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EFFECTS OF HIGH CONSISTENCY REFINING ON THE PROPERTIES OF THE CONSOLIDATED WEB

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Synopsis—The treatment of pulps at low consistencies in conventional beaters or refiners is partially a destructive process that severely damages and shortens the fibres. These disadvantages are overcome in high consistency refining (HCR), a technique developed commercially in the USA, which treats a pulp at consistencies of 20–40 per cent by transmitting mechanical energy to a semi-solid fibre pad between the plates of a disc refiner. The refining action is brought about by strong interfibre shearing actions, by rubbing and sliding of fibres on each other and by the intensive internal friction forces that result. This mechanism gives the fibres a unique appearance that makes it possible readily to detect the HCR pulp in a furnish.

The preservation of the average fibre length while developing extensive fibrillation is the most important feature of the HCR process. The properties of webs formed from an HCR pulp and a jordan refined stock differ noticeably in every phase of sheet consolidation. HCR fibre slurries frequently have a poorer formation, but seem to drain better—at least, in the higher freeness range. The tensile strength of wet HCR fibre mats is not much different from that of conventionally refined pulps, but they have a higher stretch. This was confirmed in commercial newsprint runs. HCR results also in a lower water retention after wet pressing and a greater web shrinkage in the dryer section.

Papers produced from HCR pulps show a very high tearing strength, a higher stretch and a somewhat lower tensile strength than papers obtained from a jordan refined stock. This is largely a result of the much lower fines content of HCR pulps.

The HCR process requires more power to produce papers of maximum strength, but a combination of HCR and light conventional refining as a compromise gives very satisfactory results.

Introduction

THE development and change of pulp properties through the mechanical treatment of fibres in a beater or refiner is a key part of papermaking, but conventional beating or refining processes are quite inefficient[1] and they develop only a fraction of the potential properties of the pulp fibres in the consolidated web. This was one of the major conclusions of the First Fundamental Research Symposium held here in Cambridge in 1957.

Probably, the main reason for these shortcomings of conventional pulp refining is its detrimental influence on the fibres. Conventional refining damages and weakens the fibre structure.[2,3] This can be observed microscopically as fibre shortening and partially severed fibre. Optimum sheet properties should be obtained under conditions that swell, make flexible and increase surface area of fibres with a minimum of fibre damage.[2] Investigators throughout the world have studied numerous types of laboratory and commercial beating machines in an attempt to find the ideal process. Although this work has considerably advanced our knowledge of beating, significant progress towards an improvement of the refining process was not made until quite recently. The work of Cumpston in the USA[4] and Brecht & Globig[5] in Germany should be noted in this connexion.

The high consistency refining process

About four years ago, it was discovered in Crown Zellerbach's Central Research Division that a Bauer double-disc refiner would accept and discharge chemical woodpulp at consistencies as high as 40 per cent. This has

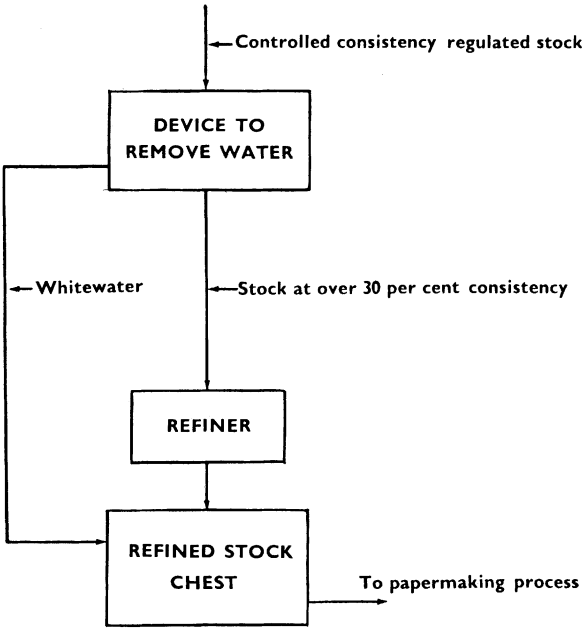

Fig. 1—The HCR (high consistency refining) process

enabled extensive studies in the field of high consistency refining—or HCR as we call it for convenience and as a registered trademark. We are reporting some of our findings here, as they may further contribute to the understanding of pulp refining and its influence on the behaviour of the fibre mat during the consolidation stage on the papermachine.

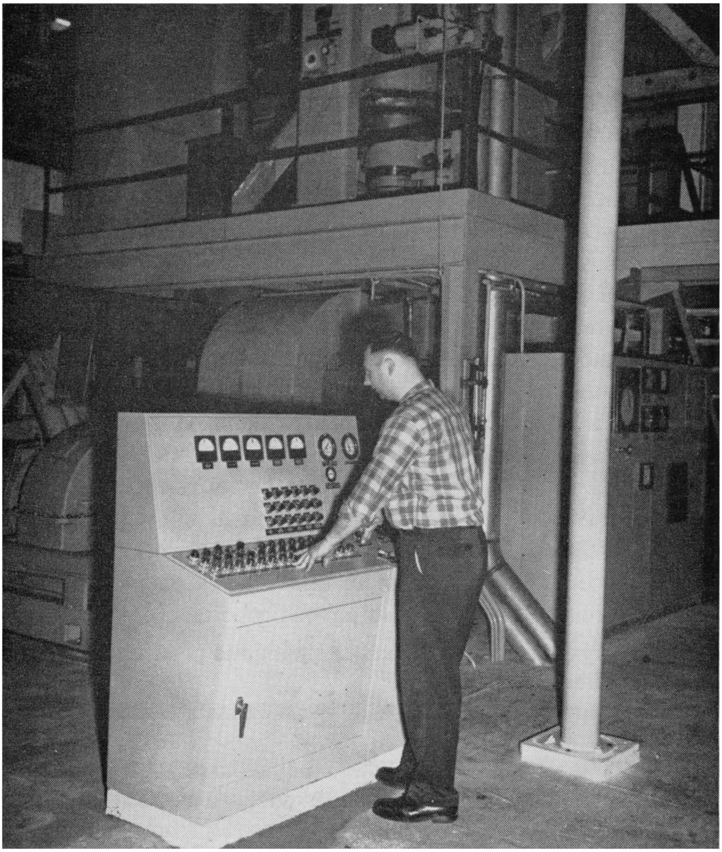

Fig. 2—Commercial HCR installation at Port Angeles mill

The process itself (Fig. 1) is quite simple, employing available machinery and equipment. It consists of a device, such as a screw press to increase the stock consistency to 20–40 per cent by removing water, of a metering device for constant stock flow and of the refiner, which may be of the single or double disc type. Fig. 2 shows a commercial HCR installation used to refine semi-bleached kraft pulp for stone groundwood newsprint. HCR has made it possible to reduce the chemical woodpulp content by 30–35 per cent, compared with the requirements for low consistency jordan refined kraft in this sheet.

West[6] has recently presented a comparison between low and high consistency stock refining and has proposed that the influence of the stock consistency on the results of the mechanical treatment of the fibres in refining was mainly due to internal friction between individual fibres. That the inter-fibre friction rises considerably with increasing consistency has been demonstrated on the tensile strength of wet webs.[7,8] A pulp in the 25–40 per cent consistency range can therefore be characterised as a somewhat compressible, semi-solid substance, in contrast to the flowable dispersion of fibres in water at conventional refining consistencies of below 6 per cent.

The HCR process therefore develops the pulp properties more through an interaction between the fibres—rubbing and kneading. In contrast, low consistency refining modifies the pulp by direct action of the refining tackle on the individual fibres and perhaps by turbulence in the refining zone. This in turn causes severe damage of the fibre structure through bruising, crushing and cutting. Although it is recognised that no beating process treats all the fibres in the same way,[9] HCR quite likely produces a more uniformly refined pulp, because fewer fibres can escape the shearing action within the fibre pad between the refiner plates. Since a major portion of the mechanical refining energy in HCR is converted into thermal energy through friction between fibres,[1] it is not surprising that this treatment temporarily raises the stock temperature close to boiling point.

These differences in the action of refiners at low and high consistencies result in several remarkable pulp and paper properties[6]—

1. HCR has very little effect on the fibre length and produces little or no fines, even at low freeness.
2. The tearing strength of HCR pulps is maintained—even improved—at all freeness levels.
3 Papers made of HCR pulps show a higher shrinkage potential, greater extensibility and superior toughness than papers from conventionally refined pulps at equal freeness levels.

Very similar results were recently reported from Germany.[10]

We have now compared the low and high consistency refining techniques in greater detail to lead us to a better understanding of the fundamentals of the HCR process, as well as of beating in general. In this work, we used a variety of analytical techniques to determine the properties of individual fibres, to explain the fibre network/water relationships in the initial stages of web consolidation and, finally, to characterise the properties of the finished sheet.

Pulp treatment procedures

A BLEACHED West Coast kraft pulp was used in this study. It was refined in a Bauer 411, 800 hp double disc refiner at 35–40 per cent consistency and at two levels of power input. The unrefined as well as the two disc-refined pulps were also subjected to a conventional type refining treatment in a Jones midget jordan refiner operating at 1 per cent consistency.

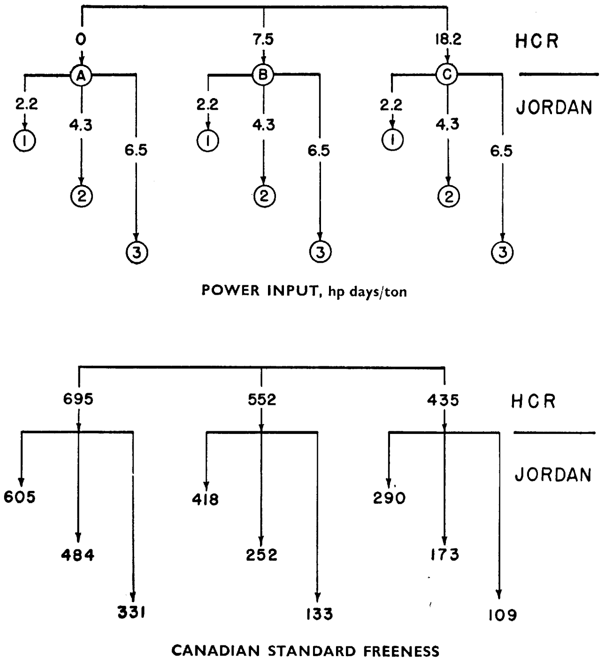

Fig. 3—Refiner power input and effect on pulp freeness

Fig. 3 illustrates schematically how these refining experiments were made. The upper horizontal in the top drawing represents the HCR pulps, with the unrefined pulp *A* on the upper left, the low energy HCR pulp *B* in the centre and the high energy HCR pulp *C* on the right. These three pulps were jordan refined at three power input levels (1, 2 and 3). The numerals indicate the refining power input for each pulp. The bottom drawing in Fig. 3 lists the freeness of these pulps.

Comparison of fibre properties

A HIGH consistency refined stock can be readily distinguished from a low consistency refined pulp without magnification. A highly diluted slurry of

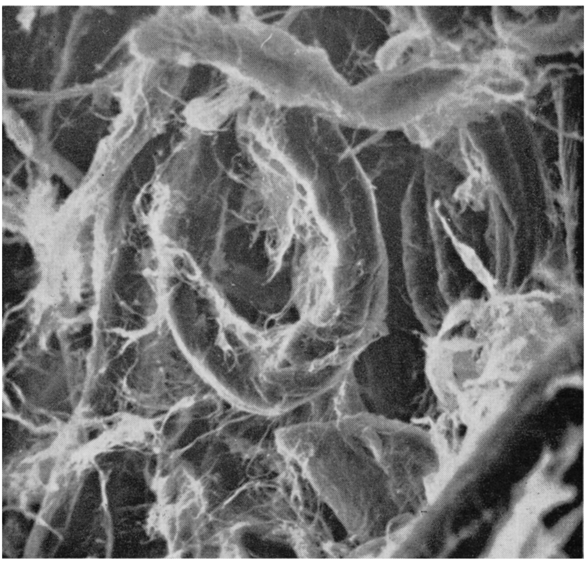

Fig. 4—HCR treatment (×400)

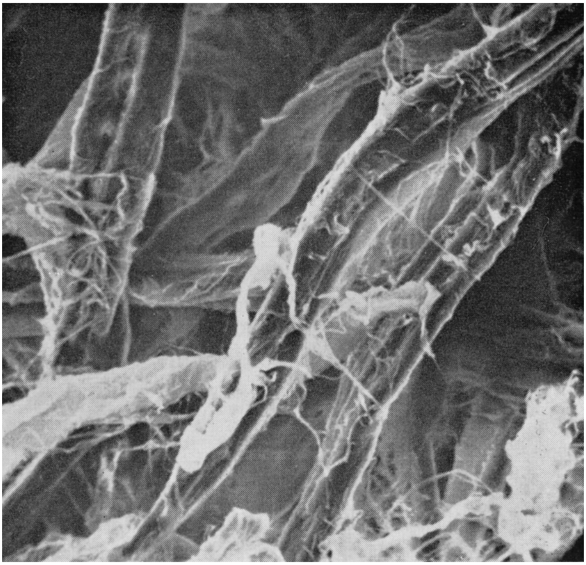

Fig. 5—Jordan refining (×400)

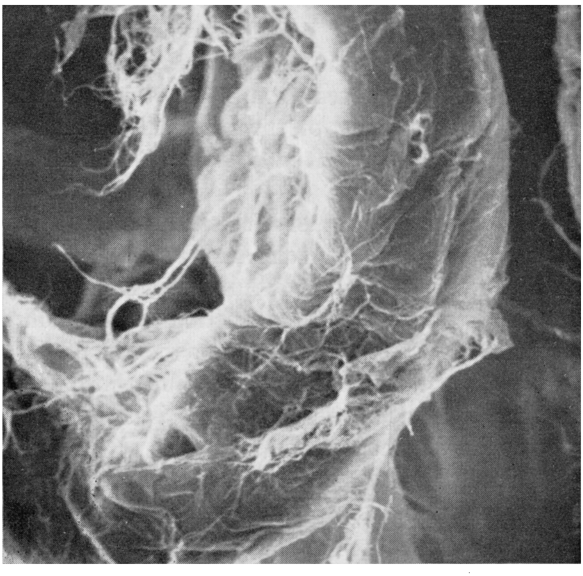

Fig. 6—HCR treatment (×1 400)

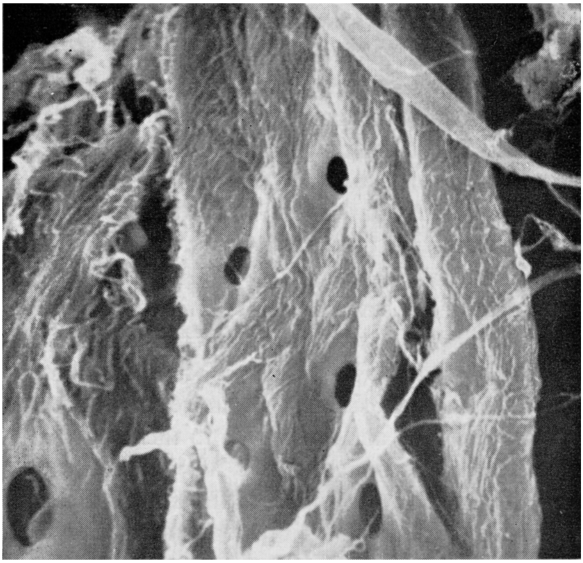

Fig. 7—Jordan refining (×1 400)

HCR pulp shows a greater tendency to flocculate and fibre sedimentation occurs at a faster rate than for a dispersion of conventionally refined fibres. The HCR fibres are also visibly longer and have a kinked, bent or curled shape, compared with the much straighter appearance of the fibres after low consistency refining. Because of this unique appearance, the percentage of HCR treated fibres in a furnish can be easily determined microscopically.

The scanning electron photomicrographs of Fig. 4 and 5 illustrate the effects of the two refining techniques on the microstructure of the fibre. At a magnification of 400, it is seen that the HCR treatment (Fig. 4) has loosened and opened up the fibre structure considerably more than did the jordan refining (Fig. 5). External fibrillation of the HCR fibre is extensive, as indicated by the fuzz on the fibre surfaces. This fibrillar fuzz, originating from splitting and rupture of the primary and secondary fibre walls, remains attached to the fibre, since HCR produces little or no loose fibre debris or fines. This is in marked contrast to low consistency jordan refining, in which the outer layers of the fibre are removed and contribute to the fines.[11]

The scanning electron photomicrographs also demonstrate the macroscopically visible differences in the shape of the fibres, mentioned earlier—the bending and kinking of the HCR fibres compared with the straightness of the jordaned fibres. These effects of the two beating techniques on the fibre structure are also shown in Fig. 6 and 7 at a high magnification.

It has already been mentioned that the small changes of the average fibre length in HCR distinguish this process from most other beating techniques, illustrated in Fig. 8. Jordan refining, on the other hand, sharply reduced the fibre length by as much as 30 per cent in both the unrefined and previously HCR-treated stock.

The fractionation analysis in a Bauer-McNett classifier gave very similar results, as can be seen in Fig. 9. The solid lines referring to the HCR pulp for the two levels of power input, *B* and *C*, run nearly horizontally. HCR had therefore no effect either on the long fibre fraction (retained on the 14 mesh screen) or on the intermediate fraction (retained on the 35 mesh screen), but the jordan refiner yielded pulps with a high degree of fibre shortening, resulting in a considerable increase in short fibres and fines. This is shown by the broken lines that drop toward lower freeness levels.

It should be mentioned, however, that fibre shortening is avoided only for strong pulps such as kraft pulps. Soft pulps such as sulphites experience some reduction in fibre length under similar refining conditions, although much less than in low consistency refining. It may be concluded therefore that the strongest forces arising within the fibre pad in HCR are strong enough to fibrillate the fibres of strong pulps, but not strong enough to rupture them, whereas the same forces exceed the strength of the fibres in a soft pulp and cause failure of the fibre structure.[3] This could be avoided by treating weaker pulps at milder refining conditions.

The swellability of a pulp (the degree to which the hemicellulosic material of the fibre is penetrated by water) has an important bearing on the behaviour of the consolidating web on the papermachine, because it influences the fibre

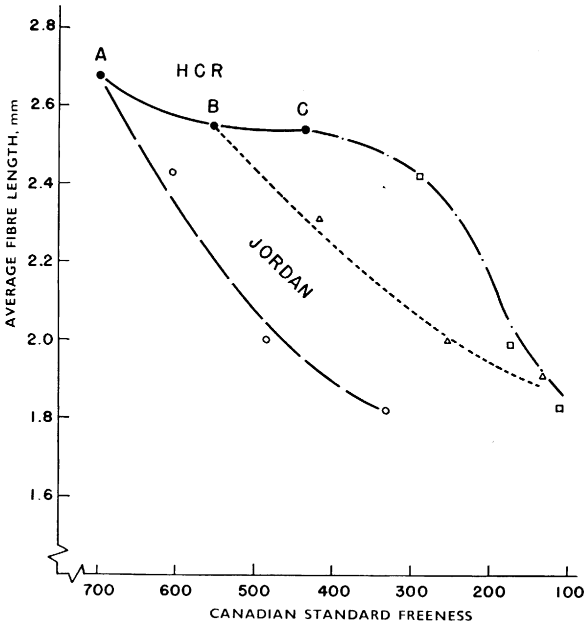

Fig. 8—Influence of HCR and jordan refining on fibre length

flexibility, fibre shrinkage, the degree of interfibre bonding and, consequently, a wide range of paper properties.[12] Unfortunately, none of the methods devised for the measurement of fibre swellability [13,14] is completely satisfactory, although an indirect indication of the degree of swelling may be obtained from the shrinkage upon drying of the fibre mat, since both properties are closely related.[15] It will be shown that paper produced from HCR pulp does indeed shrink considerably more than a sheet made of jordaned fibres, indicating that HCR develops a higher degree of fibre swelling.

Comparison of wet mat properties

THE difference already discussed in the fibre properties of HCR pulps and jordan refined stock influences considerably the behaviour of the wet fibre network in the early stages of web consolidation. It was mentioned that

HCR fibres have a greater tendency to flocculate because of their greater length and flexibility.[16] This results in a sheet of less uniform formation than a web produced from a conventionally refined pulp.

The drainage properties of the wet mat on the wire of the papermachine are of great importance to the economics of the papermaking process. Since beating has a major effect on the drainage,[17,18] one would expect to find

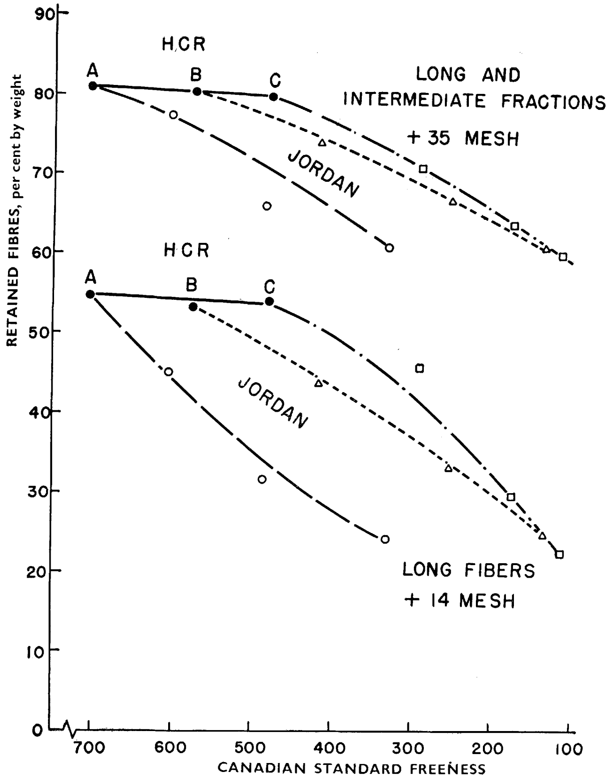

Fig. 9—Influence of HCR and jordan refining on fibre fractions

significant differences in the drainage characteristics of HCR and jordan-refined pulps. Some useful information on the drainage characteristics of fibre mats can be obtained from constant rate filtration measurements.[19] It is seen in Fig. 10 that HCR increases much less than jordan refining the flow resistance of the fibre network and Ingmanson & Andrews[18] have found that the filtration resistance of pulp mats is considerably influenced by the amount of fines, which tend to migrate towards the wire in this test to form a layer of high resistance to liquid flow. Thus, it appears reasonable to assume that a major portion of the higher flow resistance of the jordaned pulps is brought about by their greater fines content (Fig. 9).

The drainage on the wire of a papermachine differs significantly from the filtration test in that it occurs under dynamic conditions[20] that prevent the formation of a layer of fines on the wire by the agitation of the table rolls. In addition, the filtration measurement does not take into account the removal of water by suction. One might expect the HCR pulps to show

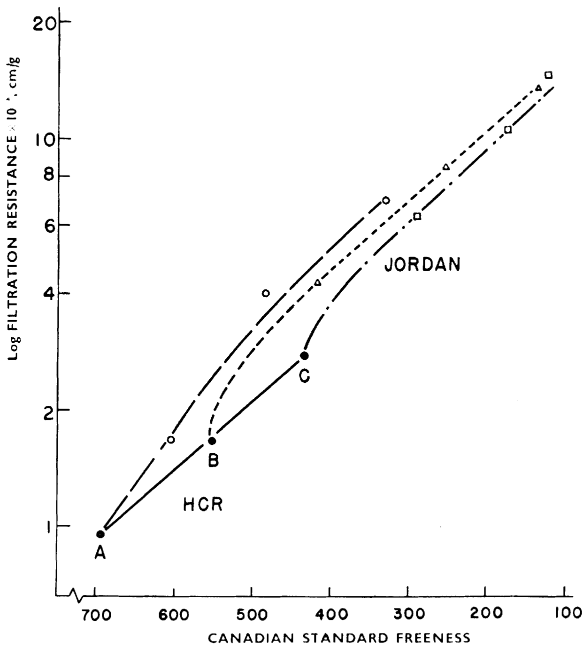

Fig. 10—Influence of HCR and jordan refining on filtration resistance

better drainage properties than conventionally treated pulps, because of their very low fines content. This has actually been observed for higher freeness ranges on commercial papermachines, although reports of slower drainage have been received from operating personnel for lower freeness ranges.

The removal of water from the fibre network on the wire brings the fibres closer and closer together as the consolidation of the web progresses. This pulling together of the fibres, caused by surface tension forces, is likely to be a function of fibre flexibility. Yet, measurements of the apparent wet mat density at constant compacting pressures have shown that beating over wide ranges has no effect on the results.[18] In contrast, the HCR treatment did increase the wet mat density by as much as 10 per cent (Fig. 11). Subsequent jordaning produced no change, confirming the findings of previous work with conventional beating equipment. This shows again that refining at high consistencies yields pulps of unique properties.

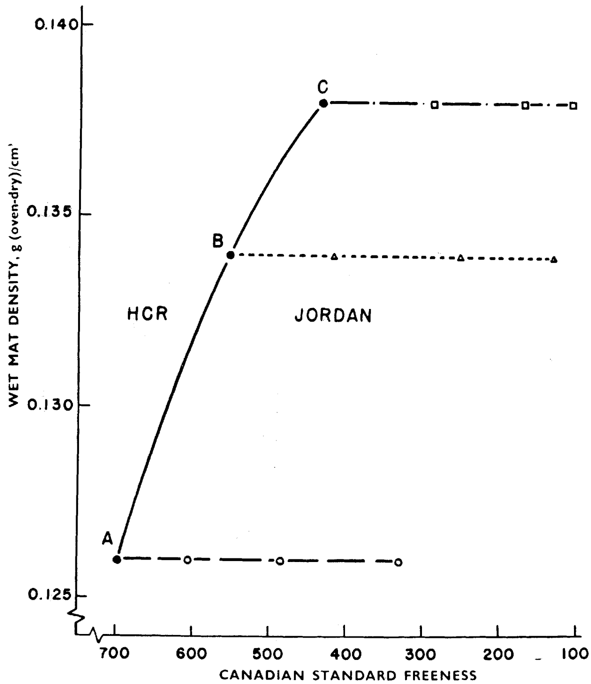

Fig. 11—Influence of HCR and jordan refining on wet mat density

Wet web behaviour

WHEN the wet web is removed from the papermachine wire, its fibre structure must be sufficiently consolidated to be able to overcome the adhesion to the wire[21] and to withstand the severe mechanical stress exerted on it between the couch and the first press in an open draw.[22] The stress/strain properties of the wet web are therefore of critical importance at this point and were determined on handsheets at moisture contents varying from 80 per cent to the air-dry state. The water was removed with blotters, according to a technique previously described.[(8)] Very little pressure was applied to the web during this water removal to permit almost unrestrained shrinkage. The stress/strain properties were then determined with an Instron tester.

Wet webs formed of HCR and jordaned pulps yielded approximately equal tensile strengths at a given moisture content over the range studied. The wet web extensibility, however, was affected by the two refining techniques in different ways, as Fig. 12 illustrates: HCR enhanced the extensibility of the wet web (indicated by the solid line between points *A*, *B* and *C*),

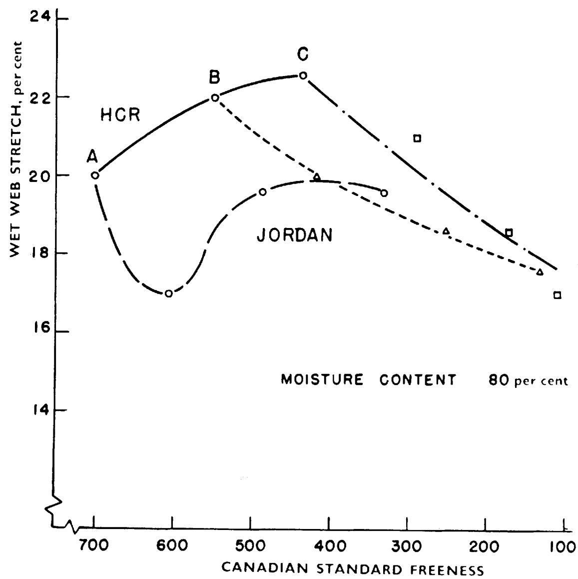

Fig. 12—Influence of HCR and jordan refining on wet web stretch

whereas jordan refining resulted in stretch losses (the broken curves). This trend continued into lower moisture ranges until the results were overshadowed by the beginning shrinkage of the web.

Brecht & Erfurt,[(23)] in a study of the fundamentals of wet web stretch, have shown that the extensibility of a fibre mat at high moisture contents is strongly affected by the curvature and flexibility of the fibres in the structure. In other work,[(24)] it was found that large increases in wet web stretch resulted from the treatment of hardwood pulps in a Curlator. The greater wet web stretch of HCR fibre mats can therefore be explained by the high degree of fibre bending that results from HCR processing.

This higher wet web extensibility of the HCR pulp was also borne out in commercial newsprint production runs. When we substituted the jordan refined semi-bleached kraft component of the furnish with the same quantity of HCR kraft, we found that the wet web began to sag considerably at the couch. It was then established that we needed a speed increase of 2 per cent in the press and dryer sections when HCR pulp was used in the furnish, equivalent to a 40 per cent increase in the draw between the wire and the press section.

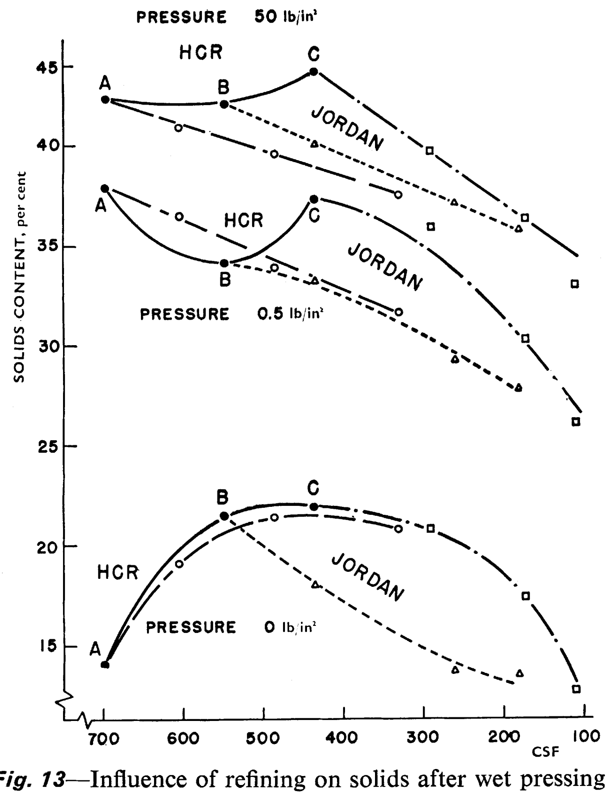

Fig. 13—Influence of refining on solids after wet pressing

The next phase in the consolidation of the web on the papermachine involves a compaction of the network in the wet presses to remove additional water. We studied the effect of wet pressing on handsheets that were placed between blotters and subjected in a hydraulic press to pressures ranging 0–50 lb/in^2. The bottom curves of Fig. 13 refer to the solids content of handsheets that were formed in a sheet mould, then couched off according to the TAPPI standard method, but not subjected to additional pressing. The solids content of these webs increased to a maximum, then dropped. Brecht & Gerspach,[25] who obtained similar curves, explained the initial rise of the solids content with the increasing pressure drop across the mat as the filtration resistance goes up with refining. The solid curve between points *A*, *B* and *C* shows that the HCR web was slightly dryer than the web from jordan refining within this range.

The pressure drop through the web is limited to the suction head of the sheet mould and drainage at lower freeness levels occurs therefore at a constant vacuum. In this range, the web holds more water as refining proceeds. It is seen in Fig. 13 that this effect was particularly pronounced when jordan refining was applied to previously HCR-treated stock. Light pressing of the wet mat between blotters increased the dryness considerably as most of the free water was squeezed out. The moisture retained by the web consisted mainly of swelling water and perhaps small quantities of free water enveloping the fibres and fibrils.

The water content of the web at a given pressure normally increases with lower freenesses, because beating enhances both the degree of fibre swelling and the specific fibre surface. Fig. 13 shows this for all jordan refined pulps. The behaviour of the HCR fibre mats again differed from the conventionally treated pulps in that their dryness, after an initial drop, increased to a level equal to or above the solids content of the unrefined pulp *A*. This quite unexpected result suggests that HCR at higher power inputs may cause shrinkage of the fibres. This phenomenon could be attributed to the very high temperatures of the stock after the HCR treatment caused by the conversion of a considerable proportion of the expended mechanical energy into thermal energy. That heating a pulp suspension results in shrinkage is well known[26] and Le Compte[27] noted that boiling increased the freeness and reduced the water retention power of a pulp. It will be seen in Fig. 13 that the lower water retention of the webs made from the HCR pulp *C* (relative to pulp *B*) was not affected by subsequent jordan refining at a given freeness.

Drying behaviour

In the final phase of web consolidation on the papermachine, moisture is driven off the fibre network by heat. It is in this phase of water removal that the sheet properties undergo the greatest changes, which largely determine the structure, strength and behaviour of the product. The consolidation of the web in this stage is brought about by forces arising from within the fibre structure by the shrinkage of individual fibres and results in measurable changes of the sheet dimensions. Campbell,[28] Rance,[15] Page & Tydeman[29] and many others have studied this phenomenon.

The effect of refining on web shrinkage was studied on handsheets that were formed according to the TAPPI standard method, then air-dried between blotters at a low pressure to permit almost free shrinkage. Fig. 14 shows that HCR developed in woodpulp a higher shrinkage potential than jordan refining did at given freeness levels. This could indicate a greater degree of swelling for the HCR stocks *B* and *C*, even though the heat produced in this process may have caused some shrinkage of the fibres. Subsequent treatment of the HCR pulps in the jordan apparently increased the web shrinkage more than jordan refining alone. Light pressing of the wet mats reduced their shrinkage, but did not change the general picture.

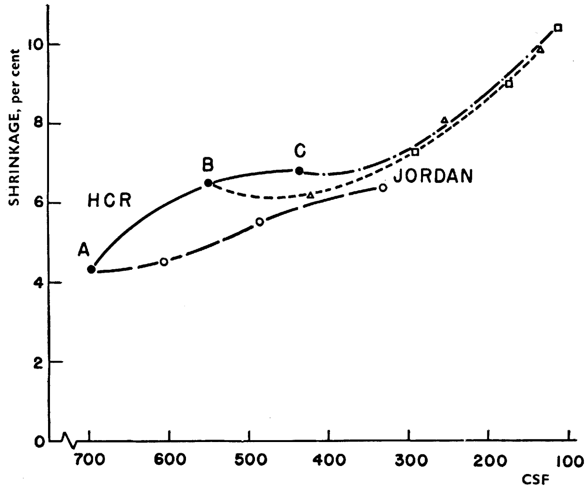

Fig. 14—Influence of HCR and jordan refining on shrinkage

Dry paper properties

THE influence of refining on the properties of the dry, consolidated web was studied on air-dried handsheets that were allowed to shrink freely during drying. We used this approach, because the web shrinkage as a natural phenomenon should be considered in the analysis of stock refining, particularly because some shrinkage occurs on the papermachine. The restraining of shrinkage produces tensions within the sheet[15,30] that markedly affect the fibre structure and thus the mechanical properties of the final paper.[31,32] The discussion will therefore be confined largely to the handsheets dried without restraint (termed extensible handsheets). We did include in our study, however, handsheets that were plate-dried according to the TAPPI standard method, preventing shrinkage in the plane of the paper. In addition, we produced paper on our experimental papermachine from the different pulps under semi-commercial conditions. No essentially new information was obtained in this way, taking into account such factors as fibre orientation, web shrinkage and heat in drying.(33)

The physical strength of a fibre structure depends in great measure on the existence of interfibre bonding, represented by the product of the number of individual bonds and the strength of each individual bond. Nordman(34) has shown that beating does not affect the bond strength for any given pulp, although this may not be true for HCR, because of the high temperatures involved in this process. An indication of the degree of interfibre bonding was

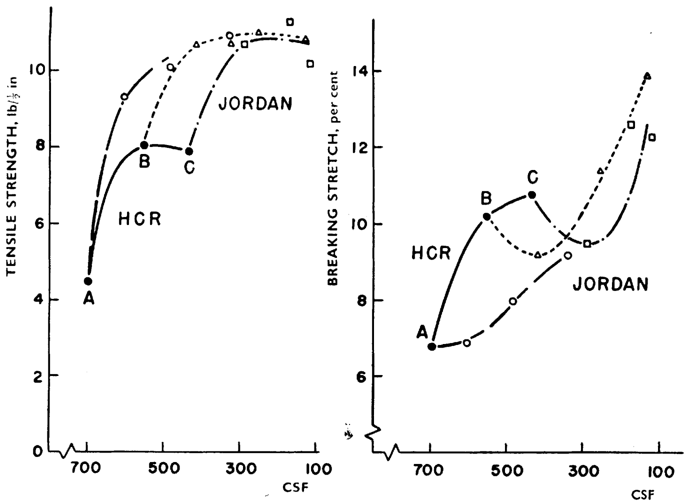

Fig. 15—Influence of HCR and jordan refining on stress/strain properties

obtained from the measurement of the scattering of light by the Nordman technique.(35) This test is believed to be related to the unbonded surface area of the fibres in the sheet and the results suggested that HCR produced a greater bonded area than did jordan refining at given freeness levels for both air-dried handsheets and machine-made papers.

The results of stress/strain measurements made on these extensible handsheets are plotted in Fig. 15. They indicate that sheets made from HCR pulps had a lower tensile strength, but a higher stretch than webs produced from jordan-refined stock at a given freeness. A possible explanation for the lower tensile strength of the HCR is found in its much lower content of short fibres and fines than in the jordaned stock. This is apparent from Table 1, which shows that the tensile strengths of HCR (*C*) and jordan-refined (*A-3*) pulps were the same after removal of the short fibre fraction. This does not mean that the two fines-free pulps have the same properties in all respects, as other tests will indicate. Abnormally heavy jordan refining was used on pulp *C-3* to make this point, which quickly increased the short fibre and fines content to the same amount as resulted from jordan refining (*A-3*) alone. This caused a corresponding increase in the tensile strength of the whole pulp to the level of straight jordaning (Fig. 15).

The higher stretch resulting from the HCR treatment relative to jordan refining is almost completely accounted for by the greater shrinkage of the HCR fibres, which is reversible as stretch upon straining.[15] This is true

TABLE 1—EFFECT OF FINES ON PHYSICAL STRENGTH PROPERTIES

Type of pulp	*A-3*		*C*		*C-3*	
Type of refining	Jordan		HCR		HCR & Jordan	
Fines content,* per cent	39.0		20.3		39.8	
Pulp fraction tested	Whole pulp	Fines free	Whole pulp	Fines free	Whole pulp	Fines free
Freeness, CSF	331	669	435	725	109	662
Tensile strength, lb/½ in	10.9	6.5	7.9	6.5	10.2	7.6
Stretch, per cent	9.2	5.4	10.8	6.3	12.3	7.5
Tear, g/sheet	95	151	166	155	88	146

* Percentage of fibres passing through the 35 mesh screen in the Bauer-McNett classifier

solely for air-dried sheets, however, because the shrinkage of papers dried on steam-heated cylinders was only partially recoverable, owing to deswelling or to irreversible hornification caused by heating.[26,36] The crinkling and bending of the HCR fibres contributed also to the higher extensibility of the webs, although to a smaller extent.

Fig. 16, illustrating the effect of the refining treatment on the tearing strength of extensible handsheets, confirms what we have found many times before, namely, that HCR causes only a minor loss in tearing strength. In contrast, the low consistency refining technique always impairs this important property considerably, disregarding the initial small improvements that are sometimes obtained. This is generally true not only for handsheets, but also for machine-made paper. The tendency of the conventional beater or refiner to reduce the tearing strength has been attributed to fibre shortening and fibre damage.[37,38] This is confirmed by Table 1 showing that the tear values of the fines-free pulps differed only slightly, irrespective of the refining method employed.

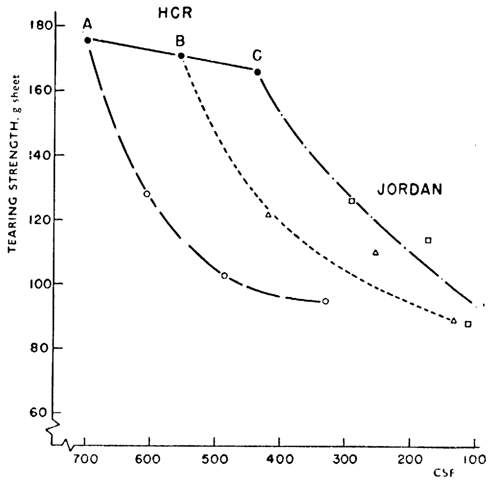

Fig. 16—Influence of HCR and jordan refining on tearing strength

Conclusions

IN reviewing the results of this refining study, one feature of the high consistency refining technique stands out—the almost complete absence of fibre shortening and cutting. This can be interpreted in terms of the direct interfibre action realised by transmitting mechanical energy to a pulp in a semi-solid state. It brings about a refining action by rubbing and sliding of fibres on each other and by the intensive internal friction forces that result. This changes the character of the pulp considerably.

The forces acting on the fibres in this system are apparently lower compared with those required to modify a pulp at low consistencies through cutting and bruising of fibres by the refining tackle. As a result, HCR loosens the fibre structure and makes it flexible with a minimum of fibre damage.

The unusual properties imparted to a bleached kraft pulp by high consistency refining have been realised also for a variety of other pulps such as hardwood pulps, sawdust kraft and waste paper. The interpretation of the results we obtained from this investigation of the fundamentals of HCR and beating in general was frequently not an easy task, because we feel we were unable satisfactorily to characterise the state of beating. We used the freeness test for this purpose in accordance with common practice, although we were aware of its inadequacies. These shortcomings are particularly apparent when the freeness is used for pulps with the different fibre characteristics that result from the mechanical treatment at low and high consistencies.

Although the HCR technique of fibre treatment certainly marks a step toward more effective development of inherent fibre properties, a few problems must be considered. One of them is the greater refining power required to produce the superior paper strength properties that have been described. Another problem may arise from the poorer formation of HCR pulps, which calls for more skill from the papermaker. A combination of HCR and light conventional refining as a compromise appears to solve these problems in most instances.

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Discussion

Dr J. S. Barton—You will be interested to know that Dr J. d'A. Clark admitted to me before coming here that he should add this additional factor to his list, based on our work.

Mr H. P. Dahm—At the Norwegian Pulp and Paper Research Institute, we have studied high consistency refining in the PFI laboratory beater. By and large, the results obtained are similar to what has been reported here, though they do differ on a few points.

Most of you are familiar with the PFI mill and know that it has a roll and a housing that both rotate in the same direction, the roll having the greater peripheral speed. Centrifugal forces press the pulp against the wall of the housing and the pulp is carried (it does not flow) into the gap between them. It is possible to measure the distance between the roll and the housing during beating and, since the roll rests directly in the pulp layer, the distance gives some information about the nature of this layer.

In Fig. Q, the distance (mm) between roll and housing is plotted against the number of revolutions of the roll for the same amount of pulp (30 g oven-dry) being beaten at different consistencies. There is a very pronounced increase in gap as consistency rises to 40 per cent. At 50 per cent, marked shortening of the fibres takes place during beating and the gap is rapidly reduced. You can see also that the gap actually increases during beating at 40 per cent consistency. This and other observations have led us to believe that, in high consistency refining (HCR), the fibres form rolls or balls that may increase in diameter during beating. A result of this is that HCR pulp needs more disintegration after beating to loosen up the fibre bundles formed.

In contrast to what has been found elsewhere, our results indicate that more fines may be formed during high consistency refining than from beating at low consistencies, but that these fines differ considerably from the usual fines. Thus, beating at 40 per cent consistency gave five times as much colloidal material as beating at 10 per cent consistency, which indicates that fibrillation is taking place. Fines production will probably depend strongly on other factors—for instance, beating load—and this may explain the difference in observations on this point. We have also found (as mentioned earlier by Page) that it is possible to obtain the HCR effect without producing fines (in fact, even without beating) by granulating the pulp with a kitchen mixer. This gives results very similar to high consistency refining. Thus, wet elongation is increased by about 100 per cent.

We think that the HCR effect is a composite effect of kinking, curling and twisting the fibres and of fibrillation, but that the kinking, curling, etc. as such is sufficient to give much of the beneficial effect.

You may have noticed that I have not mentioned axial compression as one of the HCR effects. This does not mean that we think compression is unimportant, but it is probably in addition to the effect of the changes in fibre shape and flexibility, the latter effects being the most important.

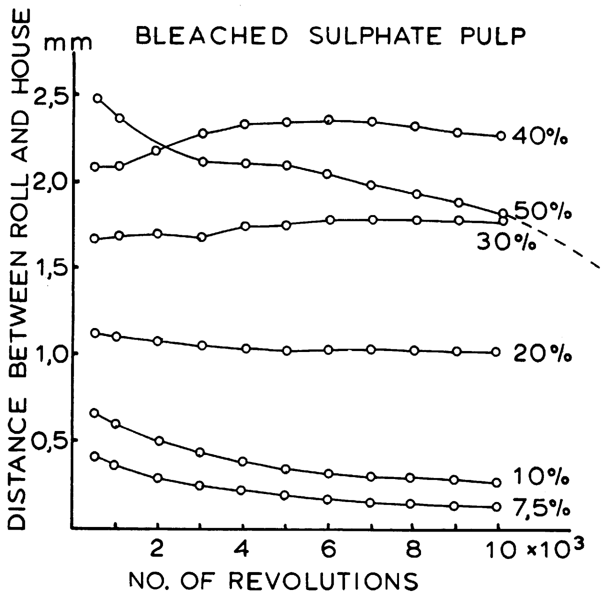

Fig. Q

Mrs R. Marton—High consistency refining is certainly one of the most important developments in recent years and deserves a lot of research. Why was most of the work carried out at the 30 per cent consistency level? Was it because the pulp came from the screwpress at 30 per cent? We have investigated the effect of refining at various levels of consistency on paper properties. Unbleached kraft pulp was beaten in a PFI mill at consistencies of 5, 10, 20 and 30 per cent, always using the same number of revolutions, to determine the variation in strength. It can be seen from Fig. R that for equal beating power input the freeness falls more slowly when the consistency increases. This is a well-known phenomenon that can be easily understood, since the fibres are not cut, but rub one against the other, so becoming fibrillated and activated.

When the strength properties of these pulps (Fig. S) are measured, it is seen that 30 per cent consistency is not necessarily the optimum for strength development. There is a marked increase in breaking length as the consistency increases to 10 per cent, then the slope of the curve reverses suddenly for each level of beating. These measurements were followed up by microscopic

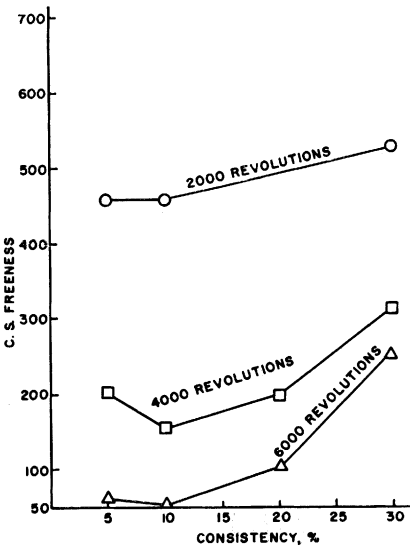

Fig. R—Changes in freeness on refining unbleached kraft pulp in PFI mill at various consistencies (freeness of original pulp was 680 CSF)

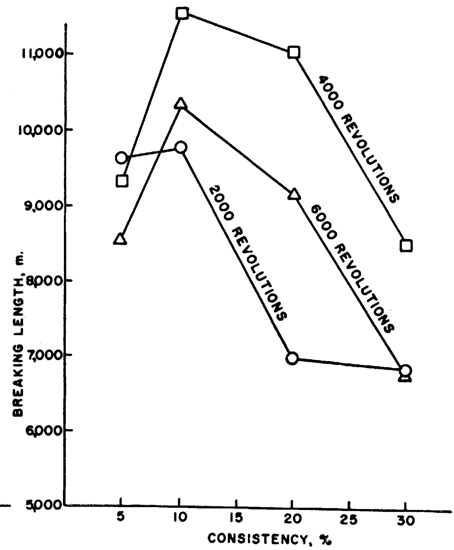

Fig. S—Changes in breaking length on refining unbleached kraft pulp in PFI mill at various consistencies (breaking length of original pulp was 5 400 m)

studies with polarised light, using cupriethylenediamine (cuene) treatment to accentuate the effect of refining damage. It was found that pulp refined at 5 per cent consistency is in general uniformly swollen by the cuene (Fig. T). At 10 per cent consistency, the fibres are much more activated, the outer layers of the wall are removed (Fig. U); the wall itself is more transparent than for the 5 per cent consistency beating, which explains why the strength continues to rise. At 20 per cent consistency, marked disintegration of the cell wall material is seen to occur (Fig. V). The fibres are extremely swollen, forming balloons

Fig. T—Kraft pulp refined in PFI mill at 5 per cent consistency for 4 000 rev: fibres treated with cupriethylenediamine [× 100]

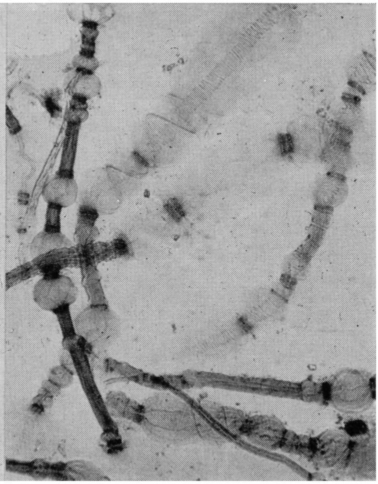

Fig. U—Kraft pulp refined in PFI mill at 10 per cent consistency for 4 000 rev: fibres treated with cupriethylenediamine [× 100]

Fig. V—Kraft pulp refined in PFI mill at 20 per cent consistency for 4 000 rev: fibres treated with cupriethylenediamine [× 100]

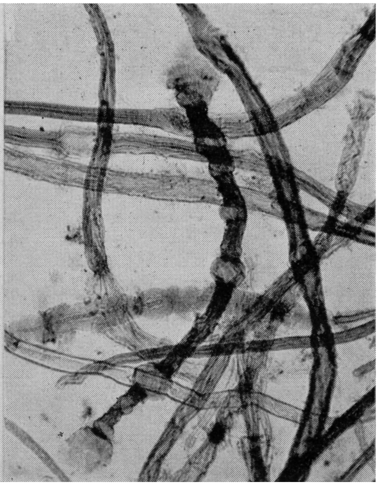

Fig. W—Kraft pulp refined in PFI mill at 30 per cent consistency for 4 000 rev: fibres treated with cupriethylenediamine [× 100] at many points and are almost dissolved in the cuene, which indicates that they are severely damaged: a fall in strength can therefore be expected. At 30 per cent consistency, the fibres seem to be less uniformly activated (Fig. W). Some of them are now swollen or even ballooned as if they were unaffected by the refining, whereas others are strongly beaten.

One point to be watched very carefully in high consistency refining is the formation of *fish eyes* (knots) during pressing of the pulp. They originate from the compressed flocs and are very difficult to disperse. Their amount in screw-pressing the pulp to 30 per cent consistency is quite appreciable and may show up as spots in the sheet of paper. When the pulp is refined at optimum consistency (which might be lower than 30 per cent), these flocs might be smaller and easier to disperse. Pulps other than that used for this work, also hardwood pulps, show a maximum in the curves of strength properties plotted against consistency: the location of these maxima depends on the yield of pulp and on the kind of wood used.

To some extent, these results obtained on laboratory equipment are supported by results from large industrial installations, which indicate that different grades of pulp may require different consistency levels for optimum results.

Mr G. F. Underhay—May I ask about the behaviour of sulphite pulp in contrast to sulphate pulp? I know that at one time sulphite pulp was not so well able to respond to HCR treatment as sulphate pulp. What is the present position?

Secondly, may I query your statement about getting away with using more mechanical pulp? We should approach this matter the other way round by telling our customers of the difficulties in putting 100 per cent groundwood into newsprint and similar papers. We should emphasise that, by doing this, the customer gets a better quality sheet with improved opacity and printability. Incidentally, we shall reduce some of our problems at the same time, including effluent disposal.

Thirdly, may I say, especially as my old friend Jim Clark is not here, that I very much prefer to see strength development curves plotted against energy consumption than against freeness. Freeness is of no direct importance to the finished sheet of paper and we pander far too much to papermachines in endeavouring to produce a range of freeness that suits them. Wet ends can now be made very flexible with the many devices for controlling drainage, therefore freeness should surely be put much further into the background than it is.

Dr Barton—We were concerned about freeness and I referred to it therefore in the way I did; perhaps we should have taken another variable, another parameter. We will certainly try that. We had quite a conversation with Dr Clark on this subject, as you can imagine.

On groundwood, this was an unfortunate piece of phraseology, because we are certainly anxious to use all the groundwood that we can, not only for economy, but for the very desirable qualities it has for many grades of paper. In newsprint, we have been able to reduce the chemical pulp requirement dramatically by HCR treatment.

It is certainly true that sulphite and sulphate pulps respond differently to beating. The only way we can explain it is that kraft is a harder beating pulp and so it takes this kind of treatment much better than does sulphite pulp. In air-dried handsheets, there is very little difference between the two pulps, but, as soon as they are dried under forced conditions, the strength improvement falls off in the sulphite pulp compared with the kraft pulp. We probably have some more work to do on the type of refiner plates we use and on the operating conditions used in treating sulphite pulp. In our own affairs, this is a very minor problem, as kraft pulp is what we are concerned with primarily. One trend we have certainly noted is that sulphite pulp cooked at a higher pH value responds more like kraft pulp.

The flocs mentioned by Mrs Marton and their effect on formation are certainly something to be careful about and it calls for more skill from the machine operators. As a compromise, we have to touch up the pulp with jordan treatment, thus we have to compromise on stretch to get formation.

I believe consistency was dealt with in West's first paper. A graph of consistency against stretch from his data would give a curve somewhat like that Page talked about. At about 25 per cent consistency, the stretch increase fell off and, because of the system geometry, we were unable to handle more than 40 per cent consistency, at which value we encountered feeding difficulties. Since the curve flattened off at this consistency, we decided to operate in this range. It was not accidental, but was probably fortuitous, since the work in Norway showed that, if 40 per cent consistency is exceeded, effects that are not at all advantageous intrude, so this seems to be the optimum range in which to operate.

Dr H. F. Rance—May I take a little further Page's comments in which he speculatively relates microcompression in the fibres from shrunken sheets to microcompression in fibres from HCR pulp. To carry the speculation a little further, I wonder what is the essential difference between high consistency refining at 40 per cent solids and planar compaction at 60 per cent water content. I honestly believe that we have microcompression of the same type in all these three phenomena and this may be the common ground of the high extensibility of paper resulting from these three different treatments.

Mr D. H. Page—That will be mentioned in my paper yet to be published.

Dr H. K. Corte—We experimented on high consistency refining 12 years ago, but we were using a fast-rotating peg mill, a production size instrument. Contrary to what we have heard here, we observed no increase in stretch at the same strength. Stretch at break increased with tensile strength as one would expect, but the property that was improved was tearing strength, as well as the folding endurance. When we looked at the fibres, we saw that they were hardly shortened at all, but were curled and they tended to be twisted into knots. Consequently, they compacted much less easily than fibres refined in a hollander or in a conical refiner. The marked effect of note was the preservation of the fibre length and a corresponding increase in tearing strength.

Dr N. Hartler—In an article some years ago,* we reported the very marked influence of mechanical treatment at high consistency upon the floating tendency of rayon pulp sheets—that is, the ability of such a sheet to be 'filled' with mercerisation lye without air inclusion. At that time, we were unable to explain the findings. The HCR results now presented seem to indicate that such a sheet would swell more readily on mercerisation, thereby reducing the chances of air inclusion.

In addition to this, is there any critical temperature during high consistency beating and is there any relationship between this and the second order transitions at high temperatures described during this symposium by Goring?

Dr Barton—We learned somewhat accidently of the importance of quenching the pulp with water immediately after refining. When this was omitted, we found that pulp strength fell somewhat after a few days. The fact that heating pulp slurries reduces strength has been observed by many others. This was something integral in the process that one had to take care of.

Dr H. G. Higgins—The PFI beater work in our laboratory by Watson & Phillips referred to by Page has been advanced considerably since the data mentioned were collated and results similar to those reported today were obtained for stretch and tearing strength, in the same consistency range.

It is suggested in the paper (page 878) that 'a pulp in the 25–40 per cent consistency range can therefore be characterised as a somewhat compressible, semi-solid substance, in contrast to the flowable dispersion of fibres in water at conventional refining consistencies of below 6 per cent'. This is in keeping with Watson & Phillips' concept of compression/decompression cycles

* *Tappi*, 1963, **46** (1), 50–52

during beating in the PFI mill. Results for 35–40 per cent consistency have been reported, but are there data for consistencies at 15–30 per cent?

Dr Barton—The effect of operating at lower consistencies is that more fibre cutting takes place; moreover, this type of refiner uses more power per ton. Unless there is some reason for doing so, it is rather impractical.

Dr S. Rydholm—In the graph shown by Dahm (Fig. Q) are the distances between the beating surfaces considered to be real measurements or just an expression of experimental conditions? What is the distance between the beating surfaces at, say, 6 per cent consistency?

Mr Dahm—The measurements are real, but I am afraid I cannot give any exact information about the distances at low consistencies.

Dr Hartler—In order to relate single fibre properties to sheet properties, we have been concerned with a somewhat similar approach to that presented

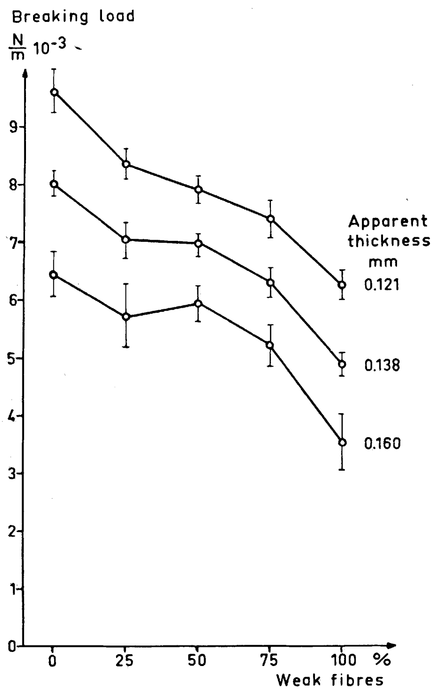

Fig. X

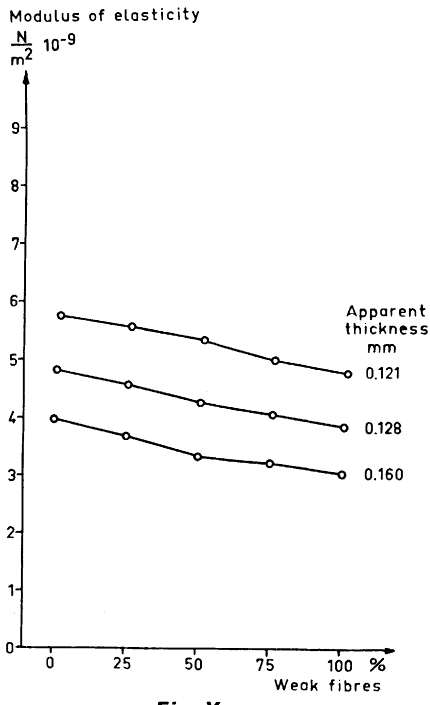

Fig. Y

by Houen. We have varied the fibre strength and followed its influence upon the sheet properties. Utmost care was taken to keep all other factors as constant as possible—in particular, the fibre length distribution and the sheet structure. Sulphite fibres were examined for their breaking strength, which was found to be 0.115 kgf. In order to reduce the strength, the fibres were hydrolysed with acid under conditions that removed no substantial amount of material, but it lowered the strength to 0.055 kgf. When preparing handsheets, no beating was carried out in order not to alter the fibre length distribution (beating would have lowered the fibre length more for the hydrolysed fibres than for the unhydrolysed). Sheet density was altered by means of varying pressures in the wet pressing. Fig. X shows the relationship between the breaking load of the paper and the corresponding proportion of weak fibres in the fibre blend for three different thicknesses of sheet. As is evident, the breaking load is lowered by the greater proportion of weaker fibres.

In Fig. Y, the same relationship is shown for the modulus of elasticity, which in this case is the initial slope of the stress/strain curve. A depreciation as a result of an addition of weaker fibres was experienced in this case, too. Furthermore, in the rupture zone, more broken fibres were found for papers made from weaker fibres. We do not wish at present to give any specific interpretation of the presented data, as the investigations will be extended.