Properties of Long, Short, Fine Fibres and Their Composites

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ABSTRACT:-- Strength and optical properties of individual fractions of bamboo–hard wood mixed mill pulps after bleaching, have been determined and compared with their admixtures as well as "whole". The difference in properties of long, short and fine fibres as well as whole and admixtures has been brought out. Higher strength properties of the "whole" compared to individual fractions has been explained in terms of packing mechanism and composite property. The optical properties of individual fractions have been critically examined according to lignin and ash contents in the unbleached pulp and fibre dimensions in the bleached pulp.

INTRODUCTION

Fines management in paper manufacturing has important bearing on paper machine operation and wet end chemistry (1-8). For retention of fines in fibre mats, 3 aspects need to be considered (9), hydrodynamic, colloidal and molecular. The wet web tensile index is reported to increase with fine content (10). The fibre fines retain 2-3 times as much water as coarser fibres and behave in many respect as gel (4). The surface area of fines is high (6, 11) compared to the fibre fraction (46.8 m^2/g and 9.9 m^2/g respectively). The high swelling of fines make them able to conform to the network to evenly distribute stress concentrations in the dried paper, thus providing a more uniform and stronger sheet (5, 8)

The fines can be divided as filler fines, white water fines, simulated fines and fibre fines (1). The first two fines have adverse effect on strength properties while the later two, increase the paper strength upto an addition level of ~20% in the pulp. The difference in properties of the four types of fines has been explained through a packing mechanism (1). Though both the fibre and its fines are negatively charged and fibre-fine interaction should be unfavourable, because of packing mechanism, such interaction is possible (1) resulting in increase in strength property. This paper is intended to focus further on this mechanism, bringing the composite property of pulp into picture.

Composites

The fibre fines apparently play similar role as short fibres in polymer and metal composites. Both bonding and packing mechanisms are explained to be responsible for the manifold increase in the strength properties of the composites over individual products.

In the nature, wood itself is an example of composite product where the long, short and fine fibres are embedded together with the lignin as binder. The natural composite properties in wood are gradually weakened during the digestion, washing, bleaching and refining processes of paper manufacturing. Stock preparation, surface sizing, paper

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machine and calendering operations are meant for restoring the lost natural composite property.

EXPERIMENTAL

The bamboo-hard wood mixed unbleached kraft pulp was collected from the nearby mill, producing quality paper. Bamboo to hard wood ratio is 80:20 and the mixed hard wood contained eucalyptus (tereticornis), casuarina and subabul.

The fibre classification was carried out in a Bauer McNett classifier using 16, 30, 50 and 100 mesh screens. The −100 mesh portion was transferred to a Britt dynamic jar having a screen of 200 mesh. The various fractions collected are as shown in Table 1.

The beating of pulp was made in a laboratory Valley beater. The lignin, kappa no. and ash analysis have been carried out on unbleached pulp. The individual fractions have been bleached at optimum (based on kappa no. as in the mill) and similar conditions. Hand sheets were made in a British hand sheet maker for +100 mesh fractions only as pulp with lower than 100 mesh fractions yield sheets with very poor strength. The FS factors were determined in Pulmac trouble shooter (Model TS-100; made in USA).

The scattering (SC) and absorption coefficients (AC) have been calculated using Eqns. (1) and (2):

$$SC = \frac{1}{W\left(\frac{1}{R} - R\right)} \ln \frac{(1-Ro-R)}{(1-Ro/R)} \quad (1)$$

$$AC = SC \frac{(1-R)^2}{2R} \quad (2)$$

where R= reflectance factor with sheets of same pulp as backing;

Ro= reflectance factor with single sheet having a black backing;

W= substance in gsm.

The reflectance measurements were made in an Elrepho brightness tester.

RESULTS AND DISCUSSION

Classification

The fibres have been classified (Table 1) as long (L-I, L-II), short (S-I, S-II), fine (F-I, F-II, F-III), composite admixtures (CA-I to CA-VI) and composite whole (C-W). Microscopic examination of the different fractions showed (Table 2) that the fines contain cellulosic debris, ray cells, parenchyma cells, tracheids and vessel elements (1). The average fibre length of L-I is 2.01 mm with 13.7 μ of fibre diameter while for S-II, the fibre length is 0.67

Table-I

Fractions taken for study

Classification of fibres	Abbreviation used	Mesh size (no.)		μm	
Long	L-I	-16,			+1190
Long	L-II	-16,	+ 30	-1190,	+595
Short	S-I	-30,	+50	-595,	+297
Short	S-II	-50,	+100	-297,	+149
Fine	F-I	-100,		-149	
Fine	F-II	-100,	+200	-149,	+74
Fine	F-III	-200,		-74	
Composite admixture	CA-I	95% of L-I	+ 5% of F-I		
Composite admixture	CA-II	90% of L-I	+ 10% of F-I		
Composite admixture	CA-III	85% of L-I	+ 15% of F-I		
Composite admixture	CA-IV	95% of L-II	+ 5% of F-I		
Composite admixture	CA-V	90% of L-II	+ 10% of F-I		
Composite admixture	CA-VI	85% of L-II	+ 15% of F-I		
Composite whole	C-W	Virgin pulp (without separation).			

Table-II

Fibre dimensions of long and short fibre fractions

Fraction	Fibre length (mm)		Fibre diameter (μm)	
	Range	Average	Range	Average
L-I	1.66 - 2.2	2.01	16.7 - 9.1	13.7
L-II	1.1 - 2.0	1.96	14.2 - 6.8	10.4
S-I	0.67 - 1.3	0.92	13.6 - 4.5	7.7
S-II	0.49 - 0.85	0.67	9.1 - 4.4	7.4

Table-III

Bauer McNett classification of unbleached mill pulp

Fibres	% Retained	
	Initial	70°SR
L-I	32.2	4.7
L-II	26.3	30.2
S-I	11.5	16.7
S-II	6.7	12.8
F-I	23.3	35.8

mm and diameter is 7.4 μm. There is overlapping of L-I and L-II but the distinction between long and short fibres is obvious. The aspect ratio of L-I is 146.7 while it is 90 in S-II. The long fibre fraction, L-I is severely effected (Table III) on beating for longer period; it is lessened by 6 times at 70°SR compared to the initial pulp.

Kappa Number

The kappa numbers of long, short and fine fractions are shown along with that of whole (C-W) in unbleached pulp in Table IV. The kappa number of C-W is 23.3. As it consists of all the individual fractions, this value fairly represents the average of individual fractions. It is observed that the kappa number increases with decrease in fibre size; it is 17.6 in L-I while it is as high as 26.5 in F-III. L-II has the lowest kappa no. of 15.3. As lignin content = 0.15 X kappa number, it is obvious that fines have higher lignin contents than the long and short fibres.

Table-IV

Kappa number for different fractions

Fibre	Kappa number
C-W	23.3
L-I	17.6
L-II	15.3
S-I	18.2
S-II	22.5
F-I	22.6
F-II	24.5
F-III	26.5

Lignin

Lignin contents of various fractions are presented in Fig. 1; C-W has 3.75% of lignin which is fairly average values of different fractions. F-III (-200 mesh fraction) contains 5.1% of lignin while L-I has about half of this value i.e. 2.84%. Like the kappa no., L-II has least amount of lignin.

Ash Content

The ash contents in different fractions (Fig.2) also follow similar trend as the kappa number and lignin; 2.7% in C-W while it is 1.9% in L-I and 5.3% in F-III, least being in L-II. The ash contains normally SiO_2 and trace metal Fe, Cu, Mn, Ca, Mg, Na and K. The fact that the levels of both lignin and ash increase with decrease in fibre size, it is probable that the lignin and ash are located together or the metals may be bonded to the lignin part. It is also possible that the individual fine fractions

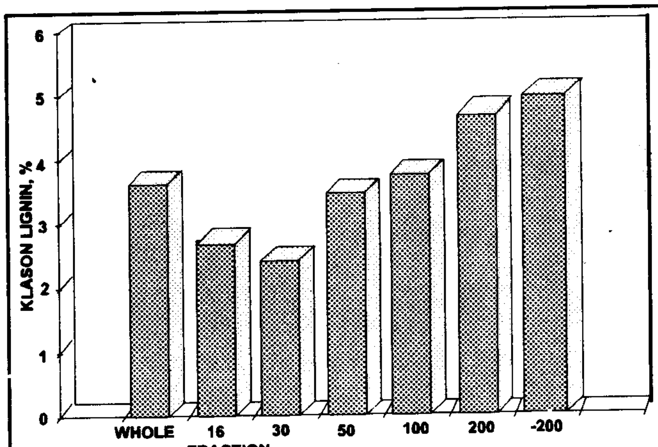

Fig.1: Lignin content of different fractions and whole.

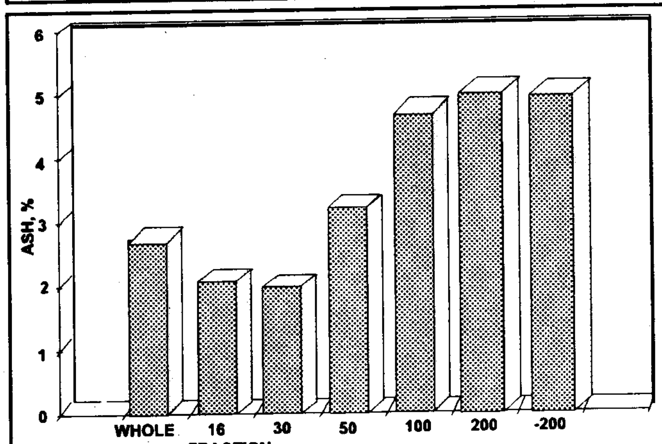

Fig.2: Ash content of different fractions and whole.

contain more of lignin because of redeposition of lignin released during the cooking process (12).

Bleaching

The bleaching characteristics of long, short and fine fibres as well as composite (whole) are also variable (Table V). The total Cl_2 consumed in optimum bleaching condition (Table VI) in C-W is 8.4% while it is 4.8% in L-II and then goes on increasing with decrease in fibre dimensions; in F-III it is 9.2%. The total Cl_2 demand corresponds to the lignin content (Fig. 1). The composite product has Cl_2 consumption which represents fairly average of the individual fractions i.e. 4.8 to 9.2%. The total Cl_2 consumption has been fixed to 9.2% in similar condition (Table VII). The loss of fibres during bleaching for L-I is 5.8%; for L-II, 5.5%; for S-I, 7.5% and for S-II, 10%.

Fines are thus difficult to be bleached requiring higher chemical dosing than that of long and short fibres. However, the composite product (CW) of these combinations has comparatively low lignin and ash contents.

Table-V

Bleaching conditions

Particulars	Chlorination	Extraction	Hypo addition
Temperature (°C)	Ambient	55	40
Retention (hr)	0.75	1.5	4
Consistency (%)	3	10	10

Table-VI

Bleaching characteristics in optimum conditions

Particulars		C-W	L-I	L-II	S-I	S-II	F-I	F-II	F-III
Chlorination									
Cl_2 added	(%)	6	4.5	4	4.5	6	6	7.5	8.5
Cl_2 consumed	(%)	5.52	4.32	3.84	4.36	5.88	5.86	7.15	7.75
Final pH		2	2.2	2	1.8	1.8	2.5	3.1	3.2
Extraction									
Alkali added	(%)	2	1.5	1.33	1.5	1.5	2	2.5	2.8
Final pH		10.8	10.8	10.6	10	10.1	11.0	10.6	10.9
Hypo									
Hypo added (as Cl_2)	(%)	3	1.5	1	1.5	1.5	1.8	1.5	1.5
Final pH		8.3	8.2	8.5	8.3	8.4	8.5	8.8	8.6
Cl_2 consumed	(%)	2.9	1.35	0.92	1.37	1.36	1.72	1.48	1.45
Total Cl_2 consumed	(%)	8.42	5.67	4.76	5.73	7.24	7.58	8.63	9.20

Table-VII

Bleaching characteristics in similar conditions

Particulars		L-I	L-II	S-I	S-II	F-I
Chlorination						
Cl_2 added	(%)	4.5	4	4.5	6	6
Cl_2 consumed	(%)	4.32	3.84	4.36	5.88	5.86
Final pH		2.2	2	1.8	1.8	2.5
Extraction						
Alkali added	(%)	1.5	1.33	1.5	1.5	2
Final pH		10.8	10.6	10	10.1	11.0
Hypo						
Hypo added (as Cl_2)	(%)	1.5	1	1.5	1.5	1.8
Final pH		8.2	8.5	8.3	8.4	8.5
Cl_2 consumed	(%)	1.35	0.92	1.37	1.36	1.72
Total Cl_2 consumed	(%)	5.67	4.76	5.73	7.24	7.58

Table-VIII	
Brightness of unbleached pulps at different freeness	
Freeness (^{0}SR)	Brightness (% El)
Initial (15)	26.3
20	24.8
30	24.5
40	24.1
50	23.7

Optical Properties

The brightness of unbleached pulp decreases with increase in freeness (Table VIII) which can be correlated to the total fine content and lignin (Fig. 1) in the pulp.

The optical properties of the long, short and C-W fibres at optimum and similar bleaching conditions are shown in Figs. 3 to 7. The brightness values

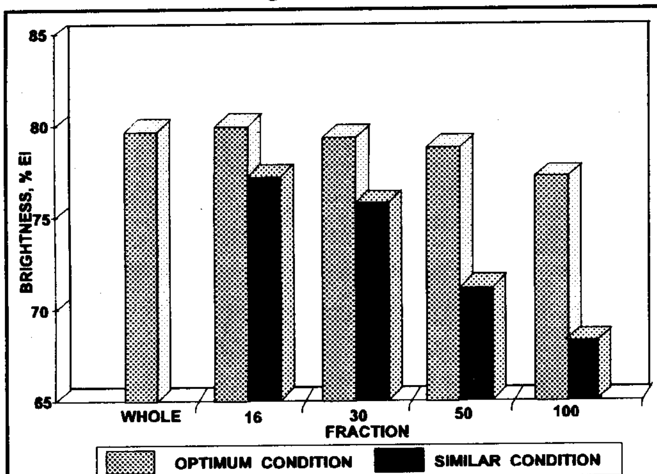

Fig.3: Brightness values of different fractions and whole in similar and optimum conditions of bleaching.

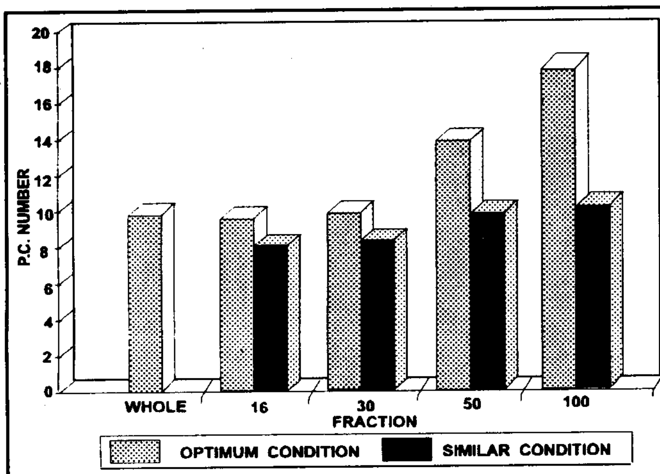

Fig.4: P.C. Number of different fractions and whole in similar and optimum conditions of bleaching.

(Fig. 3) of pulp fractions, bleached in optimum conditions are higher than that in similar conditions which are logical in view of the higher chemical dosing in case of former. The Cl_2 added in optimum conditions are based on kappa number of different fractions while in similar conditions, same amount of Cl_2 were added irrespective of kappa number. It can be seen that the whole (C-W) has fairly high brightness (80% El); the long fibres have higher brightness values than

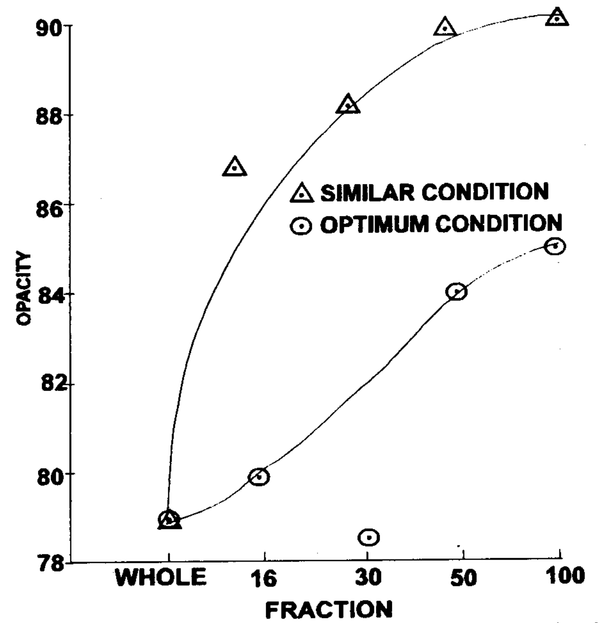

Fig.5: Opacity values of different fractions and whole in similar and optimum conditions of bleaching.

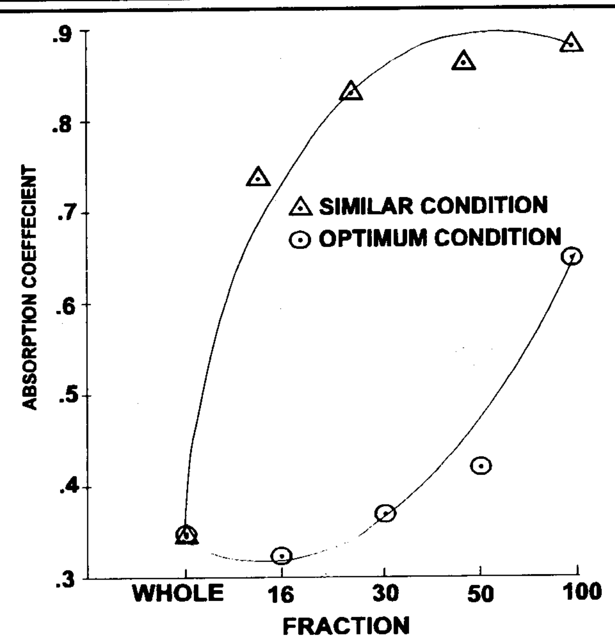

Fig.6: Absorption coefficient values of different fractions and whole in similar and optimum conditions of bleaching.

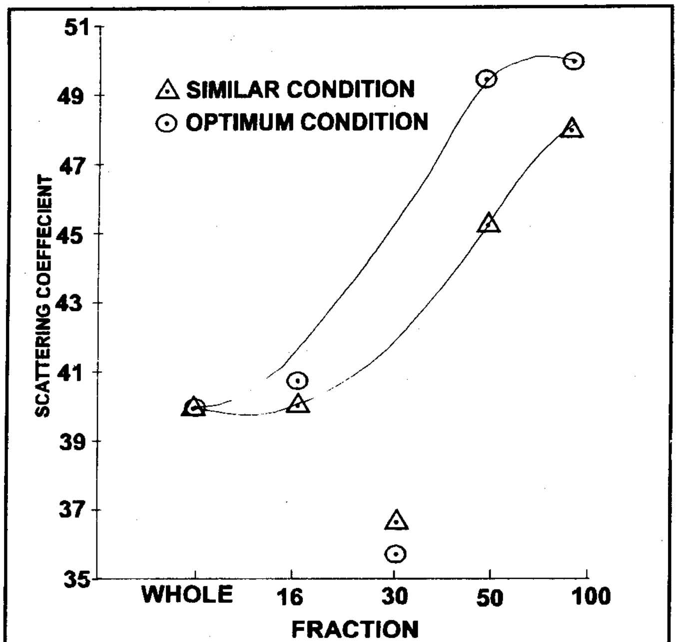

Fig.7: Scattering coefficient values of different fractions and whole in similar and optimum conditions of bleaching.

that of the short fibres. In similar condition, brightness of short fibres is only 68% El which is 76% El in L-I. The P.C. nos. (Fig. 4) show similar trend as brightness. P.C.No. of C-W (whole) is quite superior to S-I and S-II in optimum conditions of bleaching. The opacity values of pulp (Fig. 5) fractions in both similar and optimum conditions show similar trend as scattering coefficient i.e. finer the fraction higher is the opacity value. As the short fibres and fines have quite high P.C.No. compared to the long fibres, the lignin content is bound to be also high and thus opacity also becomes high. The composite product has, however, very low opacity value compared to the fractions. In view of the high tensile strength of hand sheet made from C-W, low scattering coefficient in C-W based sheet is explainable (13).

It is interesting to find that even in optimum condition of bleaching, the colour reversion property of short fibres is poor. The fact that the whole has much lower P.C.No. than that of short fibres and probably fines, the light scattering and absorption ratio of Kubelka Munk in individual fractions and in the composite cannot be conceived in the same way. It is probable that the short fibres and fines are located inside the void spaces and remain obscured to the light for scattering.

The absorption (Fig. 6) and scattering coefficients (Fig. 7) have been calculated according to Kubelka Munk theory (Eqns. 1 and 2). The scattering coefficient values given in Fig. 7 indicate in general that S-I and S-II possess higher light scattering capability than L-I and L-II. Increase in scattering coefficient with refining or freeness has been reported earlier (14). As the surface area (2) is more in short fibres than in long fibres, the scattering coefficient values of short fibres are more than that of long fibres (15, 16). The values of L-II fractions are low as the lignin content was lowest here but higher amount of chemical dosings were made. As the chemical dosing was less severe in similar condition, the scattering coefficient is lower than that in optimum conditions. The C-W sample contains fibres of all sizes which may not be favourable to exhibit superior light scattering property. The absorption coefficient values in pulps of similar conditions are more than that in optimum condition.

Strength Properties

The strength properties of hand sheets prepared from bleached pulps of optimum and similar conditions are given for different fractions in Table IX and X respectively. The bulk values of hand sheets in similar conditions are lower than that in optimum conditions of bleaching because of higher chemical dosings in case of later. The bulk values have in general increased with decrease in fibre size. However, the bulk value (2.04 cc/g) of C-W is higher than the individual fractions.

Table-IX

Strength properties of hand sheets from pulps bleached in optimum conditions

Property		C-W	L-I	L-II	S-I	S-II
Bulk	(cc/g)	2.04	1.8	1.96	1.67	1.94
Burst index	(kPa-m²/g)	1.02	0.48	0.42	0.62	0.57
Tear index	(mN-m²/g)	9.37	3.46	4.38	2.34	1.93
Tensile index	(Nm/g)	25.62	12.07	13.35	15.07	14.98

Table-X

Strength properties of hand sheets from pulps bleached in similar conditions

Property		C-W	L-I	L-II	S-I	S-II
Bulk	(cc/g)	2.04	2.46	1.42	1.59	1.72
Burst index	(kPa-m²/g)	1.02	0.57	0.51	0.73	0.68
Tear index	(mN-m²/g)	9.37	6.42	3.59	2.26	1.73
Tensile index	(Nm/g)	25.62	12.74	10.76	15.26	14.2

The values of burst index, tear index as well as tensile index (Table IX and X) indicate that the strength properties of the hand sheets made from C-W pulp are higher than that from the individual fibre fractions; the tensile index in C-W is 25.62 Nm/g which is higher than that of the individual fractions. The reason for higher strength in the C-W may be explained in terms of the packing mechanism from where the term "composite" could be conceived (1). Mixtures of long, short and fines are required for close-packing resulting in high strength properties. When fibres of one size are present, the packing criteria are poor as considerable number of voids can be present in the network. On the other hand, in the C-W pulp, the packing is optimum and minimization in void space occurs which are ideal conditions for strength properties.

In order to examine the effect on addition of fines to the long fibre fractions L-I and L-II, hand sheets have been prepared (Table XI and XII) with 5, 10 and 15% of fines (CA-I to CA-VI). The pulps here had been bleached in similar conditions. The bulk values of CA are higher than C-W and individual fractions. However, there is no improvement in strength properties on addition of fines to the long fibres. Thus the combination of long and fine fibres is also not ideal for achieving optimum strength properties in the pulp and the composite property, contributed by all the individual fibres as in C-W stands ideal.

The fibre strength properties (Table XIII and XIV) being dependent upon the fibre length, FS factors of L-I and L-II are more than that of S-I and S-II. Hand sheets made from pulp prepared under similar condition have higher FS factors than in optimum condition. Chemical dosing is thus important for the fibre strength. The composite admixture pulp samples (Table XII) have lower FS factors than L-I and L-II.

Table-XI

Strength properties of CA hand sheets from L-I and F-I (Similar condition)

Property		CA-I	CA-II	CA-III
Bulk	(cc/g)	2.37	2.44	2.19
Burst index	(kPa-m²/g)	0.48	0.61	0.5
Tear index	(mN-m²/g)	5.29	5.11	4.32
Tensile index	(Nm/g)	11.98	13.85	11.88

Table-XII

Strength properties of CA hand sheets from L-II and F-I (Similar condition)

Property		CA-IV	CA-V	CA-VI
Bulk	(cc/g)	2.35	2.25	2.22
Burst index	(kPa-m²/g)	0.44	0.5	0.47
Tear index	(mN-m²/g)	3.19	4.35	3.52
Tensile index	(Nm/g)	11.27	12.47	10.11

Table-XIII

FS factors of hand sheets from long and short fibres

Bleaching condition	L-I	L-II	S-I	S-II
Optimum	16	16.5	8.5	11.5
Similar	24.5	23.6	19.5	13.3

Table-XIV

FS factors of CA hand sheets of pulps bleached in similar conditions

Property	CA-I	CA-II	CA-III	CA-IV	CA-V	CA-VI
FS factor	19.4	19.96	17.36	17.6	17.2	10.2

Long and Short Fibres

On examination of the strength properties in Table IX and X, it can be seen that the difference in ranges for long and short fibres are quite distinct. For L-I and L-II in Table IX, burst index values are 0.48 kPa-m^2/g and 0.42 kPa-m^2/g while for S-I and S-II, these are 0.62 kPa-m^2/g and 0.57 kPa-m^2/g; the corresponding tensile index values are 12.07 Nm/g and 13.35 Nm/g for L-I and L-II while it is 15.07 Nm/g and 14.98 Nm/g for S-I and S-II; the tear index are 3.46 mN M^2/g and 4.38 Nm m^2/g for L-I and L-II and 2.34 mN m^2/g and 1.93 mN· m^2/g for S-I and S-II. The values of L-I and L-II are quite close and similarly between S-I and S-II. The same is true in Table X also. The strength properties of fines are not given as the hand sheets from F-I, F-II and F-III, could not be prepared because of poor strength.

Composite Property

The fines (Table XI, XII) have been able to increase the strength properties of L-I but not of L-II; the maximum being at 10% addition, though increase is observed even on addition of 15% of fines also. However, the highest values of strength properties are found in the "whole" which is composite product of all fractions. Thus the superior strength properties can be attributed to the composite property.

It was shown previously (1) that filling-up of the voids in the fibre network with fibre fines forming close packing comes into existence. As the short fibres and fibre fines are not tenacious, these can easily reside inside the voids over the long fibre surfaces. The close packing in the voids by the fines as well as short fibres brings in reinforcement in the strength of long fibres. The strength of long fibres alone is not spectacular, neither for short fibres but when short and fine fibres are incorporated, the tensile strength of long fibre increases similar as in composite materials. The tensile strength of the composite can thus be expressed as:

$$T_{CW} = T_L + T_S + T_F \qquad (3)$$

which is higher than any one of the individual fractions and

$$T_{CW} > T_{CA} \qquad (4)$$

indicating that the composite property is due to combination of all the 3 varieties of fibres i.e. long, short and fine. Each fibre fraction possesses both fibre strength and bonding capacity. Many theories on tensile strength of paper have been advanced (17-21) till recently (22). It has been correlated to the properties of both fibres and bonding (17) as:

$$\frac{1}{T} = \frac{1}{F} + \frac{1}{B} \qquad (5)$$

where T= Tensile strength of strip, F= Index for resistance of fibres to breakage, B=Index for resistance of bonds to breakage.

It can be seen in the SEM micrograph (1) that both breaking and pulling of fibres occur during fracture of a paper sheet. However, in either cases, the fracture is apparently at the ends of fibres or at the joints between two fibres (the fibres may be the fines or short fibres also).

The nature in fibre arrangement is described to be random (19). Zero span tensile strength is correlated to be the product of fibre tensile strength and proportion of fibres bearing load (18). The tensile strength is also shown (20, 21) to be a function of RBA (relative bonded area). These theories may probably be reexamined correlating tensile strength with the 3 types of fibres, out of which the fines are unique in their bonding capability (1). In the present work, the high tensile strength of the "whole" is conceived to be due to the composite property attributed by the short and fine fibres to the long fibres.

CONCLUSIONS

Fibres in pulp can be classified as long, short and fines. The fines in the unbleached pulp contain higher amount of lignin and ash as well as kappa number than the long and short fibre fractions. The bleaching chemical requirement of fines is more than the other fractions. The fines from bleached pulp have comparatively lower brightness and higher P.C.no. than in other fractions. However, the fines have better light scattering property and opacity values than long and short fibre fractions.

The composite (whole) pulp has the optimum strength because of composite property, imparted due to blending of all the 3 categories of fibres i.e. long, short and fines. The hand sheet from composite pulp possesses about double the tensile index values (25.62 Nm/g) than that of the individual fractions (12-15 Nm/g).

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