

Fundamentals of strength loss in recycled paper

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ABSTRACT: *One of the most challenging aspects of recycling is understanding the cause of loss in potential fiber bonding when fibers are dried. Since mechanical pulps do not seem to suffer from the same problems as chemical (low yield) pulps, difficulties in paper recycling seem to be related to the structure of the lignin-free cell wall. The damage usually manifests itself in hornification and surface inactivation of the fibers. Various ideas proposed on the cause of hornification and surface inactivation in predried cellulosic materials are reviewed, and the importance of the hornification is pointed out. Areas of necessary further research on cellulose (fiber) are outlined.*

KEYWORDS: *Cell walls, chemical pulps, hornification, hydrogen bonds, losses, mechanical properties, reclaimed fibers, surface properties, water, water repellence, wettability.*

It is assumed that the need for recycling of fiber sources will increase in the future. Such pressure is primarily due to a rapid decrease in the number of suitable landfill sites, need for sustainable development and public awareness of these problems. Most likely, this will create situations of temporary post-consumer paper oversupply, which may also lead to a deterioration of raw material quality and have a negative impact on the competitiveness of the recycled paper industry. To effectively deal with the problem, a com-

bination of the talents in recycling partnerships will be required to generate new processes, and products.

The practical effects of recycling on papermaking properties of fibers have been discussed thoroughly by different workers (1-17), and an excellent review on this subject was recently published by Howard (15). These investigations showed a dramatic loss of tensile and bursting strengths on repeated remaking of low-yield chemical pulp into paper (Fig. 1). Furthermore, recycled fibers become more brittle and break

like match sticks when beaten (18). It is thus predicted that due to these limitations the useful recycled fiber content in paper should be limited and a surplus of recycled paper will become available that will need to be disposed of by incineration or in cogeneration facilities, as suggested by Götttsching (19).

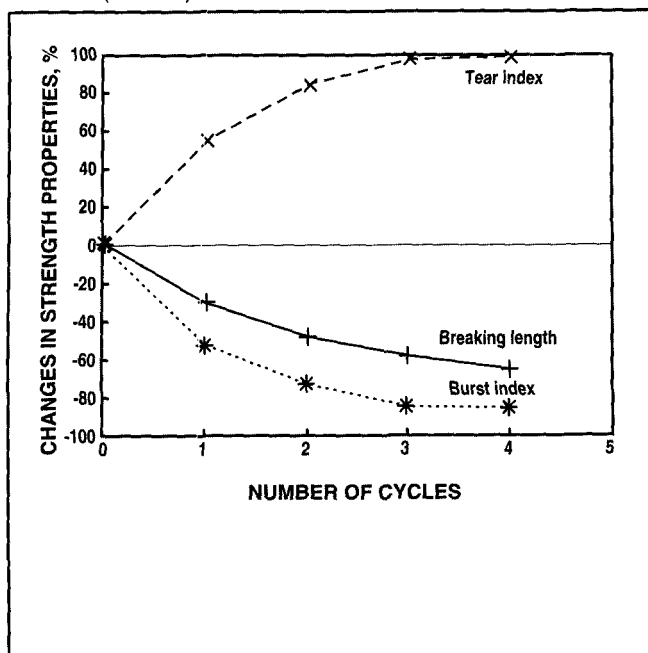
In spite of the considerable amount of work on upgrading of recycled paper (20-25), only limited improvements have been achieved in this field. Therefore, the problem of upgrading recycled fibers is still unsolved. For instance, there was a patent issued in 1954 to Schlosser (25) which described the addition of a series of soluble substances to pulps in order to suppress hornification after drying. The best results were obtained with wetting agents, but they were found to work for only one cycle (25).

The refining process, which could constitute an efficient method for regenerating the papermaking properties of recycled pulps, causes at the same time further worsening of their drainage properties. For instance, Szwarestajn and Przybysz (9) attempted to upgrade recycled papers by refining. They refined the recycled pulp during each cycle till the maximum breaking length was achieved. The fines content of the pulp (in spite of losses in the con-

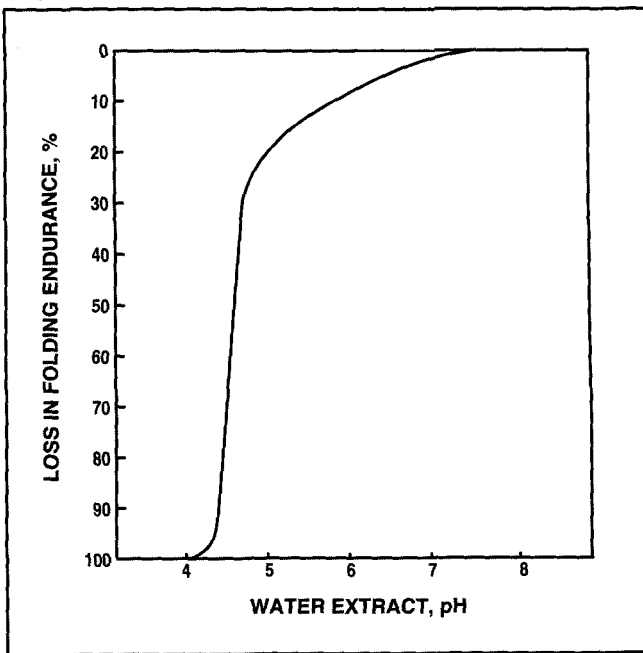
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1. Changes in strength properties of kraft paper due to recycling (17). The original pulp was never dried, beaten (310 mL CSF), and bleached (CEDED).



2. Change in flexibility of fiber by acidity of paper. The fiber retains its flexibility when it is in a neutral or slightly alkaline environment (18).



secutive formation processes) increased during recycling by about 70% (9). Such a result could severely limit traditional methods for regenerating the papermaking capacity of recycled pulps by refining. The negative effect of refining as a tool for upgrading of recycled fibers has been confirmed by many others (4, 6, 7, 26–28). Therefore, traditional methods of upgrading of recycled paper material are not adequate, and the need for developing the necessary mechanical properties of recycled fibers still remains an enigma. It will be necessary to develop and implement new systems which will upgrade recycled papers without worsening their papermaking properties.

Understanding the causes of such inferior fiber quality in recycling is at the heart of a number of key operations in upgrading recycled fibers. Such findings point the way forward to probably effective methods that could bring about considerable improvements in recycled paper quality, thus diminishing the flow of waste streams to landfills, and thereby restrain excessive depletion of the for-

est resource by reducing the amount of virgin fiber required for maintaining paper quality for most grades.

Postulated mechanisms for loss of strength in recycled paper

The review of the literature on recycling of chemical pulps (1–17) clearly reveals that the losses in paper strength are brought about by loss of bonding or, in other words, a reduction in the resistance of bonds to an applied force. This is in agreement with previous reports (4, 7, 9, 15–17). On the other hand, the loss of bonding, could be a function of two parameters (9, 29): fiber flexibility and surface condition. Flexibility in this context refers to the wet-plasticity of pulp fibers. It is defined as the inverse of the product of the moment of inertia of the body and the modulus of elasticity of the material from which the body is made.

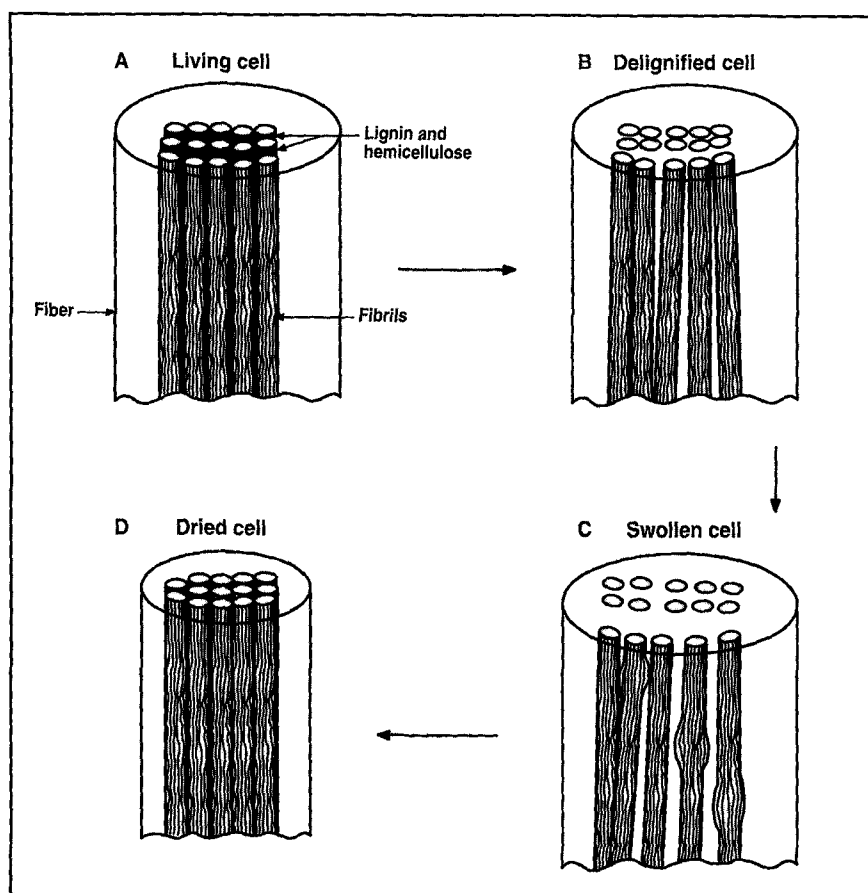
It is not yet certain why loss of surface condition or flexibility of fibers occurs during recycling. Furthermore, it has not been established which of the above factors in recycling

plays the major role in recycled paper strength loss. The following sections elaborate on these two parameters.

Fiber flexibility

The effect of drying of pulp fibers has been reported by many workers (30–35). The consensus is that the swelling capacity of fibers is lost, and irreversibility of their swelling property is increased with the level and duration of drying. This irreversible fiber swelling property is called the loss in flexibility of wet pulp fibers, or "hornification." The effect of drying on high-yield mechanical pulp fibers is minor (7, 35, 36). On the other hand, low-yield chemical pulp fibers show a progressively greater loss in recovery of associated water with the extent of drying (1–17, 20, 21, 36–45). The mechanism responsible for hornification has been the subject of a long debate and is not resolved satisfactorily, as yet.

Irreversible pore closure. The irreversible changes of cellulosic cell walls upon exposure to drying has historically been attributed to the closure of pores and cracks (38, 39, 42,



72). Thode *et al.* (38, 72) reported that the hornification is caused by the irreversible closing-up of micropores and cracks during drying.

Stone and Scallan (39, 42) carried out comprehensive studies on the effect of drying on the structure of the cell wall. Solute exclusion was used in characterization of the structural changes in the cell wall. It was observed that the large and intermediate size pores were reduced upon drying. This concept was also discussed by Jayme and Hunger (43). Hornification by both groups were defined as irreversible changes in the capillary system of the fiber cell wall. However, many questions remain still unanswered in the area of fiber science. For instance, no explanation is offered as to why the cell wall pores are lost and do not open again when

the fibers are rewetted (20). The effects of wood components, such as hemicelluloses, in the closing up of the pores were not detailed comprehensively. Furthermore, the solute exclusion technique suffers from some practical difficulties. For instance, the lower molecular weight polymer could be adsorbed easily on the fiber surface (46). Aside from this problem, molecules or particles in the size range 1000–10,000 Å are not easy to handle (47). These shortcomings could also cloud the final conclusions proposed for changes at the structural level.

Crosslinking. The auto-crosslinking hypothesis, as an origin of fiber hornification during recycling, was supported by several workers (48–55). Back and his co-workers (48–50) believe that natural aging or heating in an acid environment (ac-

celerated aging) of the paper mainly promote hemiacetal type crosslinking between cellulose and hemicellulose chains. Such bonds can restrict the swelling and make the fibers brittle.

Lundberg and de Ruvo (56), by examining the equilibrium moisture content of commercial never-dried bleached kraft pulp of 44% yield, concluded that the hindrance to swelling, after drying, in the fiber was not due to occurrence of crosslinking or the formation of sites inaccessible to water. The change in swelling was not reflected by changes in the equilibrium moisture content. Scallan and Tigerstrom (57) observed that, for low-yield bleached kraft pulp, the elastic modulus of the wet fiber is doubled during recycling. However, they could not attribute this change to any chemical mechanism other than increased hydrogen bonding between the microfibrils.

Cellulose chain cleavage. Paper acidity, which may be present in papers because of the processes or chemicals used in their manufacture, is a major factor in the hydrolysis of cellulose (58). Acid penetrates the open amorphous regions of the fiber and cuts the carbon-oxygen glycosidic bonds that link the glucose units in the cellulose chain (18). Oxidation, a reaction between oxygen and the cellulose unit, can break carbon-hydrogen bonds, as well as carbon-oxygen bonds (58). These reactions simultaneously liberate the portion of the fiber plasticized by humidity, lower the overall degree of polymerization, and make the fiber more fragile and more susceptible to breakage during subsequent beating (18). McComb and Williams (18) concluded that recycled fibers from alkaline paper behave more like virgin paper and can make better recycled products (Fig. 2).

Stockman and Teder (59) studied the effect of drying on the degree of polymerization (DP) of different chemical pulps. They did not observe any significant change on the DP of

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chemical pulps on heating in the range of 70°C to 140°C. The bleached kraft pulp, however, was very sensitive to temperatures exceeding 140°C.

Other factors have been observed to influence chain cleavage. Burgess (60) reported that tap water or calcium sulfate washed fibers exhibited less degradation after accelerated thermal aging (70°C, 50% RH, 70 days) than distilled-deionized water washed fibers. However, it is not certain to what extent chain scission of cellulose contributes to the embrittlement of fibers at regular conditions of commercial recycling.

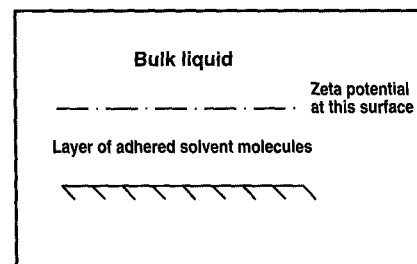
Reorganization in the fiber (cell) wall. Reorganization and co-crystallization of cellulose chains during drying, as a source of hornification, was discussed by some authors (62–68). Such possibility initiates from the fact that upon drying, bonding forces which develop are sufficiently large and regular to unite two or more crystalline regions as one (62), thus resulting in a swelling restriction in dried fibers (Fig. 3). This implies that, the possible increase in crystallite size and/or order in the fiber cell wall could be responsible for the hornification effect and consequently for brittleness and loss in flexibility of the recycled fibers. It is worth to mention that, the smaller the crystallite in the fiber wall, the larger will be the surface area capable of hydrogen bonding and, therefore, the greater will be the moisture sorption for a given weight fraction of polycrystalline material (69).

Clark (65) suggested that, when the fiber is dried, adjacent surfaces of cellulose and hemicellulose, previously separated, may come together. If parts of the areas coming into direct contact match sufficiently well in composition and orientation, they could well form additional crystallite zones and consequently restrict swelling on rewetting. This concept was also suggested by Peterlin *et al.* (66) and examined by

Ehrnrooth *et al.* (62) on paper recycling, in order to evaluate the possible co-crystallization of the fibers during recycling. The method which they developed was acetylation, by which recovery of fiber properties was enhanced after drying. This method was assumed to prevent co-crystallization of fiber crystallites during drying. However, the method thus adopted was indirect and did not allow formulation of accurate conclusions because acetylation at high degrees of substitution could convert the cellulose to a hydrophobic material with concomitant loss in bonding (70). Due to the possible induction of hornification by structural changes in the cell wall during drying, a systematic investigation is required. In fact, removal of lignin and hemicelluloses from the cell wall should make the fibers particularly vulnerable to such “secondary crystallization” taking place on drying.

Bond strength. A strong hydrogen bond is defined as a hydrogen bond in which both members of the H-bonded complex experience significant structural changes. Thus, when H-bonded complex in its minimum energy structure demonstrates a structure not too dissimilar to isolated monomers, the bond is called a “weak” hydrogen bond. According to this theory, weak hydrogen bonds are least firmly held and could be easily opened upon moisture uptake. Milichovsky (73) suggested two or three types of qualitatively different hydrogen bonds. He proposed that these different types of hydrogen bonds are responsible for oriented (crystalline), less oriented, and unoriented (amorphous) zones in native cellulose. It was suggested that (73) the reason water causes cellulose to swell rather than dissolve it, lies in the existence of strong hydrogen bonds in its oriented zones. However, this does not mean that the water does not penetrate the oriented zones without causing any substantial changes (73). Therefore, the ability to destroy hydrogen bonds

4. Diagram showing the adhering solvent layer on surface when a surface is submerged in a liquid



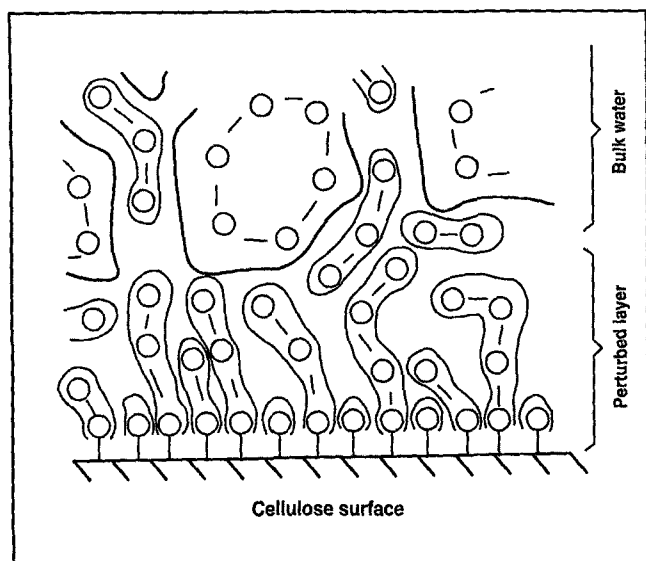
with water will depend not only on their strength but also on the nature of the hydrogen bonds. Higgins (71) interpreted the irreversibility of bonding on recycling to occurrence of stronger hydrogen bonds rather than recrystallization and/or co-crystallization. He proposed that existence of weak and strong hydrogen bonds are the basis of the whole question of recycling, and suggested that irreversible changes during recycling were brought about by the latter type of hydrogen bonds.

In general, elucidating the mechanical properties of paper from the existence of different types of bonding mechanisms has not been discussed thoroughly in the literature and remains speculative. Therefore, more extensive work will be required to substantiate why certain hydrogen bonds in cellulose H-bonding are stronger than others.

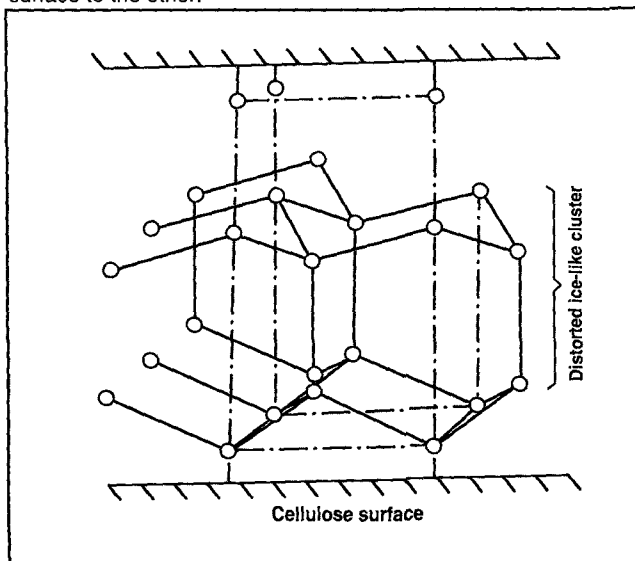
Surface condition of fibers

Theories in the field on the surface condition of fibers are diverse. They originate from observations on fiber surface accessibility and extend to the mutual relation of fiber and water. The investigations focus on relatively few fundamental problems relating to the surface condition of recycled fibers and fiber–water interactions. For instance, the presence of accessible hemicelluloses on fiber surface, and their abundance in the cell wall, enhance both fiber-to-fiber bonding and wet-flexibility of the fibers. Disappearance of these bonding agents, either through re-

5. Schematic cross-section of a broken hydrogen-bonded water near cellulose surface (112)



6. Schematic representation of the adsorbed water between two cellulosic surfaces (113). The network was demonstrated as a distorted ice-like cluster with extension of hydrogen bonds from one surface to the other.



distribution of fatty acids on the fiber surface or inactivation of the hydroxyl groups by any other mechanism during drying, may reverse the end-use performance of the recycled fibers. Surface conditions could also be affected by induction of microcompressions or a diminished surface area. It is also suggested that, perhaps, the formation of hydrophobic molecules is responsible for fiber surface inactivation. What happens to the surface bonding capacity of the fibers during drying should be established. Does the surface bonding capacity disappear from a fiber surface during recycling, or does the interaction with water create a shield around the bonding agents? Hypotheses in this field are abundant, but little is known on the real nature of the problem.

Hemicelluloses-loss effect. The role of hemicelluloses in the manufacture of strong paper sheets has been known to papermakers for a long time. The precipitation of hemicelluloses on the pulp fiber surface in the final stages of alkaline cooking improves the paper-forming properties of fibers. Precipitation of the hemicelluloses on the fiber sur-

face also occurs during beating (120). Thus, some authors attributed deactivation of fiber surfaces to the loss of hemicelluloses from the fiber surface. Simultaneous hornification on drying of fibers high in hemicelluloses was also observed (82).

Hillis (64) speculated that strength loss of wood is caused by hemicellulose losses or conversion during high-temperature drying. Meller (83) observed on drying fibers at high temperatures that the solubility of the hemicelluloses in alkali decreased substantially. These findings were also confirmed by Davis and Thompson (119) by heat treatment of different woods. Stamm (80) suggested that hemicelluloses in wood are converted to a furfural polymer at high temperatures, which has less affinity to swelling.

Eastwood and Clarke (29) proposed that the effects of recycling on the flexibility and surface condition of the fibers is possibly brought about by loss in hemicelluloses. They determined the loss of hemicelluloses quantitatively and considered them as an indicator for loss in fiber flexibility. Nevertheless, their results were not conclusive, because of the complicated behavior of hemi-

celluloses in the strength development of paper (74-77).

Indeed, it is possible to remove a certain amount of the hemicelluloses from the fiber matrix without any detectable changes in the strength of paper (77-79). That is so because hemicelluloses in fibers have an optimal concentration (77) at which maximum paper strength is obtained. Higher than that amount will not contribute to strength development, but it can inversely affect the strength properties of the paper (76) due to lowering the proportion of large molecule populations in the fiber cell wall. Therefore, such complexities in the behavior of hemicelluloses in paper strength development make formal conclusions regarding their effect on the surface properties of fibers more difficult.

Inactivation of the fiber surface.

It was suggested that aging and high-temperature drying cause the migration of extractives to the surface (110-115). The migration of fatty acids, or some extractive component, was suggested as a main cause of surface inactivation in dried cellulosic materials. Back (61) suggested that the loss in surface accessibility of fibers upon recycling is

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due to redistribution of fatty acids initially present in the pulp. Additionally, such effect may also originate from rosin size and resin acids which may have been added to the paper during the sizing operation. Nissan (81) confirmed this hypothesis, and added that these reactions occur very fast on the fiber surface at paper drying temperatures.

Troughton and Chow (116) did not find any correlation between fatty acid concentration and quality of wood surface. It was suggested that fatty acids have a catalytic role in the inactivation process (116).

A critical review of the literature on over-drying of wood and fiber was published by Christiansen (117). The review suggested that surface inactivation by heat-treatment or aging, caused basically by exudation of extractives to the surface, deactivated the fiber surface and prevented the surface from hydrogen bonding. The other mechanisms, such as reorientation of wood surface molecules and closure of large and intermediate pores in cell walls during drying, which reduce surface activation and decrease the internal bonding points, was also confirmed.

Reports (118) on mechanical pulps, in contrast with chemical pulps, did not show any distinguishable loss on bonding capacity of dried fibers. This does not coincide with reported data on wood. The disagreements could be due to the conditions of drying or many other parameters involved in defining the pulp and the process of recycling. Furthermore, the question remains as to the significance of surface inactivation during drying. If the reason is the migration of extractives to mask the fiber surface area, mechanical pulps should be more susceptible than chemical pulps. Therefore, larger reductions in fiber quality should be observed for mechanical pulps than chemical pulps. This is not the case in recycling. It seems more plausible, therefore, to state that, recycling mostly suffers from changes in the

fiber structure (stiffening) rather than changes in surface condition.

Microcompressions. It was suggested that recycling could cause microcompressions (15), which could alter the surface condition of the fibers. This expectation arises on account that the fibers shrink between 20% and 30% transversely and 1–2% longitudinally. Fiber length in paper has been observed to shorten by as much as 20% during drying (84–85). According to literature citations (86–88), sheets containing large proportions of longitudinally compressed fibers were found to demonstrate superior extensibility, high tear, and impact resistance, but reduced elastic modulus. These properties already contradict some of the findings reported on recycling. For instance, on recycling, impact resistance, stretchability, and elongation decreased and elastic modulus increased (4, 5, 12, 57). Furthermore, fiber length shortening has not been detected in recycling (89, 90). Therefore, the possibility of changes in occurrence and intensification of microcompressions in the fibers upon recycling must diminish considerably. There remains the question of permanency of microcompressions in recycled fibers.

Fiber-water interactions. For a breakthrough in the improvement of recycling, a detailed knowledge of fiber-water interactions is required. These interactions could be interpreted to dominate the role played by the fiber surface in defining the structure and properties of the water, as well as influence of water in imposing a structure on the fiber (73, 91, 95, 96, 98).

Studies on the properties of liquid water revealed that water is not a homogeneous solvent system, but rather it exists in a dynamic equilibrium between the ice-like and non-ice-like forms which are present in room-temperature water (109). (The term ice-like is used in describing the extent of hydrogen bonding in a liquid water at room temperature. It does not necessarily imply that

the associated water molecules have the tridymite-like arrangement of ordinary ice.) Indeed, the cellulose surface is very sensitive to this equilibrium (95) and can be influenced profoundly by the addition of any third component such as additives. Thus, the reactivity of any surface agents on fiber interfaces depends on the mutual effect of water on the property of the agent. The subsequent section will concentrate briefly on exploring the significance of proposed theories on fiber-water interactions.

The electric charge of paper surfaces in water. Many authors (92, 99–104) discussed the problem of fiber surface accessibility in terms of interfacial potential differences of fiber-water compositions. Generally, most substances acquire a charge when immersed in water and migrate under an applied electric field. This is usually interpreted in terms of an ionic double layer adjacent to the adsorbing surface. The zeta potential is defined as the potential at the surface between the freely mobile liquid and the liquid firmly adhering to the particle surface (92) (Fig. 4). According to the double layer theory, the thickness of the double layer should be reduced by the presence of electrolytes; consequently, the forces of repulsion will decrease and the potential for fiber surface adsorption will increase. Furthermore, at higher repulsion forces, a significant portion of the added fillers and some of the fines will disappear from the wire section and become part of the white water. The main drawback of this theory in experimentation results from the vague location of the plane of shear. Generally, zeta potential is useful in the case of massive particles with a well-defined impenetrable surface, but loses a good deal of its meaning with swollen gels (92). In addition, the electrostatic interactions are not the only forces governing the fiber-water interaction phenomenon (95).

Changes in water structure due

to fiber-water interactions. Mutual effects of fiber and water were discussed by different authors (91, 95, 96, 97, 105–107), but because of the complexity of the interactions, the subject is not well understood.

Goring (91) considers the problem of surface condition to be due to the changes in the hydrophobic bonding system in cellulose. It was suggested that in cellulose there is a hydrophilic and hydrophobic bonding system (73) and that, perhaps, changes in the hydrophobic bonding system play an important role in the formation of an irreversible fiber surface condition. Furthermore, by measuring the thermal expansion of cellulose in different states (i.e., wet and dry), he concluded that a carbohydrate surface disturbs the adjacent bulk water in such a way that cellulose acts as a structure breaker (96) (Fig. 5). This is actually the extension of Kauzman (93) and Nemethy and Scheraga's (94) work on proteins. The result of calculations of hydrophobic bonding in proteins confirmed that a considerable part of the free energy arose from changes in the water structure, whereby the van der Waals interactions themselves contributed only part of the total energy of formation of the hydrophobic bond (94).

The role of hydrophobic bonds in fiber-water interactions on the fiber surface condition was also emphasized by Dobbins (95). He suggested that the increase in flocculation of cellulose by rising temperature is only compatible with hydrophobic bonding, rather than hydrogen bonding, which is an exothermic process. Thus, he concluded that the addition of simple solutes to a cellulose-water system often produces effects that are difficult to explain in classical terms of coulombic association between positively charged ions and the negatively charged cellulose interface. He suggested that there is a third class of ions that have hydrophobic character, which could explain swelling un-

der neutral or alkaline conditions in terms of one unified mechanism.

The problem with hydrophobic bonding in cellulose remains speculative and arises from unknown sources of those bonds. For instance, 35–45% of protein is made up of nonpolar side-chains which have low affinity for water. In an aqueous environment, the nonpolar groups adhere to one another forming hydrophobic bonds (93–94), whereas the possible source of such hydrophobic bonds in cellulose is unknown. Nissan (108) questioned the method of evaluation of the interaction of cellulose surfaces with water by Goring. He proposed that a higher thermal expansion for cellulose might have resulted from its higher degree of freedom due to breaking down of its hydrogen bonding network in water. Caulfield (98) supported the idea that water near a cellulose surface is restructured by the cellulose surface rather than destroyed by it. He suggested that such a model cannot explain a fractional decrease in tensile modulus, which is constant up to the fiber saturation point on adding water to a moisture content equivalent to about eight layers of absorbed water (Fig. 6). Both Goring (91) and Caulfield (98) based their hypothesis on Frank and Wen's (109) "flickering cluster" theory in aqueous solutions. (The term flickering cluster is used to explain the cooperative nature of cluster formation and dissolution in a liquid water at room temperature, and it is governed by local energy fluctuations.)

Milichovsky (73) emphasized that the water molecules rather than the solute are the actual swelling agent. He concluded that swelling which occurred on beating is a result of the changes in the composition of the phase interface between the pulp and water medium rather than the structural changes in the fiber. This theory is based on the dipole nature of water molecules and on their two possible orientations in hydration

spheres. The enigma with Milichovsky's approach to the problem of cellulose swelling is in understanding the possible causes of different orientations of water molecules on the surface of the fiber.

It now appears that the bonding problems experienced in low-yield chemical paper recycling are due to a number of physico-chemical factors, of which the fiber-water interaction may predominate. More explicitly, the change in surface condition could not only be brought about by loss in surface accessibility of the fibers, but also by the changes in the nature and organization of the hydrophobic and hydrophilic bonding of the fiber-water vapor system.

Considerable work remains to be carried out in the area of fiber-water interactions as it may hold, at least in part, the key to resolving the problems associated with free surface inactivation in recycling and indeed papermaking itself.

Areas of further study

Some hypotheses which should be explored in this regard are as follows:

- What is the role of chemical components of mechanical pulps (hemicelluloses, lignin, extractives) in preserving the original physical properties of fibers? The process could be traced by gradual delignification of the cell wall and monitoring the changes in hornification and surface inactivation.
- What cell wall structural changes are responsible for hornification of fibers during recycling?
- Does the fiber amorphous phase experience any reorganization during recycling?
- Is there any secondary aggregation of crystallites during recycling?
- Is disappearance of internal or

external fibrillation of the fibers during recycling a major issue in manifesting the inferior properties of recycled fibers?

- Which parameter (fiber surface area or accessibility) undergoes drastic changes during recycling?
- What physico-chemical evolutions occur on the fiber surface during recycling of fibers?
- What is the impact of fiber-water interactions on fiber surface deactivation in recycling?
- Do fiber hydrophilic agents experience any changes in regard of reorganization as a result of fiber-water interactions?
- What is the feasibility of direct measurement of changing hydrophobicity of fiber surfaces?

Our laboratory is conducting some parallel experiments on evaluating some of these hypotheses.

Conclusion

The importance of this study arises from the view that the lack of scientific basis for explaining the causes of strength loss (bonding capacity) on recycling of fibers prevents papermakers from developing an effective method for upgrading and, indeed, widespread use of recycled fibers to avoid burning post-consumer paper as "nonrecyclable" or converting it into pulp and paper "sludge."

This review suggests that strength loss in recycling is brought about by the loss in flexibility and/or changes in surface condition of the recycled fibers by emphasizing hornification. It is plausible for the cell wall of chemical pulps (low yield) that drying, perhaps, creates new and more perfectly aligned lamellae through hydrogen bonds, as in crystalline cellulose. However, little information is available on the cause of these changes. In other words, any explanation for the cause of strength loss requires an understanding and eluci-

dation of structural evolution of the fibers and fiber surface inactivation during recycling. Furthermore, a comprehensive study of the surface inactivation of fibers requires the understanding of the phenomena related to both fiber surface and fiber-water interactions. **□**

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