Saturation technology for corrugated containers

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ABSTRACT: Saturation offers an attractive alternative to increased basis weights as a means to increase strength in corrugated containers. Changes in sheet physical properties on saturant addition indicate that the additives act as reinforcing networks, increasing strength without crosslinking the cellulose, thereby preserving the recyclability of the sheet. The development of saturants based on lignins will provide an economic means of extending fiber use and producing high-strength materials.

KEYWORDS: Additives, binary systems, binders, compression strength, container boards, corrugated boards, cost effectiveness, extenders, impregnation, lignin, mechanical properties, reinforcement, saturation, starch, water resistance.

Changes in packaging and distribution systems have led to performance-based standards for corrugated containers, especially with respect to compressive strength and the retention of strength and rigidity in humid conditions. Enhanced strength can be achieved in part by using heavier weights of linerboard and fluting medium, but this approach leads to wasteful use of fiber, higher conversion and transport costs, and a greater mass of waste for disposal. Industry and environmental pressures demand not only lower container weight in proportion to strength but also moisture resistance, liner printability, runnability on the corrugator, and recyclability, plus the use of recycled fiber in the original furnish. It is often difficult to reconcile these demands with papermaking techniques alone, but by using saturation techniques extra properties can be engineered into a standard base sheet.

Saturation has been practiced in corrugated manufacture for a number of years. In Europe and elsewhere, starch is added by means of a size press to improve stiffness properties in test liners and recycled fiber (RF) flutings (Concora, ring crush, etc.). In other markets, wax dipping is widely practiced to saturate the fiber matrix and give high moisture resistance to the container. Each of these methods has drawbacks. Unmodified starch addition alone does not generally improve compressive strength at high humidity. Wax-saturated containers are hard to recycle and do not have a pleasing external appearance at a time when container graphics are seen as an important part of brand image.

The work described in this paper was undertaken as part of a Pira multiclient study on polymer systems for performance improvements in corrugated case materials (CCMs), with the specific objective of identifying and developing cost-effective additive systems to enhance the strength and durability of corrugated containers (*1*).

Application techniques

The size press (**Fig. 1**) has been used for many years for starch application to RF materials. It is not usually found in kraft liner or semichemical fluting mills, where the inherent strength of the fiber used to be considered sufficient. The size press inevitably requires enhanced drying capacity and, in its simple twin-roll form, limits speed to about 800 M/min. Therefore, there is interest in off-line systems, where product could be brought in from different paper machines and saturated with various materials according to end use.

In devising our project, two constituencies were recognized among the sponsoring companies:

1. RF mills, where the prime interest was in the development of saturant systems for on-machine application by a size-press system
2. Virgin fiber mills, where the prime interest was in off-line saturation techniques.

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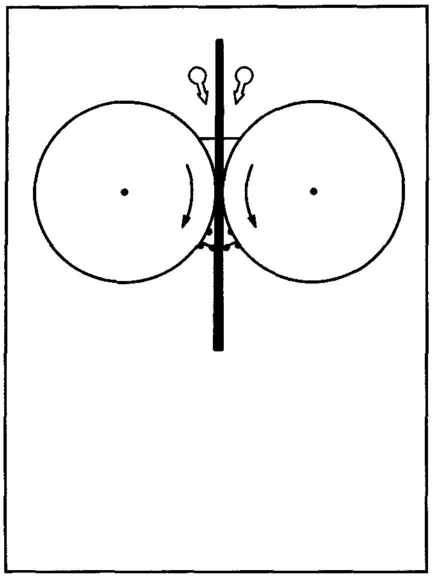
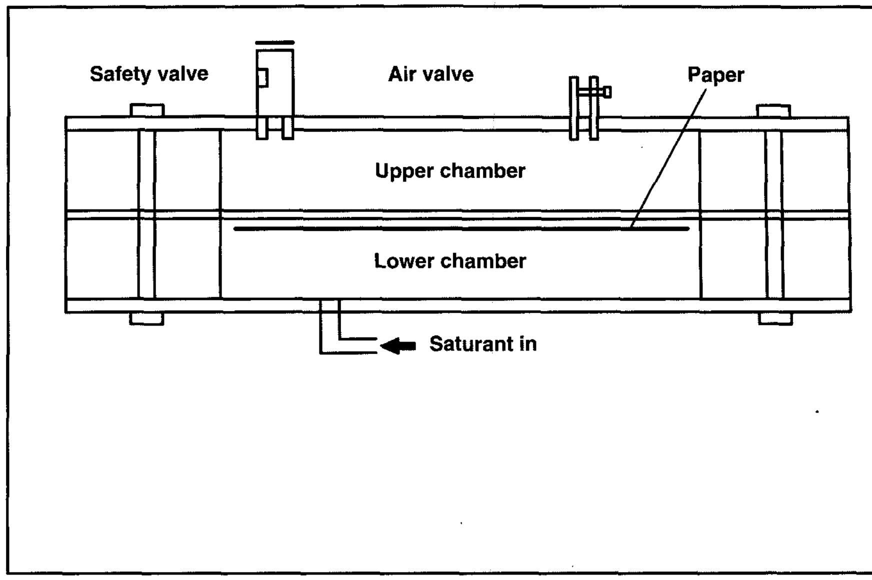
1. Size press



2. Cross section through pressure impregnation unit



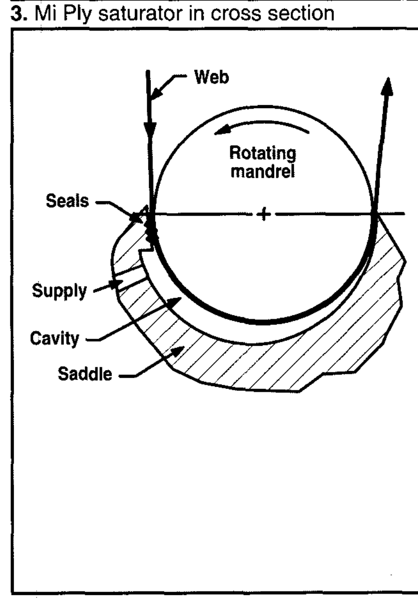
Experimental

The project program was organized at two levels: laboratory scale and pilot-plant scale. At the laboratory level, base paper samples were dip saturated, passed through metering rollers, and dried under restraint on a felted steam cylinder for 2 min at 95°C. The papers were conditioned at 23°C and 50% RH or at higher humidities for 24 h before physical testing. A variation of this technique was to apply the saturant in a pressurized container rather than a dip bath. Here the saturant was applied through the paper sheet from below (**Fig. 2**) before the liquid pressure was increased. In this way, air could be displaced from the sheet by the saturant before pressure was applied.

The pilot-scale trials were conducted at Vits Maschinenbau, Langenfeld, Germany, and utilized a conventional twin-roll size press in comparison with a hydrodynamic saturator linked to the same drying section (heated cylinders). The saturator was of the type developed by Mi Ply Equipment Inc. (**Fig. 3**) and relies on the hydrodynamic pressure generated between the rotating mandrel and the walls of the shoe cavity of diminishing cross section (*2*). Air is forced out of the sheet into grooves on the mandrel surface and is released as the sheet exits the seals at the tip of the shoe. This air release factor is an important advantage over the conventional size press in which the liquid is forced into the sheet from both sides, trapping the air within and causing it to impede penetration of the sheet interior by the saturant.

Recyclability was measured by repulping saturated papers in a British standard laboratory pulper at 1.5% consistency. Handsheets were made from the fiber, and the speck count was determined using the TAPPI dirt estimation chart (TAPPI Test Method T 437 om-90).

3. Mi Ply saturator in cross section



Results and chemistry development

The following saturants were tested as single additive systems: acrylic copolymers, polyvinyl alcohols, styrene–butadiene rubber lattices, aliphatic polyurethanes, thermosetting resins, and various naturally derived materials including starch, cellulosic ethers, lignosulfonates, and lignin dispersions. These materials were applied to the following base sheets; 150-g/m^2 kraft liner, 128-g/m^2 RF base sheet (no starch), 112-g/m^2 RF fluting, and 108-g/m^2 semi-chemical fluting. The increase in strength properties was measured as short-span compressive strength (SCT) and expressed as the ratio of percent strength increase over the control value to the percent add-on (dry basis) of chemistry to fiber. The SCT values were measured at both 50% and 95% RH to provide an index of strength retention at high humidity.

For the kraft liner and RF liner base sheet, two of the more effective chemistries were found to be a 95% hydrolyzed polyvinyl alcohol and a sty-

I. Strength increases with linerboards

Polymer	*Paper*	*Percent add-on*	*Percent increase in CD SCT index*		*Ratio of percent strength increases to percent add-on*	
			50% RH	*95% RH*	*50% RH*	*95% RH*
Polyvinyl alcohol	Kraft	2.0	20	<10	10.1	...
Styrene–acrylic	Kraft	8.2	39	42	5.1	5.1
Polyvinyl alcohol	RF base sheet	3.0	38	26	13.1	9.1
Styrene–acrylic	RF base sheet	7.2	50	35	7.1	5.1

II. Strength increases with fluting mediums

Polymer	*Paper*	*Percent add-on*	*Percent increase in CD SCT index*		*Ratio of percent strength increases to percent add-on*	
			50% RH	*95% RH*	*50% RH*	*95% RH*
Polyvinyl alcohol	RF	4.4	74	<10	17:1	...
Styrene–acrylic	RF	7.1	50	20	7:1	3:1
Polyvinyl alcohol	NSSC	3.0	53	98	17:1	33:1
Styrene–acrylic	NSSC	4.5	35	<10	8:1	...

rene–acrylic emulsion polymer with a glass transition temperature (Tg) of 52°C and minimum film forming temperature (MFT) of 40°C (**Table I**).

The polyvinyl alcohol gave the highest dry-strength increase to pickup ratio, but its solution viscosity limited the add-on achieved. It gave substantial increases in the moist (95% RH) compressive strength of the RF base sheet but was less effective on the kraft liner. The styrene–acrylic was less efficient than the polyvinyl alcohol but could be applied at higher solids, giving a greater net strength increase over the untreated control. Breaking length was increased in proportion to SCT in all cases.

When the solutions were applied to the fluting samples, the polyvinyl alcohol did not increase retention of compressive strength at high humidity with RF fluting, but it did give a considerable increase to the semi-chemical material (**Table II**). The styrene–acrylic improved compressive strength retention with the RF fluting but not the semichemical material. Clearly the selection of a saturant chemistry will be heavily influenced by the chemistry of the fiber, especially surface energy effects. With the semichemical material, better results were obtained when an ethylene acrylic acid copolymer (Tg 38°C) was substituted for the styrene–acrylic. The ethylene acrylic copolymer gave an 81% increase in SCT index at 95% RH with 10.2% pickup; the styrene–acrylic showed no significant improvement at high humidity.

It was evident from these examples and others in the study that synthetic polymers had the potential to increase compressive strength at both ambient and high humidities. Starch, the traditional additive for RF grades, could not improve compressive strength retention at high humidity, being itself hygroscopic. For example, 3% of a thermochemically cooked cornstarch applied at 5% solids to an unsized kraft base sheet gave an increase of 15% in SCT values at 50% RH, but no increase in SCT values at 95% RH. However, in view of its lower cost, starch will retain its importance where only dry-strength increases are required. Fiber addition could raise SCT by only 1–2% per 1% of fiber added and, therefore, would be less efficient than a saturant.

The next stage in the investigation was to see if the cost of the synthetic saturants could be reduced by mixing them with inexpensive extenders such as starch, lignins, or lignosulfonates. The starch or lignosulfonate–acrylic blends gave good increases in dry compressive strength but poor retention at high humidity. Mixing the acrylic resins with dispersions of lignins from kraft and solvent pulping production gave very good retention of SCT at 95% RH (**Table III**). The ratio of lignin to polymer was 2:1 (actual solids). The lignin dispersions were produced by dissolving the lignin in acetone and reprecipitating with ammonia prior to addition of the ammonia-stabilized styrene–acrylic emulsion. (Acetone is a toxic and flammable solvent and should only be used with the appropriate

III. Strength increases with lignin-derived saturants on a RF liner base

	Percent add-on	Percent increase in CD SCT index 50% RH	Percent increase in CD SCT index 95% RH	Ratio of strength increase to add-on 50% RH	Ratio of strength increase to add-on 95% RH
Kraft lignin mix	13.7	103	112	7:1	8:1
Solvent pulped lignin mix	19.5	120	94	6:1	5:1

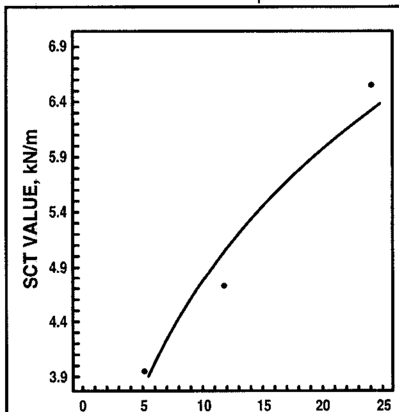
IV. Effects of additives on retention of compressive strength at high humidity

Base sheet	Polymer	Percent pickup	CD SCT index, Nmg[1] 50% RH (a)	CD SCT index, Nmg[1] 95% RH (b)	Percent ratio of b to a
150-gm^{-2} kraft liner	Styrene–acrylic	8.2	27	9.4	35
127-gm^{-2} base sheet	Lignin + Styrene–acrylic	13.7	31.5	12.5	40
RF fluting	Styrene–acrylic	7.1	18.4	6.4	35
NSSC fluting	Polyvinyl alcohol	3.0	28.9	11.5	40

V. Effect of styrene–acrylic polymer addition on MD:CD ratio at 50% RH

Base sheet		MD:CD ratios SCT	MD:CD ratios Elastic modulus
Kraft liner	Treated	1.8:1	1.6:1
	Untreated	1.9:1	2:0
RF Base	Treated	1.4:1	1.6:1
	Untreated	1.6:1	2.6:1
RF Fluting	Treated	1.5:1	2.4:1
	Untreated	1.8:1	3.0:1
NSSC Fluting	Treated	1.5:1	1.3:1
	Untreated	1.7:1	2.5:1

4. CD SCT at 50% RH vs. percent add-on



safety precautions as recommended by the chemical supplier.)

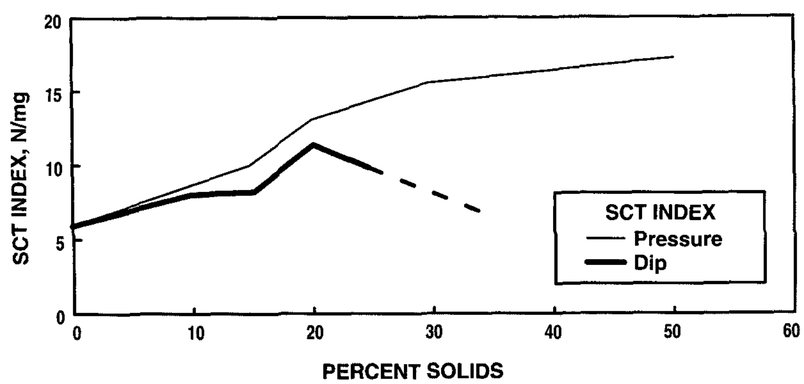
The lignin-acrylic mixtures were found to be more effective than the lignins on their own, when prepared by the same means, and more cost-effective than the acrylics alone. Subsequent privately commissioned work showed that very good strength retentions could still be obtained with lignin–acrylic ratios of 4:1 or more. The key to the commercialization of this process would appear to be the production of lignin dispersions of very low particle size and the correct surface chemistry. Acetone–ammonia treatment is not recommended on a commercial scale. Binders other than acrylics might also be used. Cross-linking systems, particle size, and surfactant formulation would have a significant influence on their performance.

Application techniques and effects

From the many results obtained with different saturant chemistries, a number of common observations were made which held true despite differences in saturants and base sheets:

- The retention of compressive strength was generally 35–40% of the value at 50% RH for the treated sheet. This was broadly true whether the increases in the "dry"-strength value were 20% or 120% over the control (**Table IV**).
- The MD:CD ratio of SCT generally declined with increases in strength and add-on (**Table V**).
- The ratio of percent increase in SCT to percent increase in add-on always reduced with higher add-on (**Fig. 4**). The examples shown in Table V and Fig. 4 were from a RF-liner base paper treated with the 50°C Tg styrene–acrylic.

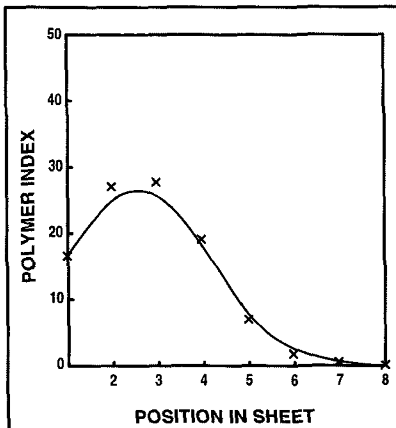
5. SCT index at 95% RH vs. solution solids



VI. Comparison of size press and pressure impregnation unit during pilot-scale trials (70 m/min)

Treatment	Percent add-on	Testing, % RH	SCT index increases Nm/g[1]	%	Ratio of percent strength to percent add-on
Size press	10	50	5.2	39	4:1
		95	0.9	16	<2:1
Mi Ply	16	50	11.2	84	5:1
		95	3.7	69	4:1

6. Polymer distribution through the sheet



These observations relate strength increase to add-on but say nothing direct about the effects of saturant distributions in the base sheet. There are two aspects of saturation: micro-scale distribution of chemistry between voids, fiber wall, and crossover points and macro-scale distribution in the z-direction of the sheet structure. In the micro-scale, the penetration of the fiber wall and crossover points was thought to be related to the pressure of application. Static laboratory experiments showed that pressurized application tended to give greater increases in SCT than dip bath impregnation. This was apparent for the compressive strength retention at 95% RH (**Fig. 5**) with the RF liner base and the styrene–acrylic saturant. Pressure impregnation also enables much higher solution solids and viscosities to be used, and this equates to lower moisture content and less drying energy in a full-scale plant.

While fiber-wall penetration could not be authenticated in relation to pressure, subsequent pilot-plant trials confirmed the benefits of pressure saturation in a comparison between a twin-roll size press and a Mi Ply pressure impregnation unit. On a 127-g/m² RF base sheet with the 50°C Tg styrene–acrylic, the Mi Ply unit gave not only greater add-on but also greater efficiency, manifested as percent strength increase to add-on ratio (**Table VI**) at 30% solution solids, especially at 95% RH.

Similar benefits also were obtained at 10% solution solids with the same base sheet. When the experiment was repeated with an RF-fluting base sheet, the Mi Ply unit gave higher net strength increases and add-ons than the size press, but at marginally lower strength to add-on ratio, indicating that base-sheet chemistry interactions were important at lower solids levels.

The determination of the polymer distribution within the sheet at the micro level proved impractical, but the macro, z-direction distribution was successfully measured through the sheet by sheet sectioning and X-ray elemental analysis with a scanning electron microscope. This gave a characteristic skewed Gaussian curve for a Mi-Ply-treated sheet with the peak nearest the side of polymer entry (**Fig. 6**). This suggested that the saturator was operating below optimum speed and not generating sufficient hydrodynamic pressure. It was proved that the line was dryer limited by comparing results for the customary 50°C Tg polymer with a 34°C Tg polymer having an MFT of 0°C. This provided better wetting of the fiber and greater strength increases at limited temperatures. The dryers, rather than mechanical constraints, limited line speed and hydrodynamic pressure.

In a later series of trials, the effects of basis weight upon hydrodynamic saturator performance were evaluated using kraft liners of the same origin but different basis weights. The 50°C Tg styrene–acrylic was used as the saturant at 70 m/min line speed (**Table VII**).

The results showed that the higher grammage, more resistant sheet gave an increased efficiency in polymer use as a greater internal pressure gradient was built up across the thickness of the sheet.

Information obtained through regression analysis of additional trial data showed that at speeds below 120 m/min solution solids and basis weight were more important than speed in determining polymer add-on and strength increase. At higher speeds (i.e., 200 m/min^{-1}), the speed itself should have been the more important variable. The interactions between speed, basis weight, and solution solids are complex and will need further matrix experimentation to clarify them.

VII. Comparison of high- and low-grammage sheets

Sheet type	Percent add-on	SCT index strength increase Nm/g^{-1}	SCT index strength increase %	Percent strength to percent add-on ratio
400 g/m² kraft	4.2	6.5	39	9:1
125 g/m² kraft	11.1	7.5	40	4:1

Discussion

The laboratory work showed that significant increases in moist and dry compressive strength could be attained with the addition of acrylic and vinyl copolymers to both recycled and virgin CCMs. This was confirmed by pilot trials which showed that base sheets up to 400 g/m² could be successfully treated on a continuous basis. The question then arises about how the saturants exert their effect. There are three possible mechanisms:

1. Provide strong covalent bonds between cellulose chains to inhibit swelling and reinforce interfiber bond.
2. Encase the whole fiber network in a moisture-proof barrier layer.
3. Provide an internal reinforcing network which distributes the compressive tensile loading forces more evenly within the sheet.

The "reinforcing network" theory was the one most favored and was supported by three pieces of evidence:

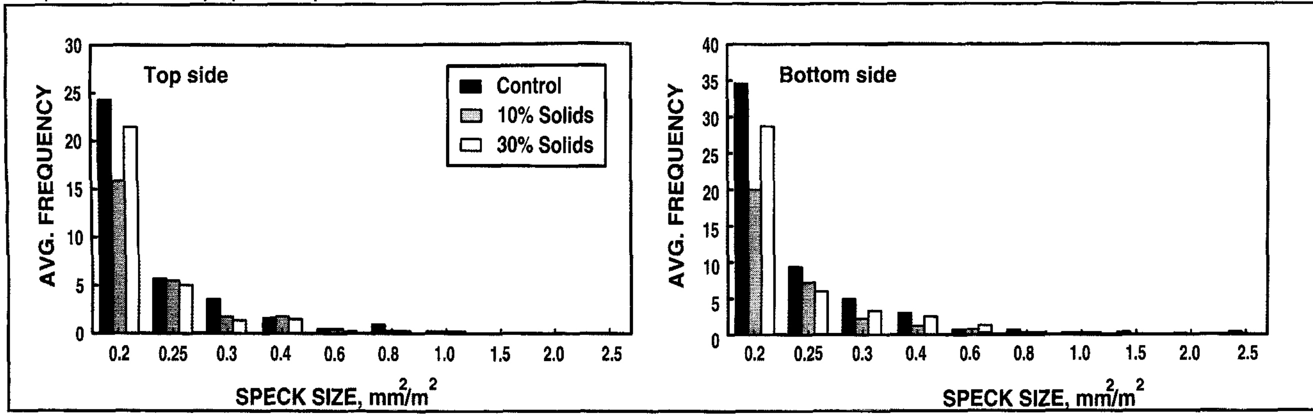
1. The nearly constant ratio between SCT values at 50% and 95% RH indicate that the increase in strength retention at high humidity was chiefly related to the increase in "dry" compressive strength and not to any independent mechanisms such as cellulose crosslinking. If crosslinking had taken place, then the increase in SCT values at 95% RH could have been up to 100% of the increase in values at 50% RH and not ~40% as observed.
2. The reduction in MD:CD ratio with saturation indicates that the fiber orientation becomes less important in the load bearing properties of the sheet as add-on increases; the fiber is "sharing" the load with the external reinforcement of the saturant.
3. The decline in the strength increase to add-on ratio with increasing add-on is characteristic of a system in which property improvement tails off as the available sites in the fiber matrix are filled up by saturant.

This last point underscores the necessity for securing uniform distribution of the saturant through the sheet to get the greatest economic benefit from saturant addition. One of the advantages of a hydrodynamic saturator over the conventional size press is its ability to secure penetration at high solution solids and basis weights. The importance of distribution effects also underscores the weakness of treating the saturation process simply as one of densification. The denser a material, the greater its stiffness. However, paper is not a simple planar material but a complex three-dimensional network, and any mathematical model must include terms representing the distribution of the saturants between fibers and voids.

It may be possible to manipulate the *z*-direction distribution of additive with the Mi Ply to alter the balance between the strength properties, i.e., to change the relationship between SCT, RCT, tensile, burst, and folding properties. This aspect has not been rigorously explored. It also may be possible to "steer" the polymer away from the outer surfaces of the liner to preserve flexographic print quality or corrugator glueability, or both. Opportunities will exist for improvement of saturant efficiency by distribution control. At add-on levels above those likely to be economical, the strength increases will tail off as excess saturant simply becomes a void filler and plays little part in load distribution once the main saturation sites have been filled up.

Apart from optimizing distribution in the paper web, the other obvious means of cost reduction is to formulate a cheaper saturant. The acrylic–lignin combinations are an excellent example of how, by building on the

7. Speck count for repulped samples



simple binary concept of water-resistant resin plus extender, a cost-effective saturant system can be developed to compete with fiber addition as a means of strength improvement. It has the added merit of utilizing pulping by-products (the "whole tree concept") such that a greater area of corrugated board, at constant compressive strength, could be obtained per ton of wood consumed through lowering the basis weight and substituting lignin saturants for fiber to maintain strength. Thermoplastic acrylic or vinyl resins as saturant binders would ensure good flute formation because they soften readily when heated beyond their glass transition temperature.

The Tg and MFT values that can be run in a saturant system are limited by the drying temperature attained in the paper. If the polymer is not raised beyond its MFT it cannot spread and bond effectively to the fiber. Low strength increases will result. Hence, the polymer MFT must be related to the drying cycle of the saturation line (*3*).

Drying temperature and duration can have a significant effect on the movement of liquid saturant within the sheet. High initial drying rates, which could draw the saturant back toward the surface, are best avoided since over-drying could undo the beneficial distribution achieved at the saturator. In webs of high basis weight, drying energy might be beneficially exploited to draw the saturant further into the fiber matrix. There is plenty of room for experimentation here.

An advantage of the reinforcing-network-type saturant over a cellulose crosslinking system is the ease of repulping. The fiber can be easily dispersed (**Fig. 7**) without the major clumps or specks associated with thermosetting "wet-strength" resins. Good corrugator runnability also can be obtained, provided that care is taken with respect to saturant distribution (avoid concentration at the surface) and surface chemistry. Factors such as surface compressibility and thermal mass of the CCMs also will be important. These aspects are currently under investigation in a multiclient study at Pira and will be reported at a later date.

The SCT test samples cover a small area of the entire treated web. The inevitable local variations in formation, web density, and absorbency will influence variance of the SCT result, typically ± 8% of the mean results at 95% confidence intervals. In the corrugated board, the weaker areas of the liners or medium are supported by stress distribution in surrounding stronger areas, so the SCT test may be an unfair estimate of the strength increases achievable in the corrugated board as distinct from its components. The final justification for saturation must lie in the performance of the container, and we hope this is where future work will lead.

From economic calculations made during the project, application costs for an off-line system were estimated at about 25% of the polymer cost. This indicated that a binary system would need a lignin-to-acrylic ratio of 4:1 to be economical. Further work needs to be done on chemistry optimization, but higher lignin-to-acrylic ratios with good strength properties are certainly possible. Binder chemistries based on starch rather than lignin are an alternative route to development. The thermochemically oxidized cornstarch used in the project had little moisture resistance, but there may be other starch types that have better resistance to moisture. Likely contenders include high-amylose starches, cyanoethyl starch, and dialdehyde starch with crosslinker. We hope to examine these possibilities in future work.

Conclusions

Saturation techniques offer reliable and effective means of increasing the moist and dry compressive strength of corrugated container materials.

Gains in strength of 40% in short-span compression can be obtained at low saturant add-ons; increases of over 100% are possible.

The most cost-effective chemistries are likely to be binary systems based on a moisture resistant, thermoplastic binder and a cheap extender, especially lignin or possibly a modified starch.

Saturant addition may be made with a conventional size press on- or off-machine, but the best available method is a hydrodynamic pressure saturator, which has the potential to handle higher saturant viscosities and solids and higher basis weights than the size press, with better control of distribution.

The development of saturant technologies for corrugated case materials offers opportunities for saving fiber while maintaining container strength. This would allow mill output to be effectively expanded, without the cost of new paper machines, by erecting a saturation line to compensate for the reduced basis weights necessary to increase speed and output. Saturation also would enable increasing amounts of recycled fiber to be used without compromising sheet performance. In addition, it opens new opportunities for higher-value products incorporating features such as delayed stiffness (on corrugator crosslinking for stiffness), fire retardancy, electrical conductivity, and high water resistance to allow corrugated board to compete with other materials for electronics packaging, military stores, construction products, bulk liquid and powder distribution, etc.

Saturation with the appropriate chemistries can give producers greater recyclability than wax dip and, by reducing basis weight, can reduce the volume of waste for disposal. Saturation can use renewable raw materials as major constituents of chemistry formulations.

Apart from saturant chemistry, there are opportunities for further research in application techniques, especially speed-viscosity-basis weight and penetration studies. In addition to off-line techniques, there is the idea of adding saturants at the press section, using vacuum boxes to draw chemistry into the sheet from a fountain applicator head. If developed, this could lead to the unification of saturation with press consolidation and hot pressing as a means of generating unique physical properties in CCMs. TJ

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