Multilayered paperboard from kraft pulp and TMP

Z. Koran and D. P. Kamdem

Professor and graduate student, Pulp and Paper Research Center, Universite du Quebec a Trois-Rivieres, C.P. 500 Trois-Rivieres, Que., Canada G9A 5H7

ABSTRACT *Multi-ply paperboard (120 g/m²) was made by the centrifugal dynamic former from various blends (0–100%) of kraft pulp and TMP in one, two, and three layers. The physical properties of the multi-ply construction changed as TMP was incorporated into the paperboard furnish in a laminated structure.*

The highest machine-direction rigidity (8 mN·m) was recorded for the three-ply construction in a blend of 15% kraft, 70% TMP, and 15% kraft. For a single-ply kraft sheet, the maximal rigidity was obtained for the jet–wire speed difference of 400 m/min. Other strength properties changed correspondingly as a result of lamination and a change in the ratio of jet speed to wire speed. These results have industrial implications concerning fiber economy and improved product quality.

KEYWORDS
Flexural stiffness
Formation
Paperboards
Physical properties
Strength properties

Multilayered paperboard has traditionally been made using bleached and unbleached kraft pulp in the face and back layers, respectively, and a material of lower cost, such as stone groundwood (SGW), in the intermediate layer (*1*). The aim in this type of construction was to develop equal or better paperboard performance at an appreciably lower furnish cost as a result of an increase in pulp yield. It is with this principle in mind that various researchers have introduced into the paperboard furnish the various types of high-yield pulps, including SGW (*1*), CTMP (chemithermomechanical pulp) (*2*), TMP (thermomechanical pulp), and possibly hardwoods (*3*). As a result of these experimentations and promotional efforts, the production of multi-ply paperboard is now an industrial reality. At West Point, Va., for example, the Chesapeake Corp. now operates a multi-ply machine involving three different fourdriniers (*4*). This machine is essentially making three separate sheets of paper and combining them wet together into a tri-kraft paperboard.

The physical properties of the various multi-ply configurations have been studied by a number of researchers (*5–9*). The most important properties included burst, tear, fold (*10*), tensile strength (*5, 10*), compressive strength (*1, 11*), ring crush strength (*1*). Flexural rigidity is the center of attention (*1, 5, 6, 10–14*) because it was identified as the principal property responsible for the stacking strength of containers. It is a fortunate coincidence that the flexural stiffness is the unique property that can be best developed in a multi-ply configuration.

The specific objective of our research was to work towards the development of superior flexural stiffness in paperboard through the construction of various multi-ply configurations produced out of kraft pulp and TMP in various proportions and at varying ratios of jet and wire speeds.

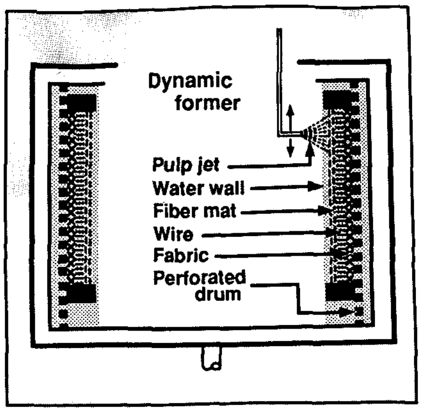
Experimental procedures

In the first part of this study, single-ply paperboard (120 g/m²) was produced from pure kraft pulp (700 mL CSF; 60% yield) by a centrifugal dynamic former (**Fig. 1**) that was described in detail elsewhere (*15–17*). In this study, the jet speed was kept between 1250 m/min and 1350 m/min, while the drum speed was varied from 910 m/min to 1600 m/min to yield various speed differences up to a maximum value of 400 m/min. These conditions enabled us to form paperboard possessing various degrees of preferential fiber orientation in the machine direction (MD).

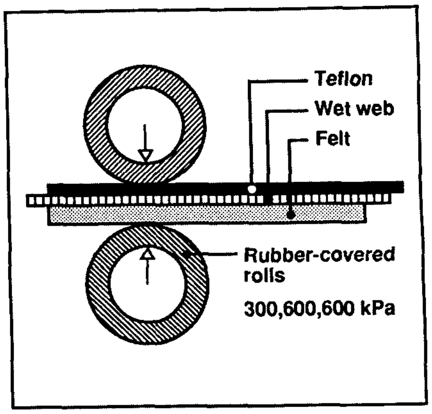
After its formation, the wet sheet (21.3 cm × 88.6 cm) was placed felt-side down on a piece of fabric with a sheet of Teflon on top of it. The sandwich was passed three times (at a speed of 4.5 m/min) between two medium-hard rubber rolls at 300, 600, and 600 kPa of pressure successively (**Fig. 2**). The fabric was then removed, and the paper was dried at 100°C for 2 min in the dryer (**Fig. 3**) furnished with the dynamic former. The sheet of Teflon was then removed, and the paper was left on the dryer at 100°C for another 5 min before being placed in a conditioning chamber at 23°C and 50% RH (relative humidity). According to Glynn *et al.* (*18*), this drying procedure produces a minimum degree of curl for a randomly oriented sheet.

In the second part of this study, multilayered paperboard was prepared from two types of pulp, including bleached kraft pulp (700 mL CSF; 60% yield) and thermomechanical pulp (*19*) with the aid of the centrifugal dynamic former (*16*) in four different structural configurations (**Fig. 4**). For each one of these sheet configurations, the TMP content was varied from 0% to 100%, while the basis weight (120 g/m²), jet speed (1325 m/min), wire speed (1350 m/min), and the wet pressing and drying conditions were kept constant. The various paperboards were then conditioned and tested according to recommended methods.

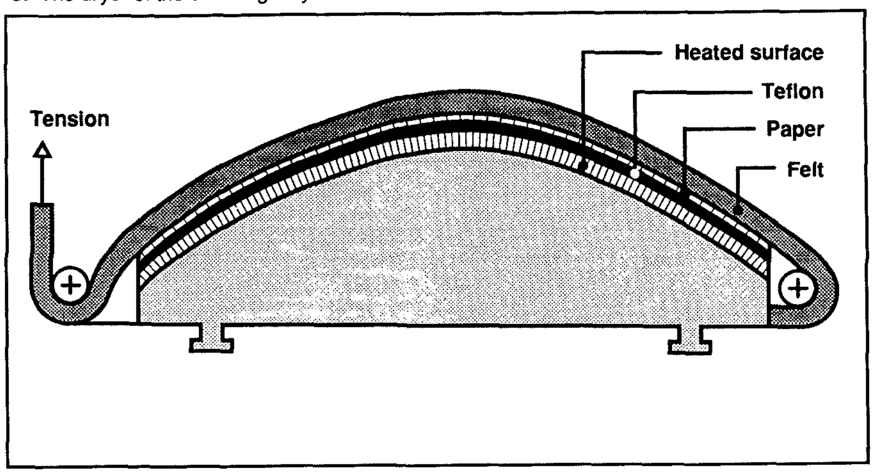
1. A diagram of the centrifugal dynamic former used



2. Wet pressing of the experimental paper



3. The dryer of the centrifugal dynamic former



Discussion

Effect of the ratio of jet speed to wire speed

The physical properties of the single-layer paperboard (120 g/m²) produced at various ratios of jet speed to wire speed are summarized in **Table I** and are plotted in **Fig. 5**. For breaking length, for example, an increase in the jet-to-wire speed ratio from 1.0 to 1.4 produces a significant increase in the MD tensile strength and a corresponding decrease in its CD value (cross-machine direction). An identical increase is evident when the jet-to-wire ratio is reduced by the same amount from 1.0 to 0.6. Thus, from the point of view of strength anisotropy, it does not matter which one is greater, the jet speed or the wire speed; the controlling factor remains the magnitude of the jet-to-wire speed ratio, or the difference in speed.

The changes in breaking length can be quantified by a mirror image on the two sides of the vertical line drawn through the jet-to-wire speed ratio of 1.0. Another mirror image can also be identified on the two sides of the horizontal line that intercepts the y axis at a breaking length of 8.5 km. Thus, an increase in the MD tensile strength corresponds to a proportional decrease in the CD tensile strength.

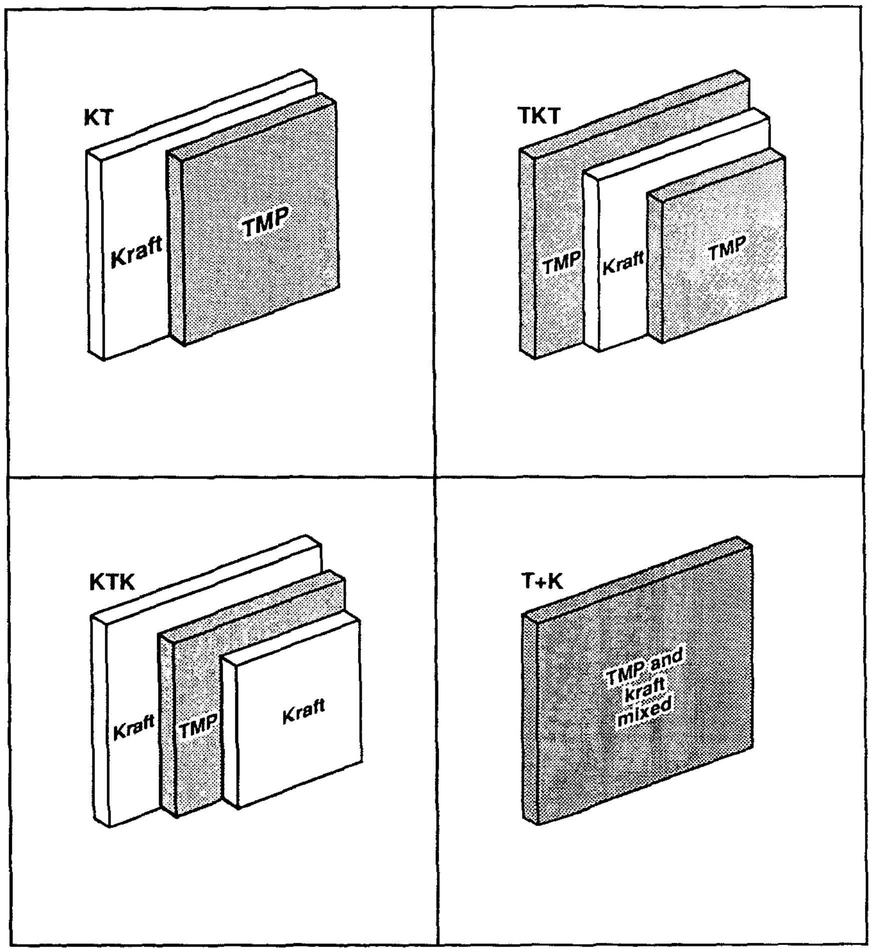
Similar relationships exist for flexural stiffness and tear resistance (Fig. 5). The horizontal line intercepts the y axis at 2.8 mN·m in the case of stiffness and at 13 mN·m²/g for the tear strength. These symmetries show that at any given jet-to-wire ratio, a superior strength property in the machine direction is produced at the cost of a proportional reduction in CD strength. This approach could serve useful in the case of a specific product for which superior strength property is required only in one direction.

The changes observed in flexural stiffness, breaking length, tear resistance, burst strength, stretch, and elastic modulus as a function of the jet-to-wire speed ratio can be attributed to the preferential alignments of many fibers in the machine direction. The greater the jet-to-wire speed ratio, the greater will be the anisotropy of the sheet with respect to fiber orientation.

The influence of lamination

One way to produce improved unidirectional stiffness in paperboard is through a change in the jet-to-wire speed ratio. Another way to achieve the same objective is through the construction of laminate structures out of different types of pulps. Thus, in this study, four types of layered configurations were constructed out of kraft pulp (K) and TMP (T), and these were identified as KT, KTK, TKT, and T+K composites, as shown in Fig. 4. In the T+K configuration, the single-layered paperboard (120 g/

4. Diagram of paperboard (120 g/m²) made with the dynamic former of TMP (T) and kraft (K) pulp in three layers (KTK and TKT), two layers (TK), and in a single layer (T+K). The T+K paperboard was made of identical proportions of TMP and kraft pulps blended to form the control structure.



m²) was formed from various blends of kraft pulp and TMP. This paperboard, in fact, was intended to serve as a control, to show the differences in properties between the single-ply and multi-ply constructions at identical kraft/TMP blends, ranging from 0% to 100% kraft content.

The physical properties of the multi-ply structures are summarized in **Table II** and are plotted in **Fig. 6** as a function of kraft pulp content. This figure shows that for each paper board, the values for the MD properties average 2.5 times greater than those for the corresponding CD properties at each percentage of kraft content. This phenomenon was attributed to the preferential orientation of fibers in the machine direction (*17*). The figure also shows that the elastic modulus increases from 2750 mPa for pure TMP to 5650 mPa for pure kraft pulp. This increase yields a 2-fold increase in the machine direction and increases the CD values by a factor of 2.8.

Among the four paperboard configurations, the highest elastic modulus curve was obtained for the single-layer structure (Fig. 6) produced from various blends of kraft pulp and TMP, while the lowest curve was produced for the TKT configuration. The superior elastic modulus of the K+T structure over that of the KTK configuration can be attributed to improved fiber bonding, which in turn is due to an 8% increase in the density of paperboard itself (Table II).

In contrast to the elastic modulus, an increase in kraft pulp content from 0% to 100% exhibits a maximum in the flexural stiffness of paperboard in both the machine direction (1.8 times) and cross-machine direction (1.4 times), as shown in Fig. 6, although a 100% kraft pulp sheet has significantly lower flexural stiffness than the TMP sheet. In the middle part of the graph, the four curves separate, and the KTK configuration yields the highest stiffness values at each percentage of kraft pulp content. The figure further shows that the peak stiffness of 8 mN·m is obtained at a pulp composition of 15K/70T/15K. This is the configuration in which the central TMP layer (70%) is sandwiched between two thin layers (15%) of kraft pulp. Even a 100% TMP furnish consisting of stiff mechanical pulp fibers yields an MD rigidity value of only 7 mN·m.

The superior flexural stiffness of the 15K/70T/15K composite over the three other structures can be attributed to its structural configuration, where the high-bulk core TMP (70%) is sandwiched between two thin layers of high-strength kraft pulp. The thin layers are well situated to withstand the maximal compressive and tensile stresses, respectively, on the upper and lower surfaces of the paperboard when it is subjected to bending stresses. At the same time, the thick central layer of TMP attributes the necessary bulk to the three-ply structure.

Sheet bulk is an important geometry factor, since the flexural rigidity (S) of a homogeneous sheet is directly proportional to the third power of the sheet thickness (t^3) in the definition of its flexural stiffness (*14*):

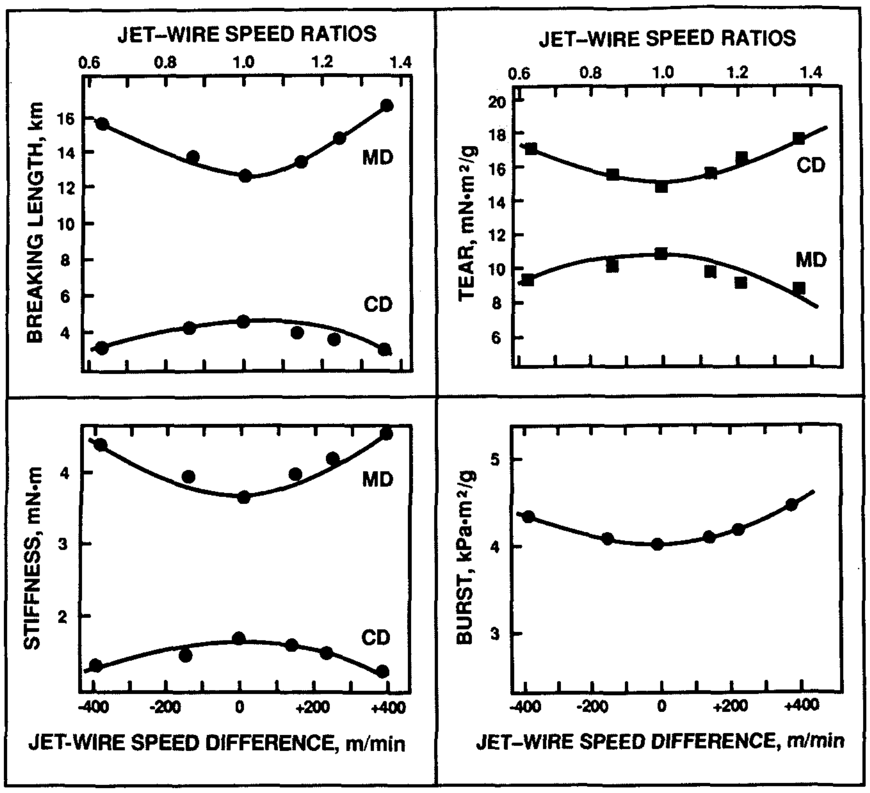
$$S = EI/a = Et^3/12 \quad (1)$$

where

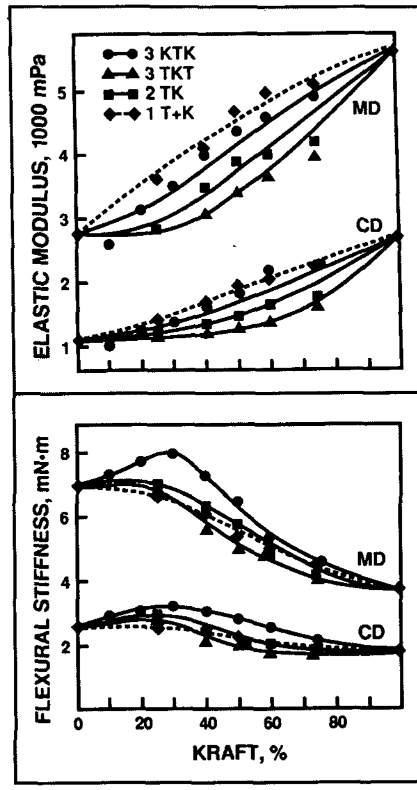
I = moment of inertia, m⁴
= $at^3/12$
t = sheet thickness, m
a = sheet width, m
E = elastic modulus, Pa, or N/m²
S = flexural stiffness, mN·m.

Even in the opposite TKT construction, the contribution of TMP (70%) to bulk is unchanged. However, the high-strength kraft layer (30%) is now sandwiched in between two TMP layers (35% each), thus occupying the low-stress core region on the two sides of the stress-free neutral plane. Therefore, its capacity to contribute to flexural stiffness is greatly reduced, simply because of its geometric location. This, in fact, is the reason that a 28% reduction can be observed in the flex-

5. Strength properties of single-layered paperboard (120 g/m², 0.6 g/cm³) made by the dynamic former at various jet-to-wire speed ratios from pure kraft pulp at 700 mL CSF and 60% yield



6. The effect of kraft pulp content on the rigidity and elastic modulus of paperboard (120 g/m²) made of various proportions of kraft pulp (700 mL CSF) and TMP (120 mL CSF)



I. Physical properties of paperboard (120 g/m²) made from kraft pulp (700 mL CSF) with the centrifugal dynamic former at various speed ratios

Speed, m/min						
Jet	1325	1250	1250	1325	1350	1300
Wire	925	1000	1100	1325	1500	1700
Difference	+400	+250	+150	0	-150	-400
Ratio	1.43	1.25	1.14	1.00	0.90	0.76
Breaking length, km						
Machine direction	16.5	14.5	13.2	12.5	13.8	15.5
Cross direction	3.2	3.6	3.9	4.5	4.3	3.2
Stretch, %						
Machine direction	3.8	3.4	3.3	3.2	3.2	3.0
Cross direction	4.4	4.8	5.0	5.1	4.75	4.6
Burst strength, kPa•m²/kg	4.5	4.2	4.1	4.0	4.0	4.3
Tear strength, mN•m²/g						
Machine direction	8.9	9.5	10.0	11.0	10.3	9.3
Cross direction	18.0	16.8	16.0	15.0	15.8	17.0
Modulus of elasticity, mPa						
Machine direction	6890	6370	6070	5640	6000	6580
Cross direction	2030	2260	2420	2750	2330	2000
Flexural stiffness, mN•m						
Machine direction	4.60	4.25	4.05	3.76	4.00	4.39
Cross direction	1.35	1.49	1.61	1.83	1.55	1.33

ural stiffness of the TKT panel, in comparison with the KTK configuration (Fig. 6) at the same kraft pulp content (30%). (Compare with the bending stiffness analogy of I-beam steel.)

These results show that sheet lamination offers an excellent opportunity for developing superior flexural stiffness in the machine direction of paperboard. If, for example, a manufacturer's specific objective is to produce containers with superior stacking strength, greater flexural stiffness is needed in the vertical direction. This improvement could be achieved by developing superior MD rigidities in each one of the components, then assembling the combined corrugated paperboard such a way that the machine direction corresponds to the vertical direction in the finished box.

Briefly, the approach of sheet lamination implies improved product quality and economic benefits through the utilization of high-yield pulps, possibly hardwoods (*20, 21*), at reduced cost.

II. Physical properties of paperboard (120 g/m²) made from kraft pulp (700 mL CSF) with the centrifugal dynamic former at various speed ratios

	Caliper, mm	Density, g/cm³	Breaking length, km		Stretch, %		Burst strength, kPa•m²/g	Tear strength, nM•m²/g		Modulus of elasticity, mPa		Rigidity, mN•m	
			MD	CD	MD	CD		MD	CD	MD	CD	MD	CD
TKT (TMP-kraft-TMP)													
12.5-75-12.5	0.23	522	10.8	3.8	2.5	4.5	3.7	9.0	13.7	3975	1640	4.01	1.66
20-60-20	0.25	480	10.0	3.7	2.2	4.0	3.5	8.6	12.4	3620	1380	4.78	1.79
25-50-25	0.26	462	9.5	3.2	2.0	3.7	3.3	8.1	11.5	3400	1240	5.0	1.8
30-40-30	0.28	429	8.5	3.0	1.9	3.5	3.0	7.2	10.2	3100	1200	5.6	2.2
40-20-40	0.31	387	7.2	2.7	1.5	3.0	2.5	6.8	9.8	2740	1130	5.8	2.8
KTK (kraft-TMP-kraft)													
5-90-5	0.32	375	6.6	2.6	1.3	2.9	2.5	6.5	9.3	2625	1040	7.17	2.8
10-80-10	0.21	387	7.5	3.1	1.5	3.2	2.7	7.0	10.0	3166	1230	7.86	3.05
15-70-15	0.30	400	8.2	3.3	1.8	3.4	3.0	7.4	10.5	3535	1420	7.95	3.9
20-60-20	0.28	429	9.8	3.8	2.1	3.8	3.2	7.7	11.0	3970	1615	7.26	2.95
25-50-25	0.26	462	10.5	4.3	2.3	4.0	3.3	8.0	12.0	4390	1840	6.42	2.69
30-45-30	0.24	500	11.0	4.5	2.6	4.4	3.6	8.9	12.6	4590	2160	5.30	2.5
37.5-25-37.5	0.225	533	12.2	4.9	3.0	4.7	3.8	10.0	14.0	4790	2300	4.51	2.18
KT (kraft-TMP)													
75-25	0.23	521	11.6	4.6	2.2	4.1	3.6	9.5	12.5	4175	1770	4.2	1.8
60-40	0.24	500	10.5	4.1	2.0	3.7	3.3	8.4	12.0	4050	1690	4.7	1.95
50-50	0.26	462	9.7	4.05	1.7	3.5	3.2	7.5	11.3	3870	1520	5.7	2.2
40-60	0.28	429	8.5	3.3	1.5	3.2	3.0	6.8	10.5	3450	1375	6.3	2.52
25-75	0.31	387	7.5	3.0	1.3	3.0	2.8	6.4	9.6	2830	1170	7.0	2.9
T+K (TMP and kraft)													
100-0	0.20	600	12.5	4.5	3.25	5.1	4.0	11.0	15.0	5650	2750	3.76	1.86
75-25	0.22	545	11.0	4.0	3.0	5.0	3.8	10.5	13.9	5160	2240	4.58	1.99
60-40	0.23	522	10.5	3.8	2.8	4.8	3.4	10.0	13.0	4900	2090	4.97	2.12
50-50	0.24	500	10.5	3.5	2.5	4.3	3.2	9.3	12.5	4640	1920	5.34	2.21
40-60	0.26	462	9.0	3.1	2.2	4.0	3.1	8.9	12.0	4120	1680	6.03	2.46
25-75	0.28	429	7.8	2.7	1.8	3.7	2.8	7.5	11.0	3610	1390	6.65	2.54
0-100	0.31	387	5.5	2.3	1.2	2.9	2.2	6.0	8.5	2760	1090	6.85	2.53

Conclusions

In the KTK configuration, the MD rigidity of paperboard (120 g/m²) increased by 82% from 3.8 mN•m for pure kraft pulp to 6.9 mN•m for 100% TMP. An even greater increase (111%) was recorded (8 mN•m) for the 15K/70T/15K construction, showing that the 3-ply sheet containing 70% TMP in its central layer produces the highest possible flexural stiffness. In contrast, when the layering is reversed, the TKT structure produces consistently the lowest flexural stiffness at each level of TMP content. Corresponding changes could be observed in burst strength, breaking length, stretch, and elastic modulus.

MD flexural stiffness could be further increased as a result of an increase in the jet-to-wire speed ratio. For example, the MD rigidity (4.6 mN•m) was 1.2 times greater for the jet-to-wire speed ratio of 1.43 than for the jet-to-wire ratio of 1.0. Similar increases were recorded for burst strength (1.1), breaking length (1.3), stretch (1.2), elastic modulus (1.2), and tear strength (1.2).

As to industrial implications, the layering principle enables us to engineer a composite sheet with special design characteristics for specific purposes. At the same time, the three-ply structure permits us to incorporate low-cost, high-yield pulps into the central layer, while maintaining or even improving paperboard properties. The increase in overall pulp yield from about 60% to 85% implies a highly significant economic savings for the paperboard industry.□

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