LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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EFFECT OF PULPS FRACTIONATION ON FORMATION AND STRENGTH PROPERTIES OF LABORATORY HANDSHEETS

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ABSTRACT

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Effect of pulps fractionation on formation and strength properties of laboratory hand sheets

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The objectives of the work were to study the effect of dewatering time varying on formation properties of papersheets, to determine the role of fines fraction in creation of paper with good formation and strength properties of papersheets, and also to study the effect of charge modification of fibers fractionations on formation properties of hand sheets. The paper formation is one of the most important structural properties of paper. This property has effect on physical and optical characteristics of paper. In this work the effect of formation on tensile strength was determined. The formation properties were analyzed by using the AMBERTEC Beta Formation Tester. The PAM addition as a f;locculant agent did some changes in the formation of paper. Paper sheets were also made from different furnishes of both birch and pine pulps. The fibers particles as a fines have great effect on drainability changes. Fines fraction played important role in papermaking. The two kinds of pulps (pine and birch pulps) were also used in this work for investigation of fines role. As it was expected the fines fraction gave positive effect on paper formation, but when fines fraction was added above initial fines content the formation of paper was deteriorated. The effect of paper formation on tensile strength was also determined. In many cases the poor formation of paper had negative effect on strength properties of paper.

FOREWORD

This Master`s Thesis has been carried out at the Laboratory of Paper Technology at Lappeenranta University of Technology.

At first, I would like to thank my Professor Isko Kajanto for giving me the subject of the thesis.

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1. Introduction

1.1. Background knowledge

The paper structure is the main property that determines the quality of many paper types. Fibers fraction composition, chemical additives and many parameters of forming section of the paper machine affect the final paper structure. For retention of fines and fillers some additives are introduced into the stock before paper mass appear on the wire section of paper machine. Besides mentioned factors, it is also known that refining process may affect formation. There are two opposite processes by effect on paper formation take place during beating of fibers. First one is fiber shortening usually leads to improving of paper formation [1]. The second group of processes includes external and internal fibrillation during of which new surfaces and new particles such as fines are created. The external and internal fibrillations, to be exactly, the changes what they bring to the fibers, are known to make the formation properties worse [2]. It has effect on drainability of fiber mat. It is known that dewatering time is higher for more beaten fibers compared to fibers which have lower beating level. Increasing of dewatering time makes the paper formation poorer due to more flocculation [3]. The fines fraction play important role in paper making. They act as the binders between fibers and as fillers between long fibers [4].

1.2. Objective of this work

The first objective of the work was to study the effect of dewatering time varying on formation properties of papersheets.

The second objective of the work was to determine the role of fines fraction in creation of paper with good formation and strength properties of papersheets.

The third objective was to study the effect of charge modification of fibers fractions on formation properties of handsheets.

LITERATURE PART

2. Wood fiber structure and composition

Wood fibers are cells with complex structure. Wood cell wall has also complex structure associated with the distribution of chemical components as a cellulose, hemicelluloses and lignin [5].

2.1. Cell wall layers and its distribution

Pulp fibers are cells extracted from plants [6]. In paper making process the fibers with length of about 1-4 mm long and width of 30 μm are used. The cell wall thickness is about of 3-15μm depending on the wood species. Cell wall consists of several layers with different structure, physical properties and chemical composition. Cells are jointed with each other by middle lamella ML [5]. The cell wall consists of two main structural parts: the primary and the secondary walls. The secondary wall is divided in S1, S2 and S3 layers (Fig. 1). The primary wall is connected with middle lamella, and S3 layer is near the fiber lumen. The thickness of the primary wall is 0,1 ... 0,3 μm. Macrofibrils take part in creation of each layer and macrofibrils are built from microfibrils [6].

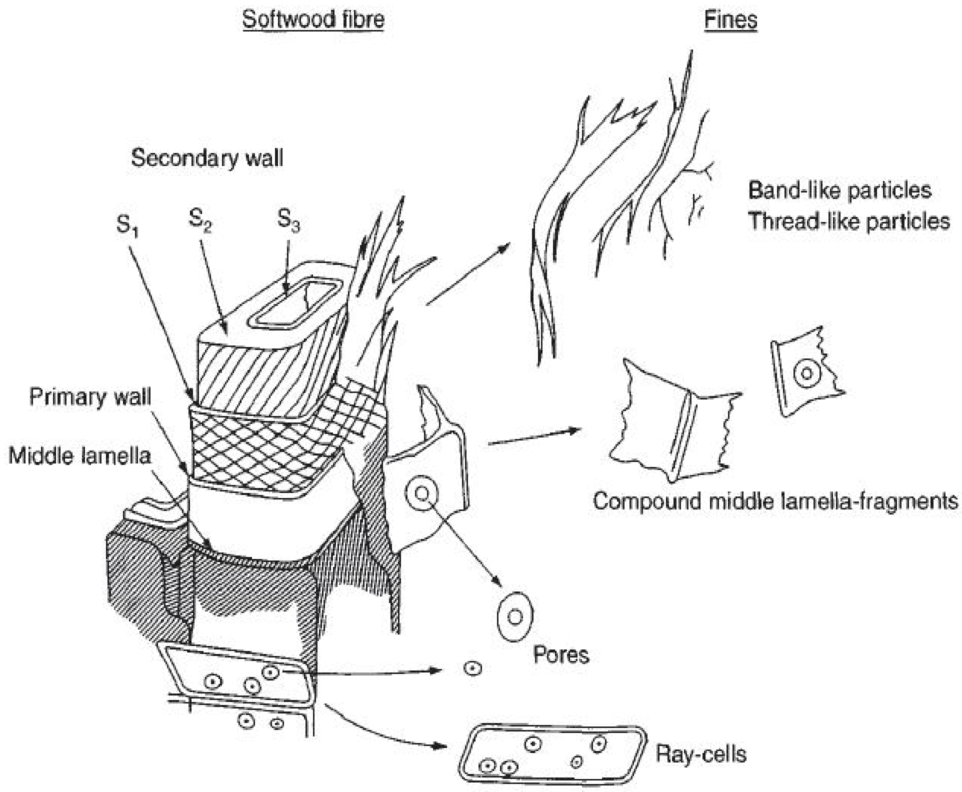

Figure 1 *Structure of softwood fiber showing the architecture of the fiber wall with a lignin-rich middle lamella, the primary wall enforced by a network of cellulose fibrils, and the secondary wall built up of three layers with different fibrilar orientations [7].*

The main components of fiber are cellulose, hemicelluloses and lignin (Fig.2). Macromolecules of cellulose consist of amorphous and crystalline parts. The macromolecules include the microfibrils. A cellulose macromolecule monolayer has a thickness of 0.6 nm. Fatty acids and fatty acid esters, rosins and sterols are also found in the fiber and are usually referred to as extractives [6].

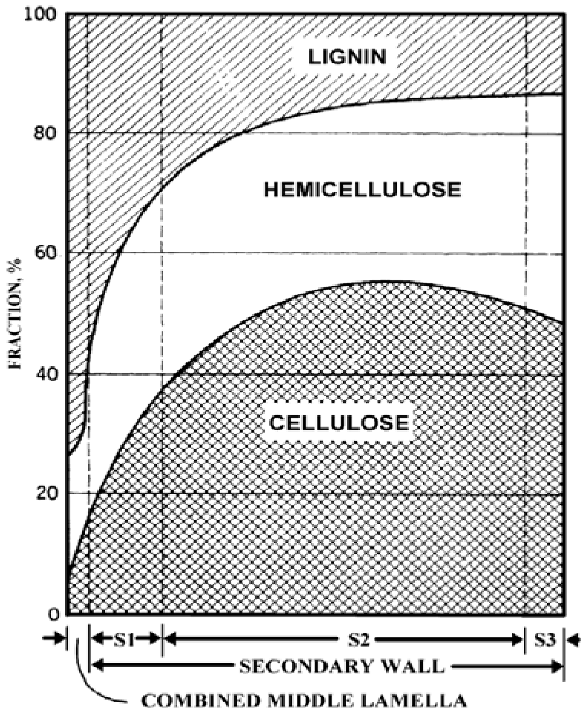

Figure 2 *Chemical compositions of combined middle lamella and secondary walls [5].*

2.2. Cell wall ultra structure

Microfibrils are the main elements of cellulosic nanostructure (Fig.3). Microfibrils can assemble into the large aggregates - fibrils (macrofibrils) and also the microfibrils can break up into the thin longitudinal elements, which name is elementary fibrils (nano-fibrils). Oriented in one direction fibrils in the cell wall create thin layers - lamella. Fibrils and lamellas can be detected after the mechanical effect on the wood fibers (crushing, grinding, beating) - mechanical fibrillation. Microfibrils can be detected also after the chemical fibrillation (mechanical treatment after delignification by chemical action) [8].

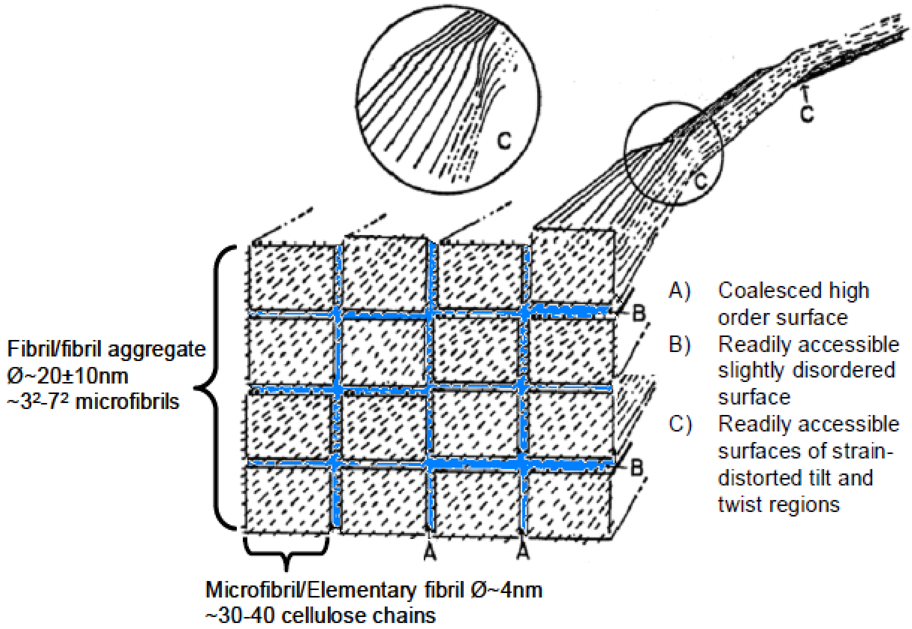

Figure 3 *Approximate sizes of microfibrils and fibrils in wood pulp fibers and a theory of cellulose crystallinity [5].*

3. Fines fraction

By definition fines fraction of a pulp - is that fraction which passes a screen or a perforated plate with a diameter of the holes of 76 µm (mesh of № 200) [9]. Fines fraction play a significant role in the paper making process. Fines affect the fiber network structure, physical and optical properties of paper. Furthermore it is known that fines significantly affect the drainage properties of pulp slurry. Fines make dewatering of fibrous suspension worse due to the ability of fines fraction to retain water. [10] The fines can be obtained both from a chemical and from mechanical pulps. In this chapter chemical pulp fines fraction is discussed.

3.1. Chemical fines fraction

Chemical pulp consists of different fiber and fines fractions with different size, shape and surface characteristics. The properties of fines fractions differ from other fractions. The fines fraction of chemical pulp is divided into two main types: primary and secondary fines. The primary fines are fines containing wood cells and other material that is initially presented in the pulp before beating, resulting from the cooking process, which are mainly ray and other cells from the tree stem, like vessels. The secondary fines are fines produced by refining. The secondary fines contain fiber fragments and more fibrillar and lamellar material originating from the fiber cell wall [11,12,13].

Both cellulose and hemicellulose content of fines fraction different from the fiber. In chemical pulp the hemicellulose content of fines is higher than in the fiber fraction. Chemical pulp fines have high cellulose content, about of 75.7 - 82.8 % (w/w) [10].

Primary fines of chemical pulp include:

- ray cells and axial parenchyma cells originating in wood;
- fiber fragments from the wood chipping process;
- damaged fiber fragments from cooking and bleaching; [14]

At first, the properties of chemical pulp fines can be defined by the types of raw material and used pulping process. Secondly, the properties of chemical fines are defined by the method of fibrillation and intensity of fibrillation. The fiber fibrillation will be considered in the paragraph 3.4. Chemical pulp fines have tendency for water retention and network formation. It is known that the smaller fines fraction, the slower the settling and drainage, and the higher the viscosity. The ability of lignin and extractives to be concentrated on the chemical pulp fines surface is stronger than that on mechanical pulp fines [10].

Specific surface area of fines is considered as an important characteristic which affect ability to form bonds and dewatering of fiber's mat. It can be indirectly measured by the settling rate because the settling rate depends strongly dependence on the specific surface area. Suspension of fine fibers is composed of heterogeneous small particles in water. Measurement of the suspension viscosity can give information about fines. Such characteristics of fines as the settling rate, the suspension viscosity with fine fibers are closely related to the specific surface area of fines [15].

3.2. Types of fines

The chemical pulp fines have two main forms: flake and fibrillar fines. The proportion of flake fines is typically very low, because the middle lamella and primary cell wall are mostly removed during the pulping process. High fibrillar chemical pulp fines are known to be with high aspect ratio [10].

The main differences between fiber and fines (exclude of size) are specific surface area and surface charge density of fines. These differences influence on the ability of fibers and fines to interact with each other and adsorb other components of the pulp suspension. The retention of fines during filtration is in turn better than those for individual filler particles [16].

3.3. Composition and properties of fines

Papermaking fiber by chemical composition is more or less same with wood cell, while the fines are fragments of the same cells or the middle lamella [17]. And these fragments have similar composition that a fiber (cellulose, lignin, hemicelluloses and so on) but in different quantities. For example, fibrillar fines are ribbon-like, cellulose-rich particles with good bonding ability. And flakes include many types of particles with different shapes and sizes. Flakes are usually lignin-rich and have property to increase the light scattering of the paper, while fibrils increase the strength properties [16,18]. Fines are added as a filler or pigment to improve optical properties. Typically the mechanical pulp fines influence the light scattering coefficient of paper more than the chemical pulp fines [19].

According to work of Kangas and Kleen, fines contain more extractives and lignin (on their surface and in the bulk) than fibers. It was also noticed in the same work that fibrillated fines had more amount of extractives and lignin. The fines fraction with high content of lignin had more fibrillated fines. It was explained by origination of fibrillated fines from primary wall rather than from secondary wall. Flake fines had also a large amount of lignin on their surfaces. The results also showed that the fibers with a high amount of cellulose had more fines. "*It was* *also observed that their surface was covered by 50% of polysaccharides and in most cases extractives on the surfaces of fibers and fines were fatty acids." [16]*

3.4. Beating process as a main source of fines fraction

Beating process is one of the main operations of papermaking processes that strongly affect properties of paper. Refining of chemical pulp means treatment of fibers to make them more suitable for papermaking. Refining is an attainment process of desirable structural changes in the cell wall of the fibers [20].

The main consequences of refining are creation of new surfaces, creation of new particles and generation of structural damages and modifications. There are two main beating effects: primary and secondary. Primary effects are external and internal fibrillation, cutting, and formation of fines, structural changes, dislocations, micro-compressions, fiber curl and release of chemical components. The secondary effects include previous effects and changes of the pulp properties, such as: internal splitting, longitudinal compression, consecutive cleavage of external cell wall layers and delamination of internal cell wall layers. Fibers are broken as the result of changes in length distribution, namely fiber length is decreasing [20,21].

3.4.1. External fibrillation

External fibrillation (Fig.4) is a peeling off of fibrils from the fiber surface, while leaving them attached to the fiber surface [22].

For strength properties the external fibrillation is more significant in case of mechanical pulp fibers than in chemical pulp fibers. It is explained by peeling-off mechanism. The primary wall and S1 layer are peeled off. Layer S2 is subjected to the bonds between fibers. Membranes, ribbons, fibrils play role as binding agents for the bonding [4,22].

Fines in chemical pulp contribute to the densification of the paper sheet. Chemical pulp fines are effective in stress transfer because of their high bonding potential. "*External fibrils attached to fibers may behave similarly to loose fibrils* *in the stress transfer mechanism, because external fibrils contribute to the formation of "skirt" or a "covering layer" at the edge of the fiber bond" [22].* External fibrillation leads to fines formation. Some of the external fibrils peel off from the fiber surface, that causes increasing of fines formation [4,22].

3.4.2. Internal fibrillation

Internal fibrillation (Fig. 4) as a result of the weakening and partial destruction of the bonds between microfibrils increases flexibility and plasticity of the fibers. Fibrillation increases the outer fiber surface and releases hemicelluloses from internal structure of the fibers which in turn can participate in the creation of inter fiber bonds in the paper. Fibril splitting creates conditions for a better network and increasing of mechanical strength in the paper sheet with a simultaneous decreasing of its absorbency [3].

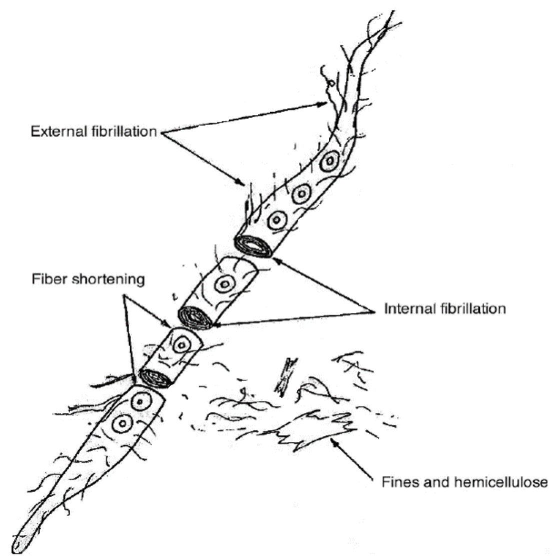

Figure 4 *The effect of refining on fibers of chemical pulp [23].*

3.5. Fiber and fines charges

The cellulosic fibers in water suspension normally have a negative charge due to the presence of ionisable acidic groups in the lignin and hemicelluloses. The fiber charge is a complex function of the chemical composition, ionization state of the acidic groups, the nature and amount of additional substances adsorbed on the fiber surface. Ionisable groups such as carboxylic, sulphonic acidic, phenolic and hydroxyl groups are contained in cellulosic fibers. Fibers origin and the chemical treatments such as pulping and bleaching influence on amount of ionisable groups [24,25]. The characteristics of any particular fiber surface also greatly depend on the degree of mechanical treatment. The glucuronoxylan concentrations in the outer secondary wall and the main secondary wall in hardwoods are slightly different. But the glucuronoxylan concentration in the outer and inner secondary walls in softwoods is much higher, than in the main secondary wall. The hardwood fibers have a higher charge density than softwood pulp fiber [26].

The fibers surface area plays an important role in the bonding of the fibers. A large fiber surface area provides higher fiber surface charge, more areas for contacts between fibers and therefore more bonds between fibers [27].

According to results of Nishi K. Bhardwaj refining increased the surface charge, specific surface area and specific volume of fibers, but did not change the total fiber charge [27,28].

In the work of Horvath and Lindström the following conclusions about the fibres charge were made: the total and surface charge contents were varied between hardwood and softwood and also between different types of bleaching sequences. However, the charge ratio (surface charge/total charge) was virtually the same. Beating increased the charge ratio and this relation could be used as a measurement for the beating rate [29].

It was observed by Mosbye *et al* that the fines fraction from different parts of the fiber wall had different amounts of charged groups. The fines produced at early stages of refining process had more charged groups than the fines produced later. Galacturonic, glucuronic and 4-O-methyl glucuronic acids were found in amount of 80 - 90% of all the charged groups in the different fines fractions. The measurements of charged groups were made by polymer adsorption (see the results on Fig. 5) [30].

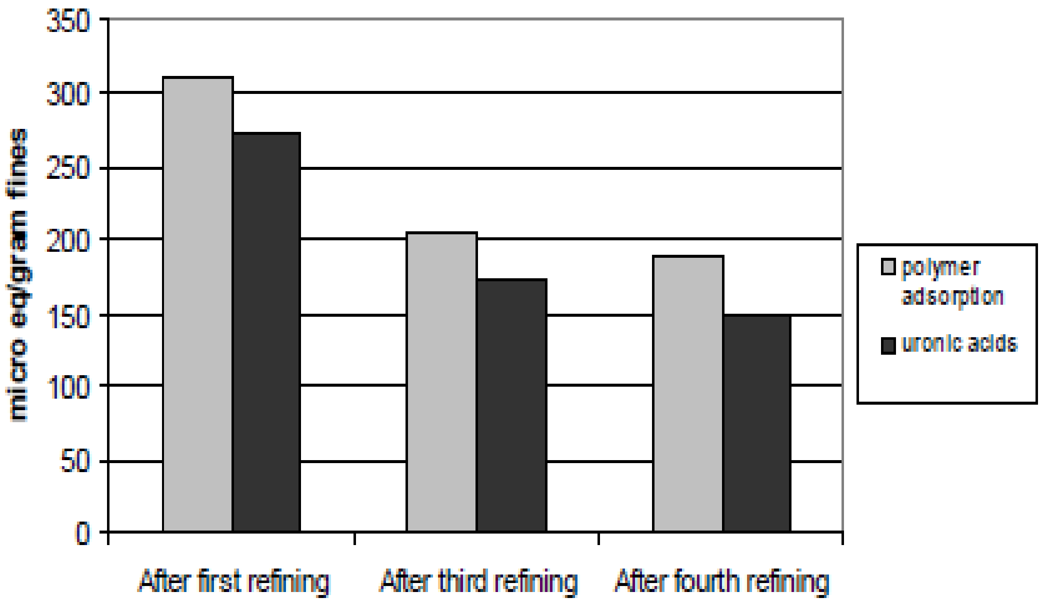

Figure 5 *The total charge measured as polymer adsorption compared to the amount of uronic acids (glucuronic-, galacturonic and 4-O-methyl glucuronic acid) in different alkali treated fines [30].*

3.6. Effect of fines on dewatering

"Drainage rates and viscous resistance coefficients are a function of the physical properties of the paper furnish." Such factors as pulp composition, average fiber length, fiber length distribution, fines content and chemical aids (starch, coagulants, flocculants, and wet-strength additives) have effect on drainage. [31].

The mechanical beating of pulp has a dramatic effect upon the fibers water drainage [10]. According to the results of Kenneth W. Britt and John E. Unbehend, with increasing of refining degree (i.e. increased fines content) the time of water removal was increased too as was expected. The results are presented in the Table 1 [32].

Table 1 The effect of refining on drainage properties of sulfite pulp. The beating was carried out in a laboratory Valley beater. The chosen pulp was easy-beating sulfite pulp – Storafite [32].

Duration of beating, min	Fines fraction, %	Drainage time, sec
0	3.95	8.5
10	7.0	21.2
20	9.57	43.1
30	12.10	81.7
40	12.24	180
50	10.59	316.9
60	11.38	583
70	14.89	1060
80	18.38	1519

When fibers suspension has a significant amount of fines, it can have a dominant influence on dewatering. Pulp suspensions drain rapidly if the fines are removed [32].

Also works of Chen, Park, and Heitmann (who used refined bleached hardwood Kraft pulp) showed that resistance to dewatering was decreased with decreasing of fines content. Results showed that dewatering time was higher for fibrous slurries with fibrillated secondary fines than with compact primary fines [33].

3.6.1. Surface area model of fines effect on dewatering process

The model of surface area of fines effect on dewatering process of suspensions by filtration through the screen due papermaking is illustrated in Fig. 6. The central “empty” spaces in each fiber represent the lumen. [34].

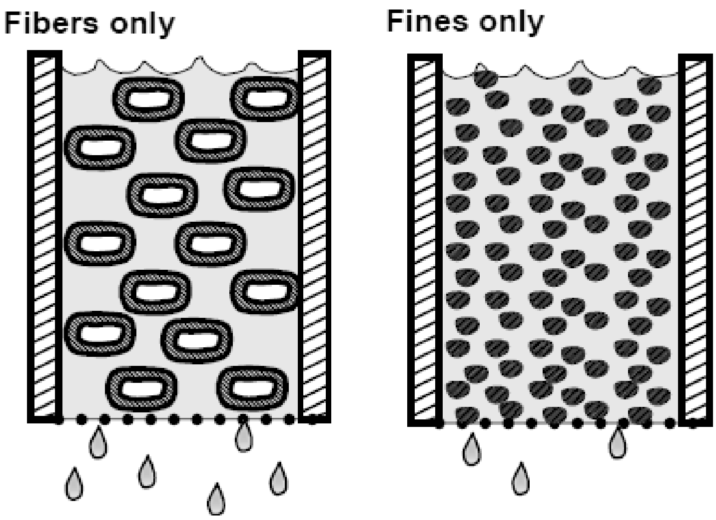

Figure 6 *Idealized model to account for the effect of fines on drainage based on the different surface areas of fine materials relative to fibers [34].*

Specific surface area of fines is much greater than that of fibres. The high specific adsorption (in case with fines fraction) is attributed to higher surface area.

The solid surface area and resistance to dewatering of pulp mass have a relationship with each other. The superficial velocity through the mass packing tends to follow Darcy's law (equation 1):

$$v_{supervisual} = \frac{K\Delta P}{\mu L} \qquad (1)$$

Where:

$v_{supervisial}$ is supervisial velocity, m/sec;

K is permeability, m^2;

ΔP is the pressure difference across the pad or mat, Pa;

μ is shear velocity, Pa-sec;

L is the thickness of the pad or mat, m.

The superficial velocity is the flow rate divided by the area, neglecting the packing material [34].

3.6.2. *Choke-point Model of fines effect on dewatering process*

According to this model, "*fiber fines tend to accumulate to a disproportionate degree under a pure filtration mechanism*". Fiber fines, which are not agglomerated with fiber, block the available pore area for drainage during the dewatering process. The fines can move through the wet pulp web with water until they stick in so-called "choke points," i.e. locations where dewatering efficiency is low. It can be one of the reasons of slow dewatering process [4]. Fig. 7 illustrates the choke-point hypothesis:

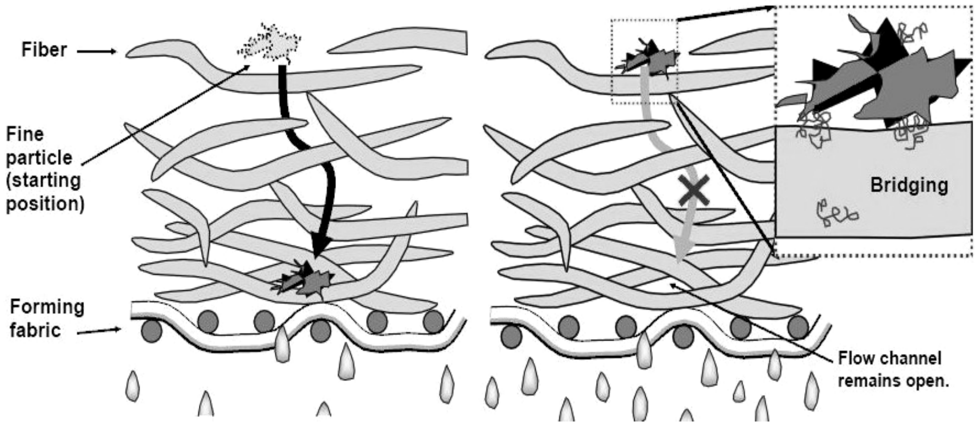

Figure 7 *Left: Schematic illustration of "choke-point" mechanism in which unattached fine particles move through drainage channels to vulnerable points at which they block the flow; Right: Proposed effect of bridging polyelectrolytes on defeating choke-point mechanism by keeping fiber fines attached to fiber surfaces [4].*

The fine particles move through the forming mat of fibers. They stuck at points where they obstruct flow. *"The flow of water during drainage is expected to favor build-up of fines at precisely those locations where their presence is least advantageous for further dewatering.*" [34]

3.6.3. *Mat density model*

The stock suspension dewatering can occur according to two mechanisms: filtration and thickening [35]. The mat density model is shown in the Fig. 8. That figure explains the effect of fines on dewatering process. On the left-hand part of the figure the limiting case is shown. In this case the fine particles play role of spacers between neighbor fibers. The fines can inhibit densification of the fiber mat and they can save relatively large water flow channels through the mat during the dewatering process. On the right-hand part of the figure the alternative limiting case is shown. And in this case all fines particles move into spaces between the fibers, thereby mat becomes denser [34].

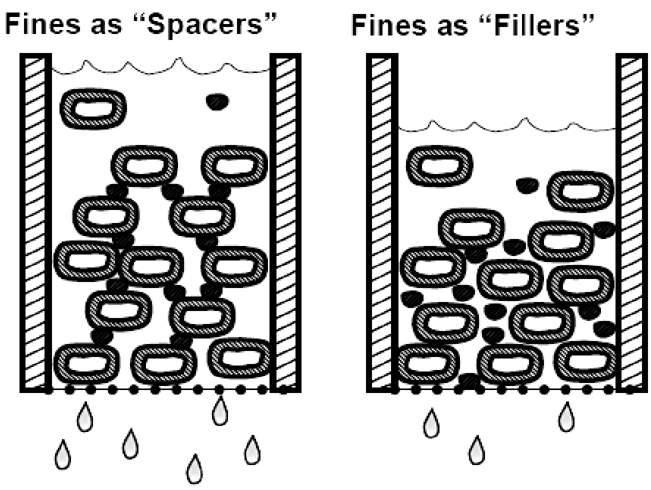

Figure 8 *Illustration of how fines may act as either spacers or fillers in a wet mat of fibers, thus affecting its density and permeability [34].*

Commonly, these models show the negative effect of fines on dewatering. From the results of Hubbe (Fig. 9), the fines fraction (in this work the fines fraction that passed a screen with a diameter of the holes of 100 µm was investigated) from the highly refined Kraft pulp had a higher negative effect on dewatering compared to the other types of fines. As it is shown in figure bellow, the primary fines from hardwood had large resistance to dewatering due to increasing of fines content [34].

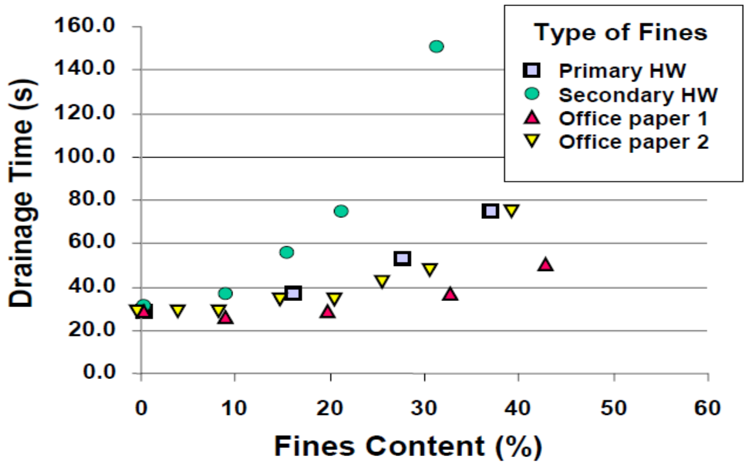

Figure 9 *Effects of increased amounts of different types of fines on drainage through mats formed mainly from the fiber fraction of repulped office paper [34].*

4. Flocculation as a main factor affecting formation

The tendency of the fibers to flocculation is one of the most important factors that determine paper structure and the mechanical properties [36]. Two types of flocks can be formed in a papermaking. They are undesirable permanent flocks (also called coherent flocks) and weak flocks which can be broken apart. The permanent flocks form when the suspension exceeds a critical consistency. Theory of limit concentration, which deals with critical consistency of fibres of suspension, is considered below. Permanent flocks are detrimental to paper properties. For example, for long fibers of aspect ratios in the range 100-300, the critical consistency is in the range 0.5–1.5%. The aspect ratio and the critical consistency have weak effect on the crowding number. The crowding number theory is also considered below [37].

4.1. Theory of limit concentration

The theory of limit concentration or critical fiber concentration (CFC) was defined by Mason. This concept is shown on the Fig. 10. According to theory, each fiber has certain space around itself. And fibers can rotate about its center without any collisions [38]. The freedom of fiber movement decreases when the volume concentration of fibers enhances. When the fibers content in unit volume exceeds a required limit, the fibers begin attach to each other and they cannot straighten out. The fibers have deformed and trapped state and thereby they release the shearing stress [36]. The concept is useful when volume concentration (C_v) is predicted for which collisions between fibers are either increasingly frequent (C_v>CFC) or relatively rare (C_v<CFC) [38].

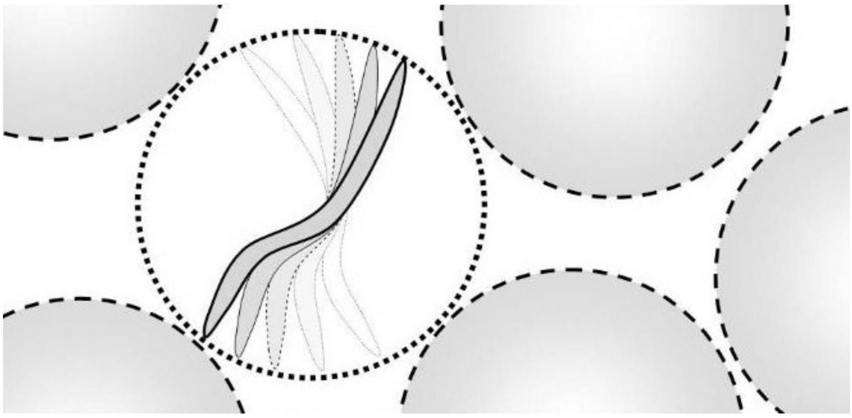

***Figure 10** Schematic illustration of the volume required for individual fibers to rotate freely without colliding with neighboring fibers [38].*

4.2. Crowding number theory

The “fiber crowding factor” is defined as the number of fibers in the spherical volume produced by a single fiber in rotation [36,38]. The schematic illustration of crowding number is shown in the Fig. 11.

The volumetric concentration of the fibers, the fiber length and the fiber diameter have effect on the crowding factor:

$$N = \frac{2}{3} \times C_v \times \left(\frac{L}{d} \right)^2 ; \qquad (2)$$

Where:

N is a crowding factor;

C_v is volumetric concentration, %;

L is a fiber length, m;

d is a fiber diameter, m.

This equation is written using the expression derived by Meyer and Wahren, for the volumetric concentration C_v [36]

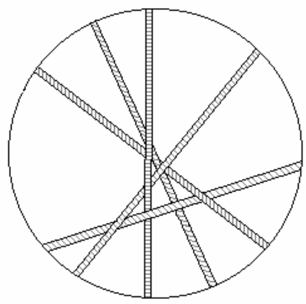

Figure 11 *The crowding factor, N, represents the number of fibers in the volume having a diameter equal to a fiber length [36]*

The crowding number has following values:

- N < 1, no fiber network can be formed. All fibers move freely relatively to each other. They sometimes impact with each other and remain together for a very short time.

- With increasing values of N, the fibers have a stronger tendency to collide with each other by displacement. With larger value of N, impacts also take place as a result of rotational motion.

- When N = 60 the number of contact points per fiber is about three. This number is enough for establishment of coherent fiber network. The related fibers move either by rotation, or by displacement. The fibers are blocked in a bent condition by the frictional forces. These frictional forces at the contact points between the fibers give the mechanical strength for the network. If the value of the crowding factor is more than 60 then fibers network get a considerable strength.

- When the value of crowding factor is more 60 the fibers become completely locked into the network. In this way the contact points must be arranged in an alternate manner [36,39].

4.3. Mechanisms of mechanical flocculation

The main factors that have effect on mechanical flocculation are fiber length, coarseness and concentration of fibers in slurry. These factors provoke the formation of strong flocks. Refining process essentially affect mechanical flocculation since during refining all mentioned parameters of mechanical flocculation which belongs to fibers properties undergo a change. It is well known that mechanisms of mechanical flocculation have higher contribution to the fibers flocculation than chemical mechanisms of flocculation [40].

4.3.1. The effect of fiber length on the flocculation ability of the fibers

Fiber length is a main factor related to flocculation. Fiber length is a criterion included to the formula for the calculation of crowding factor (see paragraph 4.2 formula 2) Results of Yan and Norman who studied the effect of fiber length on flocculation using mixture of softwood and hardwood fibers by flow loop system image analysis showed that : the fiber length, represented as the crowding factor, was the dominating factor of flocculation of fibrous suspension , fiber length is increased with increasing the ratio of softwood pulp in the mixture, fiber flocks size is increased when the ratio of softwood has enhanced and when fibers length was reduced the tendency to build the flocks was diminished [41].

The similar results were obtained by Hartley *et al*. They studied the fiber flocculation using PAM (polyacrylamide) by imaging the fibers that remain free during flocculation. The degree of flocculation was increased with increasing of fiber length. The big flocks were formed in mixtures of short and long fibers. Short fibers did not flocculate by themselves but they were caught by flocks formed with longer fibers. The short fibers strengthened the flocks and gave them greater shear resistance [42].

4.3.2. The effect of fiber coarseness on flocculation ability of the fibrous suspension

"Fiber coarseness is defined as weight per unit length and is normally expressed in units of mg/m or g/m." The fiber diameters, cell wall thickness, density of cell wall and fiber cross section have effect on fiber coarseness. The value of coarseness has a great effect on the paper structure. A high value of coarseness corresponds to the thick fiber wall. It gives stiff fibers ability to resist to collapsing of fibers. As a result, the paper has higher tensile strength [40].

The results from the work of Ramezani showed that fibers with higher value of coarseness gave paper with poor formation properties [43]. In addition, from the work of Kerekes it was founded that coarser fibers also tend to be longer. It was noted that it is not easy to separate the results about paper formation caused by coarseness or fiber length. [41]

4.3.3. The effect of refining on flocculation ability of fibers

As was mentioned earlier, refining has affects on structure of fibers. The flocculation behavior of refined fibers is changed. The most obvious change brought by refining is internal fibrillation (see 3.4.2.). Beating can expose more of the fiber's specific surface area. With increasing of fiber surface area the bonded area is increased. The refining process leads to shortening of fiber length. The fines fraction which is manufactured by beating has a negative effect on drainage filling spaces between fibers. These characteristics together can influence fiber flocculation.

The refining has also effect on fiber flexibility. The papersheets, made from unbeaten fibrous material, have unsatisfactory physical and mechanical properties. It can be explained by the fact that the comparatively long hard fibers convolve into flocks, and settling on the web, they give the heterogeneous structure of the sheet. Unbeaten fibers have low flexibility, poor surface and not enough hydrated. It was confirmed that flexible fibers have lower flocculation tendency to compare with stiff fibers [44].

4.4. Mechanisms of chemical flocculation

Usually the investigation of high-mass polyelectrolytes effect on fibers is applied for explanation of chemical flocculation. The main factors that influence on chemical flocculation are fines aggregation, effect of retention aids and formation aids [45].

4.4.1. Fines aggregation

The main mechanisms of fines aggregation are bridging flocculation, patch model, and charge neutralization [40]. The detailed description of these mechanisms is discussed bellow.

4.4.1.1. Charge neutralization mechanism of flocculation

The charge neutralization mechanism is based on the low molecular weight polymers or electrolyte salts which included in fiber suspension. They can compress the electrical double layer. The repulsion among fibers can be diminished. Then, van der Waals forces can attract fibers that lead to coagulation [40]. If the charge of the low molecular weight polymers is strong enough to attract the adjacent particles, the mechanism will change to patching as described in part 4.4.1.2.

4.4.1.2. Patch mechanism of flocculation

The mechanism of patch flocculation is based on charge neutralization mechanism. The polymers according to this mechanism usually have high charge density and relatively low molecular weight. According to this mechanism, the polymer with high charge (polymer charge density is more than the surface charge density) adsorbs to form a cationic patch on the anionic particle. This action gives to second negatively charged particle to approach the positive patch to give a doublet [65]. The process is illustrated in the Fig 12.

Other words, the cationic polyelectrolyte attach to the fiber surface and neutralize the anionic charge of the fibers or fines. The neutralized areas usually remain strong cationic charge. These areas are as "patches" on the surfaces of the fines and fibers. They can attract the anionic neighbor particles if the "patches" on the particles surface are enough large to compete the thickness of electrostatic double layer. "*Furthermore, when half of the particle surface is covered by "patches", the maximum flocculation occurs for low molecular weight retention aids. The coverage is decreased with increasing of the retention aids molecular weight"*. The patch flocculation makes flocks of rigid structure. They are stronger than flocks formed by charge neutralization model but the patch flocks are something intermediate between flocks by bridging flocculation and by charge neutralization [40,67].

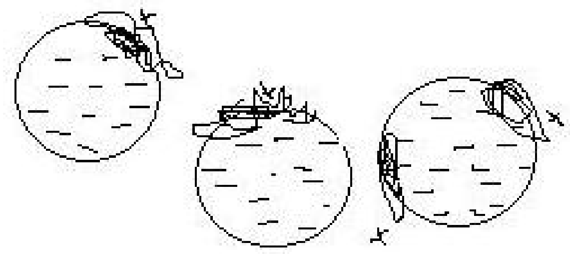

Figure 12 *Model of patch flocculation [40]*

4.4.1.3. Bridging model of flocculation

Under this mechanism, a polymer has a role of “bridge” for connection of one polymer with other one or several neighbor particles. Normally, high molecular weight polymers can perform this mechanism. The contact time of retention aids with fibers or fines, the properties of solution and the characteristics of the particles have effect on bridging flocculation. This mechanism is illustrated in Fig. 13. The mechanism of bridging flocculation can be divided into three parts. Firstly, the beginning of the adsorption takes place when retention aids are attracted on the surface of one particle. Secondly, the rest of the polymer becomes longer into the surroundings like a tail. Thirdly, a second particle is absorbed by the same polymer, and, thereby, flocculation occurs. The second particle can also perform the same mechanism for connection with other one or several particles together. The charge density of retention aids greatly influence on the maximum f;locculant dosage. Also the initial charge of the whole system can have a great effect on maximum flocculation [40].

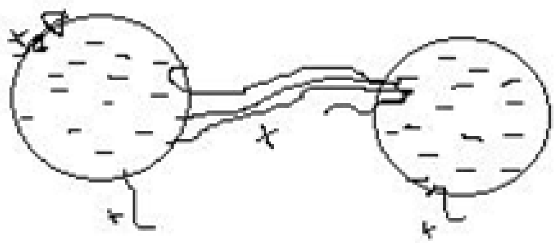

Figure 13 *Model of bridging flocculation [40]*

4.4.2. The effect of retention aids on fiber flocculation

The widely used method for retention of fines is addition of very-high mass polyelectrolytes. Such polyelectrolytes can negatively affect paper uniformity because the high polymer dosage or hydrodynamic shear forces are not appropriate for fiber deflocculation [45].

With polymer addition the strength of bonds between the fibers are increased. *"When the dosages of retention aids are varied, the surface coverage of polymer and microparticles will be changed and hence the area of sticky sites on the fiber surface will vary as well. The more sticky sites exist, the higher the bridging strength between fibers, which would lead to increased fiber flocculation and hence a poorer formation. The degree of flocculation is determined by how easily a single fiber can be entrapped inside a flock and how easily a fiber can escape from a flock." [46].*

According to the results of Swerin, the shear strength in a cellulosic fiber suspension (bleached softwood pulp and hardwood Kraft pulp) was increased by the addition of the high molecular weight C-PAM. Increasing of shear strength is a combination of increasing of the active fibers number in the network and increasing of the bonds between fibers [26].

4.4.3. Formation aids effect on fiber flocculation

The formation aids can be divided according Yan in the three main groups. The first group is the formation aids as additives for increasing of dispersion medium viscosity. The second group is such additives that can decrease the friction force between fibers. The mucilage and gums can be those. In result, the final paper has more uniform structure. The last group of formation aid is that when the high molecular weight polymers affect the rheological properties when the fibers are in suspension [47].

"For high shear viscosity the additional of formation aids can be used. But some formation aids with high molecular weight polymers can reduce the turbulence in fiber suspension. This effect has name of the drag reduction effect." [48]

According to the research of Zhao [48], the higher shear stress and high shear viscosity can improve the paper formation. It can make flocks more uniform in papersheets. Shear stress is the stress which resists the deformation caused by external force.

5. Paper Formation

"Formation is defined as the uniformity of spatial distribution of solid materials such as fiber, fines (fiber fragments) and filler (colloidal particles) in paper." The paper formation is one of the most important structural properties of paper. This property has effect on physical and optical characteristics of paper [40].

Also paper formation is defined as the variation of local grammage. It can be determined by measuring the mass distribution in the plane of the sheet. The scale of formation includes the scale of the flock structure and ranges from 1mm to 100mm [40].

Two scales of mass density variations take place in paper:

1) Small-scale variations are due to natural fiber flocculation and flocculation which caused by high frequency pulsation;
2) Large-scale variations are caused by the variability in the manufacturing process.

"Formation refers to small-scale grammage variations and is defined by the International Standards Organization as "the manner in which the fibers are distributed, disposed, and intermixed to constitute the paper." [49].

The degree of flocculation or the formation of the dispersion of the fiber can directly influence the result of forming the paper. Formation is the distribution of fiber within the plane of the sheet, and may refer to the transmission of visible light (optical formation) or β-radiation (paper formation). Definition of paper formation can be determined through the light passing through the paper, using only the naked eye. However, this is very subjective. The β-radiation is preferred because it is less subject to scattering of incident rays. The wavelength of the visible light (400 to 700nm) is sometimes longer than the diameter of fines, the visible light can be scattered by them [40].

5.1. Effect of fiber length on paper formation

Fiber length has a major influence on the micro-uniformity (formation) of paper. According to the results of Kerekes and Schell, the fiber length had strong effect on uniformity through the number of contacts between fibers and flock size. With decreasing of fiber length the mass uniformity is significantly increased. Also coarseness had effect on uniformity through the number of contacts, flock size, and mobility of fibers. It was determined that mixtures of long and short fibers of a given length-weighted average length give the same non-uniformity as individual fractions of the same fiber length [44].

Based on results of Ramezani and Nazhad, formation can be a function of fiber length and coarseness. The sheets of longer and coarser fibers have a worse formation than sheets of shorter and slender fibers. It happens because long and coarse fibers have a great tendency to flocculate during papermaking that is damaging the formation [43].

5.2. Effect of beating on paper formation

As it was mentioned earlier, the beating has strong effect on fiber properties (length, width, coarseness, amount of fines fraction and *etc*) that in turn determines the flocculation behavior of the fibers in suspension. As it is known flocculation has a strong effect on a paper formation and if the beating brings the changes to the flocculation tendency it can be concluded that beating process influences on paper formation. The beating makes fibers shorter and more flexible – these two factors diminish flocculation tendency [20,21].

According to the result of Ramezani, improving of formation takes place when the beating effect of fibers outweighs the opposite effect of refining of the fiber and fiber straightening [50].

The similar results were obtained by Store. Formation was worsened as a result of external fibrillation when fiber length is constant. And also pulp refining improved formation only when the influence of fiber shortening outweighs the effects of fibrillation and fiber straightening [51].

The results of Helmer showed that paper formation was improved with increasing of beating degree and with freeness decreasing. As it was expected, with increasing of beating the fiber length was decreased and the fiber width was increased. It indicates on swelling and fibrillation of cell wall and also fiber cutting. Increased refining led to better formation which was related to changes of fiber and slower drainage [52].

5.3. Effect of dewatering on paper formation

It is well known that increasing of shear forces on the wire and short dewatering time have negative effect on runnability, paper quality and paper formation [53].

During the drainage of water, the web structure is formed layer by layer. According to Norman, when the sheet is formed on the wire, the fibers in suspension tend to migrate to the areas with low basis weight. This process has name of the self-healing process. Therefore, the papersheet becomes more uniform. The reason for self-healing process is that areas with low grammage have a high volumetric flow of water through the porous layer, and fibers tend to accumulate in those areas. Thus, the flocks can be broken by the mixing [54].

5.3.1. The effect of refining process on drainage properties of fibrous slurry

As it was mentioned earlier, the main impacts of beating are the following:

1) Fiber shortening, which has insignificant effect on the ability of fiber mass to release water;

2) Fibrillation of the fiber surface, which slightly reduces the ability of the mass to release water;

3) External fibrillation of the fibers, which has great effects on the ability of fiber mass to release water

Increasing of the plasticity and flexibility of fibers, caused by their fibrillation during the beating process, leads to denser fiber mat during water removing. Fiber plasticity and the presence of fibrils prevent rapid movement of fibers. This effect reduces the formation of temporary small holes, through which water with fiber fragments is moved [55].

5.4. *The effect of flocculation on formation properties of paper*

The fiber flocculation can directly have effect on paper formation. *"Formation is the distribution of fiber within the plane of the sheet, and may refer to the transmission of visible light (optical formation) or β-radiation (paper formation)" [40].*

The effect of flocculation on paper formation was studied in the previous works [47,56]. It was noticed that with increasing of fiber length the value of formation index was increased. It means that paper formation is getting worse (Fig. 14). As it is known, the increasing of fiber length leads to more flocculation effect (see 4.3.1.). In the Figure 14 the following scales formation are shown: 0,3 mm represents small scale formation, 3-30 mm represents large scale formation and 0,3-30 mm represents total formation [47].

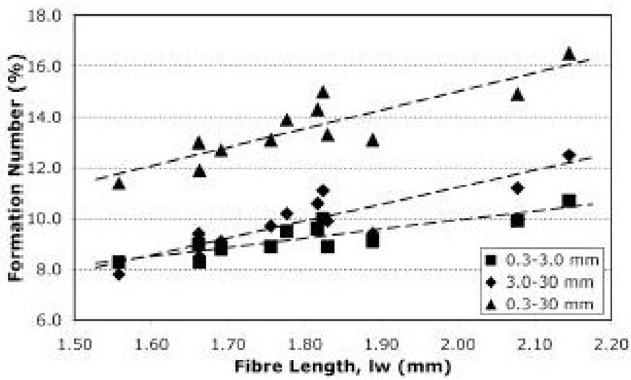

Figure 14 *Influence of fiber length on formation number of paper sheets. The different fiber lengths were obtained with Bauer-McNett. The increasing of formation number corresponds to deterioration of paper formation [47].*

It was observed that large scale formation increases more than small scale formation with increasing of fiber length.

According to Waterhouse the fiber flocculation produced by a time delay in drainage, cationic strength additives and increased forming consistency have an adverse effect on formation [56].

6. Effect of paper formation on tensile strength

It is known that poor formation decreases the tensile strength of paper. As it was mentioned (see paragraph 5.1) the paper formation is influenced by fiber properties. In particular, increasing length and coarseness cause poorer formation [57].

Fiber length and coarseness also influence the tensile strength of paper. With increasing of fiber length the papersheet becomes stronger. Poor paper formation decreases strength as a result of stress concentrations. It is caused by the non-uniform mass distribution in the sheet. Also paper strength is decreased through decreased consolidation [57].

7. Effect of fines on formation

"The gradients of fines in a fourdrinier machine may indicate a gradient of pore structure in the thickness direction as fines are caught in higher layers to form smaller and smaller pores". The electrostatic repulsion between negatively charged particles can overcome by addition of multivalent ions, polyelectrolytes, or other colloidal additives. The increasing of the retention aids can help retention but it damages formation. Retention is a complex relationship between process conditions (degree of refining, drainage rate, jet wire ratio, and web speed), particle size distributions, pH level, electrical charge, ionic strength, flocculants and coagulants added to furnish. In the aggregate, retention is interaction of hydrodynamic forces and non-hydrodynamic forces [58].

The fines fraction increases the strength of paper by improving the bonding between long fibers. However maximum fines content deteriorates strength properties as the continuous fiber network is disrupted [49].

As it was mentioned earlier, fines have great effect on drainage time of pulp slurry during manufacture of paper. The tendency of the fibers in suspension to concentrate around drainage sinks leads to a smoothing mechanism of fibrous mat [59].

For example, the results of work of Xintong Lu showed that fines fraction and drainage time have great effect on paper formation. With increasing of settling time, the formation was deteriorated. He used TMP containing different amount of fines. The degree of flocculation was also increased since longer settling time gave the fibres more chances to entangle with each other. Results also showed that at the highest fines level (40%), these changes with settling times are minor, since the long drainage time corresponds to 40% fines pulp. (see Fig. 15). With increasing of drainage time, there is more opportunity for fibres to entangle. "*Therefore a settling time of 120 seconds had a significantly reduced effect on fiber entanglement for the 40% fines content sample since the drainage time is already long (70 seconds)*." [49]

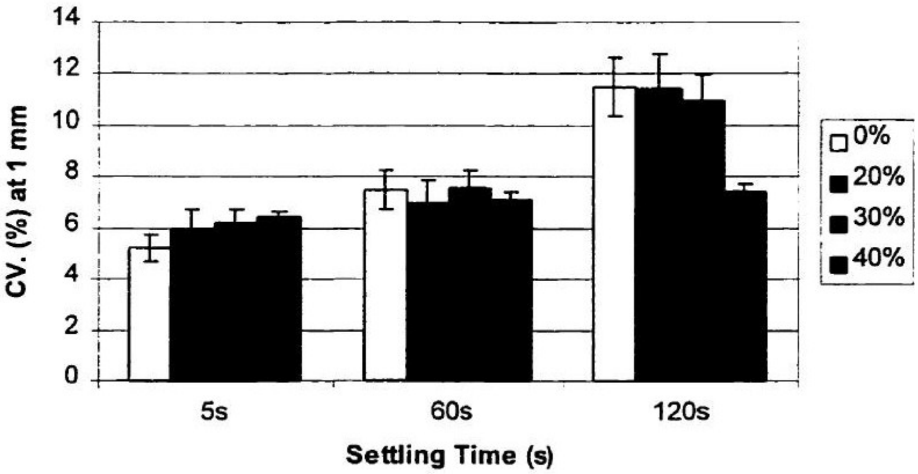

Figure 15 *The effect of settling time (time before drainage) at different fines content levels on the CV (coefficient variation) of mass density of the handsheet samples (the error bars covers ± two standard deviations). The drainages time for each pulps were following: 0% of fines-5 seconds, 20%-7 seconds, 30%-12 seconds, and 40%-70 seconds [49].*

EXPERIMENTAL PART

8. Materials and methods

8.1. Materials

The used pulps in this work were never dried bleached softwood Kraft (Nordic Pine) and dried bleached birch (Nordic Birch). The target refining degree of each pulp was SR 40 *Schopper-Riegler degree*. Refining was made in Valley Hollander (SCAN-C 25:76).

Aqueous solution of a cationic polyacrylamide (PAM), Fennopol K 3400, was used as a flocculant agent. For laboratory trials, 0.2 % solution of PAM was produced using the following procedure: at first, 49.9 g of water was taken in a conical flask. Then water was stirred vigorously using a magnetic stirrer until whirlpool was appeared. Then, 0.1 g of PAM granules was slowly added in the middle of whirlpool. The flask was covered by plastic film to avoid evaporation. Mixing was slow and continued for a long time until the granules were totally dissolved (about 10 hours). The ready solution was stored in the refrigerator. Then ready for use and it was used within 1 hour. For the use solution was diluted to concentration of 0.01 %. Used chemicals dosages were 0.02%, 0.025%, 0.03% and 0.04%. Mainly used dosage of PAM was 0.03%.

8.2. Beating of pulp

At first, beatings of never dried Pine and bale birch pulp were done in Valley Hollander beater according to ISO 5264/1 (times of beating were 62 minutes and 37 minutes respectively). The target degree of Shopper-Riegler was 40° SR. Then beaten pulp was analyzed by Shopper-Riegler method according to ISO 5267/1.

8.3. Adjusting and measurement of pulp fines content

After beating of fibers related value which reflects fines content was determined with L&W fiber tester. The sample of pulp in quantity of 0.05 g. of o. d. pulp was given in the laboratory glass. Then, 200 ml of water was added there and the amount of fines fraction in each pulp samples was determined using Laboratory Fiber Master. These values named “related” because in L&W fiber tester, fines are expressed as the percentage of material shorter than 0.2 mm in relation to the number of fibers longer than 0.2 mm. Based on the measurement principle of L&W it was concluded that this devise may give some value which approximately reflects the true amount of fines fraction. To measure true amount of fines one should perform fractionation in a Bauer-Mc Nett Classifier according to standards SCAN M6 and TAPPI T 233. This method has one advantage which compensates all others disadvantages – it gives true amount of fines. But in producing of pulp with removed fines fraction this method has disadvantages. These are complexity and low capacity of this method (only 10 g o. d. pulp) [66]. Since for the preparation of papersheets a lot of fractionation is needed it was decided to choose the DDJ (dynamic drainage jar) for rough fractionation based on the bigger capacity of this method to compare with Bauer-Mc Nett. In order to receive accurate data three parallel tests were done and average of the tests results used as a result

In the result, for partial fines removing the DDJ was used. The used mesh was №200 (75 μm). Washing was done by using continuous supply of water with stream that was equal with the outgoing stream. The schematic illustration of this method is shown in the Figure 16. In the down part of cylinder the fines fraction was going. The agitator was used to mix the pulp slurry.

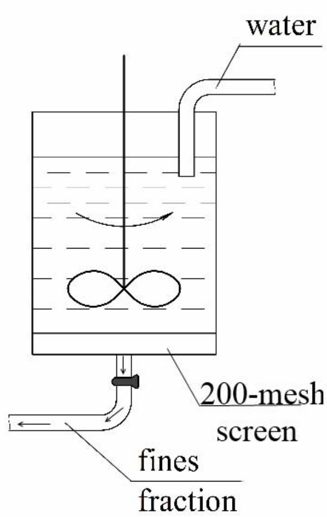

Figure 16 *Schematic illustration of method for removing of fines using DDJ method.*

For purpose to create different amount of pine and birch fines in suspensions variation of washing time was applied. However, used method have limit of the removal of fines. It was determined that the process of fines removal slowed down after 10-minutes of washing. The following results (Table 2) were obtained:

Table 2 Effect of washing time on fines content

Washing time, min	**Fines content, %**	
	Pine pulp	**Birch pulp**
Initial fines content	**5.3**	**7.0**
1 min	3.0	3.0
3 min	2.0	Not measured
5 min	Not measured	1.8
7 min	Not measured	1.5
10 min	1.0	1.5
15 min	0.9	Not measured
20 min	0.8	Not measured

In the Table 2 the results from each washing were shown. For each washing the certain amount of pulp slurry was taken. It was about 6.3 g of o.d. pulp. The optimal concentration was 6.3 g/l. Several batches were made with each washing time and then those were blended together. For getting a pulp with 5% fines fraction washed and unwashed birch pulp were mixed in a specific ratio.

Bauer-McNett method for removal of fines was used in case with pine pulp. This method showed effective removal of fines using the same pulp (pine pulp). The fines content of 0.2% was obtained.

In case with investigation of the effect of birch fines content on paper formation the washing times were changed. It was obtained the following results with birch pulp: for the concentrations of fines equal to 1.5%, 2.5% and 3.5% for birch pulp, washing times were 7, 5 and 1 minute respectively. The initial amount of fines in birch pulp was also changed; it was 5 % of fines. In this seriess the addition of extra fines was also made. For production of 6.5%, 7.5% and 8.5% fines fraction in birch pulp (extra fines) the fines fraction to unwashed pulp was added. Fines fraction was obtained by sedimentation of fines after pulp washing. Then the separation of fines from water was done.

After beating of fibers related value which reflects fines content was determined with L&W fiber tester. This value named "related" because in L&W fiber tester, fines are expressed as the percentage of material shorter than 0.2 mm in relation to the number of fibers longer than 0.2 mm. Based on the measurement principal of L&W it was concluded that this devise may give some value which approximately reflects the true amount of fines fraction.

8.4. Preparation of laboratory handsheets

In this work three approach of preparation of handsheets were made. They were standard preparation of the laboratory sheets, the preparation of the sheets with different drainage time and also the preparation of the sheets with different pulp consistency.

8.4.1. Preparation of the sheets with standard method

The target basis weight was 60 ± 3 g/m^2. Paper sheets for the trials were made on the KCL Laboratory Sheet former (SCAN-CM 11:95). Then sheets were pressed with L&W sheet press (SCAN C 26:76). The sheets were made without white water circulation. After drying on drum dryer samples were conditioned overnight in the room with standard conditions (23°C, 50% Relative Humidity) (SCAN-P2).

8.4.2. Adjusting the drainage time

Method of adjusting of drainage time during papersheets forming was applied. Drainage time was modified by introducing special calibrated plate with help of which it can be possible to open valve at 4 different positions (see sketch in the Figure 17). The quickest drainage corresponds to maximum opening of valve and vise versa, the slowest to the minimal extent of valve opening. Also in this work, the effect of initial time delay on specific formation of papersheets made from pine pulp was determined. Settling time was applied and it was the time after mixing of pulp slurry in the camber of sheet former and before the valve opening. Chosen initial times delays were 20, 30, 60 and 90 seconds. In case of study of influence of pulp consistency on paper formation for pine and birch pulps with applying of time delay, the initial time delay after mixing was 15 second.

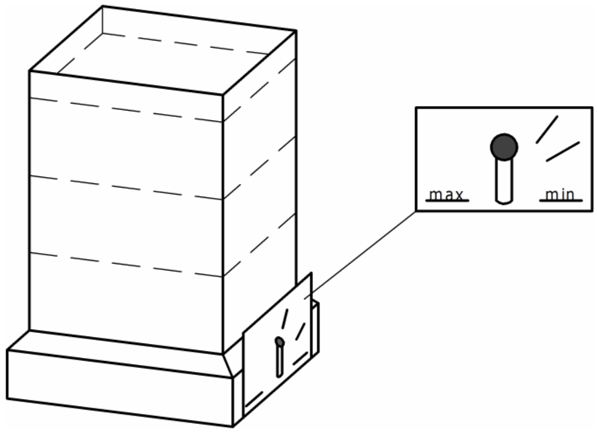

Figure 17 *Schematic illustration of time adjusting method (valve method)*

8.4.3. Adjusting the consistency in the sheet mould

For consistency variation of fibrous slurry nonstandard method was used: the tank of KCL-sheet mould was divided on three sections to achieve different consistencies (Figure 18).

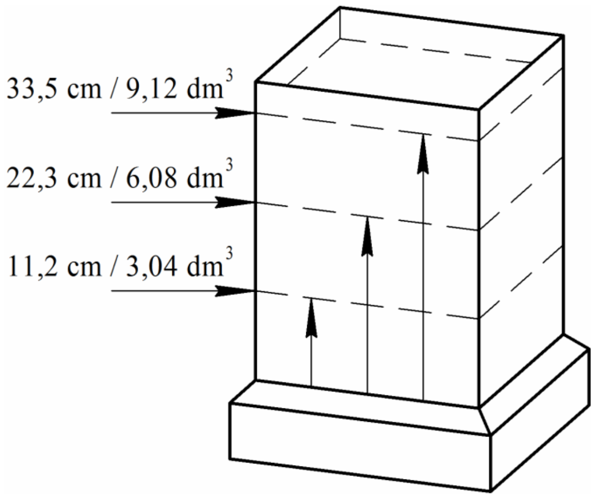

Figure 18 *Chosen water levels (cm) of the tank of KCL-sheet mould. Total height of the tank was 40 cm.*

The corresponding consistencies of pulp slurries to the level of sheet former filling are shown in the Table 3.

Table 3 Ratio volume and consistency of the pulp slurry in the sheet mould

Volume of the pulp slurry, V, dm3	Consistency of the pulp slurry, g/l
3.04	0.536
6.08	0.268
9.12	0.179

8.5. Addition of flocculant in the pulp slurries

For the purpose of choosing the right way to add the f;locculant two methods of flocculant additional were analyzed. They are addition of PAM straight into pulp mass before papersheets making (pulp slurry was mixed about 10 minutes) and addition of PAM during papersheets making. The results with addition of f;locculant into the pulp before handsheets making did not show any changes of paper formation. The used dosages in that method were 0.02%; 0.025%; 0.03% and 0.04%. The absence of any noticeable changes of paper formation when the flocculant added can be explained by the fact that flocks could be broken down, and since they were formed by bridging mechanism the flocks could not form again. It could happen if to mix suspension vigorously for a long time between the addition of PAM and making of the sheets. It was proposed to use second method of PAM addition. Used dosage of PAM was 0.03%. Addition level of PAM was calculated on dry pulp. In this method PAM was added to the pulp slurry during the air mixing of pulp in the sheet former.

8.6. Testing of papersheets

8.6.1. Measurement of paper formation

Measurements of paper formation were made on an AMBERTEC Beta Formation Tester. The operation principles of this equipment are beta radiation absorbency and stepping scanner.

For measurement of paper formation for KCL type paper sheets, calibrated mode was chosen. The settings for this mode were:

- Number of points per measurement was 400
- Measuring area was 66,5 mm x 66,5 mm
- Distance between measuring points was 3,5 mm

The used parameter of paper formation in this work was specific formation. It is normalized standard deviation of the basis weight. The normalized standard deviation is obtained through division of the standard deviation of grammage by the square root of the basis weight.

8.6.2. Tensile strength

The tensile strength values of the tested papersheets were determined with L&W tensile tester (ISO 1924 2). In seriess of tensile strength measurements standard and non-standard methods were used. In standard method test sheets were cut into 10 strips with standard width – 15 mm. Standard errors of the means were calculated (TAPPI T 220).

Non-standard method for measurement of tensile strength was used in this work in some cases. For non-standard method paper sheets were cut into 4-5 strips with non-standard width – 45 mm. Each 45 mm strip was folded twice so that it becomes 15 mm wide. The similar calculations were made and result was divided by 3. Approximate picture of this method is shown in Figure 19.

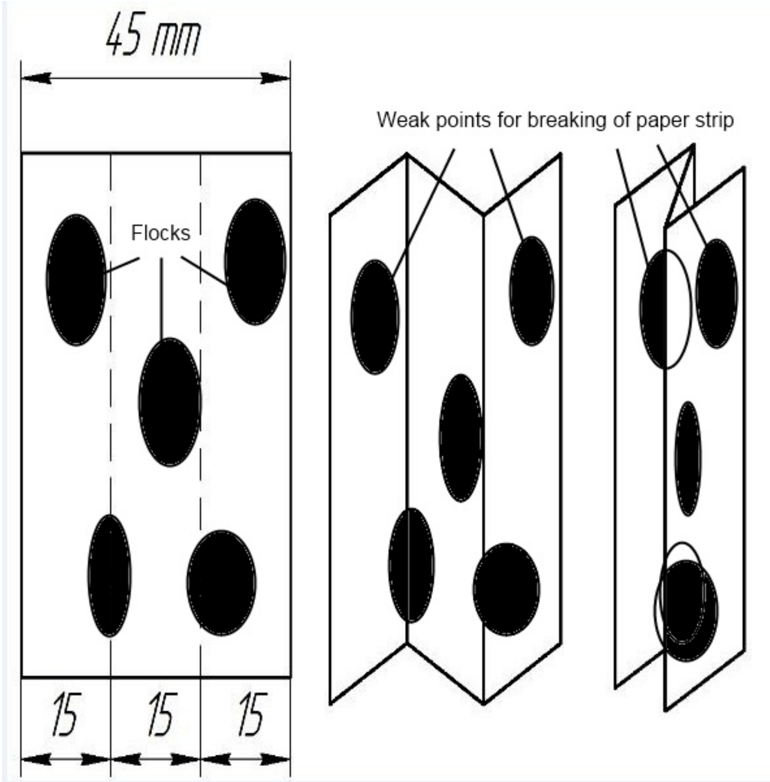

***Figure 19** Schematic illustration of non-standard method of tensile strength measurement*

This method was used for more accurate measurement of strength properties. Since the paper has an uneven distribution of fibers in the plane, mainly flocks, it was assumed that the standard method can give more accurate results. Flocks are distributed in the plane of the paper randomly. If to use the standard method, the sheet break occurs exactly at the location of flocks that corresponds to weak point of strip. Using the non-standard method of strength measurement of paper, strip samples of paper have more proposed locations of break since more flocks are in the plane of the strip. Some schematic illustration of discussed is shown in the Figure 19.

9. Experimental design

In this paragraph the used raw materials and used methods for preparation of handsheets are presented. The used methods were investigation of fines content by washing, the investigations of PAM addition in pulp slurries, variations of drainage time due papermaking by valve method, investigations of pulp consistency and furnishes from pine and birch pulps.

Table 4 The handsheets composition made from pine pulp.

№ of seriess	Name of seriess	Used pulp	Value of SR	Fines content, %	Addition of PAM
1	Investigation of fines content effect on formation and strength properties of papersheets	Unwashed pine pulp	40 SR	5.3%	—
		Washed pine pulp		0.2%	—
				1%	
				2%	
				3%	
2	The effect of flocculant addition on formation properties of laboratory papersheets	Unwashed pine pulp	40 SR	5.3%	Dose of PAM was 0.03%
		Washed pine pulp		1%	
				2%	
				3%	
3	The investigation of the dewatering time effect on paper formation	Unwashed pine pulp	40 SR	5.3%	The papersheets were made without and with PAM (dose of PAM was 0.03%)
		Washed pine pulp		3%	
4	The effect of fiber consistency on formation properties of paper sheet	Unwashed pine pulp	40 SR	5.3%	The papersheets were made without and with PAM (dose of PAM was 0.03%)
		Washed pine pulp		3%	
		Unwashed birch pulp	40 SR	7%	
		Washed birch pulp		3%	
5	The effect of mix ratio of different pulps on paper formation	Unwashed pine pulp	40 SR	5.3%	—
		Washed pine pulp		3%	
6	The investigation of initial time effect	Unwashed pine pulp	40 SR	5.3%	—

Table 5 The handsheets composition made from birch pulp

<table>
<tr><th>№ of seriess</th><th>Name of seriess</th><th>Used pulp</th><th>Value of SR</th><th>Fines content, %</th><th>Addition of PAM</th></tr>
<tr><td rowspan="7">1</td><td rowspan="7">Investigation of fines content effect on formation and strength properties of papersheets</td><td>Unwashed birch pulp</td><td>40 SR</td><td>5%</td><td>—</td></tr>
<tr><td rowspan="3">Washed birch pulp</td><td rowspan="3"></td><td>1.5%</td><td rowspan="6">—</td></tr>
<tr><td>2.5%</td></tr>
<tr><td>3.5%</td></tr>
<tr><td rowspan="3">Birch pulp + extra fines</td><td rowspan="3"></td><td>6.5%</td></tr>
<tr><td>7.5%</td></tr>
<tr><td>8.5%</td></tr>
<tr><td rowspan="4">2</td><td rowspan="4">The effect of flocculant addition on formation properties of laboratory papersheets</td><td>Unwashed birch pulp</td><td>40 SR</td><td>7%</td><td rowspan="4">Dose of PAM was 0.03%</td></tr>
<tr><td rowspan="3">Washed birch pulp</td><td rowspan="3"></td><td>1%</td></tr>
<tr><td>3%</td></tr>
<tr><td>5%</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">The investigation of the dewatering time effect on paper formation</td><td>Unwashed birch pulp</td><td>40 SR</td><td>7%</td><td rowspan="2">The papersheets were made without and with PAM (dose of PAM was 0.03%)</td></tr>
<tr><td>Washed birch pulp</td><td></td><td>3%</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">The effect of fiber consistency on formation properties of paper sheet</td><td>Unwashed birch pulp</td><td>40 SR</td><td>7%</td><td rowspan="2">The papersheets were made without and with PAM (dose of PAM was 0.03%)</td></tr>
<tr><td>Washed birch pulp</td><td></td><td>3%</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">The effect of mix ratio of different pulps on paper formation</td><td>Unwashed birch pulp</td><td>40 SR</td><td>7%</td><td rowspan="2">—</td></tr>
<tr><td>Washed birch pulp</td><td></td><td>3%</td></tr>
</table>

For investigation of the effect of fiber consistency (№ 4 in the both Table 4 and Table 5) the following approaches of papermaking were used:

- without PAM and initial time delay
- with PAM without initial time delay
- with 0.03 % PAM and initial time delay of 15 seconds

All sheets were made with three different consistencies of pulp slurry in the sheet mould. The consistencies were adjusted to 0.54 g/l, 0.27 g/l and 0.18 g/l as described in chapter 8.4.3.

When it was investigated the effect of initial time delays (№ 6 in the Table 4), the chosen initial time delays were 20, 30, 60 and 90 seconds. Formation and tensile strength of the papersheets were measured with standard and non-standard methods.

With target to study the effect of mixture of pine and birch fibers (№ 5 in the both Table 4 and Table 5) on formation of handsheets, the mixtures were prepared according to the ratios presented at the Table 6. Since it is very interesting to see the contribution of fines fraction of mixed slurries on formation, the fines removing was done.

Table 6 Chosen furnishes of birch and pine. The similar compositions were for both washed birch and pine pulps having fines content of 3%.

Number of furnish	Amount of birch pulp, %	Amount of pine pulp, %
1	100	0
2	80	20
3	60	40
4	50	50
5	40	60
6	20	80
7	0	100

Mixtures of both pine and birch pulps in different ratios with and without fines removing were prepared according the Table 6. Fines removing was performed by washing on DDJ according to method described in paragraph 8.1 Fines content of both pulp slurries was 3%.Then papersheets were made from prepared slurries. The papersheets were made according to standard method of preparation.

From the handsheets the measurements of formation and tensile strengths were made.

10. Results and discussions

10.1. Variations in papermaking affected formation properties of papersheets

In this seriess of experiments effect of fines fraction of pine and birch pulps on specific formation was determined. The extra birch fines effect on formation and strength properties was also analyzed. The washing of pulps was made according to instruction in (see 8.3.). In this work, the effect of flocculant addition to birch pulp, which contained different amount of fines, was determined. The effects of drainage modifications using valve method (see 8.4.2.) and initial time delay were also analyzed. Paper sheets made from different mix ratios of pine and birch pulps with partial removing of fines were analyzed on paper formation. The effect of pulp consistency variation on papersheets formation was analyzed.

10.1.1. The effect of fines content on paper formation properties

The influence of fines content on specific formation was determined in this seriess of experiments. Increasing of specific formation means the deterioration of paper formation. The drainage time in each point in the Figure 20 is also shown.

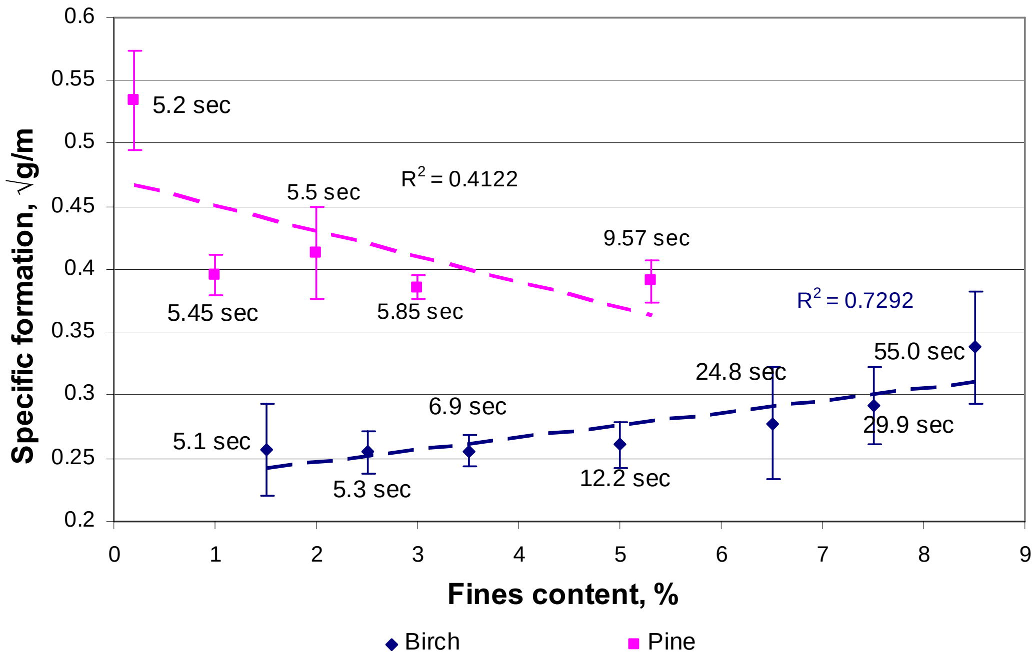

Figure 20 *Effect of fines content on specific formation. The fines content was adjusted by removing part of the fines from beaten (SR 40) pine and birch pulps. The initial birch fines content was 5%, the initial pine fines content was 5.3%. Fines contents above 5 % were adjusted by adding fines fraction to unwashed pulp Basis weight of tested sheets was 60 g/m*^{2}*. .The times indicate the drainage time.*

From Figure 20 it can be seen the difference between formation for pine and birch pulps containing different amount of fines. It is known that softwood pulp has longer fibers compared to hardwood pulp. Long fibers tend to create larger flocks than short fibers. As a result, the papersheets made from birch pulp has more uniform distribution of fibers, and with increasing of fines content it was noticed that formation properties were improved. But extra fines addition deteriorated paper formation. It can be explained that high value of fines can give negative effect on paper formation. As it is know the fines fraction increases the pulp slurry viscosity [10]. But elevated viscosity make difficult for fibers to move in suspense and collide with each other [48].

We can see that with increasing of pine fines content the specific formation is decreased, that means improvement of paper uniformity. The fines can play role of fillers between fibers; in result the fibrous mat becomes more uniform [34]. Also the fines fraction can act as a dispersant agent that leads to improvement of paper formation. The schematic illustration of that mechanism is shown in the Figure 21 bellow.

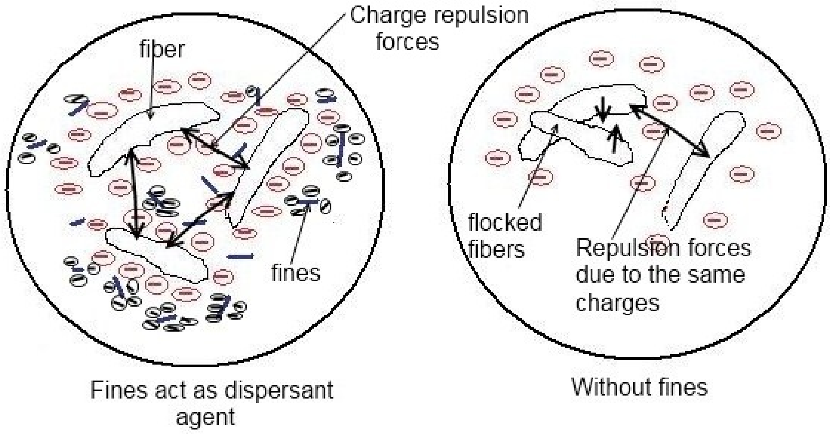

Figure 21 *Schematic illustration of high charged fines that act as dispersant agent*

The fines have the same magnitude of the charge (negative) as a fibers therefore they repel from each other and also they slow down the flocculation since they locate between the fibers and prevent their physical contacts. Also the positive effect of “hydrodynamic smoothing” (Figure 22) on formation should be noted [59]. Fines fraction during the formation of paper sheet by conventional laboratory methods has a tendency to targeting to the areas with less material, since these areas have smaller hydrodynamic resistance.

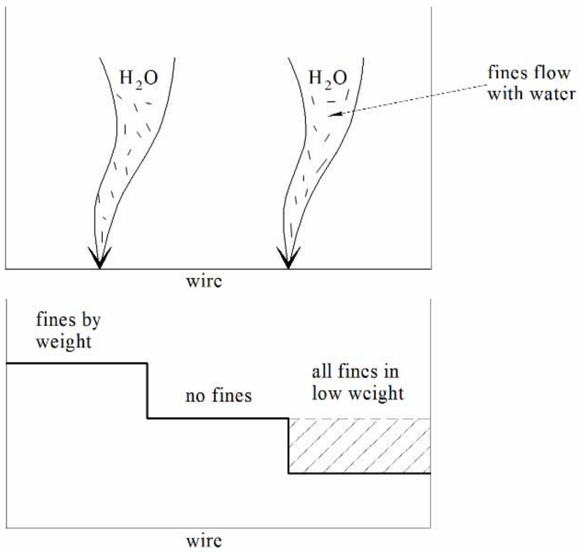

Figure 22 *Schematic illustration of hydrodynamic smoothening.*

In case with birch fines we can see other dependence. The Figure 23 shows that in larger scale.

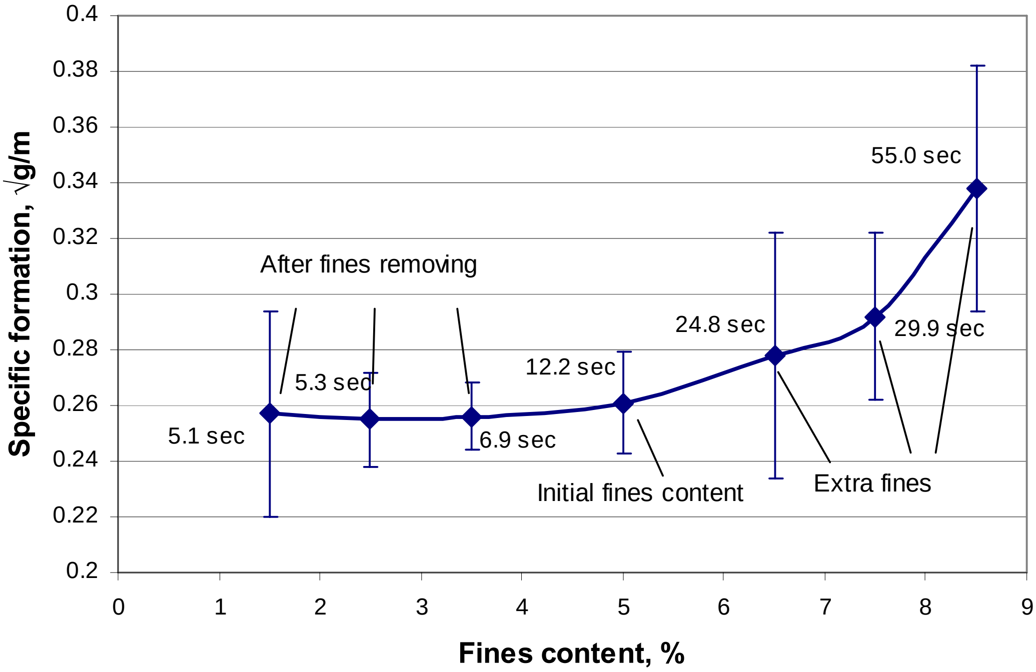

Figure 23 *Effect of extra fines content of birch pulp on specific formation of the sheets. The initial fines content of the pulp was 5 %. The fines contents below that were adjusted by removing part of the fines (washing) from birch pulps (SR 40). Fines contents above 5 % were adjusted by adding fines fraction to unwashed pulp. Basis weight of tested sheets was 60 g/m^2.*

From the Figure 23 it is seen that paper formation is changed by hyperbolic trajectory when the amount of fines is varied. It means that in first stages the partial fines removing leads to improving of formation. When the extent of fines removing is high (up to 1-2%) the formation of paper sheets is getting worse. First step – improving of formation by lowering the amount of fines, the trend of this step is explained that when the fines content is diminished its makes the drainage better, since it is known that fines fraction dispersing in the fibrous suspension blockades the drainage channels between the fibers. Drainage improving in turn leads to formation improving because fibers spend less time in conditions favorable for flocculation. The second stage (5-3%) is plateau when the lowering of fines content does not give notable effect on handsheets formation. At the third stage (0-2.5%) the tendency to increasing of formation index during diminishing of fines amount can be seen as in Figure 20 for the pine samples, as in Figure 23.

To summarize said above, fines fraction plays very important role in creation of papersheets with good formation properties. To make explanation of that easy it one can imagine the balance. One side of which is drainage (improving of which by removing of fines leads to the bettering formation) and on the other side it is hydrodynamic smoothing and dispersant action of fines. By removing the fines from the system, this balance is get broken that leads to improving formation when the effect of drainage is dominating, but formation is getting poorer when the extent of fine removing is so higher when the drainage is not change so strong anymore and the others processes like dispersant action and hydrodynamic smoothing start to be important [60].

10.1.2. The effect of PAM addition to the birch pulp with different fines content on formation and strength properties of papersheets

In this seriess of experiments the effect of f;locculant addition on paper formation was determined. The different fines fractions of both pine and birch pulps were used. The dose of PAM was constant (0.03%).

In this Figure 24 the point of 7% of fines content for birch pulp is reference point (Unwashed birch with initial fines content).

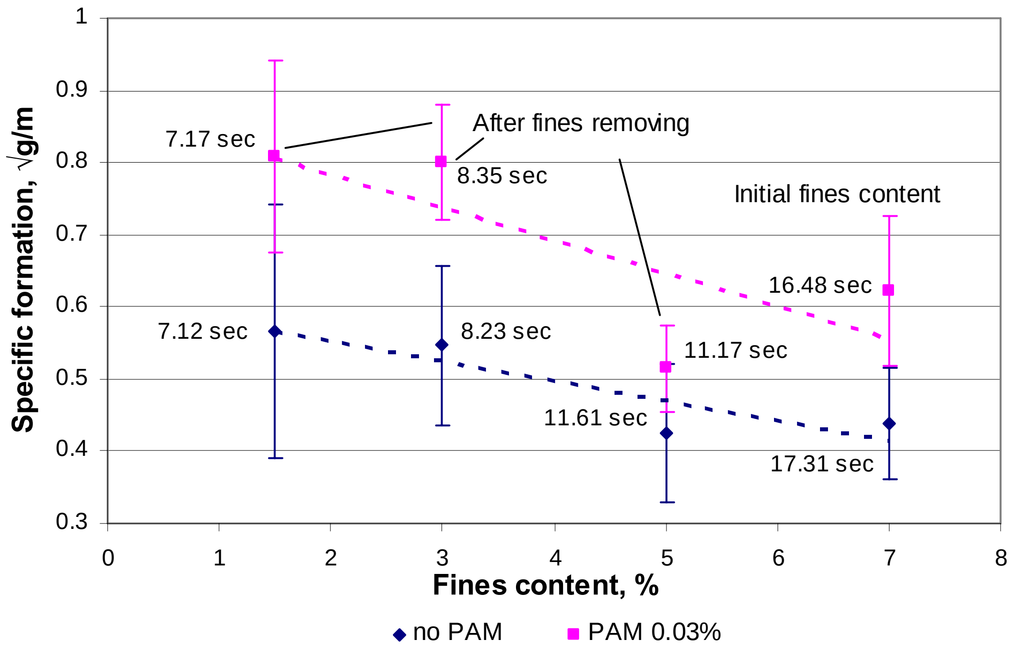

***Figure 24** Effect of PAM addition on specific formation of sheets made from birch pulp containing different amount of fines. The initial fines content of birch pulp (SR 40) was 7 % (unwashed pulp). The fines content to 1.5 % and 3 % was adjusted by removing part of the fines (washing) from birch pulp and the fines content of 5 % was achieved by mixing unwashed and washed pulp. Basis weight of tested sheets was 60g/m^2. **Note:** in this seriess of investigation the fines effect on paper formation plotted points for both unwashed and washed birch pulp (5%) and birch pulp do not correspond to the plotted points of the previous figures since this seriess of experiments were made long before with another wire. As a result, the values of specific formation are changed and drainage times were also variated.*

From the Figure 24 it can be seen that with increasing of fines content the formation of paper is improved. Using PAM during preparing of papersheets, the paper formation was deteriorated. PAM is a cationic polymer, which is used as drainage agent and it works by flocculation mechanisms agglomerating the fines and “cleaning” the drainage channels between the fibers. So, PAM should improve drainage and, in result, it leads to improving of formation [61]. In this case we combine the both approaches partial fines removing and addition of f;locculant. So, since fines fraction was partially removed, those amount of PAM which should be consumed by fines adsorbed to the fibers surface. That means that PAM stimulated fibers flocculation

10.1.3. The effect of drainage modifications on papersheets formation

In this study for the purpose to study the effect of drainage time on formation the drainage time was varied. The variation of drainage time was made by regulation of opening valve position (see the methodic description in the paragraph № 8.4.2.). Selected times were 10, 20, 30 and 40 sec. The effect of drainage time on specific formation of paper is presented in Figure 25.

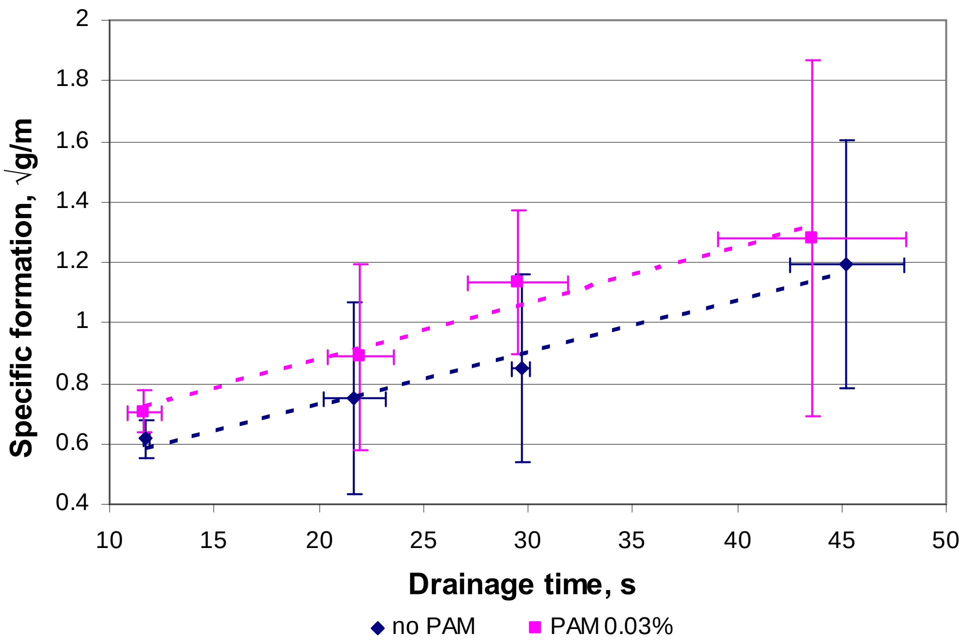

***Figure 25** Effect of drainage time and use of flocculant (0.03%) on specific formation of sheets made from unwashed pine pulp (SR 40). Fines content of the pulp was 5.3%. The drainage time was adjusted by reduction of water flow through the outlet valve of the sheet mould. Basis weight of tested sheets was 60 g/m^2.*

From the Figure 25 it can be seen that with increasing of drainage time specific formation is increased (paper formation is worse). It can be explained by the fact that when the drainage time increases the fibers have more time to build flocks and with the addition of the flocculant this effect is intensified. We can see some visible but really small improvements in drainage when the PAM has been added (see last points that correspond to the highest drainage times 40-45 seconds). Based on this we can conclude that improving of drainage in highest delaying point achieved due to that PAM needs some time to operate in so diluted conditions (diluted to compare with realistic industrial levels). Especially the improving of drainage time by PAM addition can be seen in Figure 26. PAM and fines removing improved the drainage, but they made formation worse.

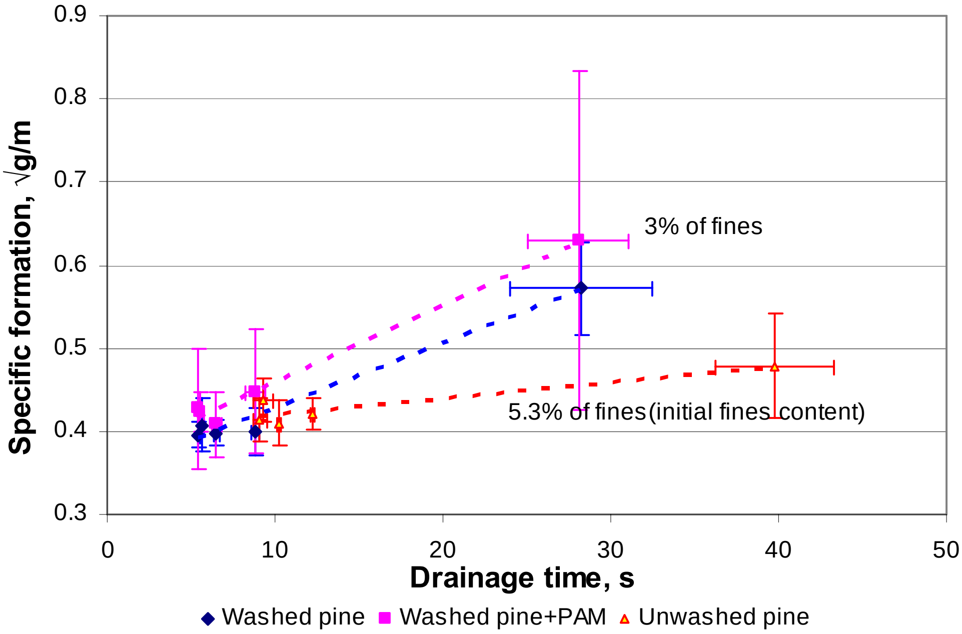

Figure 26 *Effect of drainage time and use of flocculant (0.03%) on specific formation of sheets made from pine pulp (SR 40), containing different amount of fines. The fines content was adjusted by removing part of the fines from pine pulp (SR 40). The fines content of unwashed pine pulp was 5.3%; the fines content of washed pine pulp was 3% and was adjusted by removing part of the fines from pine pulp. The drainage time was adjusted by reduction of water flow through the outlet valve of the sheet mould. Basis weight of tested sheets was 60 g/m2.* ***Note:*** *the plotted points for unwashed pine pulp (5.3%) do not correspond to the plotted points of the previous Figure 25 since this seriess of experiments were made long before with another wire.*

In the case with pulp containing different amount of fines and using addition of PAM (Figure 26) the effect of drainage time has considerable effect on specific formation. The greatest effect was received at 30-40 seconds of dewatering. If to compare the picture with previous figure (Figure 25) the effect of PAM addition is similar. PAM should improve drainage and, in result, it leads to improving of formation. In this case we again combine the both approaches partial fines removing and addition of f;locculant. So, since fines fraction was partially removed, the PAM adsorbs to the fibers surface. That means that PAM stimulated fibers flocculation which leads to poor formation.

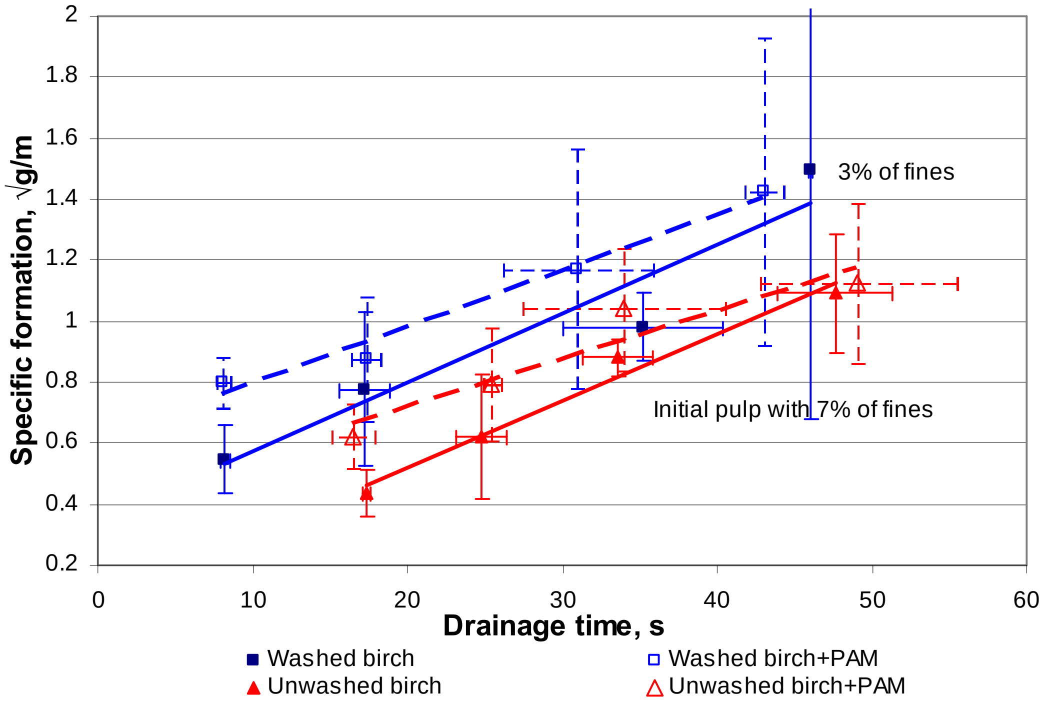

Figure 27 *Effect of drainage time and use of flocculant (0.03%) on specific formation of sheets made from birch pulp (SR 40), containing 7% and 3% of fines. The fines content was adjusted by removing part of the fines (washing) from birch pulps (SR 40). The drainage time was adjusted by reduction of water flow through the outlet valve of the sheet mould. Basis weight of tested sheets was 60 g/m^2.*

From Figure 27 it can be seen that increasing of drainage time and use of flocculant have negative effect on specific formation of sheets made from birch pulp. The addition of PAM to unwashed birch pulp slurry increased the specific formation almost for all drainage times (see Fig. 27). It can be noticed that slope of the unwashed pulp with addition of PAM (red crosses) is turning forward of formation improving when the drainage time is enhanced. That fact gave the base to consider that PAM needs time to operate in so diluted conditions [61].

Also from the Figure 27 the following observation can be done: like with pine samples when the fines fraction was removed and flocculant was added the tendency to worsening of papersheets formation were observed. If to see to the points with maximum extent of valve opening (points with minimal drainage time for each sample) one can observed drainage was improved when the fines were removed and when the PAM was added. Yes, improving of drainage is understandable in both cases; it happened because of the drainage channels "cleaning" due to removing or agglomeration of fines. But if they improved the drainage, why it affects negatively formation? Perhaps the effect of improving in drainage by removing of fines and flocculant adding on paper formation is opposed by other phenomena. For example by those which were mentioned in the explanations to the Figure 21.

The similar results were obtained by Lu. The paper formation was deteriorated when the setting time (in this case – the drainage time) was increased because the level of flocculation was also increased. It was expected since longer setting time gives the fibers more chances to entangle with each other [49].

10.1.4. The effect of pulp consistency and time delay on paper formation

In these seriess of experiments the three different pulp concentrations and two time delays were used. The concentrations of pulp slurries were 0.179 g/l (g/dm^3), 0.268 g/l, and 0.536 g/l. The time delays were 5 seconds and 15 seconds. For plotting of Figure 28 the unwashed birch pulp with fines content of 7% was used.

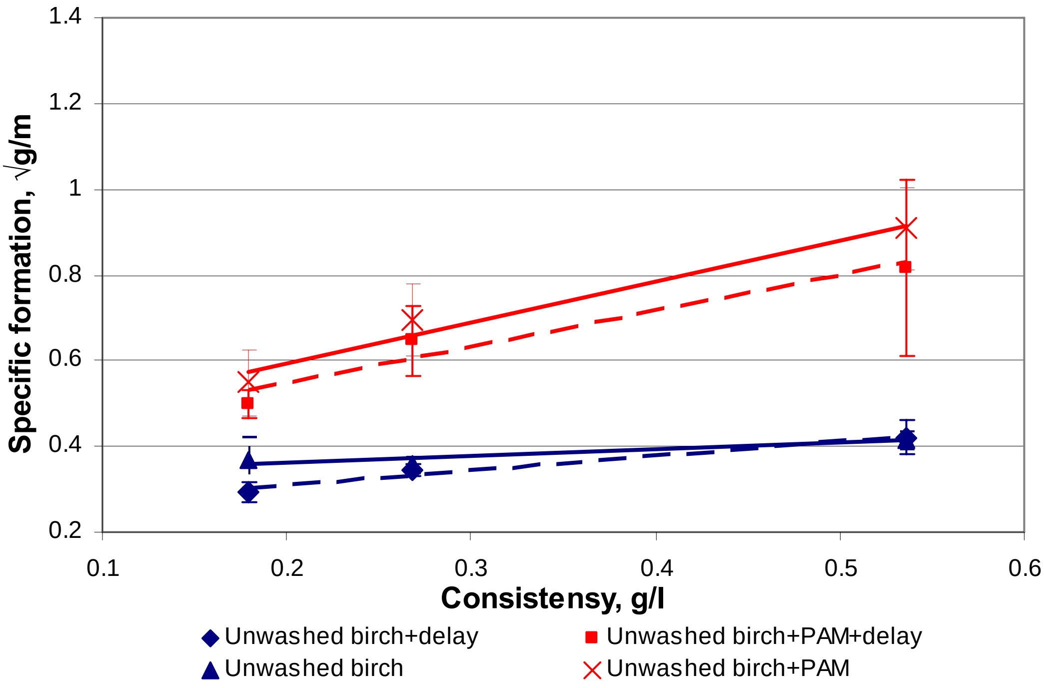

***Figure 28** Effect of consistency of pulp slurry in the sheet mould and use of flocculant and time delay on specific formation of sheets made from birch pulp*

(SR 40). Dose of PAM was 0.03%. Fines content was 7%. Basis weight of tested sheets was 60 g/m^2.

From the Figure 28 it can be seen that due to higher concentration of pulp slurry the specific formation is increased, that means poor paper formation. It could be explained that at lower fiber concentration more free water exist between fibers. In result, the fibers do not need to be compressed so much to pass the contraction [47]. Main reason of paper deterioration with increasing of pulp slurry consistency is crowding factor. It depends on the volumetric concentration of the fibers, the fiber length and the fiber diameter. In this case the volumetric concentration is the dominant parameter. The crowding factor varies with changing of the fibers number in the volume having a diameter equal to a fiber length. The fibers form flocks more readily under the high pulp concentration, because the fibers have several points of contact with each other and the freedom for fibers moving is limited (reduced). So, with increasing of pulp consistency in the sheet mould the more flocks exist in the pulp slurry; in result the paper formation deteriorates [36].

As it was expected the addition of PAM increased the flocculation under conditions of both high and of low concentrations, and especially it enhanced the effect of consistency on formation. The PAM addition stimulated the fiber flocculation. The high change of specific formation value is noticed under highest pulp slurry consistency.

We cannot say that time delay gave great effect on paper formation since of big errors but a little improvement was noticed. The next figure (Figure 29) has a similar character of pulp consistency effect on paper formation.

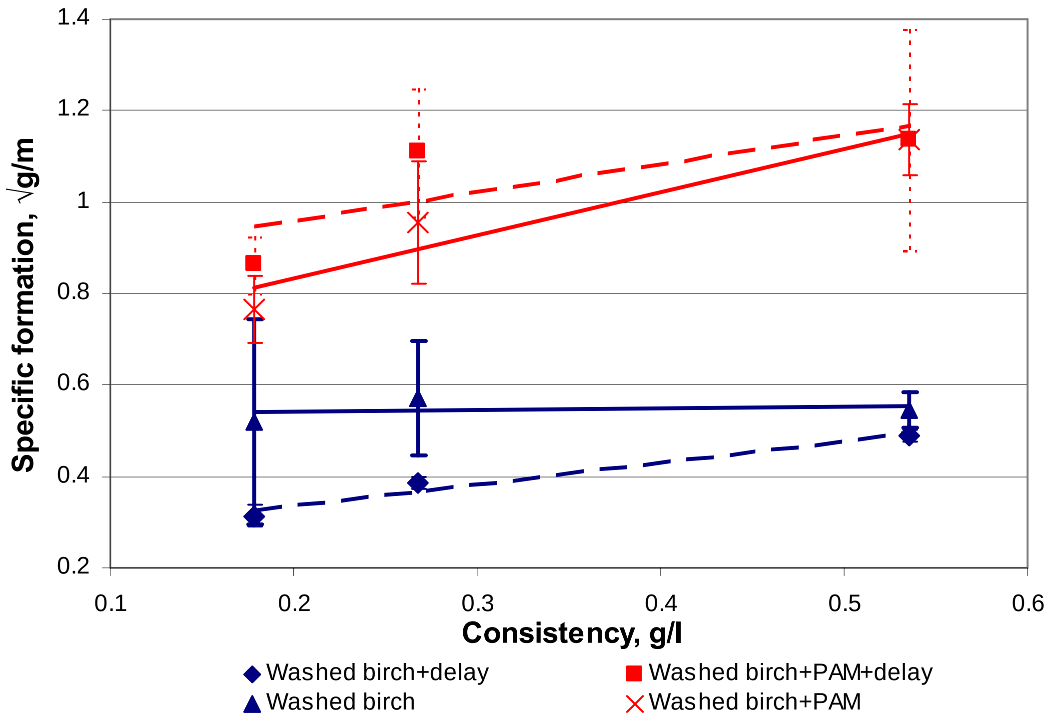

Figure 29 *Effect of consistency of pulp slurry in the sheet mould and use of flocculant and time delay on specific formation of sheets made from birch pulp (SR 40) with partial removed fines fraction. The fines content (3%) was adjusted by removing part of the fines from birch pulps (SR 40). Dose of PAM was 0.03%. Basis weight of tested sheets was 60 g/m^2.*

From the Figure 29 it can be seen that increasing of birch pulp consistency in the sheet mould with partial fines removing had a great effect on specific formation of paper. The effect of washed pulp consistency on paper formation properties is stronger using addition of flocculant in pulp slurry. From the Figure 29 it can be also seen that papersheets made from washed birch pulp at lowest concentration have a formation that worse in two times than papersheets made at the same concentration but without PAM addition. Since washed pulp had low fines content (3%) the time delay and PAM addition just deteriorated formation of sheets. There was much time for making of big flocks. Whereas using of one time delay had positive effect. The time delay gave for residual fines to attach to fibers that had place for better paper uniformity. The obtained results can be also explained by crowding factor theory as in previous figure [36].

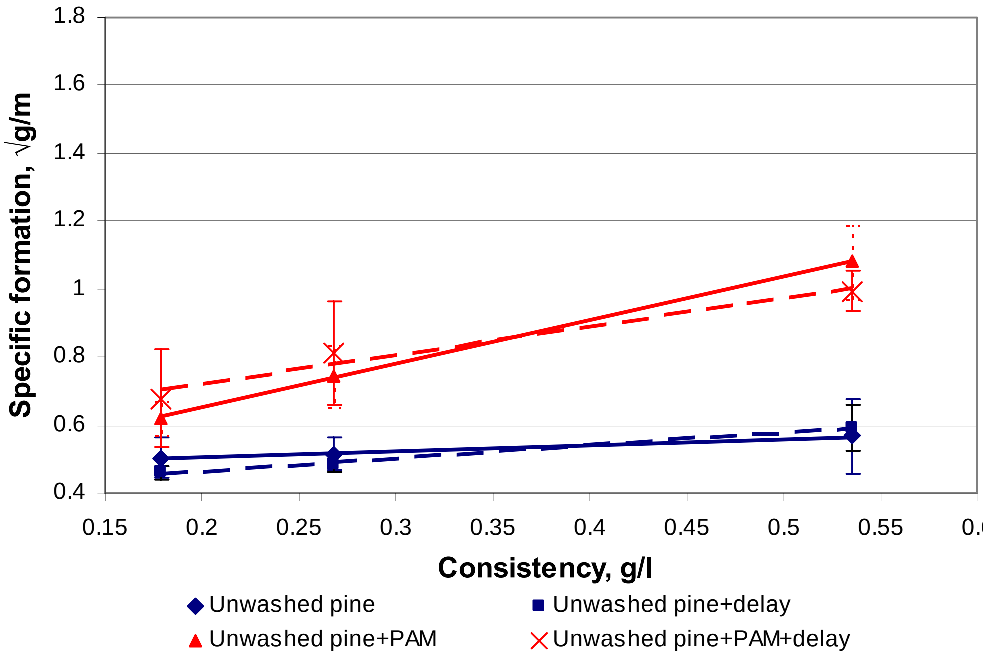

Figure 30 *Effect of consistency of pulp slurry in the sheet mould and use of flocculant and time delay on specific formation of sheets made from pine pulp (SR 40). Dose of PAM was 0.03%. Basis weight of tested sheets was 60 g/m*^{2}.

From the Figures 30 it is seen that increasing of consistency of pine pulp slurry also leads to poor formation. Usage of time delay at making of papersheets from washed pine pulp leads to more uniform structure of paper. In this case (of pine pulp) the important parameter is length of pine fibers. Compared to the Figure 28 the increasing of pulp consistency had greater effect on formation properties of paper. Under higher concentration of pulp the formation properties of handsheets were deteriorated with a factor of two with PAM addition. The crowding factor takes place in explanation of the results. The fiber length has strong effect on crowding factor that in turn on paper formation [36]. The time delay did not give some change in paper formation.

The next Figure 31 of pulp consistency effect of washed pine pulp on paper formation has the similar dependence.

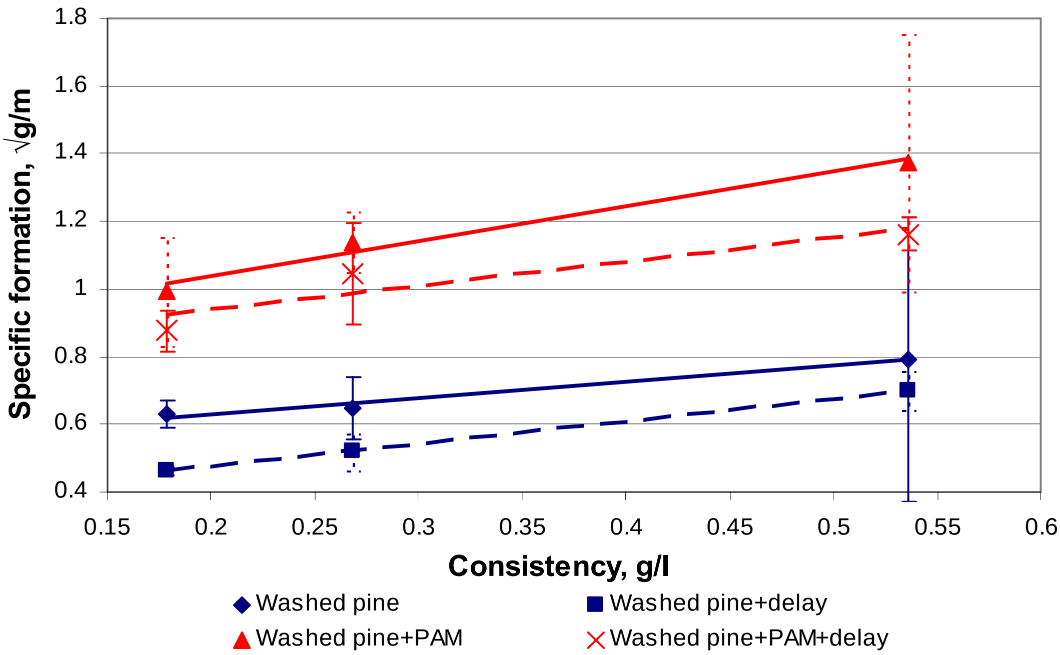

Figure 31 *Effect of consistency of pulp slurry in the sheet mould and use of flocculant and time delay on specific formation of sheets made from pine pulp (SR 40) with partial removed fines fraction. The fines content (3%) was adjusted by removing part of the fines from pine pulps (SR 40). Dose of PAM was 0.03%. Basis weight of tested sheets was 60 g/m^2.*

The pulp concentration during paper making from washed pine pulp has a great effect on paper formation. With increasing of pulp consistency the specific formation was increased. Under the high consistency the time delay also did not give changes in paper formation because of big errors. But under the low washed pine consistency in the sheet mould the time delay some positive effect towards improvement of paper formation. It can be explained by agglomeration mechanism. The improvement in formation may be due to increased fines retention, since there is a slight increase in grammage with the increase in delay time [56].

10.1.5. The effect of initial time delay on paper formation

The effect of initial time delay on specific formation is shown on the Figure 32. The fiber slurry was delayed after air mixing before valve opening for dewatering.

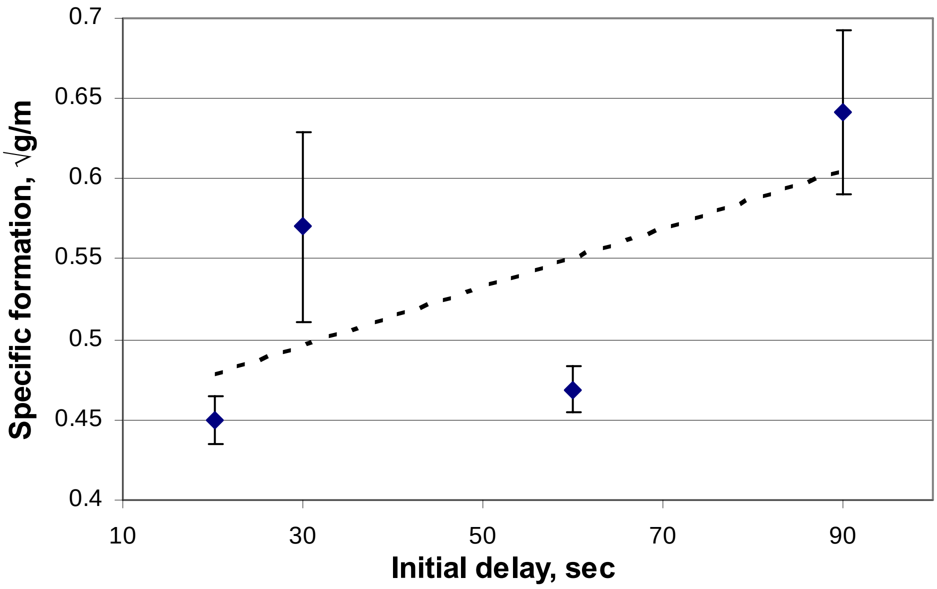

Figure 32 *Effect of initial time delay and use on specific formation of sheets made from pine pulp (SR 40). Fines content of pine pulp was 5.3 %. Basis weight of tested sheets was 60 g/m^2.*

Figure 32 shows that effect of initial time delay before valve opening on paper formation has negative character. With increasing of time delay the paper formation becomes poor that affected by flocculation. Laboratory KCL hand sheet former has very low = 0,179 g/l operating concentration. Consistency is one of the determinative factors of flocculation of fibers suspension (according to critical concentration and crowding number theories) [36]. If the consistency of fibers low the frequency of fibers to collide and entanglement is also low, moreover fibers do not have time to flocculate since usually the chamber of KCL former is drained within 10-20 sec (depending from fibers drainability). But what is happened when we delay the valve opening and do so called initial delay? Swollen fibers usually heavier than water (it means that gravity forces prevalent under the Archimedes forces (Figure 33), that's why the fibers sink to the bottom of container and separation into two fractions – water on the top, fibers on the bottom occurs. When the fibers pull down concentration of fibers at the bottom of sheet former is enhanced. Sedimentation is time depending process, more time we give to fibers to sedimentate (high delay time) – higher consistency of fibers will be observed on the bottom. And as the concentration of fibers was strongly increased it will affect flocculation ability of fibers, since flocculation is concentration depended process. Higher flocculated fibers suspense will give handsheets with poor formation properties.

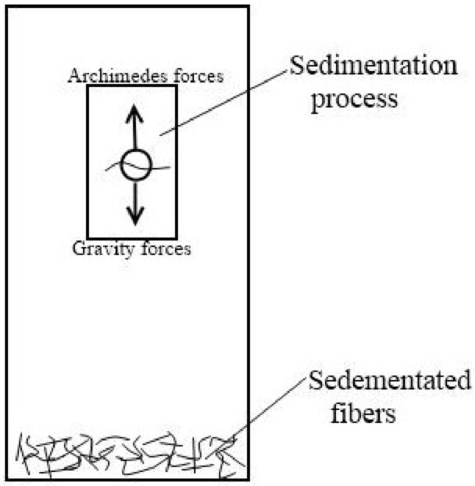

Figure 33 *Illustration of fibers sedimentation process*

10.1.6. The effect of mix ratio on paper formation

For this seriess of experiments unwashed and washed pulps (pine and birch) were used for producing of handsheets. The combinations from partial fines removing pulps were also made.

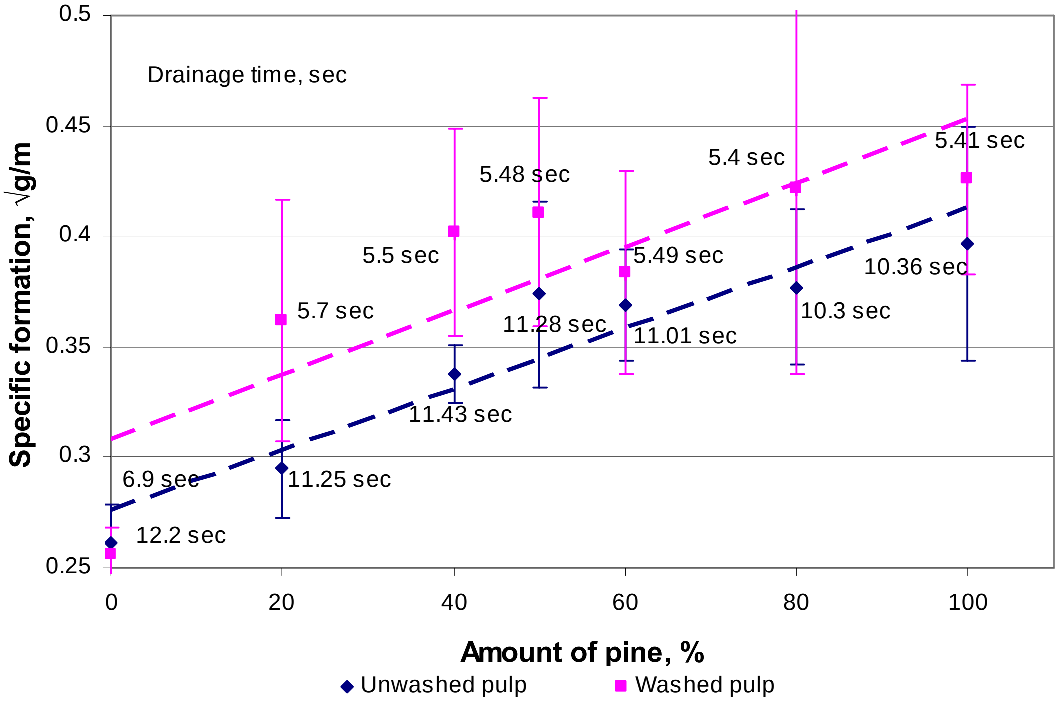

Figure 34 *Effect of mix ratio on specific formation (Birch 40SR and Pine40SR). Fines content of the washed pulps was 3 %. Fines contents of unwashed pulps were 7% for birch and 5.3% for pine. Basis weight of tested sheets was 60 g/m*^{2}.

The Figure 34 shows that increasing of content of pine fraction in mixture of pulps leads to worsening of paper formation. However, addition of the birch fibers to the pine pulp tends to improvement of paper structure. It also can be seen that the dependence with partial removed fines fraction has worse paper formation than pulp with initial fines content.

The results presented in the Figure 34 were expected and the enhancing of specific formation when the amount of pine fibres was increased. It can be explain by crowding factor theory [41]. Since long fibrous material was added to the short fibrous material, fibers length of the mixture was enhanced. Fibers length is determinative factor of flocculation (fiber length is squared in the crowding number formula). The higher fibers length means the higher value of crowding factor. In turn, the high value of crowding number corresponds to more effective flocculation process [36]. The papersheets made from more flocculated fibers slurry will give poor formation properties. Other interesting observation is that the specific formation is increased (formation getting worse) even for the samples from which the fines fraction was removed. That means that changing in fiber length is strongly prevalent under the effect of fines on drainage properties of the slurry.

10.2. Influence of some variables of papermaking on strength properties of paper

In this chapter the following results will be considered: the effect of the fines content of the birch and pine pulps; the effect long pine and short birch fibres when it mixed with different ratios; the effect of flocculant addition; the effect of fibres consistency; the effect of drainage and effect of time delay on the strength properties of resultant papersheets.

10.2.1. The effect of fines content on tensile strength

The tensile strength of papersheets made from birch and pine pulps containing different amounts of fines was measured with standard and non-standard method according to paragraph 8.6.2.

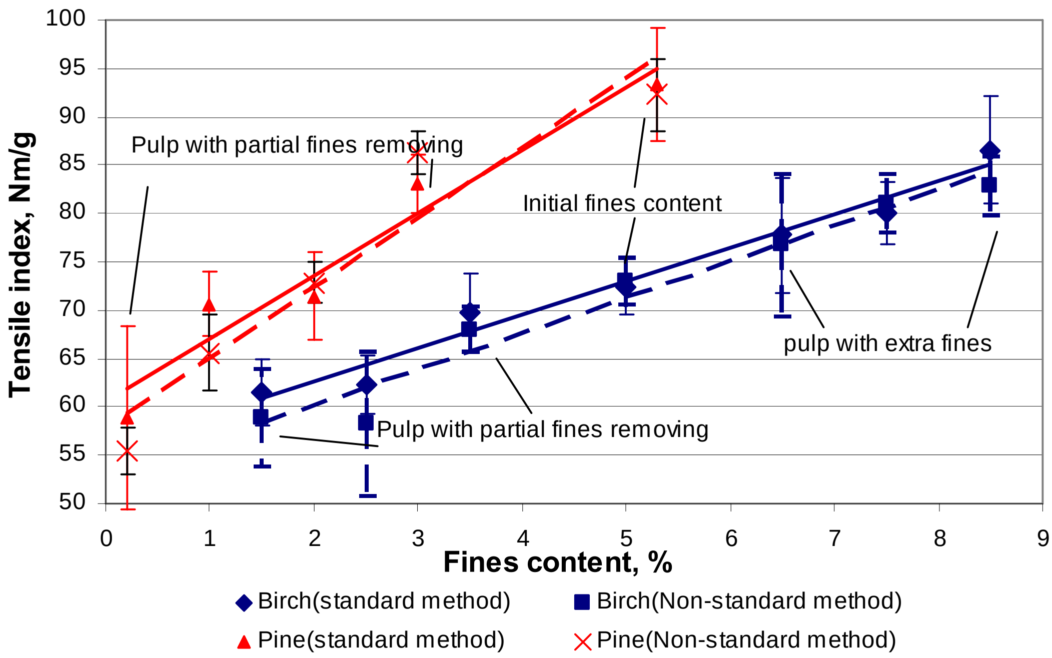

Figure 35 *Effect of fines content of birch and pine pulps on tensile index of sheets, measured with standard (15 mm strips) and non-standard (45 mm strips) methods (see 8.6.2.). The fines content was adjusted by removing (washing) part of the fines from birch pulp (SR 40) or adding extra fines to unwashed. Basis weight of the tested sheets was 60 g/m^2.*

From the Figure 35 we can see the influence of fines content of both birch and pine pulps on tensile index of papersheets. Increasing of fines content as in birch pulp as in pine pulp leads to improving of tensile strength of papersheets. Reduction of fines content leads to less tensile index. It can be explained by the fact that fines fractions are capable to pulling fibers closer to each other within a fiber network. In result, thickness and porosity are decreased and density of the fibrous mat is increased. Enhancing of papersheets density happens due to filling the empty spaces between the long fibers [62].

10.2.2. The effect of mix ratio on tensile strength of handsheets

The study of the effect of mix ratio of different pulps mixed with different ratios on strength properties of handsheets will be presented in this paragraph.

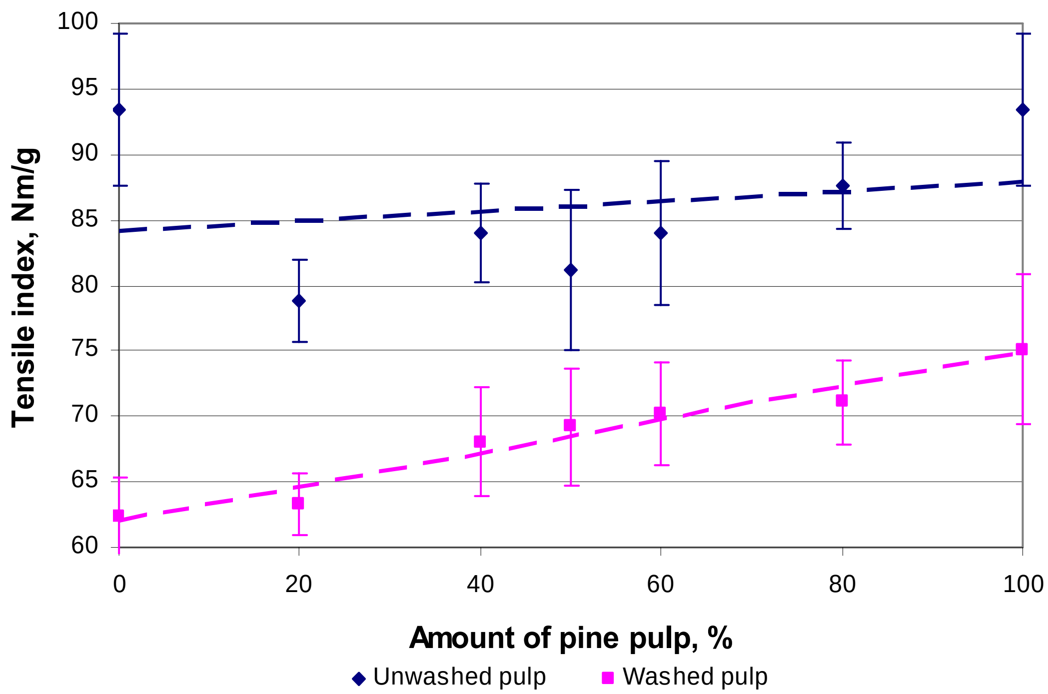

Figure 36 *Effect of furnishes containing birch and pine pulps on tensile index of sheets, measured with standard (15 mm strips) method (see 8.6.2.). The fines content was adjusted by removing (washing) part of the fines from birch pulp (SR 40) and pine pulp (SR40). Fines content of the pulps was 3 %. Fines contents of unwashed pulps were 7% for birch and 5.3% for pine. Basis weight of tested sheets was 60 g/m^2.*

Addition of unwashed pine fraction to unwashed birch pulp has not big effect on the tensile index. It was notices that tensile index was increased (Figure 36). The significant effect is noticed when the washed pine pulp was added to washed pine pulp. From figure it can be seen that papersheets made from 100% unwashed birch pulp and from washed birch pulp the difference between tensile indexes is great. As it is known fines increase tensile strength of paper [49]. So, some removing of fines corresponds to decreasing of tensile strength. From the Figure 36 we can see also that dependence of amount of pine on tensile index for unwashed pulps has weak effect. The papersheets made from unwashed pine pulp and from unwashed birch pulp had approximately similar tensile indexes.

10.3. Influence of specific formation of paper sheets on strength properties of paper

10.3.1. The effect of drainage modification on tensile strength

In the figure bellow the effect of specific formation on tensile index is shown. These results that plotted in the Figure 37 were obtained using papersheets made from birch pulp with different amount of fines and use of flocculant under different drainage times. For all cases, when the formation getting poorer under the effect of long drainage - tensile strength is also decreased as it was assumed.

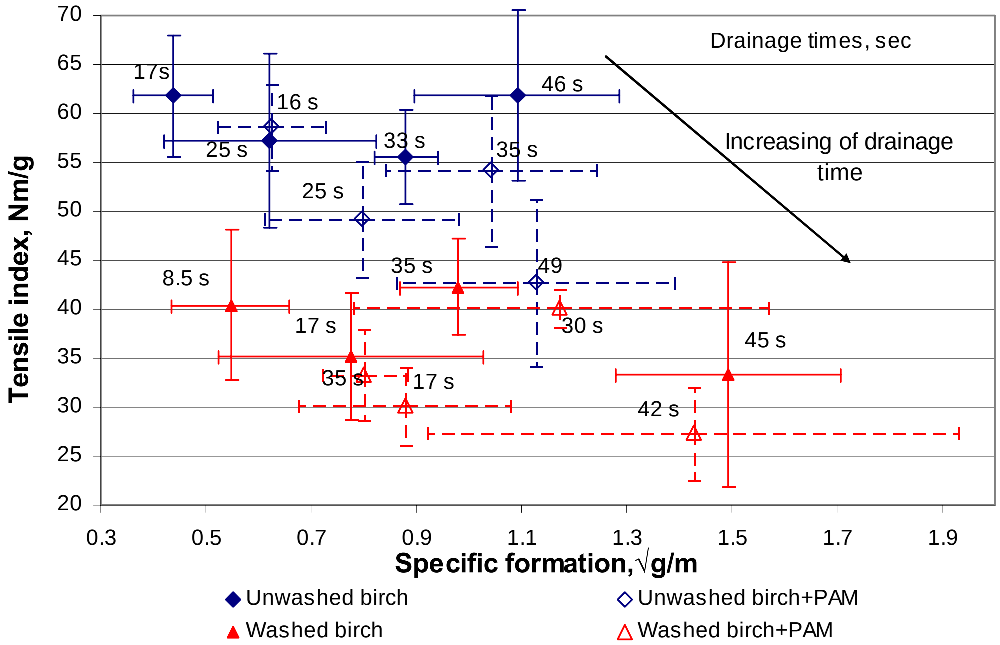

Figure 37 *Effect of specific formation on tensile index of paper sheets made from unwashed birch pulp (SR40) and birch pulp with partial removed fines fraction (3% of fines). Dose of PAM was 0.03%. The fines content for unwashed pulp was 7%, for washed pulp – 3%. On the specific formation of the sheets was influenced by adjusting the drainage time during the sheet forming. The variation of drainage time was made by using of valve method. Basis weight of tested sheets was 60 g/m*^{2}.

At the figure bellow (Figure 38) the effect of specific formation on tensile strength of paper made from pine pulp with PAM addition and using different drainage times is shown.

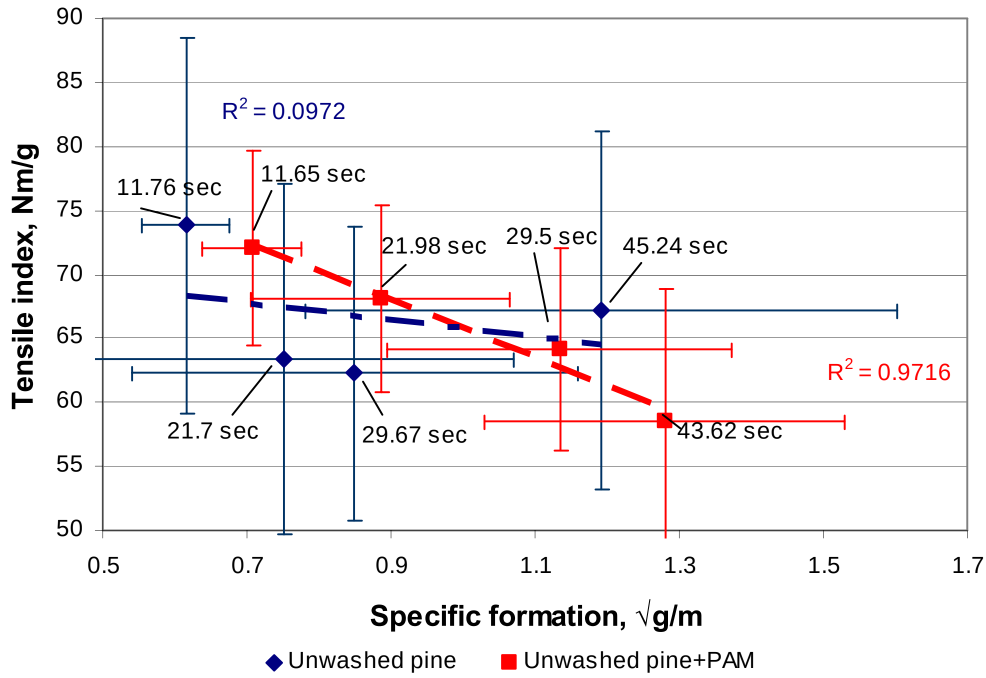

Figure 38 *Effect of specific formation on tensile index of paper sheets made from unwashed pine pulp (SR40). Dose of PAM was 0.03%. The fines content for unwashed pulp was 5.3%. On the specific formation of the sheets was influenced by adjusting the drainage time during the sheet forming. The variation of drainage time was made by using of valve method. Basis weight of tested sheets was 60 g/m^2.*

The Figure 38 has similar character with Figure 37. The tensile strength got worse when the specific formation of paper increased. The poor formation decreases strength as a result of stress concentrations caused by the non-uniform mass distribution [63].

10.3.2. The effect of pulp slurry concentration on tensile strength of handsheets

The Figure 39 was made using specific formation of papersheets made from pine pulp with different amount of fines (unwashed pulp with 5.3% of fines and washed pulp with 3% of fines).

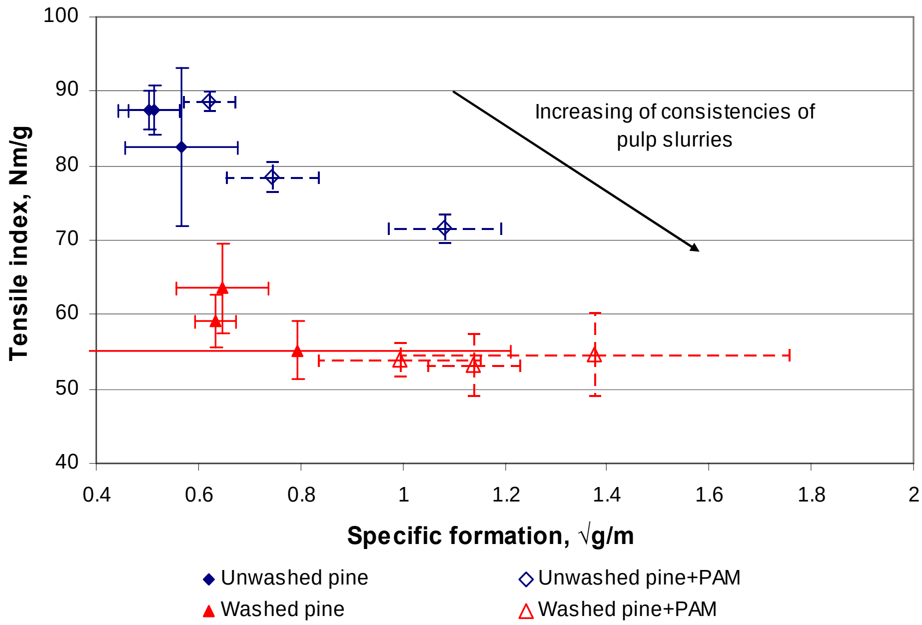

Figure 39 *Effect of specific formation on tensile index of paper sheets made from unwashed pine pulp (SR40) and pine pulp with partial removed fines fraction (3% of fines). Dose of PAM was 0.03%. On the specific formation was influenced by having different consistency in the sheet mould. Basis weight of tested sheets was 60 g/m^2.*

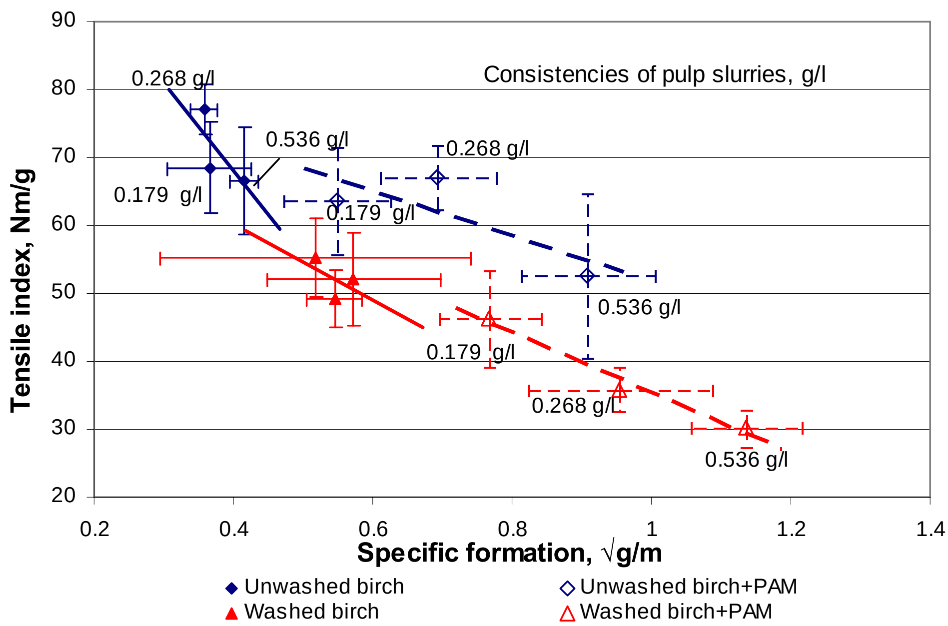

Figure 40 *Effect of specific formation on tensile index of paper sheets made from unwashed birch pulp (SR40) and birch pulp with partial removed fines fraction (3% of fines). Dose of PAM was 0.03%. On the specific formation was influenced by having different consistency in the sheet mould. Basis weight of tested sheets was 60 g/m^2.*

Based on the results of Figures 39 and 40 we can say that with increasing of specific formation the tensile index of papersheets is decreased. The figures have a similar character. As it was assumed the dependence should be the same. It can be seen that poor formation corresponds to low strength properties of papersheets. The high consistency of fibers affects paper formation negatively because of high value of crowding factor. So, distribution of fibers in plane of paper is non-uniform that leads to stress concentration of papersheets.

10.3.3. The effect of initial time variations on tensile strength of handsheets

The effect of specific formation on tensile index of paper sheets made from pine pulp using different initial time delay is shown in the Figure 41.

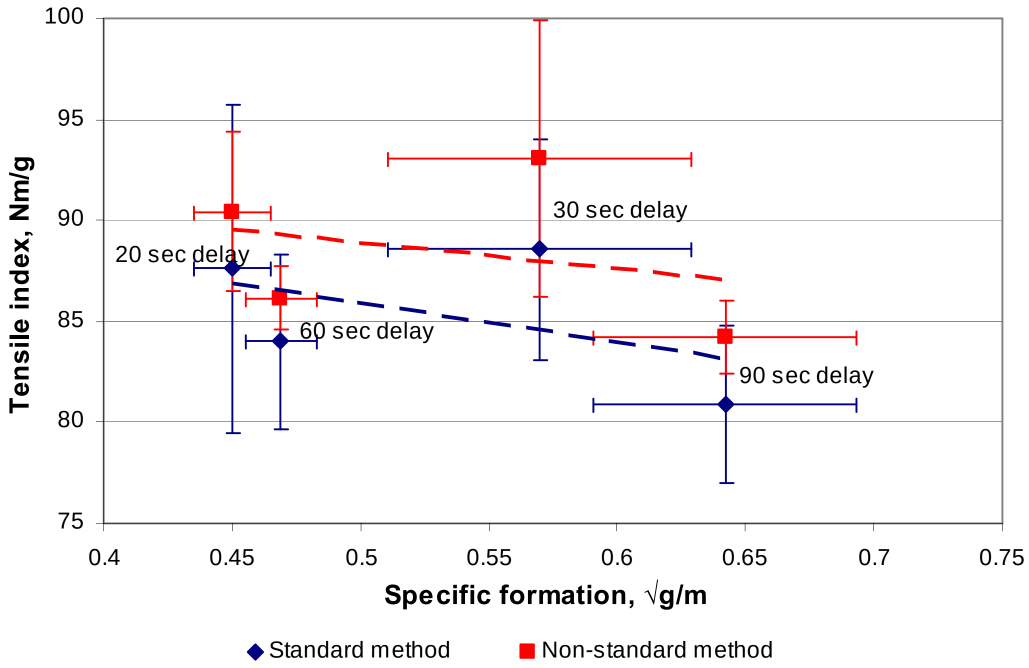

Figure 41 *Effect of specific formation on tensile index of paper sheets made from unwashed pine pulp (SR40), measured with standard (15 mm strips) and non-standard (45 mm strips) methods (see 8.6.2.). Fines content was 5.3%. On the specific formation was influenced by using different initial times delay. Basis weight of tested sheets was 60 g/m^2.*

From the Figure 41 we can see that with increasing of initial time delay specific formation of papersheets is increased that in turn negatively effect on the tensile index of analyzed samples. Errors in tensile index are less when the measurements were made with non-standard size of strips. But nevertheless the figure can not show strong dependence because of big errors. Nevertheless, we can see slow falling of tensile index value due to increasing of specific formation (deterioration of paper formation). However, it could be explained by sedimentation of fines. As we discussed earlier, the sedimentation process took place in the effect of initial time delay on paper formation. The reduction of the fibers fraction in the sheet had place, the most part of fibers located in the one side surface and the most part of fines located in other side surface of the sheet. In the result, the bonded fibers are located on the one side only [64].

10.3.4. The effect of specific formation on tensile strength of paper made from different mix ratio of birch and pine pulps

In the figure 42 bellow the influence of specific formation on tensile index of handsheets made from different both birch and pine furnishes is shown.

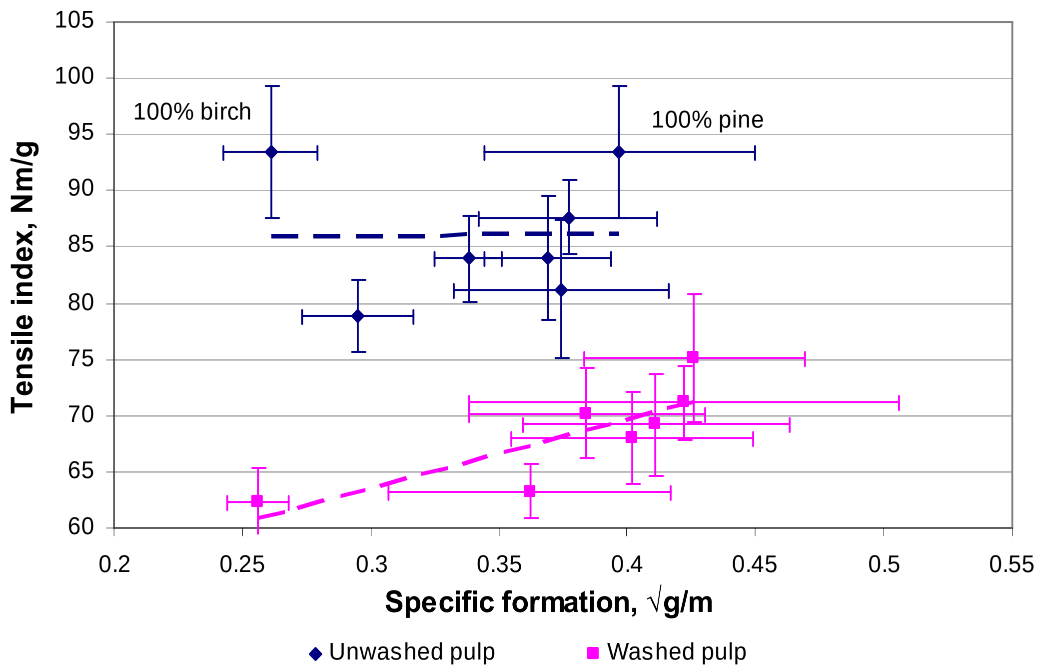

Figure 42 *Effect of specific formation on tensile index (Birch 40SR and Pine40SR, fines content of the pulps was 3 %). Fines contents of unwashed pulps were 7% for birch and 5.3% for pine. Basis weight of tested sheets was 60 g/m*^{2}.

It can be seen (Figure 42) that difference in tensile strength between washed and unwashed pulps is presented. Unwashed paper samples are stronger than one which made from the pulp with partial fines removing. The biggest interval in strength properties is corresponding to papersheets made from unwashed and washed birch. From the results we cannot see changes in tensile strength between unwashed birch and pine pulps. It can be explained that the both samples (birch and pine) have approximately the same amount of fines, and the fines fraction have strong effect on tensile strength. Moreover, enhancing of pine fibers content in mixture leads to the fiber length increasing, that from one side should improve paper strength since it is well known that appearance of softwood Kraft pulp in furnish leads to increasing of paper strength [67]. But from other side it is also known that enhancing of fibres length leads to increasing of flocculation tendency of fibrous suspense (according to the crowding number theory, fiber length is squared in the crowding number formula) that make the formation worse and that in turn effect negatively on tensile strength.

11. Conclusion

The main goals of this work were to study the effect of dewatering time varying and the effect of fines fraction on formation properties of laboratory handsheets. Chosen raw materials were never dried pine pulp and birch bleached pulp. From the results it was determined that longer drainage times provided poorer formation properties of paper. When valve method for control of dewatering time was used, the time dependence of paper formation started to be seen. With increasing of drainage time the specific formation of paper was increased that is mean poor formation. Addition of PAM made this dependence stronger. It can be explained that cationic polymer of high molecular weight (in this case it was PAM) is very effective flocculant for negatively charged cellulose fibers. As it was assumed the more clear effect of drainage time was seen for pulp with different amount of fines especially for pine pulp containing different amount of fines. With increasing of specific formation the tensile index was decreased.

The effect of flocculation on specific formation was also shown through the pulp slurry concentration in the sheet mould. As it was expected, the increasing of pulp slurry increased the specific formation value of paper. Increased consistency increases crowding factor, i.e. the level of contacts between fibers in suspension that leads to rising of fibers amount per unit volume that increases the probability to flocculation that in turn leads to uneven paper formation. It was noticed in the seriess of experiments where time delay was adjusted that time delay had negative effect on formation properties of papersheets. This phenomena was explained by the fact that high time delay gives more time for fibres flocculation and moreover sedimentation of fibres take place that leads to the enhancing of fibers consistency in the bottom of column of sheet former. And it is well known that increasing of fibres consistency leads to enhancing of flocculation and that in turn makes the paper formation worse.

In this work role of fines fraction in the paper formation process was determined. It plays significant role in paper structure. As it was expected, with partial removal of fines fraction from initial pulp slurry the paper formation became poorer. The fines played role of binder during the creation of paper web, filling the empty spaces between fibers. In this study effect of extra fines fraction was also determined. Birch pulp was used as raw material for extra fines production. The results showed that addition of some fines fraction to initial pulp slurry tended to poor formation but to improvement of tensile strength. It cab be explained by the fact that elevated viscosity makes difficult for fibers to move in a suspension and collide with each other. The effect of the fines fraction on tensile strength had the expected effect. With increasing of fines fraction the tensile index was also increased by increasing of fibers bonds

In some cases tensile index was measured using two methods: standard method of measurement with paper width of 15 mm and non-standard method using width of paper of 45 mm. The changes in measurements of tensile index by two methods had no strong differences.

In this work the effect of mix ratio on paper formation was determined. Papersheets made from 100% birch pulp had better formation compared to the sheets made from the pine pulp. Softwood pulp has longer fibers compared to hardwood pulp. Long fibers tend to create larger flocks than short fibers. In result, the papersheets from birch pulp has more uniform distribution of fibers, and it also was noticed that with increasing of fines content this dependence is increased. The value of specific formation was decreased with decreasing of pine pulp amount in furnishes. Paper produced from birch pulp with partial removed fines has better formation compared to formation of paper made from pine pulp with removed fines and, however, paper with poor formation had better strength properties. For unwashed pulp furnishes of birch and pine the tensile strength is better for paper that is made from separate birch pulp and BSK pulp while formations of paper made from these raw materials is absolutely different. The longer fibers of softwood give more strength properties although they make paper formation poorer.

In the case of pulp furnishes made from pulp containing partially removed fines fraction the dependence specific formation on tensile strength had changes. Fines play important role in strength properties for paper produced from birch pulp.

Results showed that range in tensile strength between washed and an unwashed pulp is high. The highest interval in strength properties is inherent for papersheets made from unwashed and washed birch.

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APPENDIX I

Paper properties, equipment and standards

Table 1 Paper properties, equipment and standards.

Paper Property	Unit	Equipment	Standard
Fines content	%	L&W Fibre Tester	ISO 16065-1:2001
Conductivity	µs/cm	Laboratory Conductivity Meter	ISO 6587:1992
Zeta potential	mV	SZP 06 BTG Mütek Gmbh	-
Grammage	g/m^2	KCL Laboratory Sheet Former	SCAN-CM 11:95
Tensile strength	Nm/g	L&W Tensile Tester	ISO 1924-2
Specific formation	√g/m	AMBERTEC Beta Formation Tester	-

APPENDIX II

The effect of the fines content on the specific formation of the sheets

Table 2 The values of specific formation and drainage times of the tested sheets made from birch pulp with fines fraction removing. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Fines content, %	Drainage time, sec	Specific formation, √g/m
1.5	5.1±0.16	0.257±0.037
2.5	5.3±0.08	0.255±0.017
3.5	6.9±0.03	0.256±0.012
5	12.2±0.2	0.261±0.018
6.5	24.8±0.12	0.278±0.044
7.5	29.9±1.09	0.292±0.03
8.5	55±0.14	0.338±0.044

Table 3 The values of specific formation and of the tested sheets made from birch pulp with different fines content and addition of PAM (0.03%). The value of spec. formation ± standard deviation. The result is the average of 4-5 sheets.

Fines content, %	Specific formation, √g/m	
	Without PAM	**With PAM**
1.5	0.567±0.176	0.808±0.133
3	0.547±0.11	0.801±0.08
5	0.424±0.096	0.515±0.06
7	0.438±0.078	0.623±0.104

The effect of drainage modifications on specific formation of the sheets

Table 4 The values of specific formation and drainage times of the tested sheets made from birch pulp due to variation of drainage time by valve method. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Drainage time, sec	17.31±0.25	24.79±1.65	33.57±2.28	47.62±3.67
Specific formation, √g/m	0.438±0.077	0.622±0.203	0.881±0.059	1.092±0.194

Table 5 The values of specific formation and drainage times of the tested sheets made from birch pulp due to variation of drainage time by valve method and addition of PAM. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Drainage time, sec	16.48±1.34	25.47±0.54	33.98±6.5	49.08±6.36
Specific formation, √g/m	0.624±0.104	0.795±0.185	1.041±0.2	1.126±0.263

Table 6 The values of specific formation and drainage times of the tested sheets made from washed birch pulp (fines content was 3%) due to variation of drainage time by valve method. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Drainage time, sec	8.23±0.34	17.26±1.64	35.24±5.2	46.04±0.11
Specific formation, √g/m	0.547±0.111	0.775±0.252	0.981±0.111	1.493±0.813

Table 7 The values of specific formation and drainage times of the tested sheets made from washed birch pulp (fines content was 3%) due to variation of drainage time by valve method and addition of PAM. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Drainage time, sec	8.1±0.42	17.32±0.93	31±4.88	43±1.22
Specific formation, √g/m	0.801±0.082	0.878±0.203	1.173±0.395	1.426±0.506

Table 8 The values of specific formation and drainage times of the tested sheets made from unwashed pine pulp due to variation of drainage time by valve method. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Drainage time, sec	11.77±0.15	21.7±1.5	29.67±0.41	45.24±2.73
Specific formation, √g/m	0.615±0.06	0.751±0.32	0.85±0.31	1.192±0.41

Table 9 The values of specific formation and drainage times of the tested sheets made from unwashed pine pulp due to addition of PAM and variation of drainage time by valve method. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Drainage time, sec	11.65±0.81	21.98±1.59	29.5±2.39	43.62±4.51
Specific formation, √g/m	0.707±0.07	0.886±0.31	1.134±0.24	1.281±0.59

Table 10 The values of specific formation and drainage times of the tested sheets made from washed pine pulp (fines content of 3%) due to variation of drainage time by valve method. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Drainage time, sec	5.45±0.091	5.59±1.134	6.49±0.158	8.78±0.237	28.22±4.23
Specific formation, √g/m	0.396±0.016	0.407±0.032	0.398±0.016	0.399±0.028	0.572±0.056

Table 11 The values of specific formation and drainage times of the tested sheets made from washed pine pulp (fines content was 3%) due to variation of drainage time by valve method and addition of PAM. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Drainage time, sec	5.37±0.024	5.58±1.174	6.51±0.28	8.84±0.618	28.09±3.008
Specific formation, √g/m	0.427±0.073	0.424±0.024	0.408±0.039	0.448±0.075	0.629±0.204

Table 12 The values of specific formation and drainage times of the tested sheets made from unwashed pine pulp (initial fines content was 5.3%) due to variation of drainage time by valve method. The value of spec. formation (drainage time) ± standard deviation. The result is the average of 4-5 sheets.

Drainage time, sec	9.11±0.392	9.33±0.578	10.22±0.098	12.23±0.165	39.74±3.561
Specific formation, √g/m	0.414±0.027	0.438±0.026	0.41±0.028	0.422±0.019	0.479±0.062

The effect of pulp consistency variation on specific formation of the sheets

Table 13 The values of specific formation and of the tested sheets made from birch pulp using different consistencies of pulp slurry, addition of PAM (0.03%) and time delay. The value of spec. formation ± standard deviation. The result is the average of 4-5 sheets.

Consistency of pulp slurry, g/dm3	No delay (standard time delay of 5 sec)		Delay time, 15 sec	
	Without PAM	With PAM	Without PAM	With PAM
0.179	0.366±0.06	0.549±0.077	0.293±0.022	0.499±0.033
0.268	0.358±0.02	0.693±0.084	0.344±0.014	0.647±0.082
0.536	0.416±0.02	0.908±0.096	0.421±0.041	0.818±0.206

Table 14 The values of specific formation and of the tested sheets made from washed birch (fines content was 3%) pulp using different consistencies of pulp slurry, addition of PAM (0.03%) and time delay. The value of spec. formation ± standard deviation. The result is the average of 4-5 sheets.

Consistency of pulp slurry, g/dm3	No delay (standard time delay of 5 sec)		Delay time, 15 sec	
	Without PAM	With PAM	Without PAM	With PAM
0.179	0.518±0.224	0.767±0.073	0.314±0.025	0.864±0.062
0.268	0.573±0.125	0.955±0.133	0.386±0.013	1.109±0.142
0.536	0.545±0.04	1.136±0.079	0.489±0.013	1.138±0.242

Table 15 The values of specific formation and of the tested sheets made from pine pulp using different consistencies of pulp slurry, addition of PAM (0.03%) and time delay. The value of spec. formation ± standard deviation. The value of spec. formation ± standard deviation. The result is the average of 4-5 sheets.

Consistency of pulp slurry, g/dm3	No delay (standard time delay of 5 sec)		Delay time, 15 sec	
	Without PAM	With PAM	Without PAM	With PAM
0.179	0.504±0.06	0.622±0.05	0.461±0.019	0.678±0.145
0.268	0.515±0.05	0.743±0.09	0.486±0.025	0.811±0.153
0.536	0.567±0.11	1.081±0.11	0.593±0.066	0.995±0.058

Table 16 The values of specific formation and of the tested sheets made from washed pine (fines content was 3%) pulp using different consistencies of pulp slurry, addition of PAM (0.03%) and time delay. The value of spec. formation ± standard deviation. The result is the average of 4-5 sheets.

Consistency of pulp slurry, g/dm3	**No delay (standard time delay of 5 sec)**		**Delay time, 15 sec**	
	Without PAM	**With PAM**	**Without PAM**	**With PAM**
0.179	0.633±0.04	0.993±0.16	0.465±0.012	0.877±0.06
0.268	0.648±0.09	1.139±0.09	0.519±0.056	1.046±0.15
0.536	0.793±0.42	1.376±0.38	0.699±0.058	1.162±0.05

APPENDIX V

The effect of mix ratio of pulps on specific formation of the sheets

Table 17 The values of specific formation and drainage times of the tested sheets made from different furnishes of both birch and pine pulps and also with fines fraction removing. The value of spec. formation (drainage time) ± standard deviation

Amount of pine, %	Drainage time, sec		Specific formation, √g/m	
	Unwashed furnish	Washed furnish	Unwashed furnish	Washed furnish
0	12.2±0.2	6.9±0.03	0.261±0.018	0.256±0.012
20	11.25±0.48	5.7±0.13	0.295±0.022	0.362±0.055
40	11.43±0.09	5.5±0.08	0.338±0.013	0.402±0.047
50	11.28±0.54	5.48±0.08	0.374±0.042	0.411±0.052
60	11.01±0.57	5.49±0.14	0.369±0.025	0.384±0.046
80	10.3±0.64	5.4±0.11	0.377±0.035	0.422±0.084
100	10.36±0.6	5.41±0.13	0.397±0.053	0.426±0.043

The effect of some variables in paper making on tensile strength of the sheets

Table 18 The values of tensile index of the tested sheets made from birch pulp containing different amount of fines. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Fines content, %	Specific formation, √g/m	Tensile index, Nm/g	
		Standard method	Non-standard method
1.5	0.257±0.037	61.54±3.44	58.93±5.04
2.5	0.255±0.017	62.35±3.05	58.27±7.41
3.5	0.256±0.012	69.78±3.96	68±2.27
5	0.261±0.018	72.47±2.89	72.99±2.34
6.5	0.278±0.044	77.75±5.9	76.8±7.35
7.5	0.292±0.03	80.02±3.2	81.1±3.05
8.5	0.338±0.044	86.57±5.59	82.91±2.99

Table 19 The values of tensile index of the tested sheets made from pine pulp containing different amount of fines. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Fines content, %	Specific formation, √g/m	Tensile index, Nm/g	
		Standard method	Non-standard method
0.2	0.534±0.039	58.87±9.45	55.4±2.45
1	0.396±0.016	70.61±3.3	65.61±3.99
2	0.413±0.037	71.41±4.56	72.86±2.16
3	0.386±0.01	83.1±3	86.26±2.18
5.3	0.391±0.017	93.4±5.83	92.25±3.8

Table 20 The values of tensile index of the tested sheets made from pine pulp due to different initial time delay. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Initial delay, s	**Specific formation, √g/m**	**Tensile index, Nm/g**	
		Standard method	**Non-standard method**
20	0.45±0.015	87.61±8.12	90.44±3.94
30	0.57±0.059	88.56±5.45	93.08±6.82
60	0.469±0.014	83.99±4.36	86.16±1.58
90	0.642±0.051	80.88±3.91	84.21±1.81

Table 21 The values of tensile index for tested sheets made from birch pulp with different drainage time. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Specific formation, √g/m	**Drainage time, sec**	**Tensile index, Nm/g**	
		Standard method	**Non-standard method**
0.438±0.077	17.31±0.25	61.84±6.21	50.41±12
0.622±0.203	24.79±1.65	57.26±8.94	46.87±7.3
0.881±0.059	33.57±2.28	55.56±4.81	46.21±5
1.092±0.194	47.62±3.67	61.86±8.64	52.65±7.79

Table 22 The values of tensile index for tested sheets made from birch pulp with different drainage time and addition of PAM. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Specific formation, √g/m	**Drainage time, sec**	**Tensile index, Nm/g**	
		Standard method	**Non-standard method**
0.624±0.104	16.48±1.34	58.64±4.3	60.49±6.46
0.795±0.185	25.47±0.54	49.24±5.88	49.05±5.94
1.041±0.2	33.98±6.5	54.18±7.72	37.63±14.05
1.126±0.263	49.08±6.36	42.86±8.51	47.53±5.52

Table 23 The values of tensile index for tested sheets made from washed birch pulp (fines content was 3%) due to different drainage time. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Specific formation, √g/m	Drainage time, sec	Tensile index, Nm/g	
		Standard method	Non-standard method
0.547±0.111	8.23±0.34	40.45±7.73	48.66±3.72
0.775±0.252	17.26±1.64	35.16±6.47	38.97±7.47
0.981±0.111	35.24±5.2	42.23±4.9	29.64±1.87
1.493±0.813	46.04±0.11	33.37±11.45	33.13±9.94

Table 24 The values of tensile index for tested sheets made from washed birch pulp (fines content was 3%) due to different drainage time and PAM addition. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Specific formation, √g/m	Drainage time, sec	Tensile index, Nm/g	
		Standard method	Non-standard method
0.801±0.082	8.1±0.42	33.4±4.61	46.96±4.14
0.878±0.203	17.32±0.93	30.1±4	41.33±4.5
1.173±0.395	31±4.88	40.11±1.95	29.21±2.53
1.426±0.506	43±1.22	27.37±4.74	33.38±5.53

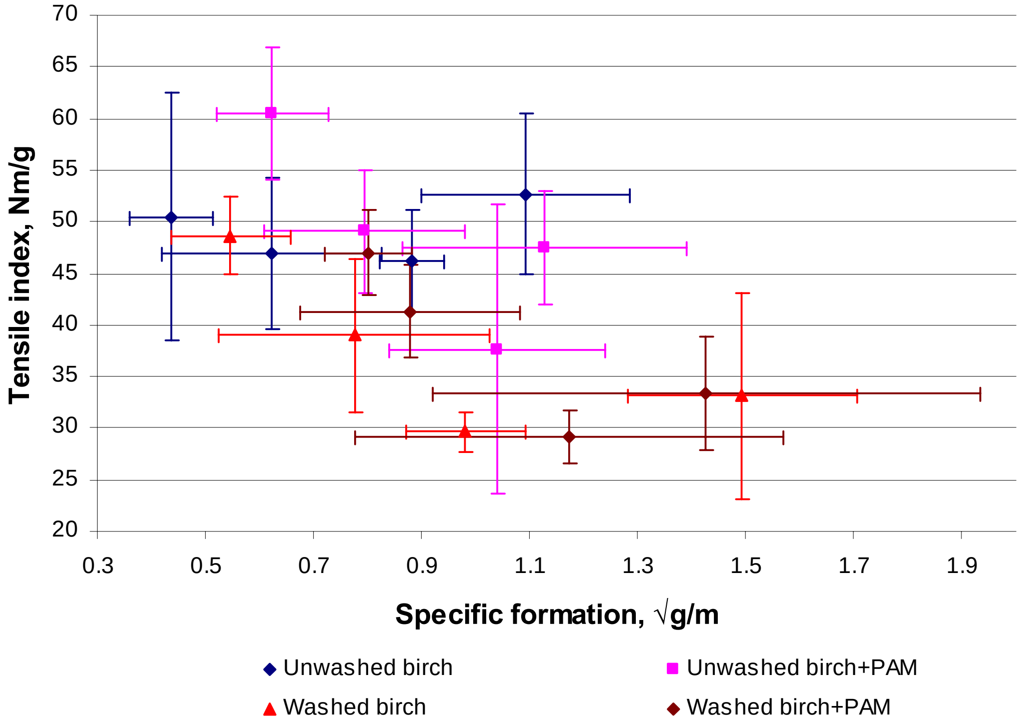

***Figure 1** The values of tensile indexes of papersheets measured with non-standard method (Fines content for unwashed pulp was 7%, for washed pulp-3%). The dose of PAM was 0.03%. The papersheets were made with adjustment of drainage time.*

Table 25 The values of tensile index for tested sheets made from pine pulp due to different drainage time. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Specific formation, √g/m	Drainage time, sec	Tensile index, Nm/g	
		Standard method	Non-standard method
0.615±0.06	11.77±0.15	73.85±14.69	82.39±8.41
0.751±0.32	21.7±1.5	63.37±13.66	70.31±7.35
0.85±0.31	29.67±0.41	62.29±11.49	66.76±9.39
1.192±0.41	45.24±2.73	67.13±14	62.48±10.06

Table 26 The values of tensile index for tested sheets made from pine pulp due to different drainage time and addition of PAM. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Specific formation, √g/m	Drainage time, sec	Tensile index, Nm/g	
		Standard method	Non-standard method
0.707±0.07	11.65±0.81	71.99±7.61	80.41±4.26
0.886±0.31	21.98±1.59	68.04±7.31	82.75±13.59
1.134±0.24	29.5±2.39	64.1±7.93	66.76±7.79
1.281±0.59	43.62±4.51	58.55±10.24	63.69±12.1

Table 27 The values of tensile index for tested sheets made from pine pulp due to different pulp consistency in the sheet mold. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Pulp consistency, g/dm3	Specific formation, √g/m	Tensile index, Nm/g	
		Standard method	Non-standard method
0.179	0.504±0.06	85.12±4.1	87.45±2.66
0.268	0.515±0.05	76.74±4.09	87.4±3.27
0.536	0.567±0.11	74.97±5.24	82.57±10.6

Table 28 The values of tensile index for tested sheets made from pine pulp due to different pulp consistency in the sheet mold and addition of PAM. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Pulp consistency, g/dm3	Specific formation, √g/m	Tensile index, Nm/g	
		Standard method	Non-standard method
0.179	0.622±0.05	86.04±4.8	88.75±1.25
0.268	0.743±0.09	72.06±4.93	78.59±2.07
0.536	1.081±0.11	73.62±5.59	71.73±1.93

Table 29 The values of tensile index for tested sheets made from washed pine pulp (fines content was 3%) due to different pulp consistency in the sheet mold. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Pulp consistency, g/dm3	Specific formation, √g/m	Tensile index, Nm/g	
		Standard method	Non-standard method
0.179	0.633±0.04	62±4.49	59.24±3.54
0.268	0.648±0.09	64.56±7.85	63.6±6.03
0.536	0.793±0.42	59.77±7.17	55.15±3.89

Table 30 The values of tensile index for tested sheets made from washed pine pulp (fines content was 3%) due to different pulp consistency in the sheet mold and addition of PAM. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Pulp consistency, g/dm3	Specific formation, √g/m	Tensile index, Nm/g	
		Standard method	Non-standard method
0.179	0.993±0.16	56.28±5.93	54.03±2.33
0.268	1.139±0.09	48.22±6.68	53.26±4.16
0.536	1.376±0.38	48.5±8.13	54.76±5.46

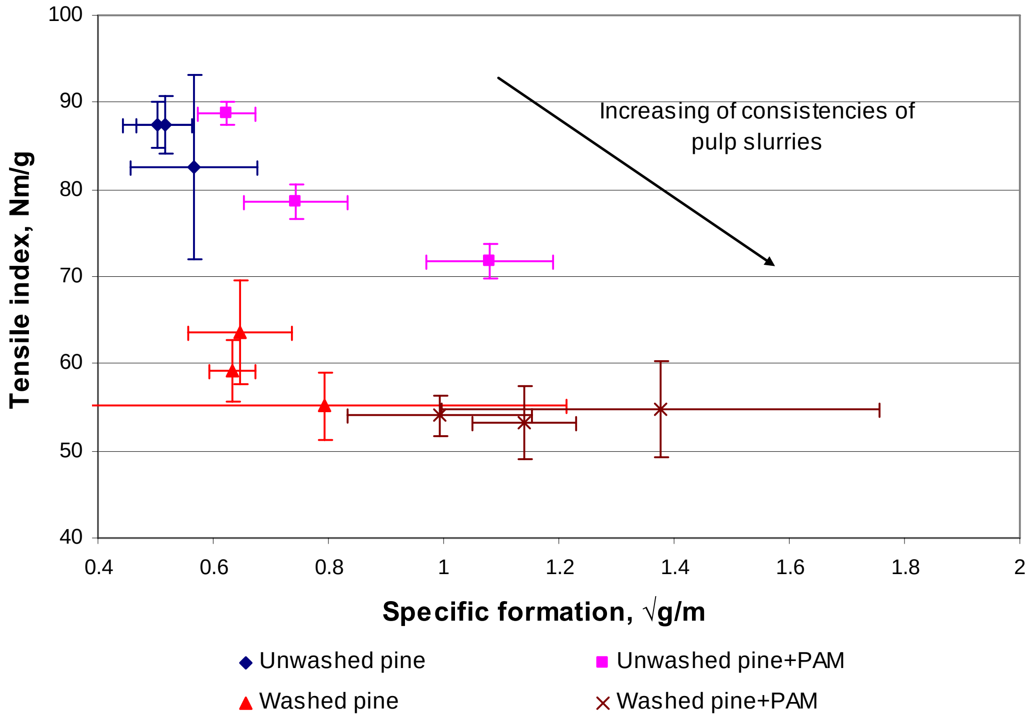

Figure 2 *The values of tensile indexes of papersheets measured with non-standard method (Fines content for unwashed pine pulp was 5.3%, for washed pine pulp-3%). The dose of PAM was 0.03%. The papersheets were made with modifications of pulp consistency in the sheet mould*

Table 31 The values of tensile index for tested sheets made from birch pulp with different pulp consistency in the sheet mould. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Pulp consistency, g/dm3	**Specific formation, √g/m**	**Tensile index, Nm/g**	
		Standard method	**Non-standard method**
0.179	0.366±0.06	68.45±6.69	70.66±2.51
0.268	0.358±0.02	77.12±3.74	82.09±3.96
0.536	0.416±0.02	66.58±8	67.12±12.08

Table 32 The values of tensile index for tested sheets made from birch pulp due to different pulp consistency in the sheet mold and addition of PAM. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Pulp consistency, g/dm3	Specific formation, √g/m	Tensile index, Nm/g	
		Standard method	Non-standard method
0.179	0.549±0.077	63.65±7.82	67.44±4.79
0.268	0.693±0.084	67.11±4.8	69.69±8.87
0.536	0.908±0.096	52.69±12.16	56.89±3.41

Table 33 The values of tensile index for tested sheets made from washed birch (fines content was 3%) pulp due to different pulp consistency in the sheet mold. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Pulp consistency, g/dm3	Specific formation, √g/m	Tensile index, Nm/g	
		Standard method	Non-standard method
0.179	0.518±0.224	55.24±5.78	55.3±6.39
0.268	0.573±0.125	52.09±6.89	56.25±4.26
0.536	0.545±0.04	49.19±4.23	49.26±2.32

Table 34 The values of tensile index for tested sheets made from washed birch (fines content was 3%) pulp due to different pulp consistency in the sheet mold and addition of PAM. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Pulp consistency, g/dm3	Specific formation, √g/m	Tensile index, Nm/g	
		Standard method	Non-standard method
0.179	0.767±0.073	46.41±7.12	43.94±3.53
0.268	0.955±0.133	35.91±3.39	41.82±3.62
0.536	1.136±0.079	30.17±2.78	32.5±2.46

Table 35 The values of tensile index for tested sheets made from mix ratio of both pine and birch pulps. The fines content for washed furnish was 3%. The value of tensile index ± standard deviation. The results from two measurement methods are presented. The result is the average of 4-5 sheets

Amount of pine pulp, %	Standard method		Non-standard method	
	Unwashed furnish	Washed furnish	Unwashed furnish	Washed furnish
0	93.4±5.83	62.35±3.05	92.25±11.4	58.27±7.41
20	78.82±3.15	63.27±2.38	78.94±2.79	60.69±1.6
40	83.94±3.76	68.02±4.16	81.79±3.04	62.59±3.36
50	81.23±6.12	69.18±4.52	81.54±1.8	66.71±4.66
60	84.04±5.48	70.22±3.95	85.12±2.87	71.5±3
80	87.58±3.29	71.13±3.22	91.89±4.4	69.45±1.41
100	93.4±5.83	75.12±5.77	92.25±3.8	75.55±4.07

The effect of f;locculant addition on specific formation

Table 36 The values of Zeta-potential, conductivity, drainage rates on specific formation formation of paper made from pine pulp (SR40)

Dose of PolyDADMAC, %	Zeta-potential, mV	Conductivity, µs/cm	pH	Drainage, sec	Specific formation, √g/m
Without chemical	-30.9±0.5	113.4±0.1	7.10	9.45	0.383±0.02
0.05	-27.6±0.5	118.5±1.3	7.13	9.34	0.397±0.02
0.1	-24.5±0.4	121.5±0.1	7.35	9.57	0.394±0.02
0.15	-25.9±0.5	119.0±0.8	7.37	9.71	0.408±0.03
0.25	-16.5±0.5	118.9±0.7	7.39	9.77	0.396±0.016

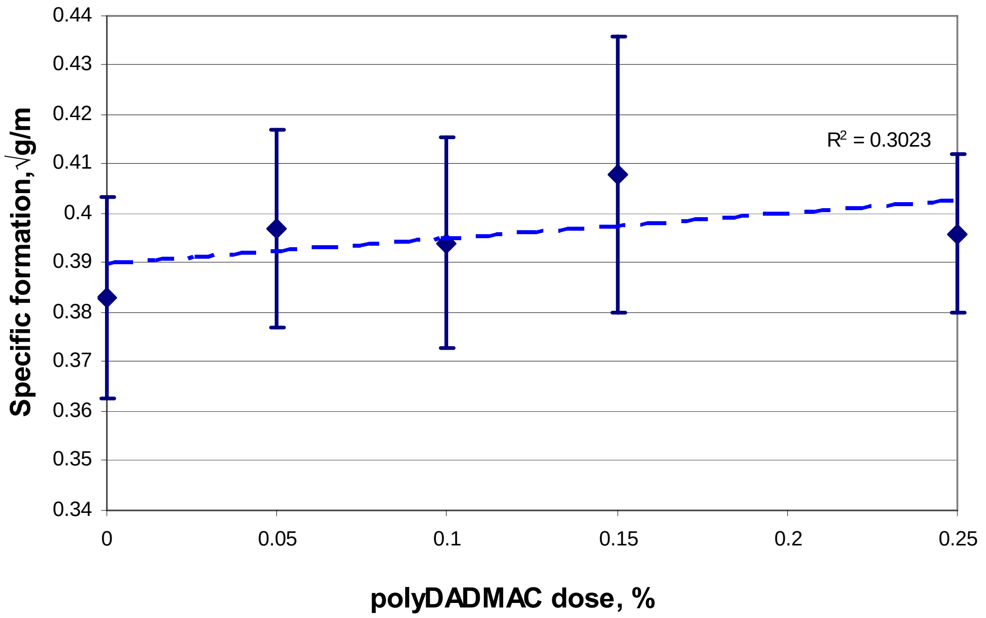

Figure 3 *The effect of polyDADMAC addition on specific formation of papersheets made from pine pulp.*

Table 37 The effect of PAM on Zeta-Potential of pulp

Dose of PAM, %	Zeta-potential, mV	
	Whole pulp (fines content is 5.3%)	Pulp with partial fines removed (1%)
Without chemical	-44.0±0.3	-53.4±1.1
0.02	-38.5±0.4	-24.1±1.0
0.025	-36.7±0.6	-19.2±0.8
0.03	-24.4±0.2	-18.2±0.8
0.04	-23.4±0.4	-7.2±0.6

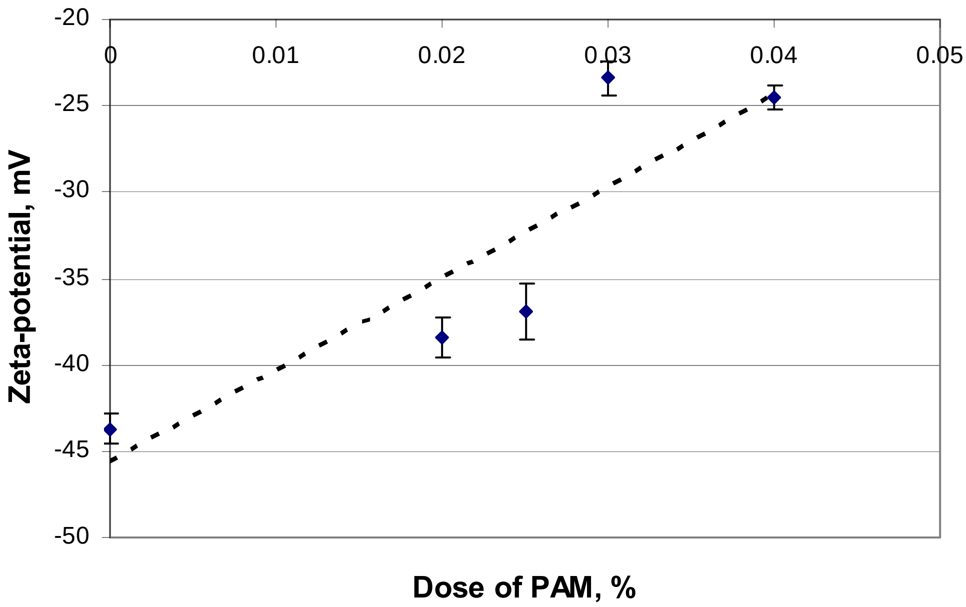

Figure 4 *The effect of PAM addition on zeta-potential of unwashed pine pulp (SR40). Fines content was 5.3 %.*

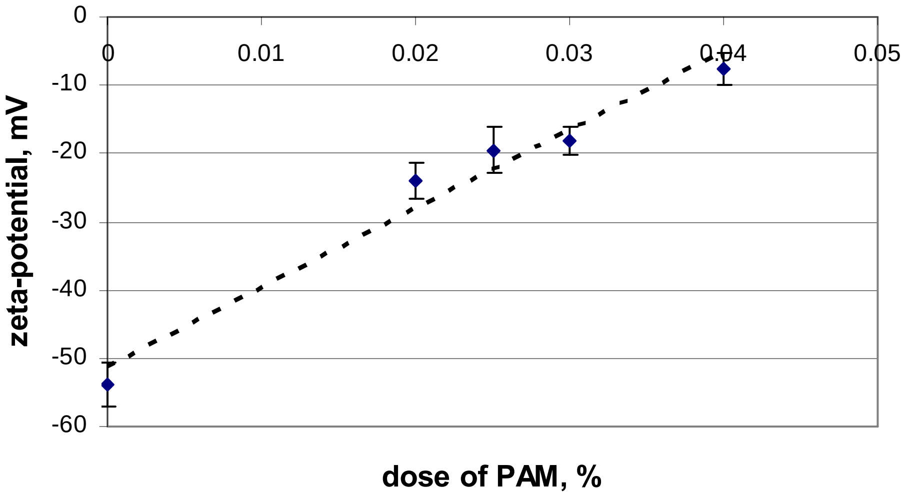

Figure 5 *The effect of PAM addition on zeta-potential of washed pine pulp (SR40). Fines content was 3 %. The fines content was adjusted by removing (washing) part of the fines from pine pulp (SR 40).*