Variations in strength and bonding properties of fines from filler, fiber, and their aggregates

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ABSTRACT: Fines from bamboo-hardwood pulp, talc, and aggregates from mill white water solids were blended in 36 different compositions. General properties of the sheets made from each composition, such as bulk, burst factor, breaking length, tear factor, and double fold, are reported. Fiber strength (FS) and bond factor (BF) were measured using a Pulmac trouble shooter. Variations in strength and bonding properties of the four different fines studies are discussed. In order to explain the filling and bonding mechanisms of the fines, schema were drawn based on optical microscopy and SEM studies.

KEYWORDS: Aggregate, bonding, fibers, fillers, fines, mechanical properties, talc, white water.

Fines have been the materials of interest in the manufacturing process *(1–3)* and in fundamental studies *(4–6)* of paper technology. A well planned fines management system *(3)* is considered vital for high productivity as well as for product quality; higher productivity because of variations in drainage properties of different fines and, consequently, on the running of paper machines. Optical properties have a bearing on the fines content as well as on paper. Fines also play a role in the economics of paper manufacturing because of the lower cost of fillers compared to that of fibers *(7, 8)*.

The fundamental properties of fines, namely particle size and distribution *(9)*, surface area *(10)*, zeta potential *(11)*, electro-phoresis and electroosmosis *(12)*, etc., are quite complex when the results are to be correlated with the bonding and filling properties.

The general characteristics of fines are summarized in **Table I.** Materials passing through 100 mesh (strands per inch) or 200 mesh in a Bauer McNett Classifier are generally termed as "fines" *(2)*. All the filler particles come under "fines" because of fine particle size (< 0.1 μm). Fiber fines have sizes ranging from 10 μm to 100 μm while fibrils are <1 μm in diameter with length of several hundred μm *(9)*.

Fiber fines are essentially the detached portion of cellulosic material consisting of lignin, ray cells, tracheids, parenchyma cells, and cellulosic debris, which are termed as primary fines. The bonding properties of these elements are variable; for example, lignin has a preventive effect on hydrogen bonding, and ray cells do not bond as well as tracheids *(13)*.

The fines from white water in the mill are normally contaminated with dyes, polymeric compounds, rosin, residual alcohol-benzene extractives *(14)*, and other additives used during stock preparation which may change the properties of the initial fines.

The results presented here will show that all these fines behave differently vis-a-vis the strength properties. Perusal of the literature shows that the fines have been studied mostly in isolation of the void spaces existing in the fiber network. This paper takes into account these spaces as being major sites for localization of fines.

Experimental

Bamboo-hardwood (80:20) mixed bleached kraft pulp after refining and white water were collected from the mill. The white water solids contained 55.8% of talc and the remaining fibrous fines.

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I. Characteristics of fines

Fines	*Source*	*Components*	*Chemical composition*	*Particle size, μm*	*Properties*
Primary	Virgin pulp	Parenchyma cell	Resin, extractives	50 - 300	-Primary fines better light scatterers -Selective adsorption -Adversely affects paper cleanliness
		Vessel elements	Cellulose, hemicellulose	40 - 200	
		Pieces of fibers	" "	30 - 600	
		Bundles of fibers	" "	2000	
		Fiber debris	Hemicellulose, polysaccharides	16 - 25	
Secondary	Refined pulp	Pieces of fibers	Cellulose, hemicellulose	30 - 200	
		Fiber debris	" "	16 - 40	-Higher water retention value than fibers
		Fiber wall (S_1&S_2)	" "	-	
	Pulp after stock preparation	Pieces of fibers	" "	30 - 200	
		Fiber debris	" "	16 - 40	
		Filler	Talc	0.2 - 20}	-Poor drainage property
		Additives	Starch	- }	
	White water	Pieces of fibers	Hemicellulose, cellulose	30 - 150	
		Fiber debris	" "	10 - 20	
		Filler	Talc	0.2 - 20	
		Additive	Starch	-	

The four types of fines studied are characterized below:

A. White water fines: collected from paper mill machine tray water

55.8% talc and 44.2% fiber fines

Fiber fines 38.7% <76 μm

B. Simulated fines: produced in the laboratory by further beating of mill refined pulp in a Valley beater

C. Filler fines: talc—10% and 20% (to simulated fines)

D. Fiber fines: +66 μm to –211 μm (+250 mesh to –72 mesh)

+66 to –152 μm (+250 mesh to –100 mesh)

+66 to –76 μm (+250 mesh to –200 mesh)

+152 to –211 μm (+100 mesh to –72 mesh)

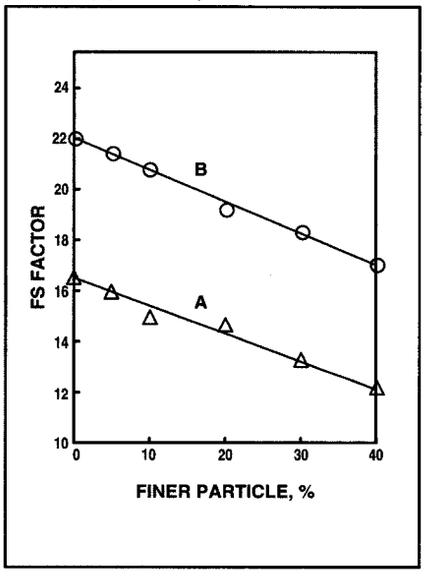
+76 to –152 μm (+200 mesh to –100 mesh).

Fiber fines D of various fractions were obtained by subjecting the bamboo-hardwood mixed bleached and refined kraft pulp to fractionation in the laboratory Bauer McNett fiber classifier.

The mixing of fines for all the systems was made in a disintegrator in the same way and therefore the results can be compared. As the mesh size employed was 250, particles finer than (250 mesh) 66 μm could not be recycled.

White water from the mill was allowed to settle for 15 min and then decanted to get solid of high consistency which is blended with the bleached pulp. Handsheets were made according to the TAPPI Method, and the strength properties also were determined according to TAPPI Methods. The fiber strength and bond factors were determined with the Pulmac trouble shooter (made in USA, Model-TS 100).

3. FS factors of handsheets with (A) 66–152 μm, and (B) 66–211 μm fractions

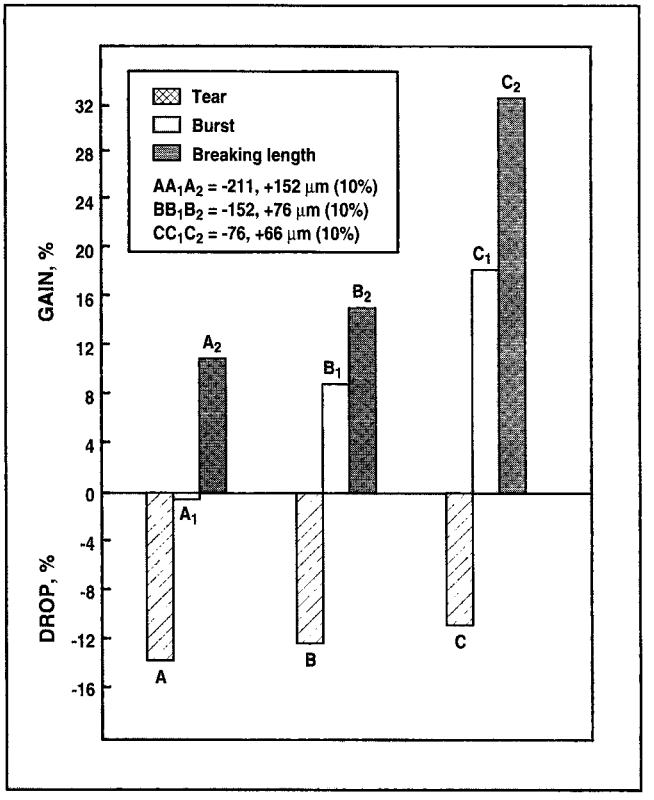


Results and discussion

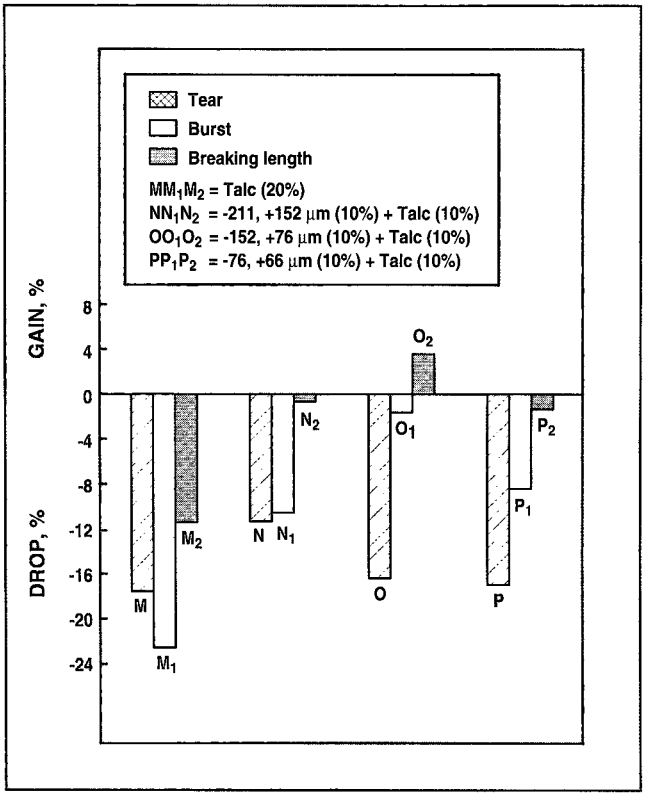
White water fines—A

Because of the high dispersion of fines, complete settling of the solids in white

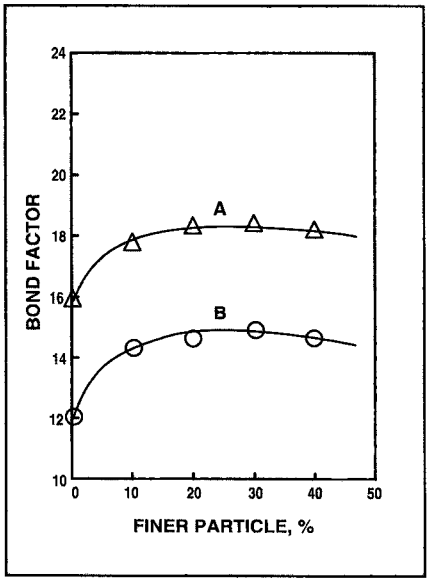
1. Strength properties with simulated fines



2. Strength properties with simulated fines and talc



4. Bond factor of handsheets with (A) 66–152 μm, and (B) 66–211 μm fractions



water did not take place after 3 min of settling time.

According to microscopic observation the fines consist of fiber debris, parenchyma cells, vessels, and talc particles which differ in texture from the fiber fines. The fiber fines here appear in form of flocs or agglomerated masses. These flocs *(15)* should possess little charge compared to the fines obtained directly after beating. The fiber classification data are shown in **Table II** where 61.3% consist of +72 mesh fraction. The finest fraction (–250 mesh) accounting for ≈ 15% of the total must be discarded as these fines cannot be collected during sheet preparation. Finally, the fines cosist of ≈ 24% of the refined pulp.

Properties of handsheets made from bleached pulp (Table II) and white water fines are shown in **Table III.** White water fines content has been varied from 0 to 50%. The bulk values decrease with increase in white water fines content from 1.62 mL/g with no fines to 1.43 mL/g at 50% of fines. As the fines are composed of 56% of inorganic material, such decrease in bulk is obvious with increase in unit weight.

The burst and tear factors, breaking length and double fold (MIT) properties decrease with increase in white water fines content. It can be seen that even at 50% of fines content, tolerable properties for quality paper are possible to be obtained; namely, 17.3 of burst factor, 38.4 of tear factor, 3060 m of breaking length and 5 no. of double fold. However, the drainage time is quite high (20 s) because of high fines percentage. At 10% addition level, the corresponding values are 35.1, 53.8, 5410 m and 16 no. which are quite appreciable. It is certain, therefore, that addition of 10–20% of fines, originating from the mill white water, can be programmed without any hesitation.

Simulated fines—B

Results of strength properties of sheets made from simulated fines of varying dimensions are shown in **Fig. 1.** Comparison of the effect imparted on strength properties between fines present in recycled white water and simulated fines shows some differences; the burst and breaking length have increased on addition of simulated fines, which is the reverse in white water fines. These two properties are improved as the fineness increases.

However, the tear factor decreases here as in the case of white water fines.

The strength properties of the sheet increase when charged bodies are present because of enhancement in bonding properties. The white water fines surfaces adhere to particles of opposite charge, resulting in a passive solid mass during stock preparation and recycling in the mill. The residual acids, oil, etc., in the system would promote flocking and passivity of the fines in white water. The filler particles may remain adsorbed onto the surface *(6)*, filled inside the lumen *(16)* or coexist with the very fine fiberlets in case of white water fines.

Filler fines—C

Strength properties of handsheets made with present bamboo-hardwood furnish and talc were extensively evaluated recently *(17, 18)*, and therefore strength properties with 10% and 20% talc addition levels are reported in **Fig. 2**. It can be seen that the percentage drop in all strength properties is quite high compared to the systems with simulated fines (Fig. 1). On increasing the talc content to 20%, the strength properties are decreased further; the percentage drops in burst factor, tear factor, and breaking length are 23%, 18%, and 12%, respectively, which are 11%, 11%, and 0.5% with 10% of talc. The corresponding drops in strength with simulated fines are lower than either of these values.

The results obtained with the above three fines would tempt one to increase the fiber fines content in the white water portion if higher strength properties are required. In a situation near the paper machine where no other addition than the white water is possible, such a notion of substitution having bearing on strength properties is quite important. One would like to have a stock of fine fiber particles on the side of the headbox to take care of the emergency situation.

II. Fiber classification of mill pulp

Size, μm	*Mesh no.*	*Fibers retained, %*
+211	+72	61.3[a]
+152, -211	-72, +100	9.3
+76, - 152	-100, +200	8.2
+66, - 76	-200, +250	6.5
-66,	-250	14.7 Discarded

[a]61.3% to 6.5% classifications were used.

III. Properties of handsheets from mill pulp and white water fines

Set	*1*	*2*	*3*	*4*	*5*	*6*
Refined pulp, %	*100*	*90*	*80*	*70*	*60*	*50*
White water fines, %		*10*	*20*	*30*	*40*	*50*
Bulk, mL/g	1.62	1.57	1.54	1.50	1.47	1.43
Burst index, kPa·m²/g	3.5	3.2	2.8	2.3	2.0	1.6
Tear index, mN·m²/g	5.9	5.5	5.4	5.1	5.1	3.9
Tensile index, N·m/g	56.1	53.0	48.5	44.2	37.6	30.0
Double fold, no.	25	16	11	10	7	5
Drainage time, s	4.8	7.3	7.7	8.9	14.0	20.0
Ash, %	0.97	4.6	9.2	13.2	18.8	25.1

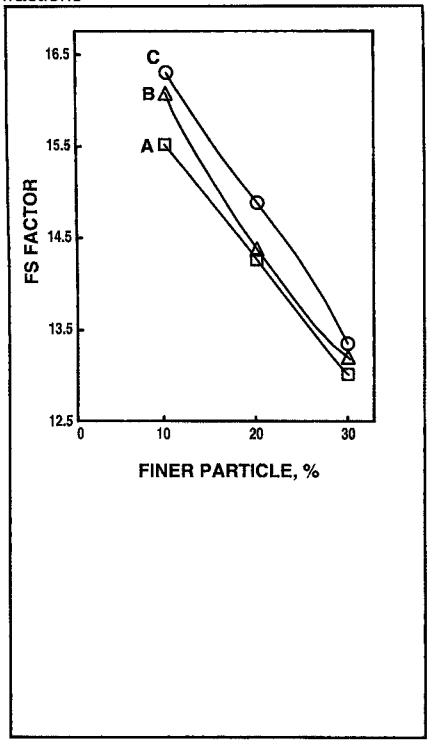
IV. Strength properties of handsheets from mill pulp with varying fiber size (+211, and +66, -211 μm)

Set	*1*	*2*	*3*	*4*	*5*	*6*
+211 μm fraction, %	*100*	*95*	*90*	*80*	*70*	*60*
66–211 μm fraction, %		*5*	*10*	*20*	*30*	*40*
Bulk, mL/g	1.95	1.84	1.78	1.69	1.68	1.59
Burst index, kPa·m²/g	2.0	2.2	2.6	3.0	2.7	2.8
Tear index, mN·m²/g	8.8	7.7	6.8	6.6	6.1	5.2
Tensile index, N·m/g	39.2	45.9	50.8	55.8	48.1	47.8
Double fold, no.	7	9	12	13	12	7
Drainage time, s	3.8	4.1	4.2	5.0	5.8	7.9

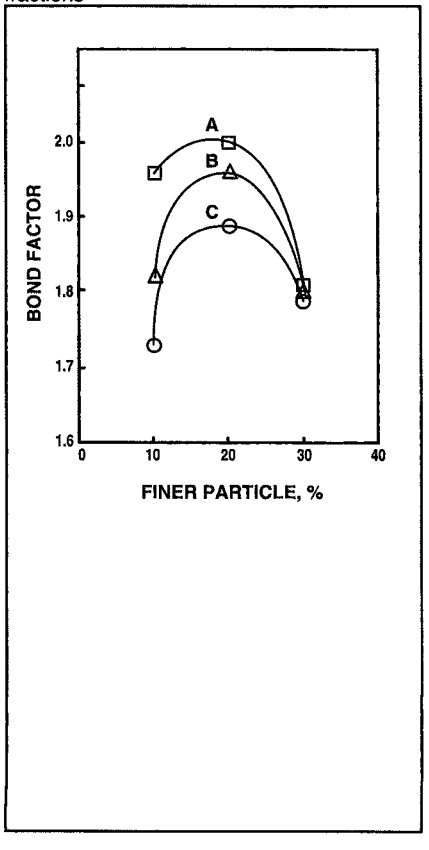
V. Strength properties of handsheets from mill pulp with varying fiber size (+152, and 66, -152 μm)

Set	*1*	*2*	*3*	*4*	*5*	*6*
+152 μm fraction, %	*100*	*95*	*90*	*80*	*70*	*60*
+66, -152 μm fraction, %		*5*	*10*	*20*	*30*	*40*
Bulk, mL/g	1.81	1.66	1.65	1.59	1.48	1.42
Burst index, kPa·m²/g	2.5	2.8	2.9	2.7	2.5	2.3
Tear index, mN·m²/g	6.8	5.9	5.5	4.9	3.8	3.2
Tensile index, N·m/g	50.2	52.0	53.2	55.3	51.3	49.2
Double fold, no.	8	7	6	5	3	2
Drainage time, s	3.9	4.5	4.9	5.6	6.8	9.5

5. FS factor of handsheets with (A) 66–76 μm, (B) 76–152 μm, and (C) 152–211 μm fractions



6. Bond factor of handsheets with (A) 66–76 μm, (B) 76–152 μm, and (C) 152–211 μm fractions



Fiber fines—D

Strength properties of handsheets made out of fiber fines are shown in **Tables IV–VI.** The fiber strength and bond factors are presented in **Figs. 3–6.** The bulk values of sheets made from all the fractions remain (1.9–1.4 mL/g) higher than the sheets made with filler fines.

The burst factor, breaking length, and double fold values increase while the tear factor decreases with increase in fineness. The burst factor, breaking length, and double fold, which depend on the bonding properties of the fibers (Fig. 4) in the sheet, increase up to 20–25% addition of fines and then decrease gradually. A breaking length value of 5690 m is obtained (Table IV) with 20% addition of –211 μm (72 mesh) fines from an initial value of 4000 m. Comparison of these strength properties with talc-based sheets shows that the fiber fines impart superior strength properties than filler fines. Moreover, the decrease in strength properties on increasing fiber fines content from 20% to 40% is not so much as in talc or white water fine based sheets. The high double fold values (36) obtained by blending the short fibers (Table VI) is remarkable compared to other combinations of fiber fines (Table IV and V) as well as white water (Table III) and filler fines.

The results obtained with other fines in Tables V and VI also show higher strength properties than the systems containing filler. However, based on the fineness, the fiber fines exhibit different strength properties. These have bearings on fiber strength (FS) and bond factor (BF) values, as shown in Figs. 4–6.

Drainage property

The drainage times of handsheets made with various fiber fines fractions were found to increase with decrease in size range of fines. The nature of the curve for white water fines was different from fiber fines. The specific filtration resistance *(1)* rises abruptly in the case of filler fines vs. that in fiber fines. The drainage time of sheets constituting 10% talc and 10% of fiber fines of varying size was in the intermediate range.

Mechanism of filling and bonding

Scanning electron micrographs (SEM) of the bamboo-hardwood mixed pulp and talc are presented in **Figs. 7 and 8.** A schema is shown in **Fig. 9** to demonstrate the distinctive features in the accessibility and localization of the fines in the void spaces. The voids can be seen in the SEM micrograph (Fig. 7), which are created due to:

- Crossing of fibers in the layers or in Z-direction
- Tapering or commencing ends of fibers
- Loose packing or tenacity in the fibers
- Defects in fiber structure.

Voids, interstitial spaces or macropores can be the results of arrangement of the above. In an ideal situation, where the long fibers initially rearrange themselves forming a fiber network, the empty spaces created may be in triangular or tetragonal form. A minute observation of the SEM micrograph can depict such arrangements (Fig. 7 marked V).

The incoming fines from the white water solids, filler or fibers will follow the path for accessibility into the empty spaces, as shown in Fig. 9 A, B, or C, respectively. The schema has been conceived based on the results obtained.

(A) Fines from white water present themselves in form of aggregates *(5)* with fiber-filler or fiber-fiber bondings. The filler particles could remain entrapped mechanically *(19)*, be adsorbed on the surface *(6)* or reside inside the lumens *(16)*. The alcohol-benzene extractives, starch, dyes, and other organic compounds present in the process water would cause the surface pit and pore openings in the fiber

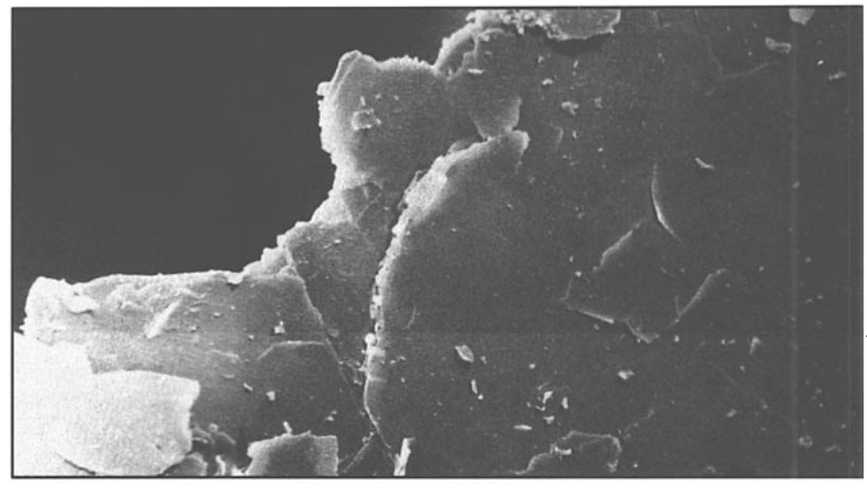
fines to clog to some extent. The overall product is thus an aggregate with reduced bonding property; at 50% addition level (Table III) of white water fines the ash content being 25%, at least 18% would have become aggregated with the fillers (Table III), totaling to 43% of fines or 80% retention. Strength properties show no enhancement on increasing the fines content. It can be explained on the assumption that the aggregates serve as an efficient filler but not for reinforcement of the structural framework by bonding. It is probable that some of the aggregates occupy positions in between the long fibers, which cause further deterioration in strength properties; such a situation is possible, especially at higher fine loading.

(B) Filler particles are the true fines as they represent "fine particles," used in general terms. It is shown that the filler particles possess different surface charge and zeta potential value *(11)*. Talc has a small negative charge, lower than in kaolinite clay *(5)*. Access of talc particles alone into the empty spaces should thus be restricted in view of the negative surface charge prevailing over the fiber surface. It was found in our laboratory *(17)* that handsheets with higher than 28% ash was not possible without retention aid, which is apparently the limit for accessibility of talc fines. The SEM micrograph (Fig. 8) of talc will indicate that the surface contains a lot of defect structures. The defects combined with the surface negative charge should reduce filler-filler bonding and thus the filling efficiency will be reduced compared to the aggregates in (A).

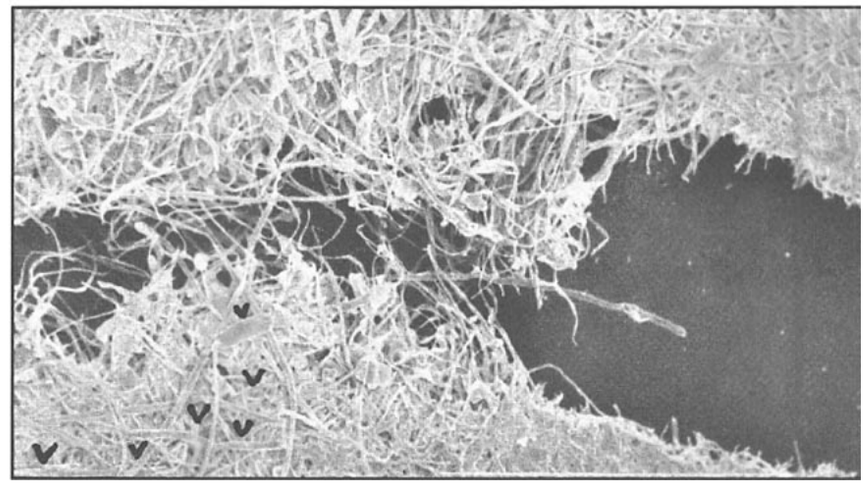
Strength properties are found to be reduced on increasing the filler content *(18)* contemplating lack of bonding with the fibers. Therefore both in filling and bonding, the talc fines are inferior to the aggregates of filler-fiber fines in white water as well as fiber fines as the following discussion will show.

(C) Fiber fines have a totally different morphology than the previous two

7. SEM micrograph of bamboo-hardwood bleached pulp (fractured surfaces) showing typical voids (V)



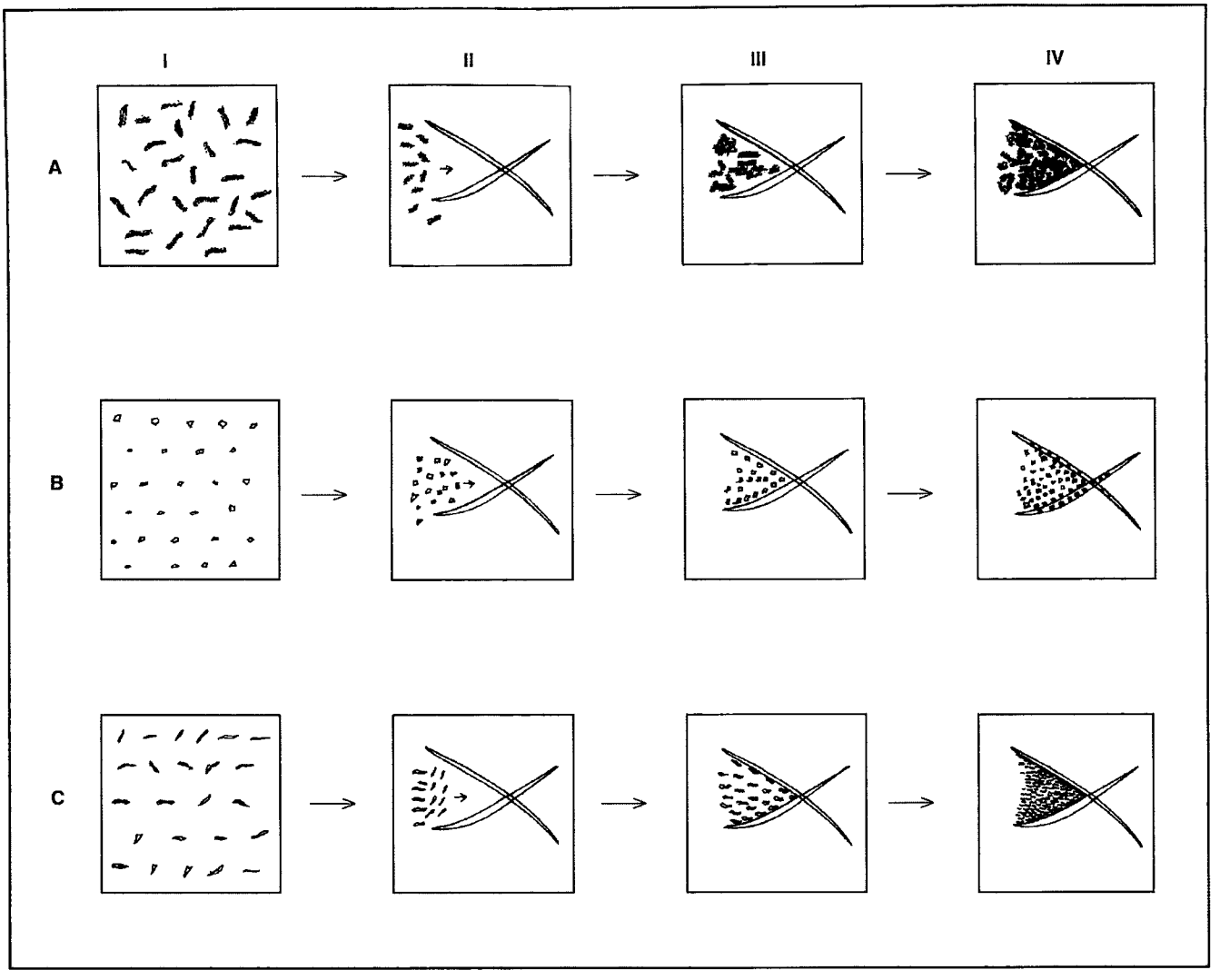
8. SEM micrograph of talc showing defect structures on the surface



VI. Strength properties of handsheets from mill pulp with varying fiber size (+76, and +66, -76 μm)

Set	*1*	*2*	*3*
+76 μm fraction, %	*95*	*90*	*80*
+66, -76 μm fraction, %	*5*	*10*	*20*
Bulk, mL/g	1.75	1.71	1.61
Burst index, kPa·m²/g	2.9	3.1	3.3
Tear index, mN·m²/g	6.9	6.6	5.8
Tensile index, N·m/g	48.1	53.0	50.6
Double fold, no.	17	23	36
Drainage time, s	4.7	5.2	6.4
Fiber strength factor	23.1	20.3	19.2
Bond factor	2.31	2.32	2.62

9. Schema showing (A) White water fines; (B) Filler fines (talc); (C) Fiber fines. I. Fines morphology; II. Migration of fines towards void; III, Localization of fines in void; IV, Optimum filling and bending of fines in void.



fines, consisting of fiber debris, parenchyma cells, and ray-cells of varying dimensions. The surface charges of the units are also likely to be quite varying *(10)*.

As the strength properties have been found to increase on increasing the fines percentage in the sheet, development in fiber-fiber bonding force in the vicinity of surface voids is obvious. The finer the fiber, the higher is the observed fiber-fiber bonding.

The fiber fines being less tenacious or more flexible than the filler or aggregates, packing will be easier in the voids compared to the filler and aggregates, especially in the presence of turbulence created by shearing forces in the dynamic stage of paper manufacturing. The opposing negative charges of the void surface and the fiber fines become less important in front of the shearing force, resulting in a better packing system. Combination of fiber fines of different fractions help in efficient packing. The system of increasing the strength properties of paper with fines from fiber may probably be compared to the effect of "short fibers" in composite materials *(20)*. The effect of filler fines here remains the same as in composite material *(21)*.

Conclusion

The fines derived from mill white water, talc, and fibers of bamboo-hardwood pulp have quite varying properties. The filler and white water fines decrease the strength properties while the fiber fines bring an improvement in strength up to 20–30% of fines addition. The fiber strength factors of longer fibers in fiber fines are higher than the finer fractions, which is the reverse for the bond factor. The finer the fines, the greater is their contribution towards fiber-fiber bonding. The fines migrate towards the void spaces and are localized inside, imparting varying bonding and filling properties. TJ

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The authors express gratefulness to the Management of the Pulp and Paper Research Institute, Jaykaypur, for giving permission to publish this paper. Thanks are also due to M/s. Straw Products Limited for supply of samples.

Received for review Sept. 28, 1992.

Accepted Oct. 12, 1993.