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THE ROLE OF PRESSING IN WET-WEB SATURATION

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Synopsis Wet-web saturation, a process developed for the addition of polymer to fibrous networks, involves three distinct stages:

(*1*) Web consolidation and water removal by wet pressing.
(*2*) Latex saturation of the wet-web by capillary and hydrostatic forces.
(*3*) Redistribution and removal of excess latex by squeeze rolls.

The results presented in this paper are part of an ongoing programme to gain a better understanding of the saturation process and its influence on the properties of polymer impregnated networks. This experimental investigation using a laboratory press is concerned with the saturation process (primarily pressing) behaviour of wood pulps in the basis weight range of 250–1 500 g/m².

Introduction

WET-WEB saturation is a process which has been developed for the addition of polymer to fibrous networks and involves (see Fig. 1), three distinct stages:

(*1*) Web consolidation and water removal by wet pressing.
(*2*) Latex saturation of the wet web by capillary and hydrostatic forces.
(*3*) Redistribution and removal of excess latex by squeeze rolls.

The results presented in this paper are part of an ongoing programme to gain a better understanding of the saturation process and its influence on the properties of polymer impregnated networks.

Wet-web saturation is by comparison with today's high speed paper machines a low speed operation, i.e. usually less than 30 meters/minute. It is best utilised in the high fibre grammage range, i.e. 250 g/m² and upwards and allows a wide variety of fibres and polymers to be combined.

Wet pressing serves to consolidate and remove water from the wet web and, as will be appreciated shortly, a balance is sought between water removal

Under the chairmanship of Dr J. D. Peel and densification. Considerable effort has been devoted to the improvement of wet pressing through advances in press design and wet web–felt interaction studies. However, according to the recent study by Heller *et al.*,[1] the basic mechanism(s) involved have not yet been delineated. The influence of wet pressing on sheet properties has received less attention.

The mechanism of water removal originally proposed by Wahlström and reviewed by Heller *et al.*[1] occurs in two phases: (1) mechanical water removal in the ingoing region of the nip and (2) rewetting of the web in the outgoing region of the nip. The mechanism of rewetting, a controversial subject, is probably the combination of several effects including capillary action, film splitting and hydrodynamic effects.

In our wet pressing experiments, using high grammage webs, an attempt was made to separate the water removal phases (1) and (2) given above. The method was simply to first wet press without, and then with a carrier felt (or wire) using a plain nip press. However, the results cannot be generalised since rewetting will be dependent on the particular pulp, felt or wire combination employed.

In the saturation stage an excess of latex is added to the web by capillary and hydrostatic forces. The two main performance factors of interest are the capacity of the web to hold latex and the rate of latex penetration into the wet web. The latex absorbed by the web is defined by the parameter θ_l which is the ratio of the weight of latex picked up per unit area to the fibre weight per unit area. It can be readily shown that the theoretical capacity of the web is given by:

$$\theta_{l\ \text{predicted}} = \frac{1}{\rho_{a\ \text{wet}}} - \left[\frac{\rho_{\text{latex}}}{\rho_f} + \left(\frac{1}{C_1} - 1\right)\right], \quad . \quad . \quad . \quad (1)$$

where $\rho_{a\ \text{wet}}$ is the density of the wet mat after pressing to a dryness of C_1 and ρ_{latex}, ρ_f are the densities of the latex and fibre respectively. Thus, the web's capacity for latex is mainly controlled by its wet mat density characteristics.

In the final stage of wet-web saturation, squeeze rolls are used to redistribute and remove excess latex from the web, thus increasing its dryness and density prior to drying. Our main concern is with the effects of the squeeze roll on the physical properties and polymer content variation of the final sheet. It is hypothesised that bonds formed during pressing are partially broken upon saturation and then re-formed to a limited extent depending on the level of squeeze roll loading.

With reference to Fig. 1, a portion of latex $M_{l_{3r}}$ at a solids fraction of α_{3r} is removed from the web by the squeeze roll and the balance M_{l_3} at solids fraction α_3 remains with the web. We are interested in the effectiveness of

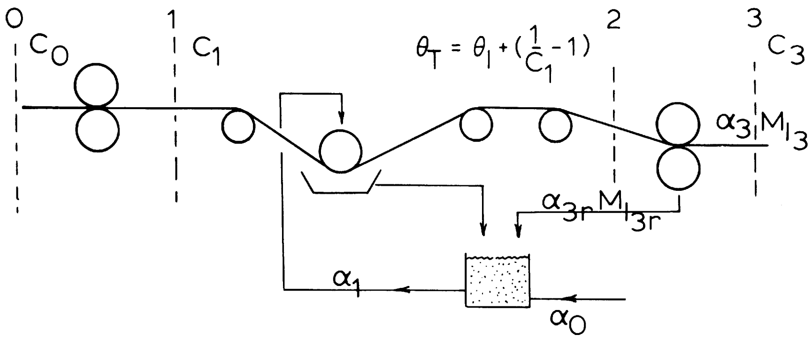

Fig. 1

the squeeze roll in removing this excess latex and the change in the latex concentration ratio:

$$\lambda = \frac{\alpha_{3r}}{\alpha_1}$$

where α_1 is the concentration of the latex picked up.

The three elements of the wet-web saturation process have been briefly examined and we will now consider their effect on the physical properties of the final sheet.

Apparent density has long been recognised as a basic independent variable of paper. This author has shown in unpublished work[2] that tensile breaking length is related to density by the following equation:

$$T = T_0 \left(\frac{\rho_a}{1{\cdot}55}\right)^n, \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

which shows that the strength of paper approaches its ultimate value T_0 (at a finite span) as the web is densified to an effectively nonvoidal structure. The index n is dependent on the level of beating.

The addition of polymer to the network may be viewed as a reinforcing agent which serves mainly to reduce the void volume and stress concentration within the network. We will, therefore, adopt the total density of the network ρ_{aT} at the independent variable (i.e. fibre+polymer weight per unit volume) when referring to polymer impregnated sheets. The total density, as we shall see in the results which follow, is controlled by the level of wet pressing, latex solids and squeeze roll loading.

RESULTS AND DISCUSSION

Wet pressing

WE will first consider the water removal characteristics of a high alpha sulphite pulp (Western Hemlock) in the grammage range of 250 to 1 500 g/m².

To investigate the mechanical mode of water removal, a series of sheets were first pressed without using a felt or wire with the following results.

Water removal as a function of ingoing moisture content

The fraction of the ingoing moisture removed by the press $(1-\beta)_{H_2O}$ variation with ingoing sheet moisture to fibre weight ratio θ_0 is shown in Fig. 2 for two press loading levels of 4·29 kN/m and 17·2 kN/m. The dryness of the web after pressing C_1 is also shown and we note that it is fairly constant over a wide range of θ_0.

Assuming that the dryness after wet pressing is independent of ingoing moisture content to the press (for a constant grammage and press load), the following expression for water removal can be readily derived

$$(1-\beta)_{H_2O} = 1 - \frac{(100/\bar{C}_1 - 1)}{\theta_0}, \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

where $\bar{C}_1$ is some constant percentage dryness. The solid lines drawn in Fig. 2 were constructed using an average of the measured values of C_1 in the above equation for each press loading. For a given press load and fibre grammage the nip opening appears to limit the net flow of water through it.

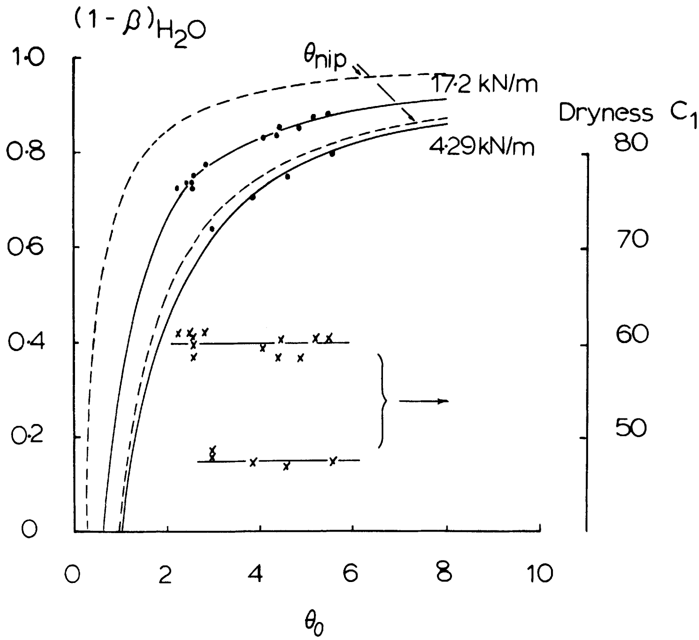

Fig. 2

Assuming that the nip is totally saturated, the maximum moisture to fibre ratio which can pass through the nip θ_{nip} at a given nip caliper t_{nip} is given by:

$$\theta_{\text{nip}} = \frac{t_{\text{nip}}}{G_f} - \frac{1}{\rho_f}, \qquad (4)$$

where G_f is the fibre grammage and ρ_f the cell wall density of the fibre (a density of 1·55 g/m³ has been assumed).

Nip caliper measurements made during the above experiments are used to calculate θ_{nip} and are compared with the measured values of moisture to fibre ratio after pressing θ_1 in Table 1 below:

TABLE 1—COMPARISON OF PREDICTED AND MEASURED MOISTURE TO FIBRE RATIOS AFTER PRESSING

Press load kN/m	θ_{nip}	θ_1 *measured*	$\Delta\theta$
4·29	0·984	1·09	0·106
17·20	0·291	0·66	0·369

G_f = 589 g/m² Speed: 0·91 m/min

The dashed lines shown in Fig. 2 were constructed by substituting the θ_{nip} values given above for $(100/\bar{C}_1 - 1)$ in equation (*3*). The deviation between measured values of water removal and those predicted from nip caliper measurements increases with increasing press load. Care was taken to minimise edge rewetting effects in the sheet and it is surmised that moisture is being 'pumped' through the nip by the hydraulic pressure gradient. Thus, the moisture flow through the nip is greater than predicted by the simple saturated nip concept embodied in equation (*4*).

Variation of fibre grammage

Measurements of web dryness C_1 and nip caliper t_{nip} using a press loading of 4·29 kN/m were made on handsheets in the grammage range of 250 g/m² to 1 500 g/m² without using a felt or wire. The results are summarised in Table 3 and are shown in Fig. 3. At this level of press loading, the dryness after wet pressing decreases with increasing basis weight. This behaviour is directly attributable to the variation in nip caliper which, as shown in Fig. 3, increases disproportionately with basis weight.

Presumably, the effective nip pressure is reduced with increasing grammage as suggested by Heller *et al.*[1] in their studies of felt grammage variation on effective nip pressure.

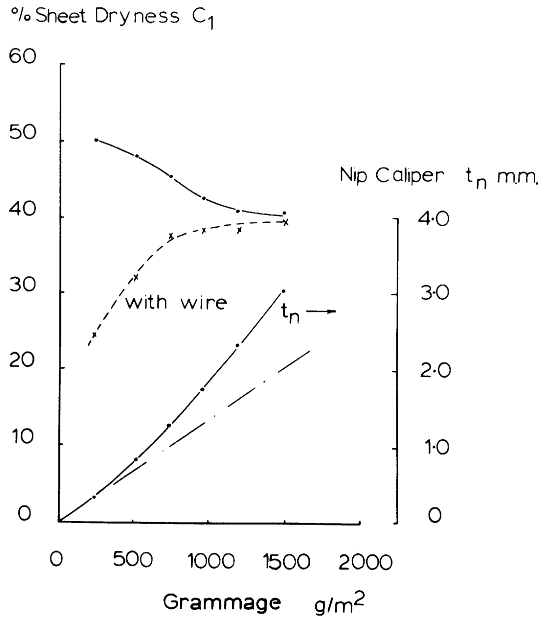

Fig. 3

Rewetting

Our investigation of the rewetting phenomena is limited and the results presented below are for a specific pulp/wire combination.

After couching, the wet web was placed on a plastic wire having a mesh size of 67 × 52 wires per inch and an overall thickness of 0·381 mm (0·015 in.) and then wet pressed with a load of 4·29 kN/m. The procedure was repeated without the wire and a comparison of the results is shown in Table 2 below.

TABLE 2—REWETTING RESULTS

With wire		*Without wire*		
C_1	θ_1	C_1	θ_1	$\Delta\theta$
34·9	1·86	47·5	1·11	0·75

Pulp: High Alpha Bl. Sulphite G_f = 589 g/m² Speed: 0·91 m/min

The significant rewetting of the web $\Delta\theta$ is presumed to be from the water carried with the wire through the nip.

The effects of grammage on rewetting was determined using the procedure given above, and the results are given in Table 3 below.

TABLE 3—THE EFFECTS OF GRAMMAGE VARIATION ON WATER REMOVAL

Grammage g/m^2	With wire C_1(%)	With wire θ_1	Without wire t_{nip}*	Without wire C_1(%)	Without wire θ_1	$\Delta\theta$	Re-wet G_{H_2O} g/m^2
238	24·6	3·07	0·338	50·0	1·0	2·07	493
514	32·4	2·09	0·838	48·1	1·08	1·01	519
745	37·5	1·67	1·295	45·3	1·21	0·46	343
964	38·3	1·61	1·753	42·5	1·35	0·26	251
1 197	38·5	1·60	2·362	41·0	1·44	0·16	192
1 503	39·4	1·54	3·048	40·8	1·45	0·09	135

* mm

Pulp: High Alpha Bl. Sulphite Speed: 0·91 m/min.

As one might expect, the impact of rewetting becomes less significant with increasing grammage. Furthermore, the amount of rewet (i.e. the weight of water per unit area G_{H_2O} transferred to the web) also reduces with increasing basis weight. The latter effect probably reflects a change in the rewetting characteristics of the wet web with grammage and is not constant as suggested by Sweet.[3]

Pulp type

We are now in a position to compare the wet pressing behaviour of different pulps in the high grammage range by measuring (1) their response to mechanical water removal and (2) their rewet characteristics. The mechanical water removal behaviour of four different pulp types at two wet pressing levels are shown in Tables 4 and 5 below.

TABLE 4—THE INFLUENCE OF PULP TYPE ON MECHANICAL WATER REMOVAL

Pulp type*	C_1(%)	ρ_{nip}†	θ_{nip}	θ_1
High Alpha Bl. Sulphite (Western Hemlock)	45·7	0·527	1·25	1·19
Unbleached kraft (Western Hemlock/Douglas Fir)	41·9	0·472	1·47	1·39
Bleached kraft (Southern Pine)	44·9	0·550	1·17	1·23
Unbleached flash dried kraft (Southern Pine)	43·6	0·498	1·36	1·29

* Once dried pulps † g/cm³

G_f = 750 g/m² Press Load: 4·29 kN/m

TABLE 5—THE INFLUENCE OF PULP TYPE ON MECHANICAL WATER REMOVAL

*Pulp type**	$C_1(\%)$	ρ_{nip}†	θ_{nip}	θ_1
High Alpha Bl. Sulphite (Western Hemlock)	58·2	0·917	0·466	0·718
Unbleached kraft (Western Hemlock/Douglas Fir)	56·6	0·806	0·596	0·767
Bleached kraft (Southern Pine)	57·0	0·826	0·566	0·754
Unbleached flash dried kraft (Southern Pine)	56·0	0·827	0·564	0·786

* Once dried pulps † g/cm³

G_f = 750 g/m² Press load: 17·2 kN/m

For a press load of 4·29 kN/m the differences in Dryness C_1 are significant. At the higher press load the difference between actual θ_1 and predicted θ_{nip} moisture to fibre ratio is attributed to flow through the nip induced by the hydraulic pressure gradient.

It is noted that a higher nip wet-mat density corresponds to a dryer sheet after pressing.

The rewet results of the above pulps are shown in the following Table 6.

TABLE 6—THE INFLUENCE OF PULP TYPE ON REWETTING

		With wire		*Without wire*		
Pulp type and symbol		$C_1(\%)$	θ_1	$C_1(\%)$	θ_1	$\Delta\theta_{rewet}$
High Alpha Bl. Sulphite (Western Hemlock)	●	34·9	1·86	47·5	1·11	0·75
Unbleached kraft (Western Hemlock/Douglas Fir)	×	40·2	1·24	46·9	1·11	0·13
Bleached kraft (Southern Pine)	+	34·5	1·90	45·5	1·20	0·70
Unbleached flash dried kraft (Southern Pine)	△	35·9	1·78	43·0	1·33	0·45

* Once dried pulps

G_f = 589 g/m² Press load: 4·29 kN/m

There are significant differences in the rewetting behaviour of each pulp and it is interesting to note that their relative dryness is dependent on the mode of wet pressing (i.e. with a wire or without a wire).

Saturation

EQUATION (*1*) shows that the web's capacity for saturant is dependent on its density $\rho_{a\ wet}$ and dryness C_1 after pressing. The variation of wet-mat

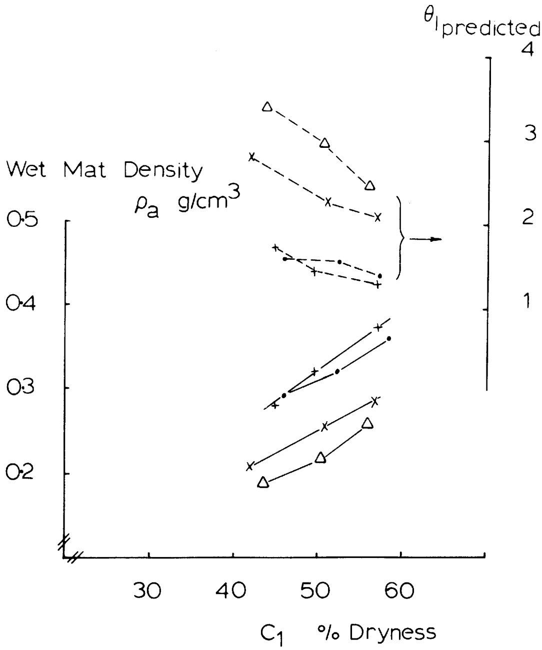

Fig. 4

density and predicted latex 'pick-up' θ_l with dryness C_1 for the pulps used in the previous section is shown in Fig. 4 (refer to Table 6 for symbol index). In practice the web's capacity for saturant is increased by the swelling of the web upon saturation, i.e. $\theta_{l\ \mathrm{measured}}$ will be greater than $\theta_{\mathrm{predicted}}$. The swelling effect increases as the wet mat density decreases.

The optimum wet-mat density characteristics of a pulp required for saturation and latex removal are not readily defined. A web having too high a wet-mat density would probably result in non-uniform saturation, while too low a density web might show a greater propensity to crush.

The ability of the web to withstand deformation is dependent on its wet strain characteristics which in turn is related to the fibre's deformation behaviour (i.e. the extent to which the fibre has been curled and micro-compressed).

Squeeze roll performance

THE fraction of latex removed $(1-\beta)_l$ and the return latex concentration ratio λ, important squeeze roll variables, will be dependent on the particular pulp, wire and latex combination employed. In the following experiments the

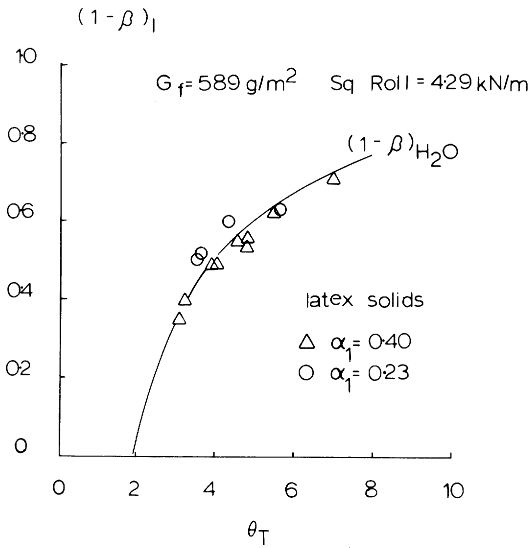

Fig. 5

wet web after pressing was saturated with a Neoprene latex and transferred to a plastic wire having a mesh size of 67 × 52 wires per inch. The excess latex was removed using a squeeze roll load of 4·29 kN/m. The results shown in Fig. 5 (for a web having a fibre grammage of 589 g/m²) indicate that latex removal is not markedly different from water removal by wet pressing, as indicated by the solid line. A similar result was obtained at a fibre grammage of 1 000 g/m².

The latex concentration ratio λ can be interpreted as a measure of the degree of mixing of the latex 'picked up' with the water remaining in the web after wet pressing. Under so-called ideal mixing conditions (where the latex picked up θ_l is completely mixed with the water remaining in the web after pressing) it can be shown that

$$\lambda_{\text{ideal}} = \frac{\theta_l}{(100/C_1-1)+\theta_l}. \qquad (5)$$

The dependence of polymer content η on the amount of excess latex removed from the saturated web and the parameter λ is given by the following equation:

$$\frac{\eta}{1-\eta} = \alpha_1 \left\{\theta_l - \lambda(1-\beta)_l \left[\theta_l + \left(\frac{100}{C_1}-1\right)\right]\right\}. \qquad (6)$$

For the case of ideal mixing this equation simplifies to

$$\frac{\eta}{1-\eta} = \alpha_1 \theta_l \beta_l, \qquad (7)$$

where β_l is the fraction of latex remaining with the web after the squeeze rolls. This equation states that under ideal mixing conditions the polymer content is independent of λ.

In the experiments described above the mode of saturation was essentially one-sided, i.e. the latex was introduced into the wire side of the sheet. A series of squeeze roll experiments were therefore made with the wire (saturated) side uppermost on the squeeze roll carrier wire and another series with the wire side down. The measured values of λ are compared with those calculated assuming ideal mixing in the following Table 7.

TABLE 7—DEPENDENCE OF LATEX CONCENTRATION RATIO λ ON MODE OF SATURATION

C_1 measured (%)	θ_l measured	λ_{ideal}	$\lambda_{measured}$ *sat. up*	$\lambda_{measured}$ *sat. down*	η_{ideal}	$\eta_{measured}$
39·6	2·74	0·64	—	0·80	33·1	23·9
38·4	2·69	0·63	0·54	—	33·3	32·4
42·1	2·13	0·61	—	0·74	30·4	21·5
42·1	2·31	0·63	0·51	—	32·1	30·7
47·8	1·87	0·63	—	0·70	29·9	24·1
47·9	1·91	0·64	0·62	—	30·6	28·8

G_f = 1 000 g/m^2 Press load: 4·29 kN/m

As anticipated, measured λ is dependent on the mode of saturation, i.e. when the wire (saturated) side is down going into the squeeze roll, λ measured is greater than ideal. This deviation is also reflected in the final polymer content of the sheet which is compared with the ideal value in Table 7 above. The above effects are, of course, less pronounced as the grammage is reduced.

It is expected that moisture variation through the thickness of the web after wet pressing will also influence the final polymer content and its distribution through the thickness of the sheet.

Physical properties

In this final section we will briefly examine the influence of the saturation process on some physical properties of the polymer impregnated sheet. In these experiments fibre grammage G_f and latex solids α_1 were varied as indicated in the following Table 8.

After wet-pressing to a dryness of C_1 = 41·5 per cent, the sheets were saturated for five seconds (for α_1 = 25 per cent, t_{sat} = 10 seconds). The excess

TABLE 8—SUMMARY OF LATEX SATURATION EXPERIMENTS AND INDEX OF SYMBOLS

α_1	G_f g/m^2 500	750	1 000
0·25	○	◐	●
0·325	□	◧	■
0·400	△	◭	▲

Pulp: High Alpha Bl. Sulphite   Latex: Neoprene

latex was then removed at various levels of squeeze roll loading which resulted in sheets having a range of apparent densities (based on fibre only) and polymer contents. Their variation with dryness after the squeeze roll is shown in Fig. 6. As the apparent density increases, polymer content is reduced but the the net effect is to produce a sheet having an almost constant total density ρ_{aT} at each latex solids level α_1.

Figs. 7 and 8 show the variation of tensile breaking length and tape mullen (a measure of Z direction strength [4]) with total density ρ_{aT}. The strength correlations demonstrate their strong dependence on total density ρ_{aT} which in turn is controlled by the level of wet pressing (held constant in this work), latex solids and squeeze roll loading. An increase in latex solids α_1 results in a dryer and denser sheet after the squeeze roll.

Over the limited polymer content range investigated, strength improvement is attributed to a reduction in stress concentration which, in this case,

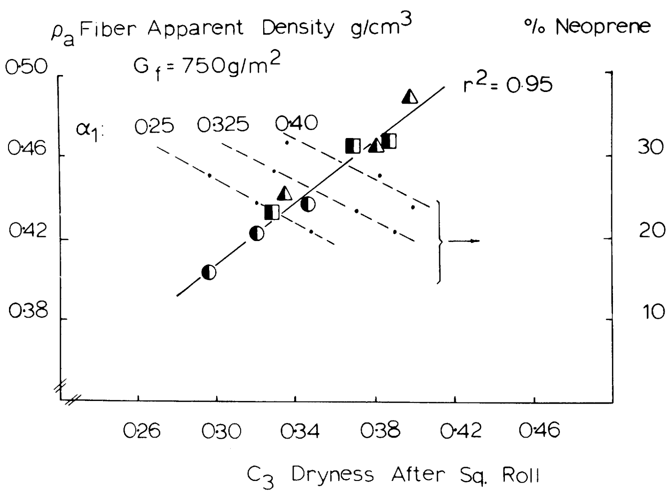

Fig. 6

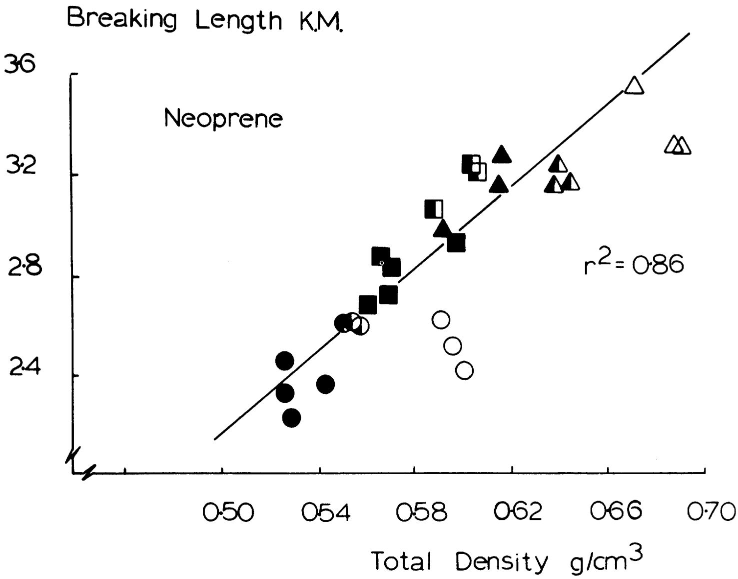
Breaking Length K.M.
3·6
3·2
2·8
2·4
Neoprene
r^2 = 0·86
0·50
0·54
0·58
0·62
0·66
0·70
Total Density g/cm³

Fig. 7

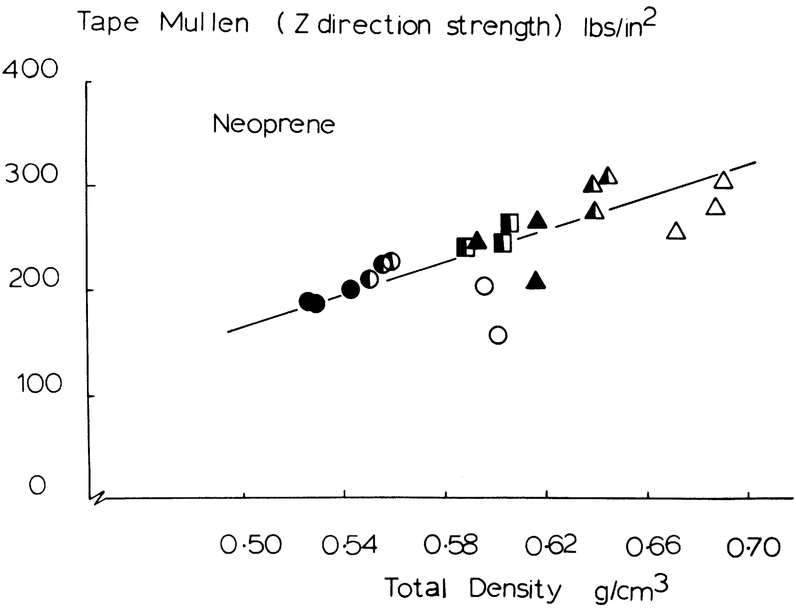
Tape Mullen (Z direction strength) lbs/in²
400
300
200
100
0
Neoprene
0·50
0·54
0·58
0·62
0·66
0·70
Total Density g/cm³

Fig. 8

is achieved by a balance between fibre network densification and polymer addition.

The wide range of physical properties which can be produced by the wet-web saturation process should therefore be an important consideration when comparing different methods of polymer addition.

Conclusions

In this paper the elements of the wet-web saturation process and their interaction have been examined.

In characterising wet pressing behaviour a significant difference in a pulp's response to mechanical water removal and rewetting has been found.

Mechanical water removal at a low press loading is limited by the extent to which the mat can be densified in the nip of the press. The pulp characteristics responsible for rewetting are not yet understood, although the intimacy of web/wire or felt contact and the degree of web expansion in the outgoing region of the nip are considered to be important factors.

Latex removal is similar in form to water removal at the wet press, although the polymer content of the sheet will be dependent on the mode and uniformity of saturation.

The total density of the sheet which is controlled by wet pressing, saturation and squeeze roll variables is shown to be an important variable to which some strength properties are strongly correlated.

Experimental method

HANDSHEETS for the wet pressing, saturation, and squeeze roll experiments were made on an 8 × 8 in. Noble & Woods sheet mould. The temperature of the slurry was adjusted to 20° C before formation and vacuum was allowed to remain on the sheets for five seconds after drainage was complete.

An M/K Systems press (Fig. 9) was used in the wet pressing and squeeze roll experiments, and the nip opening was measured using a dial micrometer. The moisture content of the sheet was measured after formation, couching and wet pressing. The couching procedure used for the majority of the sheets consisted of placing the sheet after formation between two plastic wires, each having a mesh size of 67 × 52 wires per inch and applying a load of 2·15 kN/m. The web dryness C_0 after couching lay in the range of 17 to 24 per cent depending on grammage and pulp type.

Before each wet pressing, the load was adjusted and the micrometer zeroed with the press operating at a speed of 0·91 m/min. A leader was used to ensure the smooth entry of the sheet into the press, and immediately upon its exit the wet weight and caliper were recorded. The wet caliper of the sheet was measured using a micrometer gauge having a 5·08 cm diameter anvil under a pressure of 14·8 g/cm². The sheet

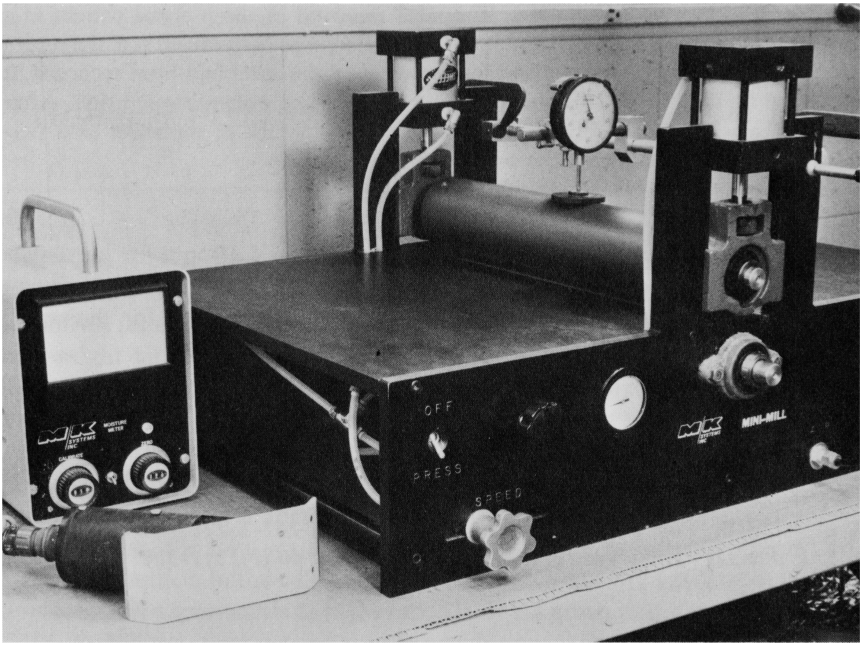

Fig. 9

was dried at 121° C under minimal restraint conditions, and after conditioning its dry weight and caliper were recorded.

The moisture distribution across the sheet after wet pressing was measured in two ways. The first method consisted of cutting the sheet into strips 2·54 cm wide and determining their moisture content gravimetrically. The second method used an M/K Systems microwave moisture meter with a reflectance probe to determine the in-plane moisture variation on both sides of the sheet. Depending on the mode of press operation, it was found that the edges of the sheet were considerably wetter than the centre portion. Therefore, after a quick check of the overall wet weight of the sheet, the nominally 8 × 8 in. sheet was reduced to a 6 × 4 in. sheet and its wet and dry weight and caliper were recorded, a procedure which was adopted for all experiments.

In the saturation and squeeze roll experiments an elastomeric Neoprene latex was used. The sheets after wet pressing were placed on a coarse mesh wire tray and brought into contact with the surface of the latex for a saturation time of five seconds unless otherwise stated. The sheet was carefully transferred onto a tared plastic wire and the saturant 'pick-up' measured gravimetrically.

The M/K press referred to above was also used in the squeeze roll studies. A plastic wire having a mesh size of 67 × 52 wires per inch was used to carry the saturated sheet through the press. The latex removed in the nip was caught in a tray below the lower press roll and its solids content was determined (i.e. the return stream latex concentration α_{3r}). After the weight of the sheet had been recorded, it was dried at 121° C with frequent turning to minimise polymer migration. After drying, the weight was recorded and the polymer content of the sheet as a percentage of the total sheet weight was determined.

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