	**CSF** ml	**Ash cont.** %	**Fibre length** mm	**Bauer-McNett 28** %	**-200** %	**Density** kg/m³	**Air perme-ability** ml/min	**Tensile index** Nm/g	**Tear index** mNm2/g	**Light scatt.** m²/kg
GW	0	29	6,04		10	40,7	465	94	35,1	3,13	77,7
Mech. pulp 1	10	25	6,9	0,74	7,5	42	486	66	41,1	3,01	76,8
Mech. pulp 2	20										
Mech. pulp 3	36	31	7,46	0,91	13,2	38,3	478	70	39,4	3,97	73,5
Mech. pulp 4	50	31	7,17	1,01	14,2	38,2	474	67	40,3	4,09	71,7
Mech. pulp 5	10	31	7,18	0,8	10,9	38,2	474	72	38,8	3,36	75,7
Mech. pulp 6	0	27	7,35	0,69	6,3	43,6	489	68	38,8	2,69	79,3
TMP	100	47	7,81	1,46	27,5	32,9	455	84	38,6	5,92	66,7
Chem. pulp		485	3,69	1,99	59,4	9	607	853	67,3	15,3	25,2
Chem. pulp 4		430	4,45	1,93	60	10,2	611	525	70,7	14,2	25,4
Broke 1			39,9	1,23	20,8	35,4					
Broke 2											
Broke 3			39,5	1,25	19,7	37,4					
Broke 4			41	1,24	21,9	35,2					
Broke 5			39,3	1,26	21,6	37,4					
Broke 6			40,4	1,25	19,7	38					
Wet web 1			30	1,18	24,8	31					
Wet web 2			30,6	1,23	25,7	29,8					
Wet web 3			30,4	1,3	27,4	29,7					
Wet web 4			28,9	1,32	29,9	26,8					
Wet web 5			29,2	1,26	26,6	29,1					
Wet web 6			30,8	1,2	22,7	32,7					

Appendix 4. Pulp qualities in the mill trial of TMP-based SC paper (chapter 6.2.)

Pulp	**TMP share**	**CSF**	**Ash cont.**	**Fibre length**	**Bauer-McNett**		**Density**	**Air perme-ability**	**Tensile index**	**Tear index**	**Light scatt.**
					28	**-200**					
	%	ml	%	mm	%	%	kg/m^3	ml/min	Nm/g	mNm^2/g	m^2/kg
Mech. pulp 1	100	45	5,85	1,42	24,7	32,5	461	72	42,2	5,61	64,8
Mech. pulp 2	75	38	4,11	1,33	23,8	31,4	463	68	43,8	5,56	62,5
Mech. pulp 3	50	33	3,92	1,11	18	33,3	452	85	40,4	4,85	65,8
Chem. pulp 1		510	0,02	2,06	63,3	12,4	595	988	68,8	14,6	25,2
Chem. pulp 2		450	0,08	1,98	53,9	20,9	611	616	72,4	14	24,8
Chem. pulp 3		495	0,04	2,05	66,5	8,4	604	978	72,8	14,7	25,1
Broke 1			38,5	1,45							
Broke 2			37,9	1,48							
Broke 3			39,3	1,4							
Wet web 1			27,1	1,58	31,6	24,8					
Wet web 2			27,6	1,5	32,6	24,6					
Wet web 3			27,4	1,33	30,7	22,5					

Appendix 5. Pulp qualities in the mill trial of TMP-based LWC paper (chapter 6.3.)

Pulp	**TMP share**	**CSF**	**Ash**	**Fibre length**	**Bauer-McNett**	
					28	**-200**
	%	ml	%	mm	%	%
Mech. pulp						
Ref. 1	0	43		1,43	26,9	27,6
Mixture	50	41		1,17	21,3	30,6
GW	100	53		0,79	10,7	34,7
Ref. 2	0	39		1,51	31,5	28,6
Chem. pulp						
Ref. 1		590	0,19	2,16	63,2	11
Mixture		550	0,11	2,09	67,4	7,1
GW		550	0,05	2,12	68,9	4,8
Ref. 2		615	0,19	2,24	70,8	7,7
Machine chest						
Ref. 1		162	9,51	1,8	36,7	36,2
Mixture		159	13,5	1,72	33,4	38,3
GW		180	12,4	1,62	33,7	36,4
Ref. 2		153	14,3	1,87	36,3	38,3

Pulp	**Density**	**Air perme-ability**	**Tensile index**	**Stretch**	**Fracture energy**	**Scott-Bond**	**Tear index**	**Light scattering**
	kg/m^3	ml/min	Nm/g	%	Jm/kg	J/m^2	mNm2/g	m^2/kg
Mech. pulp								
Ref. 1	524	39	50,8	2,4	7,5	244	6,08	62,7
Mixture	508	56	44	2,1	6,4	257	5,55	69,4
GW	509	87	39	1,9	3,9	242	3,44	77,1
Ref. 2	538	31	50,2	2,3	8,5	261	6,27	63
Chem. pulp								
Ref. 1	804	1353	71,2	3,5	24,1	249	18,3	26
Mixture	651	881	75,8	3,5	23,3	278	16,3	26,1
GW	651	950	74,7	3,3	23,6	282	16	26,5
Ref. 2	624	1730	70,2	3,3	24,6	190	17,2	25,3
Machine chest								
Ref. 1	473	120	50	3,8	14,6	393	9,2	53,6
Mixture	541	111	50,3	3,7	14,7	457	8,76	56,2
GW	540	143	48,9	3,7	14,3	435	8,89	55,7
Ref. 2	536	112	48,3	3,6	15,8	415	8,8	56,6

Appendix 6. Pulp qualities in the mill trial of groundwood-based LWC paper (chapter 6.4.)

Pulp	**TMP share**	**CSF**	**Fibre length**	**Bauer-McNett**		**Density**	**Air perme-ability**	**Tensile index**	**Scott-Bond**	**Tear index**	**Light scatt.**
				28	**-200**						
	%	ml	mm	%	%	kg/m³	ml/min	Nm/g	J/m²	mNm^2/g	m²/kg
Mech. pulp 1	0	58	0,8	9,6	34,1	500	120	34,4	192	3,61	67,4
Mech. pulp 2	30	55	0,93	13,7	32,8	507	87	39	183	4,39	64,1
Mech. pulp 3	50	58	1,03	19,7	32,2	519	79	43,4	205	5,07	59,7
Mech. pulp 4	30	59	1,02	17,5	33,2	503	106	38,9	193	4,59	63,7
Mech. pulp 5	0	57		11,8	33,1	502	121	35,8	179	3,46	67,6