Changing Quality of Recycled Fiber Material. Part 1. Factors Affecting the Quality and an Approach for Characterisation of the Strength Potential

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The paper recycling sector has undergone major changes in recent years, particularly regarding the quantity and quality of various materials processed. Material originating from board grades will increasingly dominate the recycling market as the use of printing papers decreases and the amount of non-fiber elements increases. Users of recycled fiber material have to overcome three main challenges: price, quality, and availability. This paper focuses on the quality dilemma in terms of measurement needs and possibilities from the user viewpoint. It includes a discussion of the factors causing deterioration in the quality of paper used for recycling. Today, the average fiber age is low compared to what the fibers can tolerate. Therefore, the characteristic phenomena in the paper recycling loop are not caused by the degradation of individual fibers, but by a blending process in which different fiber grades and non-fiber components are blended in a non-optimal way. A novel method is introduced in this article for evaluating the quality of recycled fiber material using a new parameter, the fiber integrity value. Part 2 of this paper will focus on the application of this new parameter and demonstrates its correlation with paper properties.

Keywords: Paper recycling; Fiber; Strength potential; Fiber integrity values

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INTRODUCTION

The use of wood fiber-based paper for recycling began in the early 1900s. By the second half of the century, recovered fiber had become an important source of raw material for the paper industry. Raw material recovery has increased over the last few decades, from a negligible level in the 1950s to its current level of 72% in Europe and 65% in the US. This means that in Europe, 54% and in US 39% of the paper industry's raw materials are derived from recyled paper and board (CEPI 2013a; AF&PA 2016). Although the average recycling rate is high, the rate of recovery varies considerably from one paper grade to another (CEPI 2014). Recycled material contains a considerable amount of non-fibrous components and moisture, and therefore, the most often-used indicators including utilization rate and recycling rate give an overly optimistic picture of fiber recycling (Keränen and Ervasti 2014).

Modern paper mills contribute to waste reduction through a more efficient utilization of side-streams as well as increased recycling. The pulp and paper industry's competitive advantage lies in the multisectoral use of its products and their combination with other materials. Its logistic processes are efficient, and its material streams are global. Mills can handle large streams of material efficiently, especially when production and sourcing are located closer to end users. The use of recycled resources is bringing novel ecosystems to cities, leading to more intensive recycling of water and paper, as well as improved energy efficiency and the reduction of waste (Holmen 2014). Mills re-utilize large streams based on consumer everyday activities (paper, board, and water). Many options exist for re-using recycled fiber. Recycling also has a close link with municipal waste, waste sorting, and incineration. When the recycling rate increases, the relative proportion of virgin fiber-based paper is reduced, leading to a more an effective way of using resources. Recycling also plays a key role in the future of the bio-economy (CEPI 2011); the demand for biomaterials will continue to grow and, depending on geographical location, will result in a serious fiber shortage (discussed below).

Fiber Availability

Although recovered paper can be considered waste, it is also a raw material for paper production. In Europe, to emphasize its usability as a raw material in papermaking, the term “paper for recycling” has been used instead of “recovered paper” (CEPI 2013b). This nomenclature is expected to improve consumer understanding and awareness of the recycling economy, and it may also have the positive effect of motivating consumers to collect and sort paper and boards for recycling. The term “paper for recycling” is also used in this paper.

Paper for recycling is by volume the largest and fastest-growing raw material component in the paper product industry, although virgin fibers will always be needed. Paper for recycling is also a major, globally traded raw material whose price varies strongly according to demand. In contrast to Asia and Africa, which suffer from a fiber shortage mainly covered by imports, Europe is self-sufficient in the raw materials required to make paper. In recent years, Europe has exported more than 10 million tons of paper per year for recycling in China (FAO 2014). This export has a definite effect on the availability of fiber material in Europe. In Asia, the fiber supply is set to become even tighter because the population, standard of living, and paper consumption are growing faster than the available quantities of fiber (FAO 2014).

The younger generations are consuming paper differently from their predecessors and, as they grow older, the overall requirement for paper and board is changing. Communication methods have changed because of the internet, and paper has been supplanted in many applications, including advertising, which has lowered paper production levels (Pöyry 2014). However, the need for paper in packaging applications is growing. Legislation such as landfill taxes will affect production costs, pressuring manufacturers to develop products with higher recyclability and processes that generate zero or qualitatively acceptable waste that can be utilized in other products. Fiber scarcity in some geographical areas is already a reality, adding to the pressure to develop products with lower fiber consumption and to make substantial efforts to further develop ways of processing recycled material. This effort is particularly important given that paper used for recycling can include up to 45 wt.% of filler, coatings, other non-fibrous substances, and even material of non-paper origin (JRC 2001; JRC 2013).

Paper used for recycling is collected from various sources such as paper converters, printers, distributor shops, consumers in private homes, offices, and institutional settings. Typical product segments include containerboards, cartonboards, coated and uncoated grades (both wood-containing and wood-free), newsprint, and other grades. The markets for these segments are global, and prices are likewise set globally (Pöyry 2014). Paper recycling affects not only the market for paper for recycling, but also the balance of the entire wood fiber value chain. The supply of pulpwood, virgin fiber, paper for recycling, and non-fibrous materials has shifted towards paper for recycling, so recycled fibers play a key role in the paper industry as a substitute for virgin pulps. The collection of used paper often forms the basis of a successful business venture, particularly in densely populated countries with high paper consumption per capita (Pöyry 2014). However, the easily available sources are already exploited, and a further increase in the recycling rate may also raise collection costs, reduce the quality of the paper collected, and increase contaminant levels. As a result, the yield of paper for recycling in mills would also decrease. Yields at some modern mills are already surprisingly low (Göttsching 2000) for packaging paper and cardboard (90 to 95%), graphic paper (65 to 85%), hygiene paper (60 to 75%), special paper (70 to 95%), market DIP (wood-free) (60 to 70%), and market DIP (wood-containing) (80 to 85%), and the filler content has continuously increased (Vogt 2004).

The availability of fibers for recycling also depends on the competing applications. If collected paper and board is incinerated, it cannot be reused. When oil prices are high, paper and board can be an attractive source of energy (Palanterä 1996). The attractiveness, however, depends on its heating value, which is affected by the moisture content and the amount of inorganic material.

In sum, the main concerns of mills that use paper for recycling are as follows: price, quality, and availability. In addition, the utilization potential of paper for recycling is a key issue. Now that availability has been addressed from the recovery viewpoint, quality will be addressed.

Recycled Fiber Quality

Fiber production, papermaking processes, and recycling lead to deformations and damage in fiber material, only some of which are desirable. Alongside changes in individual fibers, the quality of recycled fiber material can be reduced by its mixture with unwanted fiber types, pigments, and contamination by other materials.

Recycling probably causes less mechanical damage to fibers than the pulping processes. Chemical pulping causes fiber damage and changes in morphology and chemical composition. Mechanical pulping, on the other hand, is a more drastic process that often causes serious mechanical damage to fibers, fiber shortening, and the creation of fines. The major changes resulting from pulping are mainly caused by high-consistency treatments and pumping (the fibers being subjected to mechanical energy) and high-temperature chemical processes, as well as rapid changes in temperature, pH, and pressure (Tikka and Sundquist 2001; Rauvanto 2010). The resulting chemical and mechanical changes are usually irreversible.

In paper mills, pulp undergoes a range of treatments including disintegration, screening, refining, drying, coating, calendering, and conversion. When paper is recycled, the fiber material may undergo these stages several times, potentially in addition to the deinking process. The changes in fiber properties are also related to the chemical composition of the pulp. Whereas refined chemical pulps lose density and tensile strength, mechanical pulps may show small gains in strength (Fig. 1) and density (Howard 1991; Nguyen 2001). However, all the negative changes are probably not permanent and can be reversed by refining. Additionally, recycling can result in the creation of fines and the dissolution of hemicellulose, leading to decreased fiber coarseness (Nguyen 2001). Similar observations were made by Yamauchi and Yamamoto (2008).

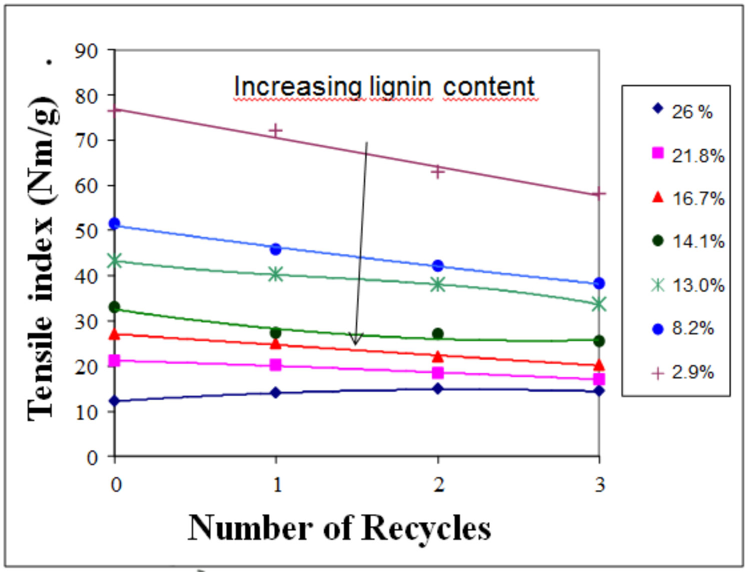

Fig. 1. Effect of lignin content of spruce fibers on strength changes in recycling (Nguyen 2001)

Evaluations of the recycling process often exaggerate mechanical deterioration and underestimate the effect of chemical changes (Hubbe *et al.* 2007). Chemical changes in fiber material can reflect the quantity of extractives, hydrophobic sizing agents, strength additives, and the dissolution of hemicelluloses. In spite of some changes in fiber bonding ability, the changes in fiber properties are minor, especially considering that it can be estimated (form data of Keränen and Ervasti 2014) that in Europe the average number of recycles the fibers experience may be less than one recycle.

A general trend in papermaking has involved an increase in the filler content of printing papers, which has also been reflected in board products *via* recycling (Vogt 2004). By adding filler, papermakers seek to reduce raw material costs, but this also increases recovery costs while leading to changes in quality and potential yield. Another trend has also been a sharp decline in the consumption of printing paper, particularly newsprint, while that of packaging grades and tissue continues to increase. The decommissioning of newsprint paper machines can have a major impact on local recycled fiber loops and the balance between the supply and demand of a raw material. Only some of these machines can be converted to produce other types of paper or board. The remaining printing paper and tissue mills are facing greater pressure to use recyclable cardboard as a raw material. Board will increasingly dominate the recycling market, which will in turn shape future consumer collection systems and logistics. However, it is also clear that such transitions could change the quantity and quality of recycled fiber. Another recycling trend in the EU lies in the move towards zero-waste processes (European Commission 2013). In the case of components that are less suitable for paper manufacturing, it would be sensible to find other uses for these material fractions.

The characterization of the properties of paper for recycling and its fractions is essential for users. Detailed classifications have been established by national and international organizations (CEPI 2013b). These classifications are typically based on the original paper grades and provide only superficial information on fiber material quality within the classifications. Material properties within a certain class can vary according to the geographical location of origin and over time. For example, producers of case material from OCC tend to use terms such as American OCC, Scandinavian OCC, and European

OCC because of the considerable difference in quality in the same class. More accurate methods are therefore required to describe the differences in fiber quality within a certain grade of paper for recycling, partly in order to be able to pay a competitive price for the recycled raw material and to maintain the high quality of any paper produced. This need is motivated by several factors. The price of paper for recycling is likely to increase while the quality will decrease as the recovery rate increases, even if the apparent grade-based classification stays the same. In most cases, easily available quantities are collected first. As the recovery rate increases, more difficult sources are used, and the collected quantities contain more non-fiber material. This increases the cost of collection and utilization because unwanted material and impurities need to be removed first. An increased recycling rate would also mean simultaneous changes in the paper market; there would be fewer mills using virgin pulps and more using paper for recycling. A mill using paper for recycling must be aware of the quality of the paper it has bought; the quality of recycled fiber material needs to be quantified. This article therefore examines the possibilities of evaluating paper quality in a simple way. A future goal is to connect quality measurement with the applicability of recycled fiber material for various end uses. This would eventually enable a comparison of the quality, utilization potential, and the price of paper for recycling.

The quality of paper for recycling decreases as more non-fibrous material is brought into the process. Non-fibrous material lowers end-product quality, increases handling and production costs, and lowers yield. It would be preferable if the key quality properties were measured directly from the paper for recycling. However, the fiber level characteristic cannot be measured directly from paper without pulping and disintegration.

When viewing a material’s utilization potential from a wider perspective and considering future concepts such as the multiproduct mill concept, it is clear that only the material components essential to the network structure and end properties should be used in papermaking. The material’s less important components can be used for other products. The role of these “less important” components may increase as more material is recycled and more utilization options are developed. Other utilization options, such as composites, could create additional value from recycled material and reduce waste (Kim *et al.* 2009; Serrano *et al.* 2014).

An Approach for Characterising the Quality of Recycled Fiber Material

When using recycled fiber material for conventional paper and board applications and for new paper and non-paper applications, such as novel fiber-based materials, composites, bioenergy and biorefinery concepts, recycled raw material has several, partly competing utilization options. Thus, for papermaking, other potential uses of fiber raw material must be evaluated in a new way. This study proposes a new, simple concept for evaluating the quality and utilization potential of recycled fiber material from the strength point of view, entitled the “fiber material integrity value”.

The new concept must fulfil several needs in order to be useful in characterizing the basic value of the material. It should be simple and provide information on the fundamental characteristics of the material and should also be easily measurable with the option of in-line determination. The next sections will ouline and explain the basic features of the proposed new concept.

Fiber Material Integrity — Fiber Material’s Ability to Create Strength

In general, strength, or the ability to bear and distribute stresses, is a fundamental property of a solid material. The same applies to fiber-based materials; without strength, the material is useless. Fiber material integrity, a new value associated with fiber material quality, should therefore reflect its strength potential. Although strength is not always the key requirement for products, it is always important. Only when the structure has sufficient strength can other material properties be optimized. Generally speaking, a higher strength potential means more freedom in optimizing optical properties or reducing the amount of material and energy used in production. High integrity means that the material has high strength potential and is therefore easier to make into a product of sufficient strength. When such potential changes during recycling or another process, this should be reflected in the fiber material integrity value

The chemical composition of the pulp must also be considered. For example, the presence of cellulose, holocellulose, or lignin fractions can reveal the origin of recycled material. Pulps (and fines) of mechanical or chemical origin have different potential for later treatments (Lehto 2011). In addition, the filler amount reduces the recycled material's ability to bear and distribute stresses around the network because of the lower amount of fiber material and reduced bonding between it (Velho 2002).

To approximate the key parameters discussed here, the following factors were included as measures of the integrity value of recycled pulp: amount of fiber-based organic *versus* inorganic material in the pulp or amount of fiber fraction; chemical pulp fibers *versus* mechanical pulp fibers; cellulose or holocellulose or lignin content (amount of cellulose or ~lignin) of the fibers; strength of fibers; effective fiber length; fiber coarseness; fiber shape; and fines content.

These parameters can illuminate much about the strength potential of recycled pulps. In practice, however, in materials such as paper, strength also depends on the number of interference connections, *i.e.*, bonding, and on the density of the structure. The integrity value should therefore be independent of the bonding degree and density of the pulp. On the other hand, structural density and bonding can be controlled through process parameters, including refining, wet pressing, strength chemicals, press drying, *etc.* Strength potential can therefore only be realized when process conditions are selected that make use of the material's strength potential. In current papermaking practices, some key properties, including optical properties (color, light absorption and, to some degree, light scattering coefficients) are almost independent of strength potential.

It is also important that new parameters can be easily measured. Fiber analyzers are developing in a manner that suggests that a vast number of fiber-level parameters can be analyzed and determined in addition to average values or their distribution. These include several parameters for certain single fibers. For example, a fiber analyzer can have interesting potential in this respect when combined with a fractionator (Krogerus *et al.* 2003; Liukkonen 2006; Laitinen *et al.* 2011). Therefore, all of the key fiber-level parameters can be determined either now or in the near future by special fiber analyzers once the required parameters have been defined.

Effect of Lignin Removal on Fiber Strength

Mechanical pulp differs in many respects from chemical pulp (Retulainen *et al.* 1998; Lehto 2011). While there are several differences between these types of pulps, from the strength perspective, the main differing factors are the fiber properties and fines content. The fibers of mechanical pulp are coarser, stiffer, and have a lower fiber strength index than the fibers of chemical pulp. One explanation for these differences is that mechanical pulp fibers basically have the same lignin content as wood fibers (approximately 27% in Nordic spruce (Sjöström 1993)). Cellulose forms the backbone of fibers and acts as its load-bearing component. Page *et al.* (1985) showed that during pulping, fiber strength increases linearly as yield is reduced for cellulose contents of up to approximately 80% in pulp, above which the lignin removal processes degrade cellulose sufficiently to cause a net loss of strength. This general relationship between yield and strength can be explained by the fact that higher cellulose content means a lower lignin content, and lignin does not contribute to tensile strength. However, lignin can bear compressive stresses (Fellers *et al.* 1979). Fibers with high lignin contents are also stiffer when wet and have a lower bonding ability. Additionally, the pulping methods applied in the production of high-lignin pulps are generally harsh and can cause damage to the fibers. It can therefore be assumed that lignin content has a strong correlation with the strength potential of pulps and pulp fibers. Thus, it can be concluded that the chemical composition (either the cellulose or lignin content) of pulp is a strong indication of fiber strength.

Effect of Filler on the Strength of Paper

Many scientists have studied the effect of filler content on the strength of paper. For example, Velho (2002) showed that the strength of paper strongly depends not only on the filler content, but also on filler type. There is an almost linear relationship between filler content and the strength of paper. This effect can be explained by two factors: 1) increasing filler content reduces the quantity of fibers, the load-bearing material in paper; and 2) increasing filler content reduces the bonding between fibers and thereby reduces the strength of the paper. Filler can therefore be viewed as a factor that directly reduces the strength potential of recycled fiber material.

Role of Fines in Recycled Materials

Cellulosic fines have profound effects on paper properties (Retulainen *et al.* 1993). They can improve bonding, reduce porosity, and strongly reduce drainage, mainly because of the ability of fines to increase the density (and relative bonded area) of the fiber network. However, the strength of a sheet made of pure fines is considerably lower than that of a sheet made of well-bonded fibers (Retulainen *et al.* 2002). Hence, fines are not primary load-bearing and stress-distributing material like fibers, but they do have a role in improving bonding between the fibers. However, the role of fines in strength properties also depends on the quality of the fines in question. During the papermaking process, they can become hornified and gather impurities because of their large surface area. Low retention causes part of the fines, which circulate for longer periods in a white-water system, to become contaminated by various impurities, further reducing their papermaking value. Fines from paper for recycling are therefore less active in bonding (Waterhouse 1994) than fresh fines created during the mechanical treatment of fibers (Retulainen *et al.* 1993; Zhang *et al.* 2000). White-water fines are an example of inert fines (Rundlöf 2002). Some of the impurities in fines are washed away during the separation of fines in laboratory conditions using the Bauer-McNett fractionator and with the application of large amounts of water. This result demonstrates that the separation method used in fines studies can lead to erroneous results. In Rundlöf's experiment, DDJ separation of fines at a higher consistency gave fines of lower quality than BauerMcNett at a low consistency, which was due to the different washing effects. However, extractives and stickies were presumably removed when the quality of the DDJ fines were improved through acetone-based extraction.

During papermaking, fines are created by mechanical actions and fractures in fibers, which have led to the detachment of fibrils, lamellas, and fiber ends from the parent fibers. The resulting effect can be considered a loss of integrity. Additionally, micro-stickies, printing ink, other non-fibrous elements, and filler are associated with fines and concentrate in the fines fraction (Lapierre *et al*. 2003; Sarja 2007). It would therefore be reasonable to consider the fines in paper used for recycling as a material with more negative than positive effects on the strength potential of pulp. Fines have an effect on the bonding, but not on the strength potential that can be achieved in well bonded sheet.

Fiber Properties Affecting Network Strength

Strength is not an unambiguous property in a material, but strongly depends on the loading mode and the direction of the applied load. Although tensile strength in paper is often considered, tear strength and fracture resistance are also commonly used. Stiffness values such as bending stiffness and tensile stiffness are also highly relevant properties describing the subfracture behavior of material.

The strength of a material refers to the ultimate value tolerated by the material before it fails. The failure of paper, *i.e.* its fracturing, can be initiated by two mechanisms: either a breakage of the fiber bonds or breakage of the fibers themselves. In typical paper grades, fractures are primarily caused by the fracturing of fiber bonds. Fiber fractures can also play a role in well-bonded sheets (Shallhorn and Karnis 1979). In the case of paper for recycling, the bonding level controls the initiation of fractures. However, when examined at the fracture zone when fracturing has already been initiated, it can be seen that fiber fractures are occurring (Helle 1965).

The role of different fiber properties can be evaluated based on theories developed on the strength of paper. Shallhorn and Karnis (1979) presented a simple, semi-quantitative model of paper strength, based on a theory of the micromechanics of crack extension in short fiber composites. This model predicts both tensile and tear strength. Shallhorn (1994) later showed that this tear strength model could also be used to predict the fracture resistance of paper. It does not provide precise strength predictions, but it does reveal the interconnections between fiber-level parameters and strength. The model for tensile strength is very similar to the Page (1969) theory, except that the Page theory assumes that fiber strength also affects paper strength in the case of weakly bonded papers. The parameters used in the Shallhorn-Karnis model can be converted into more concrete, easily measurable parameters (Retulainen 1996) as follows: strength of individual fibers (failure force); fiber length; fiber width (or perimeter); fiber coarseness (weight/length); specific bond strength (strength/area); and relative bonded area (RBA).

Shallhorn and Karnis provided separate equations for weakly bonded and strongly bonded fiber networks. “Weak bonding” means that the fiber strength is so high that fibers can be pulled intact out of the network. With regard to recycled fiber material, a greater emphasis should be placed on the approach used for weakly bonded fibers. Shallhorn and Karnis’ theory on weakly bonded structures suggests that strength (both tensile and tear strength) can be improved by increasing the relative bonded area, bond strength *versus* the area of the fiber length, the fiber width (or perimeter if the fiber is not considered flat), or by decreasing the fiber coarseness (Fig. 2).

The main difference between tensile strength and fracture resistance is that the latter is more dependent on fiber length (~length^2). In general, increasing the fiber length increases the number of bonds per fiber, which means that the fiber is bound more strongly into the network, thereby increasing the strength of the network and fiber network (Corte and Kallmes 1961; Shallhorn and Karnis 1979).

In addition to the fiber network, fiber length has a very strong effect on strength in polymer composites (Thomason 2002). As the RBA increases, the relationship between fracture resistance and tensile strength generally follows a simple, linear upward curve all the way to the point where the bond strength exceeds the fiber strength (Fig. 3). After this, the curve turns downwards.

When starting from low strength values, it is possible to move up to the right along the curve by increasing the RBA, fiber width (perimeter), and specific bond strength and by decreasing the coarseness. However, only the fiber length enables a move away from the curve on all bonding levels. Increasing fiber strength only affects the situation at high bonding levels.

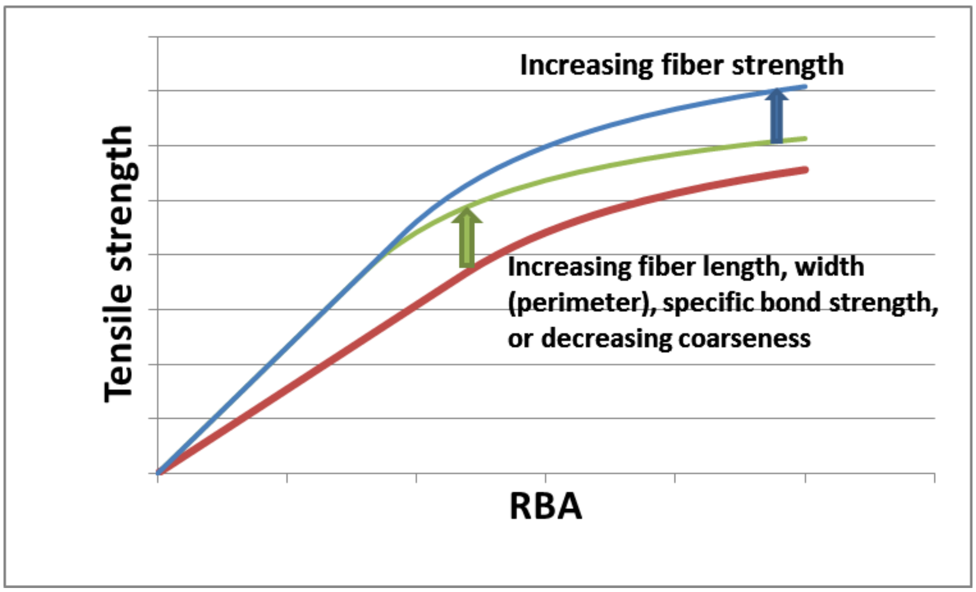

Fig. 2. Effect of fiber-level variables on tensile strength according to the Shallhorn-Karnis model (adapted from Retulainen 1996)

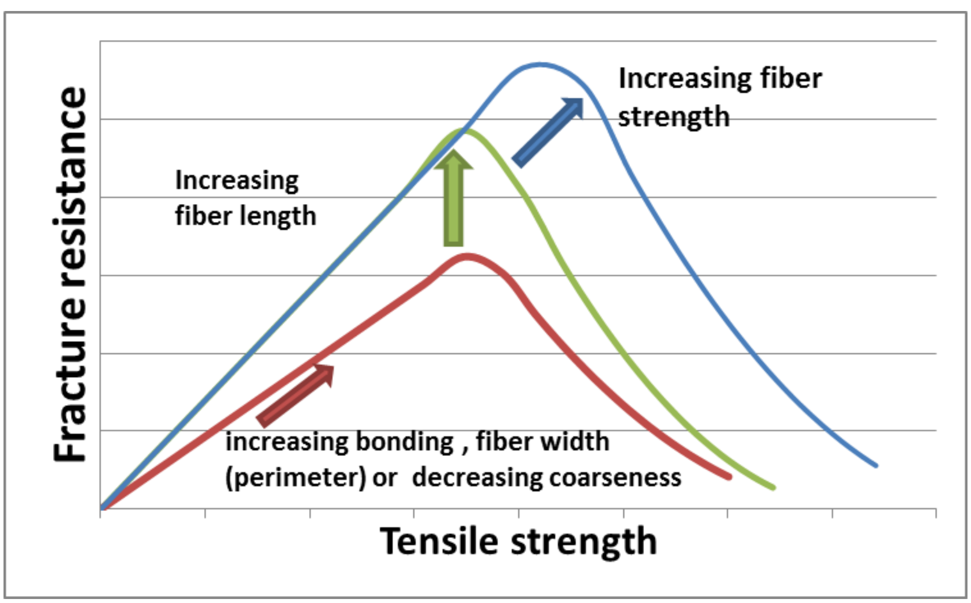

Fig. 3. Effect of fiber-level variables on the fracture-resistance tensile strength relationship according to the modified Shallhorn-Karnis model (adapted from Retulainen 1996)

Based on these considerations, the relative bonded area and specific bonding strength are important to the strength and strength potential of the fiber network but are only partly determined by the fibers, and rather are largely determined by treatments, added chemicals, and process conditions. Thus, the fiber strength, length, coarseness, and possibly the fiber perimeter are factors that affect the strength potential of the pulp at certain bonding levels. Fiber length, coarseness, and fiber width can be measured using commercial fiber analyzers. However, the fiber perimeter is rarely measured because the degree of fiber collapse strongly affects the result. It may therefore be advisable to ignore this factor. As described earlier, fiber strength can be estimated from the lignin content.

Constructing an Integrity Value Parameter for Fiber Material in Paper Used for Recycling

Next, a novel approach for estimating the utilization potential of recycled fiber material using a simple concept—the integrity value—is proposed. The integrity value is based on the notion that strength and stress distribution capability are the fundamental properties of fiber material. High integrity means high strength potential that can, if necessary, be realized under optimum conditions, *i.e.*, when the bonding degree is high. A general relationship between the strength and integrity values can be expressed as follows:

*Strength = (Integrity value) * (Bonding)* (1)

This concept had to be simple and robust, and not too complex. It contains only parameters that could be determined, possibly with a fiber analyzer-type device, which could be taken into "in-line use" and modified for special applications and cases. It should also provide information on the potential of paper for recycling for papermaking processes and/or other uses.

The integrity value of recycled pulp is calculated based on the filler, fines, and lignin contents of the fiber material, while taking into account network-forming characteristics such as length and the coarseness of the fibers. The basic equations related to the integrity value of recycled pulp are based on the experimental and literature data, as follows:

Integrity value ≈ (amount of fiber material)(fiber strength)**
(network strength forming potential) (2)

This implies that the key element of the recycled material is that which can actively contribute to the material strength in bearing and distributing stress. Here, it is assumed that filler, fines, and lignin in recycled pulp are inactive materials, although they can affect bonding. The maximum strength potential depends on the fiber material, particularly the amount of cellulose. However, the degree to which the strength potential is achieved depends on the network strength-forming potential of the fibers, which in turn depends on their geometrical properties, length of single fibers, and coarseness (total fiber length in sheet). Based on these, a more detailed equation can be formulated,

$$Integrity\ value = (1 - \alpha Filler) * (1 - \beta Fines) * (1 - \gamma Lignin) * L * \frac{L}{c} \qquad (3)$$

where the italicized terms *Filler*, *Fines*, and *Lignin* stand for the proportional amounts of these coponents.

This equation suggests that the inorganic material content should be determined first, and only then should the composition of the organic material and fines material be calculated. The process is completed by checking how much cellulose is in the fiber material. The fiber length and total length of fibers reveal how a well-connected, strong network is formed. In addition to strength, the fracture energy-related strength values are important, and therefore the square of the fiber length is justified. Here, L is the projected length-weighted fiber length, c is the fiber coarseness (of fiber fractions > 0.2 mm), and α, β, and γ are constants. These constants are used because filler, fines, and lignin are not expected to have a similar negative effect on strength potential. The constant should be determined separately in each case, but a first, rough estimate for this can be obtained from examining how the tensile strength changes. A preliminary estimate can be made based on the literature data on tensile strength (Page *et al.* 1985; Rundlöf 2002; Velho 2002), from which estimates for α, β, and γ can be derived. The values were estimated as follows: α, 1.3 to 2.5; β, 0.5 to 1.4; and γ, 1.0 to 1.9. However, the values also depend on the measurement methods used. In this case, the value of β for fines was based on weight determination using a fiber fractionator.

Equation 3 can be straightforwardly and quickly measured with either current or future forthcoming devices. The filler content can be measured based on the ash content and the fines content and fiber dimensions can be evaluated using a fiber analyzer (*e.g.*, L&W STFI FiberMaster). The most problematic parameter is perhaps the lignin content, which can be measured in several ways and using several methods (NIR, fiber staining, *etc*.). The application of the integrity value for paper is described in the second part of this article.

CONCLUSIONS

1. The three main problem areas concerning paper for recycling are quality, price, and availability. The market balance is also affected by the high calorific value of paper for recycling, which makes it attractive for energy use. When the recycling rate rises, the available pulp quality of recycled fibers decreases, as does the proportion of virgin fiber in the total mass. Because of waste prevention goals (such as the European zero waste goal), the ability to pay for paper for recycling is markedly dependent on how well low-quality fractions and recycling residues can be used in other products. In the future, the consumption of newsprint and other printing papers will be reduced, and most circulating fiber material will be derived from packaging products. The use of valuable resources will have to be reconsidered in novel ways.
2. Recycling has a clearly less degrading effect on fibers than is commonly assumed. The deteriorating quality of paper for recycling mainly is caused by the fact that different fiber grades get mixed in non-optimal ways, and the amount of non-fiber materials increases with the use of recycling. The advantage of using recycled fibers is that it consumes less energy than virgin fibers (when re-used in the manufacture of paper, for example). The quantities of recycled fiber tend to be linked to population levels and therefore consumer density. Savings in raw materials, transport costs, and carbon dioxide emissions are observed when the factory location is close to consumers. The added value of recycled fiber is much higher than in the case of direct energy use. The most readily available sources of raw material, such as industry and wholesale and

retail stores with collection bins for paper and board are already in use. Price and availability are interconnected, with price depending on both domestic and global factors. Quality, price, and availability may become interconnected if the quality of the recycled material can be easily evaluated.

3. This article introduced the novel and simple concept of integrity value for the evaluation of the quality of recycled fiber material. The integrity value of recycled pulp is a strength-based, quality-potential parameter. Strength can be viewed as a basic requirement of the material, and high strength potential provides a greater scope for optimizing the other quality properties of the product and reducing material and energy consumption. Quality can be quantified using a simple set of measurements, and utilization options for papermaking or other uses can be better selected. If quality potential is already at a low level, consideration should be given to options other than utilization in papermaking.

ACKNOWLEDGMENTS

This research was part of a REFFIBRE project that received funding from the European Community's Seventh Framework Programme under grant agreement No. 604187.

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Article submitted: December 1, 2015; Peer review completed: April 22, 2016; Revised version received and accepted: September 24, 2016; Published: October 26, 2016.
DOI: 10.15376/biores.11.4.10404-10418