Effect of Virgin Fiber Content on Strength and Stiffness Characteristics of a Three-layer Testliner

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Research results on the improvement of the strength properties of a testliner produced from recovered paper and kraft pulp are presented in this work. The effects of kraft pulp content and the fractionation of secondary fiber on testliner strength properties were determined. Primary and recovered paper pulp was produced using standard procedures. The testliner consisted of three layers, totaling a grammage of 150 g/m^2, when the center layer was made solely from the short fiber fraction of recovered paper. The weight of the surface layers each comprised 30% of the total handsheet weight, and the center layer weight was 40%. The virgin fiber content of the upper and lower layers was varied from 0% to 30% of the corresponding handsheet layer weight. The breaking length, tensile strength, modulus of elasticity, longitudinal and bending rigidity, and bursting and plybond strength, along with the effects of virgin fiber dosage on the strength properties were experimentally determined. As a result, a composition was proposed that showed the rational arrangement of virgin fibers as well as short- and long-fiber fractions of recovered paper in the layers. A comparison of the strength properties of the testliner using standard parameters demonstrated the advantages of the testliner producing technology.

Keywords: Cardboard; Recovered paper; Mechanical properties; Fractionation; Refining

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INTRODUCTION

Testliners are among the most widespread types of cardboard, and they are generally produced from old corrugated cardboard (OCC). Virgin fibers are added to the composition of a testliner to increase mechanical properties. Two of the most significant problems in testliner production are low tensile strength and low stiffness. There are two promising ways to solve these problems: using up-to-date processing methods (*i.e.*, new screening and refining systems, fractionizing, and use of efficient chemical reagents), and designing and manufacturing advanced equipment to provide multi-layer molding, extended nip pressing, and surface coatings. The most recent trend is to combine the use of efficient chemical reagents and multi-layer molding with fractionation of secondary fiber.

Binding chemical additives (specially modified starches and cationic synthetic polymers) increase strength characteristics of cardboard from 15 up to 20% (Auhorn 2001). They require sufficient dosing and careful monitoring of process conditions (*i.e.*, addition site, interoperability with other chemical additives, and neutralization of cationic demand).

Normally, these chemical additives are rather expensive. Dosing chemical additives into recovered paper stock can cause process problems.

The combination of multi-layer molding and fractionation of secondary fiber improves the cardboard macrostructure, and a decrease in the material irregularity while connecting cardboard layers in a multi-layer web. Moreover, the rational distribution of different fractions with respect to the layers is possible.

Research has been conducted on the effect of the composition and location of layers on mechanical properties of three layer handsheets (Smolin and Akselrod 1984). Figure 1, which is replotted from the cited work, shows that the best way to improve the strength characteristics of cardboard is to place the stronger semi-finished product in the top and bottom layers of tree layers handsheet. Breaking length and bursting strength considerably increased while there was little reduction in ring crush.

One of the most difficult problems is the life cycle of recovered paper. The mechanical characteristics get worse each subsequent life cycle of the recovered paper. It should be noted that neither the use of efficient chemical reagents nor multi-layer folding solve the problem of multiple life cycles.

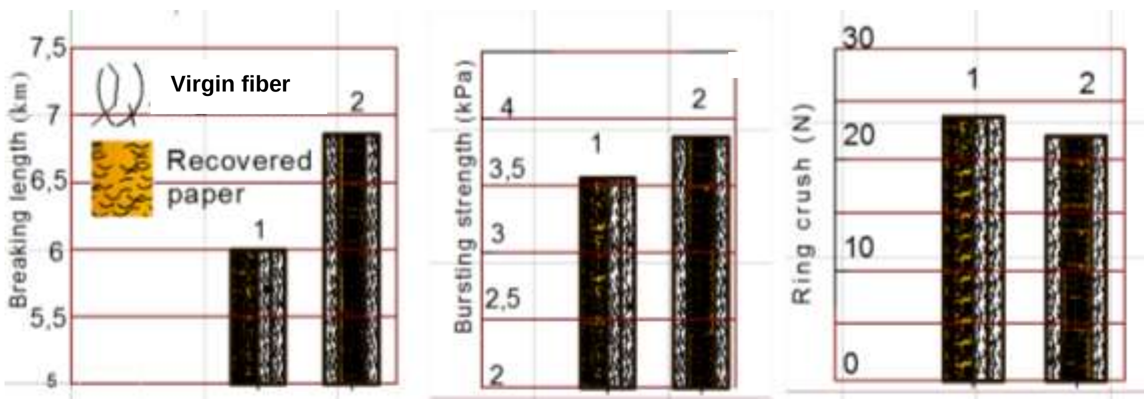

Fig. 1. Influence of different layers' location on cardboard properties (Replotted data from Smolin and Askelrod 1984).1,2 – tree layers handsheets.

The addition of unbleached kraft pulp virgin fiber into the testliner composition partially solves the problem of multiple life cycles. In such a case, the addition of virgin fiber results in a significant improvement of the strength characteristics of the testliner. Therefore, the main goal of this research was to study the influence of virgin fiber addition on the strength and stiffness characteristics of a multi-layer testliner.

EXPERIMENTAL

Materials

Recovered paper from old corrugated cardboard was used to produce the test-liners. Unbleached kraft pulp of virgin was added to the first and third layers of handsheets at various concentrations.

The experiments were carried out in the Department of Paper Technology research laboratories at the Technical University of Dresden. The flow chart of the experimental design, including all main testliner production process operations, is presented in Fig. 2. The strength and stiffness indicators of three-layer handsheets were tested.

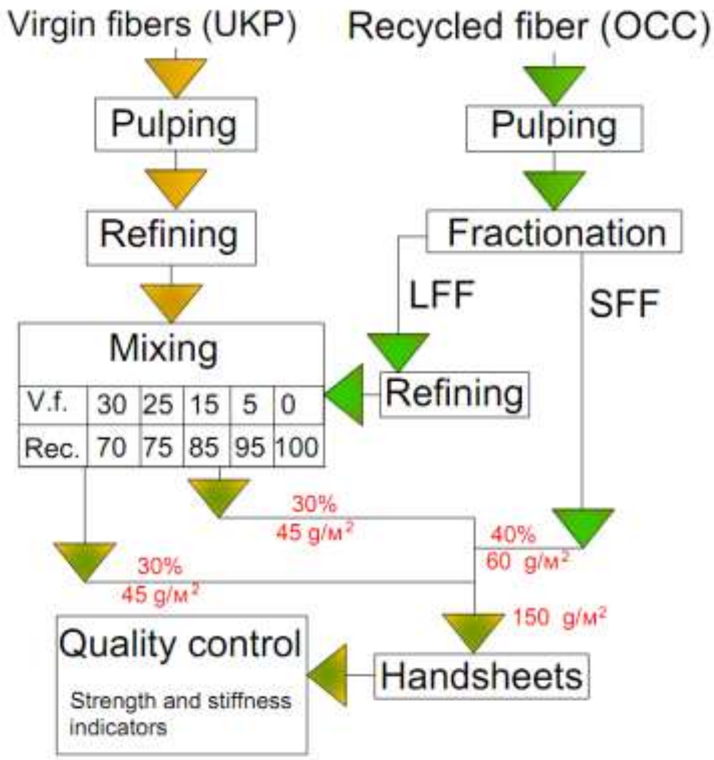

Fig. 2. Flow-chart of the experimental design. UKP- unbleached kraft pulp; LFF- long-fiber fraction; SFF- short-fiber fraction; OCC- old corrugated container pulp

Methods

Pulping and refining

The pulping of unbleached kraft pulp was carried out in a 16-L pulper at a 4% stock concentration (640 g of dry fibers). The refining was carried out in type D refining plant from Defibrator, Stockholm, Sweden. The operating parameters of the plant were 5.5 kW, 380/220 V, 50 Hz, and 2900 rpm. The refining and pulping were carried out at the same concentration and volume. The specific energy consumption of the refiner was 200 kW·h/t. The edges load setting of the cutters was 2.5 J/m. A refining time of unbleached kraft pulp was 30 s.

The old corrugated container (OCC) pulp was collected from the one of the largest retailers of consumer electronics. The recycled paper stock of OCC was pulped in a disintegrator in accordance with the standard technique ISO 5263-1 (2004). There were 20 g of the long-fiber fraction (LFF) in 1.5 L. of water. 3000 revolutions were used for the pulping of LFF. Refining of the long-fiber fraction of the recovered paper was carried out in a Jokro mill. The time of refining was 20 min. The Jokro mill speed of rotation was 150 rpm.

It was easier to use a Jokro mill than the usual refiner for LFF refining because of the low quantities of LFF. The disintegrator and fractionator yielded only 20 g of dry fiber in the course of half an hour.

The parameters of refining with the different specific energy consumption of refiner and pace of refining in Jokro mill with the different time of grinding will be published in a subsequent article. The final properties of the stock are displayed in Table 1.

Table 1. Final Parameters of Fibers and Stock

№	Parameters of fibers and stock	Unbleached kraft pulp stock	Long fiber fraction of recovered paper stock
1	Fiber length: *L*(n), mm	0.92	0.57
2	*L*(l), mm	1.87	1.09
3	*L*(w), mm	2.51	1.68
4	Fines(n), %	2.15	27.22
5	Fines(l), %	3.14	5.01
6	Refining degrees, °SR	25	30.5
7	Water retention value, %	58.94	141

The degrees of refining and the water retention value were determined in accordance with the standard techniques ISO 5267-1 (2001) and DIN 53814 (1974). The parameters of fibers, and the length and quantity of fines were determined by a Kajaani Fiber Length Analyzer (Kajaani Fiber Lab, Metso Automation; Finland).

Fractionation

The fractionation of recycled paper was carried out in a fractionator (Haindl-Fraktionator, Einlehner; Kissing, Germany). Two fractions of fibers (fiber length of up to and above 1 mm) were obtained by installing screen No. 30 in the first stage and screen No. 100 in the second stage. In the third stage, screen No. 200 was used to collect the fines (fiber length less than 1 mm).

The average fiber length was determined using a Kajaani Fiber Length Analyzer (Kajaani Fiber Lab, Metso Automation; Finland) from samples harvested at processing times of 0, 10, and 20 min. Afterward, the short-fiber fraction (SFF) and long-fiber fraction (LFF) were preserved for handsheet molding.

Handsheet molding

Unbleached kraft pulp fibers, as well as long- and short-fiber fractions of recycled paper, were used to produce the testliners as three-layer handsheets (Fig. 5). The two outer layers of the handsheets (Fig. 3, (1) and (3)) contained the virgin fibers and the long-fiber fraction of recycled paper. The inner layer (Fig. 3, (2)) was composed of the short-fiber fraction with fiber size of less than 1 mm. The unbleached kraft pulp was dosed in outer layers (1) and (3) in the range from 0% up to 30% of the layer stock content.

Layer 1 was molded and pressed according to ISO 5269-2 (2004) without drying (Fig. 3). Layer 1 together with coating cardboard 1 was combined with the layer 2 on the forming mesh, and then pressed and removed from the mesh. The result of the second stage was the combined coating cardboard 1, layer 1 of LFF of recovered paper and UKP, and layer 2 of SFF of recovered paper. This two-layer composition in combination with coating cardboard 1 was used in stage 3.

The coating cardboard 1, layer 1 and layer 2 were combined with layer 3 in the final stage 3. The composition of layer 3 and the composition of layer 1 were similar. The three layers were pressed on the forming mesh of the sheet-making machine. Then the combination of layers and coating cardboard 1 was removed from the mesh. The composition was covered with coating cardboard 2. The obtained three-layer handsheet covered with coating cardboards 1 and 2 were dried in the sheet-making machine dryer.

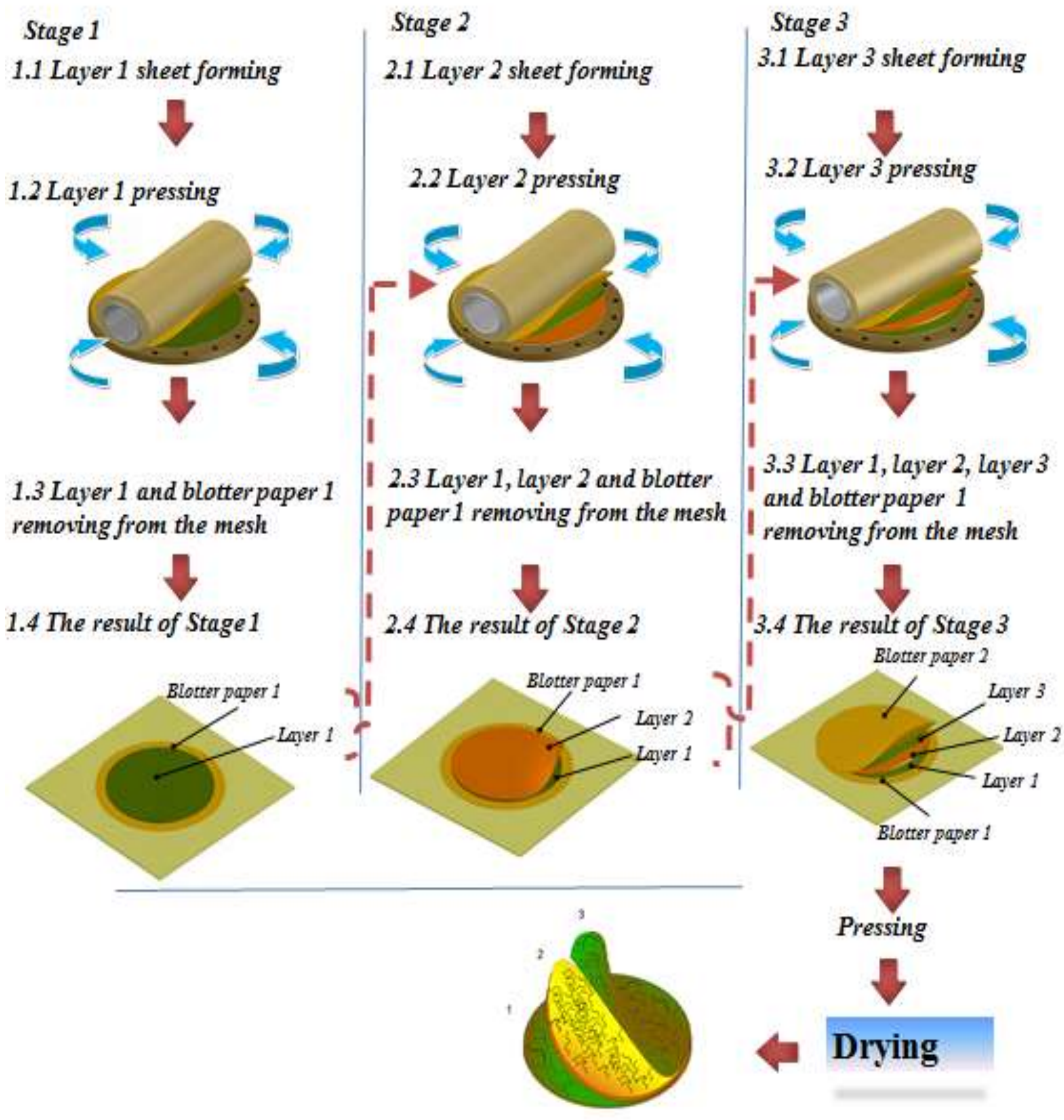

Fig. 3. Method for producing the three-layer handsheet (150 g/m^2), weight distribution 30 - 40 - 30 (%): (1) and (3) are the outer layers containing the long fiber fraction with unbleached kraft pulp; and (2) is the middle layer containing 100% short fiber recycled paper

Measurement of handsheet mechanical characteristics

The primary mechanical characteristics of the three-layer handsheets were measured in the paper and cardboard quality control laboratory using the standard instruments according to ISO and DIN methods. The breaking length, ultimate rupture strength, modulus of elasticity, and longitudinal stiffness were determined by a Lorentzen and Wettre Tensile Tester (SE 062/064, Kista, Sweden) according to national standards DIN 53112 (1981-10) and ISO 1924-2 (1994). The bending stiffness was determined by a

Lorentzen and Wettre Bending Tester (SE 114) according to ISO 2493 (1992). The bursting strength was determined by a Lorentzen and Wettre Bursting Strength Tester (SE 002) according to ISO 2758 2001. All the tests including bursting strength were conducted on the three layer handsheets. The configuration of layers in all handsheets was according to Fig. 3.

Samples were held in a test laboratory for 7 to 10 days before evaluation. The temperature in the laboratory ranged from 21 °C up to 23 °C. The relative humidity of laboratory air ranged from 52% up to 54%. The moisture content of samples during testing ranged from 7% up to 10%.

RESULTS AND DISCUSSION

Figure 6 presents the influence of virgin fiber content in the first and third layers of the combined handsheets on the breaking length (Fig. 4a) and bursting strength (Fig. 4b). The figures show that increasing the virgin fiber dosage resulted in increased strength of the three-layer combined sheets. There were 10 tests of bursting strength performed for each value of the content of fresh fiber in layers 1 and 3 (0, 5, 15, 25, 30%). The configuration of layers of three layers handsheets was constant according to Fig. 3. The average values of bursting strength for the different virgin fiber content in the first and third layers of three layer handsheets were as presented in Fig. 4b. There were also 10 tests of other mechanical parameters on each value of the content of fresh fiber in a layer 1 and layer 3. The average values of mechanical parameters for the different virgin fiber content in the first and third layers of three layer handsheets are presented in the figures (4a; 5a,b; 6a, b).

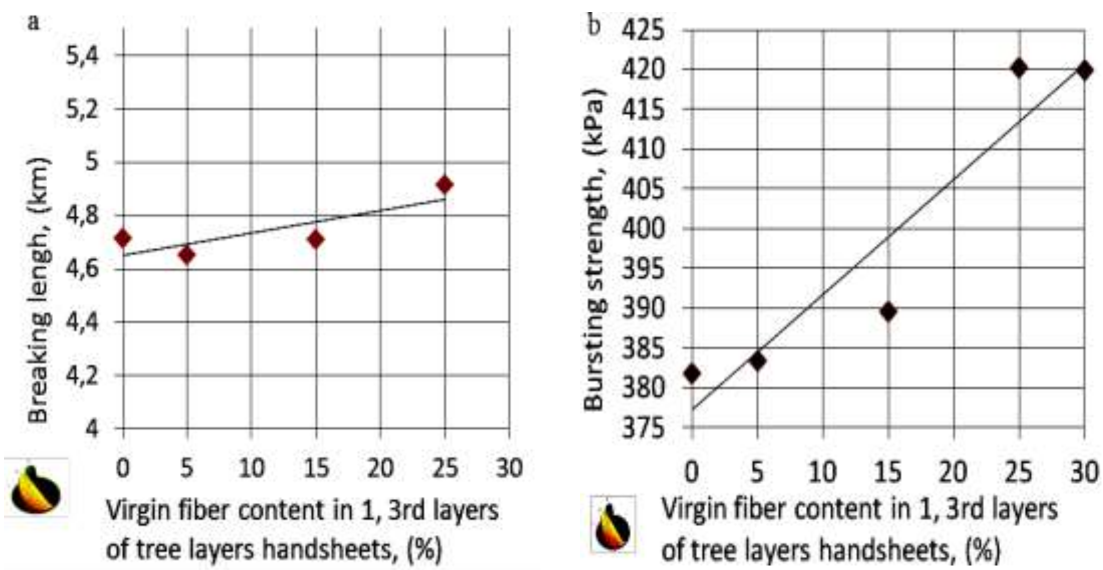

Fig. 4. Influence of unbleached kraft pulp dosage on the breaking length and bursting strength of three-layer testliner

An increase in the tensile breaking force was found (Fig. 5a), as well as an increase of elasticity modulus (Fig. 5b) with increasing content of virgin fiber in the outer plies.

The Young's (elastic) modulus (Fig. 5b) can be expected to determine the elastic properties of the testliner. The modulus of elasticity expresses the dependence of tensile stress on extensional strain. As shown, this dependence was found to be nonlinear, and the data were fitted to a polynomial equation.

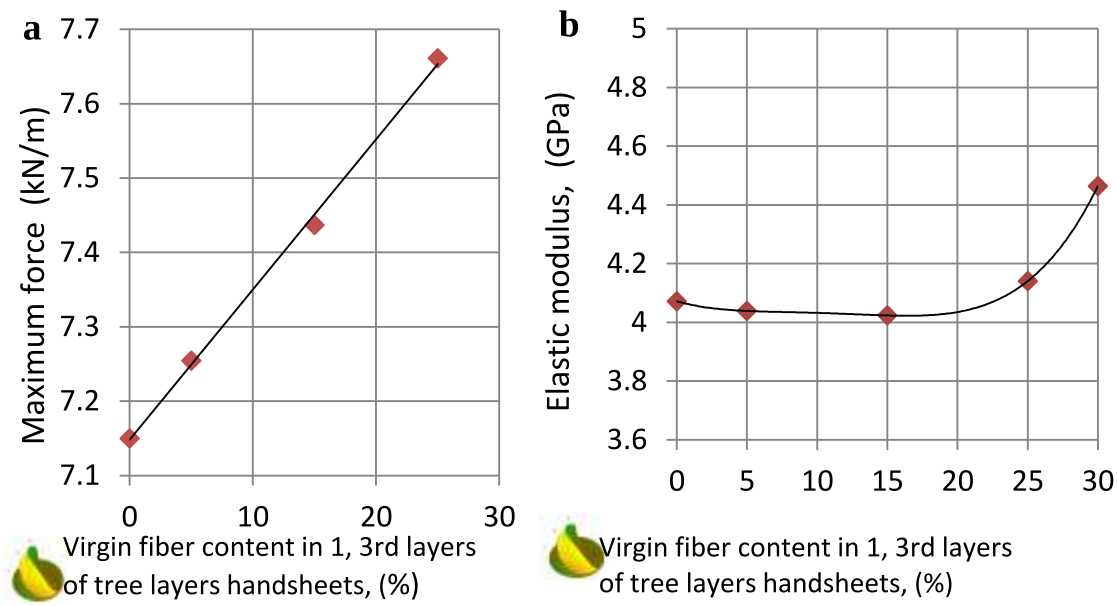

Fig. 5. Influence of unbleached kraft pulp dosage on ultimate tensile strength and modulus of elasticity of three-layer testliner

Relatively small amounts of virgin fiber addition (lower than 25% in 1^{st} and 3^{rd} layers, representing up to 15% of the total weight of the handsheet) did not considerably change the modulus of elasticity (Fig. 5b). Increasing the virgin fiber to more than 25% in the 1^{st} and the 3^{rd} layers (15% of total weight of handsheet) led to substantial increases of elastic properties of the three-layer testliner. It was connected with the increase of the interfiber connections. More than 25% of virgin fiber content resulted in a stronger virgin fibrous framework.

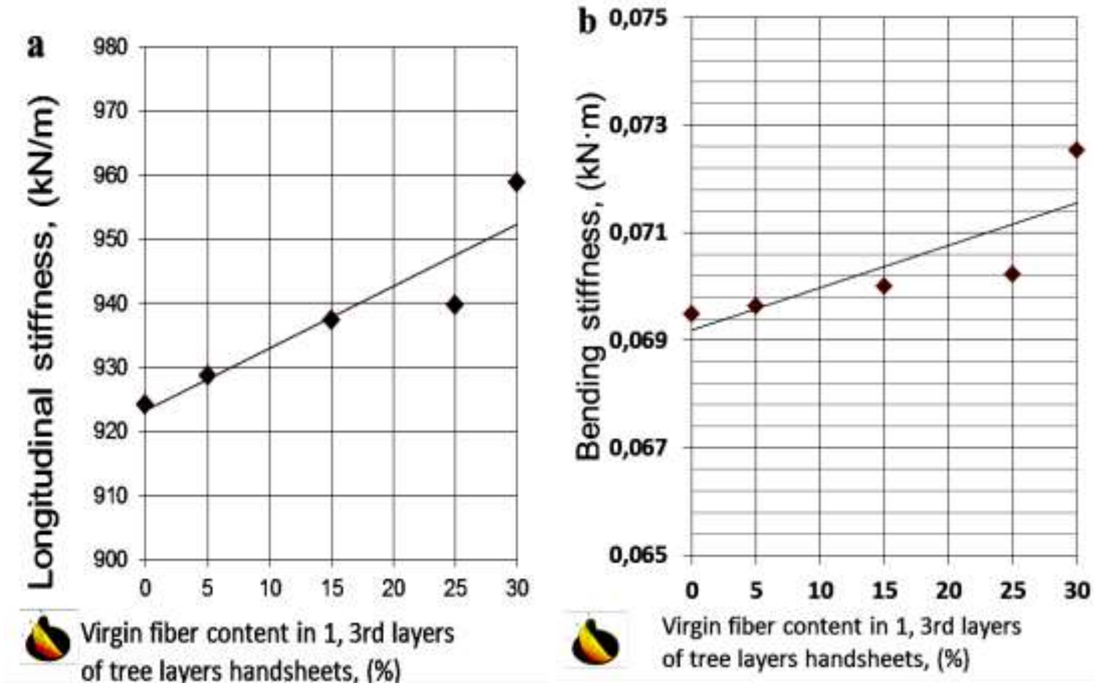

Fig. 6. Influence of unbleached kraft pulp dosage on longitudinal and bending stiffness of three-layer testliner

The experimental data on longitudinal stiffness and bending strength determination are presented in Fig. 6. The longitudinal stiffness increased similarly to strength indices in linear dependence. This index depends on the nature, average length, and bonding strength of the fiber. The virgin fiber strength is higher than that of recovered paper fibers. Therefore, value of longitudinal stiffness (Fig. 6a) and bending strength (Fig. 6b) was higher.

Hubbe (2014) reviewed information about strength characteristics, macrostructure, and nanostructure of different fiber resources and chemical aspects, and compared the dependencies of paper strength on various mechanical characteristics and fiber contents. In the present analysis, the required mechanical characteristics are set forth in the Russian standard ГОСТ 7420 (1989). The index of bursting strength is one of the primary mechanical characteristics of the generally accepted Russian standard.

The use of chemical additives cause a considerable increase in strength and stiffness characteristics of the testliner. For example, the bursting strength increased from 15 up to 20% (Auhorn 2001). Figure 4b shows that it is more reasonable to add 25% of the virgin fiber to the top and bottom layers (15% of the total weight of handsheet). The addition of 25% virgin fibers provides К-3 grade testliner production according to Russian standard ГОСТ 7420 (1989). Chemical additives (Auhorn 2001) with virgin fiber dosage 0 to 15% provide the production of testliner cardboard of grade К-2. The bursting strength of the testliner (± 150 g/m^2) is 420 kPa. It is possible to get more than 500 kPa of bursting strength value (grade К-1) using the chemical additives. It should be noted that the kraft liner (К-0, КВС grade) includes up to 80% unbleached kraft pulp. It is a very expensive way to increase cardboard mechanical properties.

CONCLUSIONS

The influence of virgin fiber additives on the strength and stiffness characteristics of a multi-layer testliner was studied. The addition of virgin fiber in the 1st and 3rd layers of three layers testliner increased the strength and stiffness parameters according to a linear dependence. The dependence between elastic properties and virgin fiber dosage was non-linear and required use of a polynomial expression to obtain a good fit. It seems more reasonable to add 25% of virgin fiber to the top and bottom layers (15% of the total weight of handsheet). The small amount of virgin fiber additives (lower than 25% in 1st and 3rd layers or 15% in total weight of handsheet) did not considerably change the elastic modulus (Fig. 5b). The increase of the virgin fiber of more than 25% in the 1st and the 3rd layer (15% of total weight of handsheet) led to a substantial increase of elastic properties of the three-layer testliner. This was attributed to an increase of the interfiber connections. More than 25% of virgin fiber content created a stronger virgin fibrous framework.

More than 25% of the virgin fiber dosage and chemical additives enables the production of the testliner cardboard of grade K-2, K-1 in accordance with Russian standard ГОСТ 7420 (1989).

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