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HANDSHEET AND PILOT MACHINE RECYCLING DEGRADATION MECHANISMS

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Synopsis Selected results are presented of new detailed experiments on progressively recycling virgin pulp in the form of handsheets and machine made paper. Laboratory beaten pulp has been made into handsheets, re-disintegrated and remade (1) over four recycles with rosin/alum sizing and touch up beating to maintain freeness, and (2) over three recycles without sizing or further beating. The same beaten pulp was made into paper on a pilot paper machine and remade over three cycles.

The work has shown clearly that, in the experiments, pilot machine recycling caused much smaller changes of sheet properties than is the case for handsheet recycling. However, the trends of change as recycling progresses are similar and it is likely that the same basic mechanisms are responsible. Differences of stock preparation and differences of formation make distinct contributions to the differences between handsheet and machine recycling. Changes in the chemical composition of the fibres occur during recycling and these were found to be more pronounced in the second handsheet recycling experiment than in the pilot machine trial. Loss of bonding strength is clearly related to a reduction of wet plasticity of the fibres. Machine recycling results support the handsheet data in suggesting a strong possibility that changes in fibre surface condition play an important part in loss of bonding strength, particularly at the first remaking.

1—*Introduction*

SURVEYS and forecasts by the FAO, CEPAC and others show that present trends of increasing prices and reduced availability of pulps will continue until the late 1980's. UK imports in 1976 cost approximately £458 million per year. Wastepaper is potentially available in large amounts and, if new uses are found, it could replace imported pulp. A recent PIRA survey for the UK estimates that 700 000 tonnes of pulp per year could be substituted by wastepaper if the collection and technical utilisation problems could be solved. In the past, effort has been directed towards the effective defibring and removal of contraries from wastepaper and the de-inking of

Under the chairmanship of M. I. MacLaurin pulp from wastepaper. However, because some of the strength properties of recycled wastepaper are inferior, a number of investigators have, more recently, sought a better understanding of what happens to a papermaking fibre on repeated remaking.

The first systematic investigations were published some years ago by Pfaler(1) and Brecht.(2) More recently, the effects of recycling on handsheet paper properties were measured at constant freeness level for an unbleached kraft pulp(3) and for an unbleached sulphite pulp.(4) Handsheet properties of different recycled pulps have been compared at equal density.(5) The effects of recycling different pulps, using constant freeness and breaking length as reference points, have been studied.(6) The effect of remaking never-dried American pulps(7) and laboratory and commercial Scandinavian pulps has been investigated.(8) Results have been presented(9) of experiments in progressively recycling a newsprint furnish in the form of handsheets and machine made paper. A study has been made(10) of the effect of repeated recycling on the strength properties of corrugated containers using a pilot paper machine. An investigation of the influence of pilot machine recycling on the suspension and paper properties of bleached pine and birch sulphate and spruce and beech sulphite pulps has been published very recently.(11)

These investigations showed that progressive loss of tensile and bursting strengths on the repeated remaking of paper were accompanied by some improvements in desirable properties such as bulk and opacity. The fall off of strength properties of mechanical pulp were not as great as the strength losses for chemical pulps. Only small changes in the fibre length of pulps after the initial beating, were observed. The strength loss on recycling was primarily due to a decrease in bonding rather than to fibre strength. The greatest loss in strength properties, specific surface and degree of swelling of the various pulps occurred at the first recycle. Losses between subsequent recycles were less. The strength reductions could be compensated for to some extent by refining of the recycled pulps which improved the strength of the sheet, but increased the drainage resistance of the fibres.

2—*Outline of previous PIRA work*

Two previous experiments used laboratory beating and handsheet methods to investigate the effects of recycling. A virgin semi-bleached kraft was beaten and made into handsheets with recirculation of the sheet machine water to retain fines. Handsheets were cylinder dried and at each cycle the handsheets were disintegrated and remade over three or more cycles.

These were two distinct experiments. For the first experiment the stock was rosin/alum sized and given a touch up beating as required to maintain freeness at about 310 Canadian Standard Freeness. The sizing and cylinder drying simultaneously provided acidity and moist heat; the factors most likely to cause degradation.

For the second experiment, there was no touch up beating or sizing. This provided a less complex set of conditions more suitable for elucidation of mechanisms of the strength loss on recycling. Evaluation was in terms of handsheet properties, stock properties and selected fibre properties.

The first experiment gave results similar to those published elsewhere. From an analysis of the results of the second experiment, two mechanisms are thought to explain the bonding strength loss which occurs on recycling and these mechanisms are explained in more detail later.

3—*Objectives of the machine recycling experiment*

IT is a normal method of working to move from handsheet experiments to pilot machine trials and then on to production machines. One(9) of the two pilot machine experiments published at the time that this work was undertaken, indicated that pilot machine recycling causes little or no strength reduction. Consequently this raised the possibility that handsheet work in recycled fibre research could be misleading. Because the complementary PIRA research project 'Laboratory Upgrading of Wastepaper Fibres' uses handsheet methods in its work, it was imperative that PIRA carry out a recycling experiment on a pilot paper machine to compare handsheet and pilot machine recycling regimes and to relate all appropriate findings to work aimed at improved utilisation of wastepaper and upgrading of recycled fibre.

4—*Outline of the machine recycling experiment*

THE pulp used for the pilot machine recycling experiment was the same brand of semi-bleached kraft which had been used for the handsheet recycling experiment.

Paper was made on the University of Manchester Institute of Science and Technology paper machine. 'Joutseno' semi-bleached kraft pulp was disintegrated in the Black Clawson hydrapulper until the fibres separated and then beaten in the number 2 beater until the °SR increased from 16 to 46. Addition of 1 per cent dry 'Pexol' size and 1·5 per cent alum (based on oven dry fibre) brought the pH from 6·0 to 4·0. The UMIST paper machine is a conventional Fourdrinier of 500 mm deckle. All the runs in the recycling experiments were made with the same machine control settings and conditions which are set out in Table 1.

TABLE 1—MACHINE CONTROL SETTINGS AND CONDITIONS FOR THE MACHINE RECYCLING EXPERIMENT

Flow box consistency	0·5%								
Wire speed	13·7 m/min								
Wire shake	6 mm at 4·6 Hz								
Suction box pressure	180 mm Hg								
Press nips (2 presses)	11 kg/cm								
Dryer number	1	2	3	4	5	6	7	8	9
Cylinder Temp. °C	71	83	93	100	102	70	111	110	110
Machine calender nip	By-passed								
Sheet grammage	80 g/m^2								

The machine settled down after half an hour's running and samples were then taken. In the successive recycling runs, paper made was repulped until the fibres separated using identical pulping conditions at 5 per cent consistency. This pulp was then treated with the same quantities of alum and size without further beating before remaking the paper. The paper was repulped and remade for up to three papermaking cycles.

Monitoring and evaluation of the trial included measurements of physical properties of both machine made paper and British Standard handsheets(12) made from the machine stocks. Stock properties were measured and chemical analysis of the machine made paper and the wire water was carried out for each cycle.

In the following tables, the nomenclature is: D = Stock disintegrated only; 0 = 1st making (virgin fibre); 1, 2 and 3 = 1st, 2nd and 3rd remaking from Cycle 0.

5—*Results of the machine recycling experiment*

THE physical properties of the machine made paper are shown in Table 2

TABLE 2—PROPERTIES OF THE MACHINE MADE PAPER. TESTING AT 23° C: 50 PER CENT R.H. ALL INDICES CALCULATED ON AIR DRY GRAMMAGE

Property	*Cycle* 0	1	2	3
Bulk(13) cm^3/g	1·48	1·58	1·62	1·63
Geometric mean breaking length(14) km	5·91	4·88	4·65	4·47
Geometric mean tear index(15) mN/g/m^2	14·0	14·8	14·5	14·3
Burst index(16) kPa/g/m^2	3·31	2·91	2·69	2·49
Geometric mean Kenley Stiffness(17) mN	6·4	6·8	6·4	6·4
Bendtsen air permeance ml/min	163	254	295	350
Scattering coefficient(18) m^2/kg	16·2	17·7	18·0	18·3
Absorption coefficient(19) m^2/kg	1·02	1·02	1·01	1·08

TABLE 3—PROPERTIES OF HANDSHEETS MADE FROM THE MACHINE STOCKS

	Cycle				
Property	*D*	0	1	2	3
Bulk cm^3/g	1·68	1·37	1·47	1·53	1·52
Breaking length km	4·19	7·70	5·95	5·71	5·59
Tear index $mN/g/m^2$	12·7	11·3	11·7	12·0	11·5
Burst index $kPa/g/m^2$	2·59	5·46	4·40	4·02	3·84
Kenley stiffness mN	4·32	3·24	3·53	3·14	3·82
Bendtsen air permeance ml/min	725	43	100	134	125
Scattering coefficient m^2/kg	16·4	15·0	17·3	17·5	18·1
Absorption coefficient m^2/kg	1·10	1·42	1·39	1·34	1·34

and the physical properties of the handsheets from the machine stocks in Table 3. The strength properties of the machine made paper in Table 2 are given as the geometric mean of the properties in machine and cross directions so as to compare these properties with those of the handsheets.

The stock property and short span tensile test results are not presented in detail. The results of the chemical analysis are given later.

6—*Discussion of the results of the machine recycling experiment*

THE main results of the machine recycling experiment show substantially the same trends as the laboratory handsheet recycling experiments. Loss of tensile and bursting strengths are accompanied by some improvements of desirable properties such as bulk and scattering coefficient. The patterns of change of all eight properties given in Table 2 on progressive recycling are consistent in two respects: the biggest change takes place at the first make and the trend of change is opposite to that shown by increased beating.

In handsheet recycling experiments carried out by PIRA and other workers, reductions of tensile strength have generally been accompanied by increases in tear strength. No equivalent changes are indicated from the tear index data presented in Table 2 and it seems that in this experiment tear strength is not affected by machine recycling. As found by other workers,[(11)] the short span tensile test results showed machine recycling caused no reduction of fibre strength and that all reduction of tensile strength was caused by loss of bonding strength.

All the stocks of the remakings were found to be just slightly slower draining than the first making, but under these conditions recycling had no major effects on machine runnability. Bauer McNett data[(20)] indicated that, as recycling progressed, the percentage of long fibre fraction decreased and the percentage of fines increased, but these fines were not retained in the sheet.

The weighted average fibre length[21] showed only a modest shortening from 1·47 mm at cycle 0 to 1·41 mm at cycle 3.

Changes taking place during pilot machine recycling are nothing like so great as the changes that occur during a handsheet recycling regime. This is made clear by Table 4, in which the relative breaking lengths for progressive recycling of the machine made paper, handsheets from the machine stocks and handsheets from the stocks of the second laboratory recycling experiment are presented.

TABLE 4—RELATIVE BREAKING LENGTHS km OF THE MACHINE MADE PAPER AND HANDSHEETS FROM MACHINE AND LABORATORY STOCKS

Regime	*Cycle* 0	1	2	3
Machine made paper	5·91	4·88	4·65	4·47
Handsheets from machine stocks	7·70	5·95	5·71	5·59
Second handsheet experiment	9·22	6·35	5·67	5·16

That the slope for change of breaking length with progressive recycling for handsheets made from machine stocks is intermediate between those for machine made paper and for handsheets from laboratory stocks, demonstrates that differences of stock preparation and differences of formation both contribute to the difference between handsheet and machine recycling.

This clearly confirms that work confined to the laboratory exaggerates the effects of recycling and may lead to pessimistic conclusions. In contrast with the laboratory work, pilot machine results indicate that the deficiencies of recycled fibre have been over-rated and that, in the industrial context, the basic problems of re-use and upgrading are not great as might have been supposed.

7—A new concept of factors influencing the loss of tensile strength of recycled fibres

TENSILE strength is one of the most important paper properties and one which is adversely affected by recycling. In previous work[22] Page has shown that the reciprocal of tensile strength is equal to the sum of the reciprocal of fibre strength and bonding strength.

Under conditions where the loss of tensile strength with progressive recycling of fibre is due to loss of bonding strength alone, direct measurement of loss of bonding strength is not essential and a property relating to bonding strength loss can be compared directly with breaking length.

It is proposed that the bonding strength loss is caused by losses of both 'wet plasticity' and 'surface condition' of the recycled fibre. The term 'wet plasticity' is well known and understood.[23,24] It is a property of wet fibres which allows the fibre surfaces to deform in order to come together for bonding under surface tension forces during drying.

An increase in the wet plasticity of virgin fibres on beating only gives a greater chance that bonding will occur. The extent of the bonding is determined by the 'surface condition'[25] of the fibres. A surface condition which is good for bonding might be a surface which is 'gummy' with cellulose and other polysaccharides, perhaps especially hemicellulose. These substances are exposed and released by beating and partially dispersed by water.

It is of both fundamental and practical importance to determine whether loss of wet plasticity or loss of surface condition makes the greater contribution towards the loss of bonding strength in recycled fibre, because any methods devised for improving the strength properties of recycled fibre should first pay attention to the bigger loss. A particular upgrading treatment might, for example, needlessly increase wet plasticity whilst doing nothing for surface condition where the deficiency might be the greater. It is considered by the authors and other workers[26–30] that the wet plasticity of the fibres is the fibre property which predominantly influences the bulk or apparent density of the sheet. Thus, apparent density is assumed to be an index of wet plasticity. Table 5 shows the relative changes of apparent density and breaking length of the handsheets made from stocks sampled during the pilot machine recycling experiment and it is seen that, between cycle 0 and cycle 1, breaking length falls at a rate which is not reflected by the comparatively small drop in apparent density. This phenomenon is not an isolated one. Six sets of data have been similarly analysed. These were from the two PIRA handsheet recycling experiments, the PIRA pilot machine recycling experiment, McKee's experiment[3] and Horn's two experiments.[7] Details of these data vary because the experimental conditions differed in several aspects. Nevertheless there are enough similarities to support the following argument.

There is an overall correlation between apparent density and breaking length. However, the contribution which apparent density, representing wet

TABLE 5—RELATIVE CHANGES OF APPARENT DENSITY AND BREAKING LENGTH OF THE HANDSHEETS MADE FROM THE PILOT MACHINE RECYCLED STOCKS

	Cycle			
	0	1	2	3
Breaking length km (%)	7·70 (100)	5·95 (77)	5·71 (74)	5·59 (73)
Apparent density g/cc (%)	0·73 (100)	0·70 (96)	0·66 (90)	0·66 (90)

plasticity, makes to breaking length is not the same for all stages of recycling. It might be supposed that a nonlinear relationship between wet plasticity and breaking length could explain the strength reduction at all stages of recycling. However, no amount of wet plasticity will provide bonding strength unless the fibres have a surface condition which is conducive to hydrogen bonding. It is therefore postulated that an additional factor, surface condition, is required to explain the major reduction of breaking length which occurs at the first remake. Even the possibility of a powerful interaction between surface conditions and wet plasticity does not diminish the importance of surface condition. The effect of surface condition in conjunction with wet plasticity is greater than the effect of wet plasticity alone. In the case of the machine recycling trial, and also for most handsheet recycling experiments, the biggest strength reduction takes place at the first remake. It therefore follows that, if surface condition or its interaction with wet plasticity accounts for the greater part of the biggest strength loss, then surface condition is a factor of the greatest practical importance. At this stage the role of surface condition has not been proved, but a very important possibility has been revealed.

Although pilot machine recycling caused much smaller changes of sheet properties than was the case for handsheet recycling, the trends are similar and it is likely that the same basic mechanisms are responsible. Loss of bonding strength is clearly related to a reduction of wet plasticity of the fibres and there is a strong possibility that changes of fibre surface condition play an important part in loss of bonding strength, particularly at the first recycle, for both handsheet and machine recycling regimes. Consequently, handsheet methods can still be used for work aimed at the upgrading of recycled fibres, although the paper should preferably be machine made, because of the differences arising from the different stock preparation procedures.

8—*Pentosan analyses of recycled semi-bleached kraft paper*

THE possible influence of hemicelluloses on the tensile strength of recycled fibres is discussed in section 10. Hemicelluloses are polysaccharides which have a lower molecular weight than cellulose and which yield, on acid hydrolysis, the sugars: glucose, mannose, galactose, xylose, arabinose and uronic acids.

Tappi Standard T 450m-44 describes the determination of pentosans in paper. Pentosans are polysaccharides which yield the pentose sugars xylose and arabinose on acid hydrolysis and which are decomposed to furfural on distillation with 12 per cent hydrochloric acid. The furfural is determined by a volumetric method and this gives a measure of the pentosan content of the paper. The pentosan determination provides a measure of one type of hemicellulose in the semi-bleached kraft. The method has an accuracy of ±0·2 per cent.

Pentosan analyses were carried out on the semi-bleached kraft pulp and on samples of paper made from this pulp from cycles 0, 1, 2 and 3 of the machine recycling experiment. Results were obtained also from cycle D (disintegrated only) and for cycles 0, 1, 2 and 3 of the second laboratory recycle experiment. The results of these pentosan analyses are shown in Table 6.

TABLE 6—PENTOSAN ANALYSES OF PULP AND PAPER SAMPLES FROM THE MACHINE RECYCLE EXPERIMENT AND THE SECOND LABORATORY RECYCLE EXPERIMENT

Sample	*Pentosan analysis (%)*
Semi-bleached kraft pulp	8·29
Machine made paper	
Cycle 0	8·18
Cycle 1	7·73
Cycle 2	7·77
Cycle 3	7·24
Laboratory made paper	
Cycle D	6·95
Cycle 0	7·15
Cycle 1	6·76
Cycle 2	6·35
Cycle 3	6·61

The results in Table 6 suggest that:

(*a*) The greater loss of pentosans occurs during the laboratory recycling of the semi-bleached kraft. Over cycles 0, 1 and 2 the pentosan content of the machine made paper is approximately 1 per cent higher than that of the laboratory made paper.

(*b*) The laboratory made paper at cycle 0 contains about 1 per cent less pentosan than the machine made paper and yet forms a stronger sheet.

(*c*) Laboratory stock preparation, especially the disintegration stage, leads to more pentosans dissolving in the process water and therefore seems to give the fibres a far more vigorous treatment.

These analyses provide a measure of one type of hemicellulose in the semi-bleached kraft pulp and paper and we make the assumption that these hemicelluloses influence the semi-bleached kraft in two ways: namely, by their effect on the beating of the virgin fibre and by their contribution to fibre bonding of the virgin and recycled paper sheets.

It has been shown that beating brings about a considerable increase of solubility of a pulp in alkali. This demonstrates that some of the hemicellulose in unbeaten fibres is inaccessible.[31] This is in agreement with Giertz's opinion,[32] that, as a result of internal fibrillation and mechanical flexing that occur during beating, some of the hemicellulose is worked from the interior of the fibre wall and is exposed on the surface of the fibre where it acts as a bonding agent and provides the fibre with a suitable surface condition. The hydrophilic nature of accessible hemicelluloses on the surface of the fibre provides the fibres with an ability to absorb water which makes them more plastically deformable—that is have a greater wet plasticity. Because of this, there should be a greater opportunity for the inaccessible hemicelluloses to work themselves on to the surface of the fibre and thereby provide a suitable surface condition.

Although the sheet strength of the laboratory made paper was greater than that of the machine made paper at a lower pentosan content, the fall off of sheet strength was less pronounced with the machine made paper and its pentosan content remained higher. This suggests that, because more hemicellulose has been lost to the process waters during the first making of the laboratory paper, less hemicellulose is available to the fibre during the subsequent remakings. This leads to a relatively greater loss of strength in the laboratory made paper than in the machine made paper.

9—*Chemical analysis of the wire water*

AFTER the water flows on the paper machine had reached a steady state during the makings, samples of the mixed wire-water draining from the paper machine wire were taken and the dissolved carbohydrate concentration of the filtered solutions was determined by a standard method.[33] In order to determine the source of these dissolved polysaccharides, an analysis of the constituent monosaccharides was carried out. The various wire water samples were filtered, reduced in volume, hydrolysed with dilute sulphuric acid, neutralised with barium hydroxide and after centrifuging, the supernatant liquid reduced to dryness by vacuum evaporation. The residue was then trimethylsilylated according to standard procedures,[34] and the derivatives analysed by gas liquid chromatography.[35]

TABLE 7—CARBOHYDRATE ANALYSES OF THE WIRE WATER SAMPLES

Cycle	*Original carbohydrate concentration (mg/l)*	*Composition of the hydrolysed samples (%)*			
		Arabinose	*Glucose*	*Xylose*	*Galactose*
0	4·16	15·5	19·4	48·2	16·9
1	2·09	24·6	16·9	45·8	12·7
2	2·40	26·9	11·1	48·6	12·4
3	1·89	26·5	11·1	52·1	10·3

The carbohydrate concentration of the various wire water samples and the composition of the constituent monosaccharides after hydrolysis of the samples are presented in Table 7.

The maximum error for the original carbohydrate concentration was estimated to be ± 5 per cent. In the calculations of the composition of the hydrolysed samples it was assumed that only four sugars were present. Mannose, if present, would be lost in the solvent peak in the gas liquid chromatogram. The error in calculation of the area under the gas liquid chromatography curves was estimated to be ± 5 per cent.

The amount of dissolved polysaccharides in the wire water, measured by the original carbohydrates concentration found in Table 7, is greater in the first making than it is in subsequent remakings. From the composition of the hydrolysed samples in Table 7 Xylose is shown to be the predominant monosaccharide of the monosaccharides measured in the hydrolysed wire water samples. This indicates that Xylan hemicelluloses are dissolved in the process water as the recycling of paper proceeds. Also Table 7 suggests that the composition of the dissolved polysaccharides in the backwater might be changing as recycling proceeds. This is most clearly suggested by comparing the percentage composition of the sugars derived from the hydrolysed samples of cycle 0 and cycle 3 wire water, but this is an indication only because the mannose content of the hydrolysed samples could not be determined by this method.

10—*Surface condition*

SOME 60 to 70 per cent of the cellulose in wood fibres is in a crystalline state[36] and the hydroxyl groups are hydrogen bonded to one another and therefore unavailable for the formation of fibre to fibre bonds.

On beating a virgin fibre, Emerton[23] thought of the wet plasticity of the fibre being increased by the plasticising effect of the water which is taken up by the accessible hemicelluloses and to a lesser extent by the amorphous cellulose. The crystalline cellulose consequently deforms more readily during the formation of the sheet and gives greater fibre to fibre contact. The surface condition of the fibre is developed by beating because part of the inaccessible hemicellulose contained inside the fibre is made available on the fibre surface for the formation of hydrogen bonds and therefore fibre to fibre bonds.

On drying the fibrous mat, hydrogen bonds (and therefore fibre to fibre bonds) are formed. On redisintegration and remaking of the paper the strength properties of the paper are diminished by loss of wet plasticity and surface condition.

We may think of the wet plasticity of the fibre being lost in the drying process as that portion of the crystalline cellulose which was deformed during the beating process becoming crystalline and hence inflexible again.

The accessible hemicelluloses are important in assisting the development of wet plasticity and surface condition because of their strongly hydrophilic nature, but are possibly not as effective for the development of a desirable surface condition and hence the final sheet strength—as the previously inaccessible hemicellulose which has worked itself out from the interior of the fibre on to its surface. Indeed, the accessible hemicelluloses are probably dissolved out of the fibre as recycling progresses, but their removal would hinder the redevelopment of wet plasticity in recycled paper.

It is not yet certain why loss of surface condition occurs during recycling, but it might be that, if the hemicelluloses are locally aligned parallel to the crystalline cellulose chain, then the bonding that takes place during drying is sufficiently extensive and regular to unite two crystalline regions as one. Thereby, the inaccessible hemicellulose that was exposed during the beating of the fibre (and was therefore able to contribute towards the desirable surface condition) would become inaccessible again and unable to contribute to the hydrogen bonding which binds the fibres together. There is also the possibility that the previously inaccessible hemicellulose remains in the amorphous phase, but that the hydrogen bonding is hindered in some way. This might arise because of a change in the surface chemistry; for example, by absorption of electrolytes or by the actual substitution of the potentially active hydroxyl groups. Even without the indirect indications from the present recycling data, the foregoing statements provide ample justification for considering changes of fibre surface condition as a factor in the reduction of bonding strength during recycling. The possibility of hydroxyl groups being inactivated towards hydrogen bonding during recycling simply cannot be ignored.

If it can be established that the change of surface condition, through inactivation of hydroxyl groups, is a major cause of the reduction of bonding strength, we have at last a truly scientific basis for the upgrading of recycled fibre.

No single investigation in the complex subject of recycled fibre research can claim to form the basis of a cure for all of the many problems encountered in the processing of wastepaper or in the recovery of certain fibre properties during the remanufacture of wastepaper. However, as a result of this investigation, some explanation as to the nature of strength loss differences between handsheet and machine recycling regimes has been provided. Changes in the chemical composition of semi-bleached kraft occur during recycling and these changes were found to be more pronounced in the second handsheet recycling experiment than in the pilot machine experiment. In addition, a hypotheses has been put forward to explain the nature of strength losses encountered during the recycling of wastepaper. Further investigation into the nature and proportions of amorphous and crystalline cellulose and accessible and inaccessible hemicellulose should provide a greater understanding of the mechanism of the strength losses occurring during the recycling of wastepaper.

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