Optimum location of softwood sulfate pulp in three-ply office paper

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ABSTRACT

The role of softwood sulfate pulp in three-ply copy paper was studied using sheets produced on a pilot paper machine. The furnish for the three-ply samples consisted of 70% hardwood (birch or birch + eucalyptus) and 30% softwood sulfate pulps. Softwood pulp was applied to either the outer plies or the middle layer. Most samples were produced with a basis weight of 80 g/m². The target basis weight for each of the outer plies was 20 g/m². Test results revealed that bending stiffness, formation, and smoothness were improved by locating the softwood in the middle ply instead of the outer layers. Substituting eucalyptus pulp for birch pulp in the hardwood/softwood middle ply gave a sheet with greater bulk and thus higher bending stiffness at a given smoothness level. The results suggest that optimum stiffness and surface properties can be achieved by using softwood and eucalyptus sulfate pulps in the middle layer and applying birch sulfate to the outer layers. Using this approach, the amount of softwood in the middle ply could be decreased, since the required fiber network for good runnability is best achieved when all long fibers are concentrated in the middle ply.

Application:

Pilot-scale test results suggest a production strategy for reducing both the softwood content and the basis weight of layered office papers while maintaining sheet properties.

COPY PAPER MUST MEET VERY demanding and comprehensive quality specifications to ensure optimum performance in today's advanced office copiers. Indeed, the sheet quality of copy papers is one of the most demanding among uncoated wood-free grades. Low curling during moisture and temperature changes, good appearance and formation, low cockling tendency, good surface smoothness, minimum two-sidedness, and high bulk and stiffness are all important properties of a copy paper.

Curl has become a critical factor for sheets produced for the high-speed, high-volume segment of the copier market. With the increasing availability of copiers that can automatically copy on both sides of the paper, the need for stable papers with minimal curl has become even greater. Curl prior to copying can affect paper feed efficiency, while post-copier curl induced by the hot fusing operation can have a marked influence on paper sorting and the ability of the paper to be copied on both sides.

There is an obvious economic incentive to reduce the basis weight of copy papers while keeping the critical properties at an acceptable level. Stiffness and opacity are perhaps the most critical properties when reducing the basis weight of a copy paper. Insufficient stiffness results in misfeeding and jamming and can cause collation problems in copying *(1)*, while adequate opacity is required to prevent look-through.

The properties of paper depend largely on the structure of the various fibers within the sheet. The most important structural characteristics are fiber length, fiber coarseness, and cell-wall thickness. Fibers with thicker cell walls resist collapse and tend to produce an open, absorbent, and bulky sheet with low burst and tensile strength but high tear resistance. Fibers with smaller cell walls collapse readily into ribbons during sheet formation, thus promoting interfiber bonding.

Fiber length has a major influence on paper formation *(2–4)*. Indeed, fiber length and headbox consistency are the two variables with the greatest effect on formation in a commercial paper machine. Increasing the level of either significantly worsens formation. Short-fiber pulp provides fine paper with good formation and printability. However, the long flexible fibers of softwood are needed for good runnability on a conventional paper machine *(5)*.

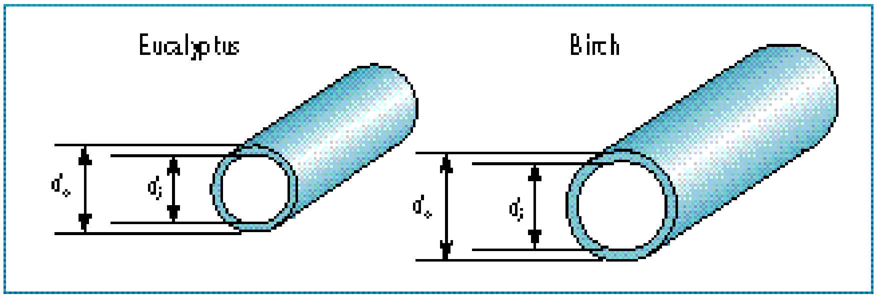
Birch and eucalyptus have roughly the same fiber length and cell-wall thickness. However, eucalyptus fibers are narrower than birch fibers, as seen in **Fig. 1**, with a gram of eucalyptus pulp containing about 50% more fibers than a gram of birch pulp. On the other hand, because birch fibers are wider than eucalyptus fibers, they have a greater tendency to collapse into wide, ribbon-like strands in the sheet.

If fiber structure is simulated as round cylinders, the collapsibility can be related to Eq. 1 *(6)*:

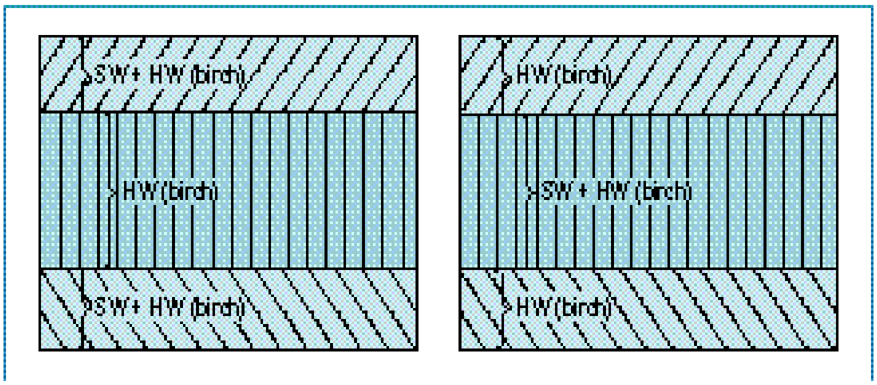
$$\text{Collapsibility} = \frac{1 - \left(\frac{d_i}{d_o}\right)^2}{1 + \left(\frac{d_i}{d_o}\right)^2} \qquad (1)$$

where

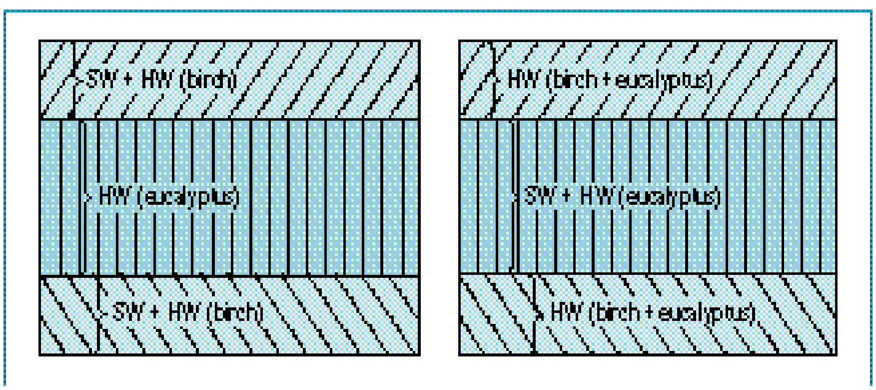
d_i = lumen diameter, µm
d_o = outside diameter of fiber, µm



1. Illustration of eucalyptus and birch fibers



2. Location of softwood pulp in three-ply test sheets containing 30% SW and 70% HW (birch)



3. Location of softwood pulp in three-ply test sheets containing 30% SW and 70% HW (birch + eucalyptus)

	Eucalyptus	Birch
Fiber length, mm	1.0	1.1
Fiber diam. (d_o), µm	16	22
Lumen diam. (d_i), µm	10	16
Collapsibility resistance	0.44	0.31

I. Comparison of eucalyptus and birch fiber characteristics

According to Eq. 1, the collapsibility of typical birch fibers is 0.31, and the corresponding value for eucalyptus fibers is 0.44 *(6)*. Table I lists the relevant characteristics for eucalyptus and birch fibers. Fiber length and coarseness relate to the number of fiber contacts in the suspension. They also affect the stiffness of fibers in bending and, therefore, the forces acting on each fiber contact. Fine fibers tend to bend more easily, thus reducing their effective length and resulting in smaller flocs *(7)*.

From a theoretical point of view, maximum stiffness for a symmetrical three-ply structure can be achieved with thin, high-elastic-modulus outer plies overlaying a thicker middle ply. According to this theory, the long, flexible northern softwood chemical fibers should be located in the outer plies *(8–10)* to maximize the stiffness of a three-ply copy paper.

AIM OF THE STUDY

This study is an extension of previous efforts to optimize a furnish for a three-ply copy paper. In the previous study, the role of the middle layer on the critical properties of a three-ply copy paper was evaluated while maintaining the furnish for the outer plies at a constant level of 30% softwood (SW) and 70% hardwood (HW) *(11)*.

The objective of the present study was to evaluate the effects of two other variables on the properties of three-ply sheets:

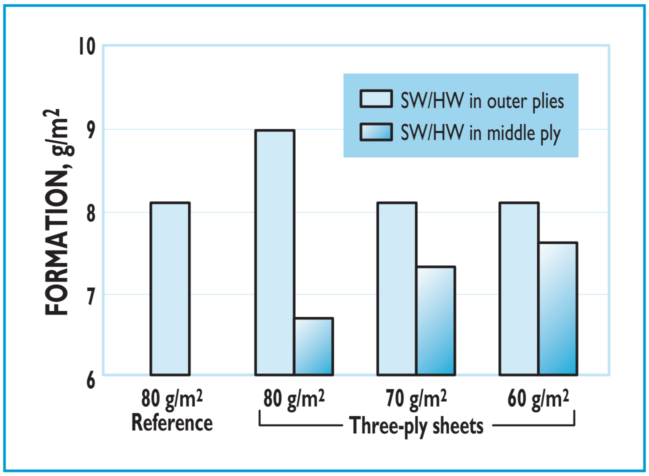
1. *Location of softwood pulp.* Three-ply samples were produced with (a) a SW/HW furnish applied to the outer layers over a hardwood middle ply and (b) a hardwood furnish applied to the outer layers over a SW/HW middle ply. In all cases, the SW component in the finished sheet was maintained at a constant level of 30% for the three basis weights produced (80, 70, and 60 g/m^2) on the pilot machine.
2. *Partial substitution of eucalyptus sulfate pulp* for birch sulfate pulp in the outer layers and the middle ply.

Figures 2 and 3 show the locations of softwood and hardwood pulp in the three-ply samples. Figure 2 shows the sheet structures when birch was the sole hardwood pulp, while Fig. 3 shows the sheet structures when both eucalyptus and birch pulps were used.

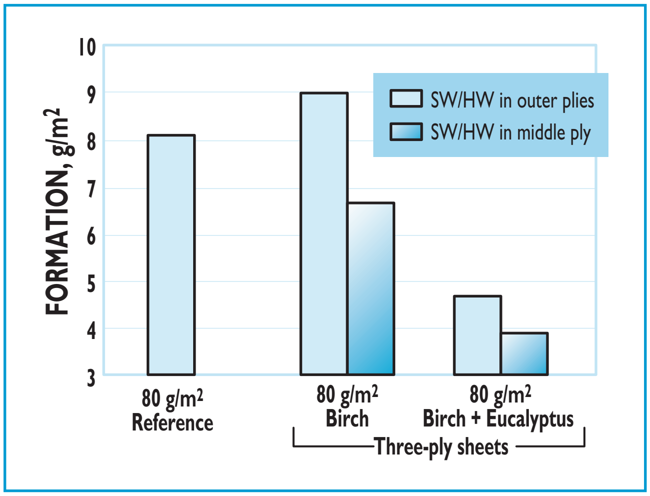
EXPERIMENTAL

Raw material

The same raw materials that were used in previous three-ply trials were also used in this study *(6)*. Scandinavian pine sulfate pulp (refined to 470



4. Formation of sheets containing 30% SW and 70% HW (birch)



5. Formation of sheets containing 30% SW and 70% HW (birch or birch + eucalyptus)

mL CSF)—in combination with hardwood sulfate pulp—was located either in the outer layers or in the middle layer, as seen in Figs. 2 and 3. The hardwood pulps used in this study were Scandinavian birch (refined to 450 mL CSF) and *Eucalyptus globulus* (refined to 513 mL CSF) sulfate pulps. The SW/HW ratio in all sheets was maintained at 30%/70%.

Sheet properties were measured to evaluate the effect of locating softwood fibers in the outer layers and in the middle ply. A single-ply sample produced using a homogenous furnish of 30% softwood and 70% hardwood (birch) sulfate pulps served as a reference.

The amount of chemicals in the layered sheets was the same as in the reference sheet, and chemicals were fed evenly in all layers. The filler used was PCC (precipitated calcium carbonate). Filler content was 20% of total basis weight and was used identically in all layers.

Pilot trial

The three-ply test sheets and the single-ply reference sheets were produced on the experimental FEX pilot paper machine at STFI. The pilot machine has a three-ply stratified headbox with vanes and a roll-and-blade gap former. The gap former was run in the roll forming mode to provide better layer purity than roll and blade forming. The basis weight of the samples was 80 g/m², with some samples also produced at basis weights of 70 and 60 g/m². **Table II** describes the sheets produced on the pilot machine.

	BASIS WEIGHT, g/m²			HW/SW CONTENT, %	
	Total	Outer plies	Middle ply	Outer plies	Middle ply
Single-ply reference	80	80		70/30	
Three-ply sheets					
SW in outer plies	80	20	40	40/60	100/0
SW in outer plies	70	20	30	47.5/52.5	100/0
SW in outer plies	60	20	20	55/45	100/0
SW in middle ply	80	20	40	100/0	40/60
SW in middle ply	70	20	30	100/0	47.5/52.5
SW in middle ply	60	20	20	100/0	55/45

II. Basis weights and fiber contents for the various sheets produced on the pilot paper machine

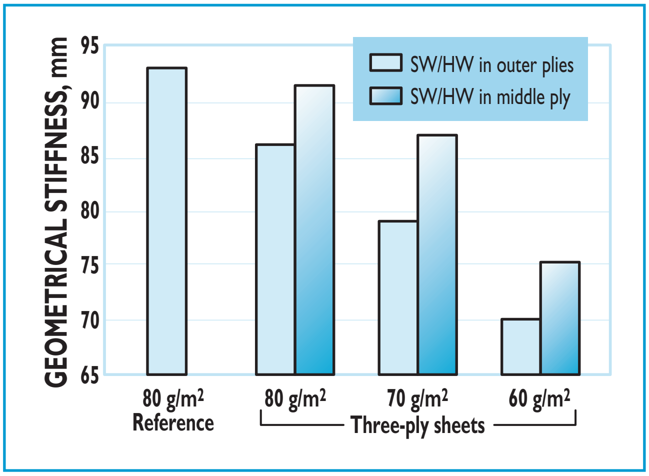
The jet speed was 600 m/min, and first-pass retention was held constant at about 80%. The target basis weight of the top and bottom plies was 20 g/m² for all basis weights. The samples were dried immediately to a final moisture content of 4.5% in a separate multicylinder dryer section.

Some samples were subsequently surface sized on one side with a film-transfer pilot coater at Åbo Akademi University in Finland. Starch was used with a solids content of 10%. Calendering was done using a laboratory soft calender. The samples were calendered once through the nip with the surface-sized side against the iron roll. Samples that were not surface sized were calendered in the same way. Two different pressures were used, and the surface temperature of the iron roll was 90°C.

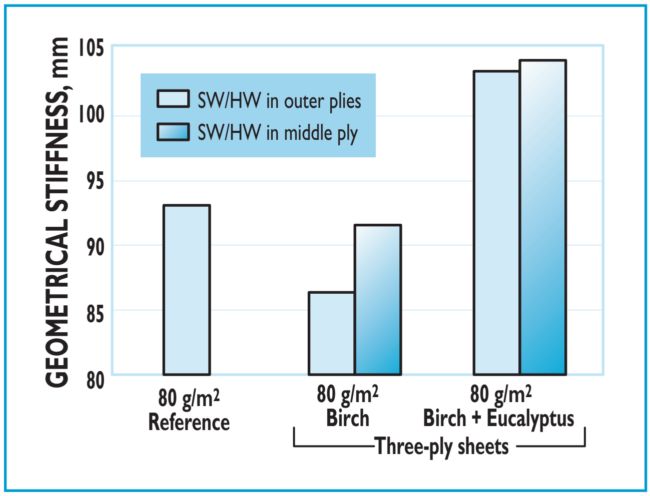
RESULTS AND DISCUSSION

β-formation

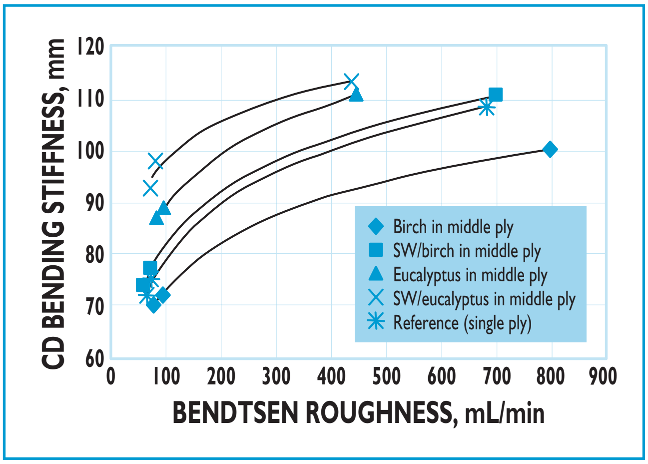
Figure 4 shows the formation of the samples produced using 30% pine sulfate and 70% birch sulfate (no eucalyptus). β-formation was measured as a standard deviation of basis weight, so a lower value indicates better formation. The results show that formation was improved when softwood was used in the middle layer. β-formation was best for the 80-g/m² sheet and then deteriorated with decreasing basis weight. On the other hand, when softwood was



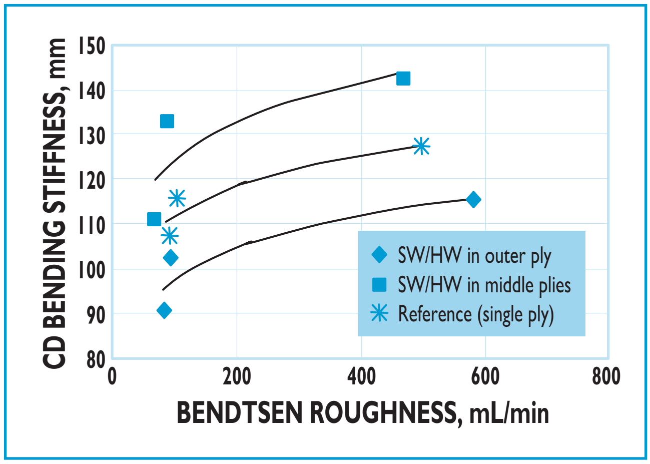
6. Geometrical stiffness of sheets containing 30% SW and 70% HW (birch)



7. Geometrical stiffness of sheets containing 30% SW and 70% HW (birch or birch + eucalyptus)



8. Bending stiffness as a function of sheet roughness for calendered papers (80 g/m²) containing various furnishes in the middle ply



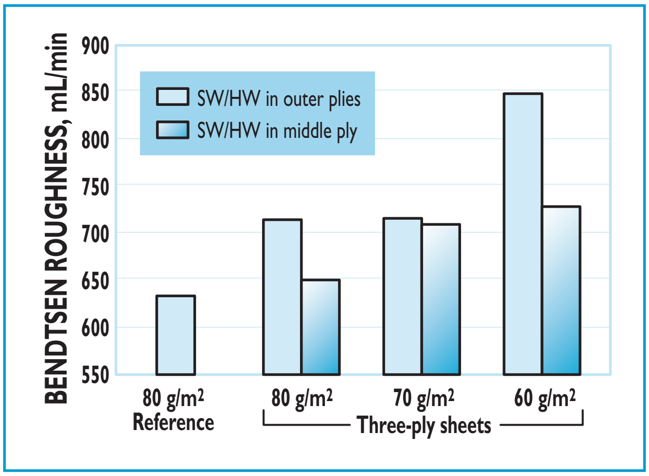
9. Bending stiffness as a function of sheet roughness for surface-sized and calendered papers (80 g/m²) containing 30% SW and 70% HW (birch)

used in the outer plies, formation was at the same level or worse than the reference sheet. Because the basis weight of the outer plies was kept constant, the worst formation was observed for the 80-g/m² sheets with softwood in the outer plies. This is because the outer plies of the heavier sheets contained fewer birch fibers with the softwood than the outer plies of the lower basis-weight sheets (70 g/m² and 60 g/m²). This causes more flocculation in the outer layers and thus hinders formation. The layered sample with softwood in the outer plies clearly had worse formation than the single-ply reference at the same basis weight of 80 g/m². Sheets with softwood in the middle layer had better formation than the reference sheet at all three basis weights. The results suggest that uniformity in the outer plies has a greater effect on formation than uniformity in the middle layer.

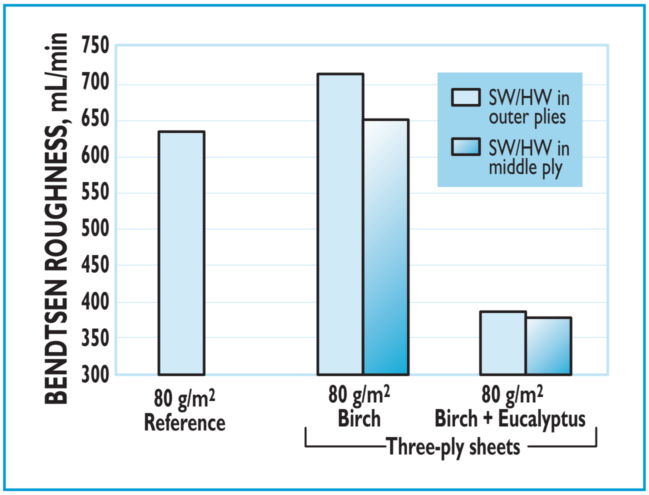
Figure 5 shows a dramatic improvement in formation when some of the birch hardwood was replaced with eucalyptus sulfate pulp. (The amount of softwood was the same in all cases.) Formation improved because each gram of eucalyptus pulp contains about 50% more fibers than each gram of birch pulp. Thus when substituting eucalyptus for birch on a weight-per-weight basis, the number of fibers in the furnish increases. In both cases, formation was better when the softwood was located in the middle ply instead of the outer plies.

Bending stiffness

Stiffness was measured with the so-called "droop" method. The paper was cut into strips 15 mm wide and 150 mm long. For each sample, measurements were made for both the top and bottom sides to reduce the effect of possible curling. The sample was pushed along an upper plane until the free end of the strip touched a



10. Roughness of sheets containing 30% SW and 70% HW (birch)



11. Roughness of sheets containing 30% SW and 70% HW (birch or birch + eucalyptus)

lower plane. The vertical distance between the planes was 40 mm. The paper is bent by its own weight, so that basis weight variations are not critical for the measurement. The stiffness value (measured in millimeters) is the horizontal distance between the free end of the strip and the edge of the upper plane. The geometrical average of the MD (machine direction) and CD (cross-machine direction) stiffness—$(MD \times CD)^{1/2}$—is used to diminish the effect of fiber orientation in stiffness values. A higher value indicates greater stiffness.

The bending stiffness values decreased with the basis weight, as seen in **Fig. 6**. This was expected, since sheet thickness influences bending stiffness to its third power *(10)*. Stiffness was higher at all basis weights when softwood sulfate was used in the middle ply instead of the outer plies. This is because the thin-walled birch fibers in the outer layers collapse easily, giving high specific surface area and thus good bonding potential. The higher bonding improves elastic modulus and, thus, stiffness.

When eucalyptus was used in the furnish together with softwood and birch sulfate, the stiffness was clearly improved, as seen in **Fig. 7**. Thin-walled birch fibers, used in the outer layers, collapse during calendering, thus imparting smoothness to the sheet. Eucalyptus in the middle layer provides bulk and stiffness. Consequently, when using birch in the outer layers and eucalyptus in the middle, smoothness and stiffness can be achieved simultaneously. At a typical roughness level for a copy paper (250 mL/min), the samples with eucalyptus in the middle layer gave about 20% higher bending stiffness over the papers with birch in the middle, as seen in **Fig. 8**.

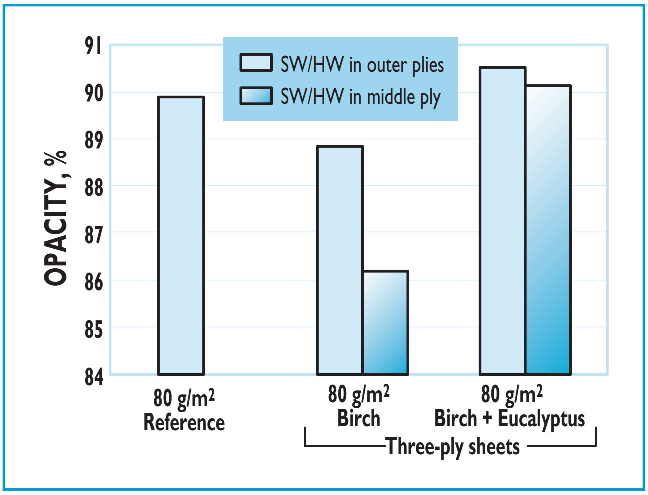
The stratified structure did not give any benefits in stiffness compared with the reference with the same furnish (30% softwood and 70% birch) and basis weight (Fig. 6). However, the surface-sized and calendered samples showed a different response. **Figure 9** shows that the highest stiffness at a given smoothness level was achieved by locating the thin-walled, highly collapsible birch fibers in the outer layers. Comparison of the results in Figs. 8 and 9 clearly shows that surface sizing significantly increased bending stiffness. With modern metering size presses, the starch stays more on the surface of a sheet compared with conventional size presses. This helps in achieving high E-modulus on the surfaces and thus improves stiffness. Furthermore, it can be seen from Figs. 8 and 9 that bending stiffness decreased dramatically at roughness levels below 150 mL/min.

Bendtsen roughness

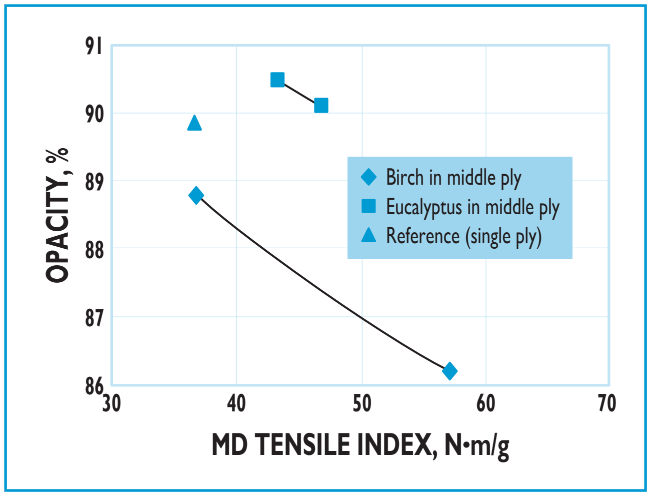
Sheet roughness depends greatly on the fiber material used in the outer layers and on the formation. Typical copy papers need a careful balance of surface smoothness and friction to ensure the best copying results. Should the paper be too rough, it could impair the ability to reproduce images with fine detail and to give uniform tone in solid areas. On the other hand, if the paper is too smooth, it could pick up residual toner from the drum in nonimage areas, resulting in poor quality backgrounds. Very smooth paper could also cause feeding problems because of insufficient sheet-to-sheet friction.

Bendtsen roughness of the uncalendered samples was lower when softwood was used in the middle layer instead of the outer plies, as seen in **Fig. 10**. However, **Fig. 11** shows that the lowest Bendtsen roughness by far was achieved in the sample containing eucalyptus. Note that roughness correlates with formation (Fig. 5). Eucalyptus together with softwood in the middle ply gave the lowest Bendtsen roughness and best formation.

Results for the surface-sized and calendered samples (Fig. 9) revealed that with thin-walled HW fibers in the outer layers, a major reduction in roughness can be achieved while maintaining stiffness.



12. Opacity of sheets containing 30% SW and 70% HW (birch or birch + eucalyptus)



13. Opacity as a function of tensile index for sheets containing birch or eucalyptus in the middle ply

Property	SW used in middle ply instead of outer plies	Additional improvement obtained using eucalyptus in middle ply instead of birch
Formation[a], g/m^2	–2 units	–2.5 units
Bending stiffness[b], mm	+10 units	+20 units
Opacity, %	–2 units	+2 units

[a] Lower value = better formation
[b] Measured at Bendtsen roughness of 250 mL/min

III. Changes in key quality properties for three-ply sheets produced with different furnishes

Opacity

Adequate opacity is required to prevent look-through. High filler and hardwood pulp contents promote sheet opacity. **Figure 12** shows that the sheets containing eucalyptus fibers had the highest opacity. Eucalyptus fibers are more resistant to collapse than birch fibers. Consequently, there is greater light scattering because of scatter from both the outer and inner surfaces of the fiber. **Figure 13** shows that the sheets containing eucalyptus fiber had the highest opacity at a given tensile level.

SUMMARY

On the basis of the theoretical model and results reported from other experiments, it was assumed that bending stiffness would improve when softwood was located in the outer plies *(12)*. However, the results obtained in this study showed no improvement in the stiffness of copy papers when long fibers were used in the outer layers. On the contrary, bending stiffness improved when softwood was located in the middle layer. One reason for this is undoubtedly the fact that layer purity was not perfect in these tests. Another reason is that the refining of the long fibers was not the optimum for an adequate elastic modulus. More highly refined softwood sulfate would have greater flexibility and fiber collapse and, consequently, a better elastic modulus. However, higher levels of refining also reduce fiber length and thus wet strength, resulting in poorer runnability on the paper machine.

Table III summarizes the results of this study for three-ply sheets with a basis weight of 80 g/m^2 and containing 30% softwood.

CONCLUSIONS

The experimental results obtained in this study demonstrate that the formation, stiffness, and opacity of three-ply sheets can be increased by adding eucalyptus pulp to the furnish. For low-basis-weight sheets, it appears that there should be less than 30% softwood to avoid major flocculation and thus poor formation.

A certain number of softwood fibers are needed to create a uniform fiber network. When softwood is located solely in the middle layer, it can be assumed that a lower total proportion of softwood will be needed to obtain the required runnability. When softwood is located in the outer plies, sheet smoothness is reduced by the presence of thick-walled latewood fibers. Moreover, formation also suffers because the long, flexible softwood fibers also flocculate easily.

The optimal structure of a three-ply office paper for good bending stiffness requires well-bonded material on the surfaces, which usually increases sheet density. Because birch sulfate consists of fibers with thin cell walls, it provides simultaneously good formation, smoothness, and greater bonding capacity.

Pulps that provide maximum thickness should be selected for the middle layer of a three-ply sheet. Because office papers require good yellowing resistance, mechanical pulps are not usually considered as an option. Eucalyptus sulfate pulp fibers have thick cell walls in relation to their diameter. These fibers resist collapse during the papermaking process, thus improving sheet stiffness. Furthermore, the use of eucalyptus improves formation, since each gram of eucalyptus pulp contains substantially more fibers than the other species considered in this study.

The results showed that layering of softwood in three-ply office paper did not provide benefits in stiffness. However, stiffness improved markedly when the furnish was changed to include eucalyptus sulfate pulp. Moreover, by using eucalyptus together with softwood sulfate in the middle ply, the amount of softwood could be reduced, since the required fiber network for good runnability can be achieved more easily when all of the long fibers are concentrated in the middle ply. The benefits of this are improved runnability and lower furnish costs. **TJ**

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