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E. L. Graminski and E. E. Toth

Polymers Stability and Reactivity Section
Polymers Division

December 15, 1975

Progress Report Covering the Period
January 1 - June 30, 1975

Prepared for

Bureau of Engraving and Printing
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1. SUMMARY

1.1 Effect of Wet Pressing and Calendering on the Stiffness Retention of Paper

Previous investigations indicated stiffness retention of paper increased with increasing paper density at a given weight per unit area (basis weight). Increased paper density can be achieved in various ways, most common of which are wet pressing, mechanical refining and calendering. The effect of each of these paper making processes on the density may vary with paper of different basis weight. As the printing process for currency is a calendering process it was decided to determine the effect of wet pressing, calendering and basis weight on the eventual density and stiffness retention of calendered paper when flexed.

Handsheets were prepared from a kraft wood pulp at three different basis weights, 50, 75 and 100 g/m^2, and wet pressed at either the minimum or maximum pressure possible with the handsheet machine press. Retention of stiffness in the course of flexing was evaluated on the NBS paper flexer.

The results indicate that fiber compaction during wet pressing increases with increasing basis weight. As the thickness of the wet mat increases, the opportunity for lateral fiber movement during wet pressing increases resulting in a more even distribution of mass and greater density. Calendering further densifies the paper and the densification appears to be greater with the higher basis weight papers which were wet pressed at the higher pressure. Although retention of stiffness decreases with increasing basis weight the stiffness of the high basis weight paper after flexing is very much greater than the stiffness of the lower basis weight paper. The increase in the decline of stiffness during flexing for the higher basis weight papers is not in proportion to the increase of stiffness with increasing basis weight for the unflexed paper.

The results of this investigation suggest that mill trials be conducted to determine the effect of wet pressing on paper density, before and after printing and on the printability of currency paper. Variation of wet pressing pressure would probably be most effective in the second and third stages of the press section.

1.2 The Effect of Refining on the Morphological Changes of Wood Pulp Fibers

The most common means of obtaining high density wood pulp papers is by increasing the amount of mechanical refining. Wet fiber flexibility apparently increases with increasing mechanical refining and the compactness of the fiber network increases correspondingly. However, increased refining results in increased fines production and a decrease in fiber length which is undesirable. High consistency refining is one possible means for achieving high wet flexibility without undesirable side effects.

Handsheets were prepared from a kraft wood pulp which had been mechanically refined to different degrees and at various consistencies. In addition, some refining was done at a high consistency, diluted and beaten further at a lower consistency to determine what effect this procedure may have on the morphological changes of pulp fibers. The physical properties of the handsheets were determined.

Fewer fines are produced as the beating consistency increases; however, the strength properties decline. The two consistency refining produces some interesting results as folding endurance increases significantly over paper made from only low consistency beating.

Apparently significant differences in morphological changes do occur at different beating consistencies. Identification of the morphological changes requires microscopic examinations. Due to the time consumption of available microscopic techniques further work on this subject will be deferred to a later time when a more rapid image analysis technique is developed for fiber analysis.

1.3 Physical Properties of Handsheets Made from Classified Currency Furnish

Papermaking furnishes consist of a wide range of fiber sizes and shapes. The distribution of the size and shape factors are of paramount importance to the mechanical properties of paper. A knowledge of the contribution of the various structural components to the mechanical properties of paper is of extreme importance in designing a paper for specific properties. One means of obtaining this information is to fractionate the fiber slurry into various components; prepare handsheets from each fraction and determine the mechanical properties of the handsheets.

A quantity of currency furnish, obtained from the manufacturer of currency paper, was fractionated into four fractions and handsheets were made from the first three fractions. The mechanical properties of these handsheets were compared to those made from the unfractionated furnish.

The handsheets made from the first fraction containing the longest fibers had poor mechanical properties. The mechanical properties of the sheets made from the remaining two fractions for the most part were better than those from the first fraction. The best properties were obtained with handsheets made from the unfractionated furnish. A rather surprising result was the relatively low percentage of long fibers in the furnish.

A greater indepth analysis of currency furnish should be performed. The information would most certainly be extremely helpful in designing a wood pulp paper for currency.

2. The Effect of Wet Pressing and Calendering on the Stiffness Retention of Paper

2.1 Background

In previous work [1] the effect of mechanical refining (beating) and wet pressing on the durability of paper was demonstrated. Both processes result in increasing the density of paper. At constant weights per unit area the retention of bending stiffness of paper during flexing increases with increasing density.

The fines and debris produced during mechanical refining form a film-like material (matrix) in the interstices of the fibers [2]. The matrix serves to restrain the lateral movement and/or twisting of fibers when paper is deformed. Stresses are then maintained along the fiber axis instead of being dissipated in transverse motion. This results in a higher modulus and bending stiffness. During flexing the matrix cracks and leads to a large decline in both modulus and stiffness.

As the density of paper increases the free volume of paper decreases precluding fiber movement when paper is strained. In essence the importance of matrix to the mechanical properties of paper decreases as the density increases. Therefore, at a particular weight per unit area, the more dense a paper is the smaller should be the decline of mechanical properties when flexed.

A third means for densifying paper, calendering, has not been investigated previously. The effect of densification by calendering on the durability of currency needs to be known, as the dry intaglio printing process for currency is in effect a calendering process. In this study the effect of calendering on the durability of wood pulp handsheets was determined.

2.2 Experimental

A kraft wood pulp was chosen for this study as it is relatively easy to refine in comparison to rag pulps. The pulp was beaten in a PFI laboratory mill at 10 percent consistency, with no clearance between bedplate and roll for 10 thousand revolutions at 3.4 kilograms force and a relative velocity of roll to bedplate of 6 m/sec. A total of 1200 grams of pulp were beaten, 40 grams at a time. All of the beaten pulp was combined in a large stainless vessel and diluted to approximately one percent consistency. The slurry was stirred for one hour prior to taking aliquots for handsheet preparation.

Handsheets were prepared at either 50, 75 or 100 g/m^2. Wet pressing was done at either the lowest or highest pressure available on the handsheet machine press. The sheets were dried on a drum drier at 95°C for approximately 4 minutes.

Calendering was done on a calender stack at a pressure of 37.3 kgf/lin cm at a speed of 3.8 cm/sec.

One half of each handsheet was flexed 1000 times over 3.18 mm rollers and constrained by a 700g free hanging weight on the NBS paper flexer. The other half of each handsheet served as the unflexed control. The results are given in Tables 1, 2, 3 and 4.

2.3 Results and Discussion

Increased wet pressing results in an appreciable increase in breaking strength, elongation to break, folding endurance, sonic modulus and density while Elmendorf tear, air permeability, cantilever stiffness and thickness decreased. Calendering results in a decrease in thickness, air permeability and cantilever stiffness and a marked increase in initial modulus, sonic modulus and density. The remaining properties listed in Tables 1 and 3 show little or no change as a consequence of calendering. It must be cautioned, however, that calendering at other pressures or by supercalendering may have produced entirely different results.

An increase in the weight per unit area (basis weight) resulted in a substantial increase in breaking strength, energy to break, Elmendorf tear, folding endurance, cantilever stiffness and thickness while air permeability decreased. There appears to be a trend towards a lower modulus and an increase in density with increasing basis weight. The increase in density may be due to better fiber compaction at higher basis weight or it may be an artifact resulting from the thickness measurement.

Paper is not smooth and its thickness is actually a measure of the highest points on its surfaces. If the roughness of paper remains the same for all basis weights then the thickness measurement of the higher basis weight paper would be closer to its actual average thickness than it would be for the lower basis weight papers. Consequently the determined volume would be in greater error for the lower basis weight papers resulting in a lower estimate of density.

There is also the possibility the density actually increases with increasing basis weight. If the ability of fibers to move laterally during wet pressing increases with increasing thickness of the wet web, higher densities would result. The higher density areas would experience pressure prior to lower density regions. If the fibrous mass were able to flow laterally, the regions under high pressure would flow towards the regions of low pressure. This means that the variance in mass distribution would decrease and the formation of the paper would be improved. Improved formation would be very beneficial to the printability of paper.

In order to prove that mass distribution is more uniform with increasing basis weight, paper would have to be analyzed by beta-radiography [3,4]. There is a remote possibility such an analysis can be made in cooperation with laboratories having the necessary analytical equipment.

The tensile and compressive stresses at the surfaces of paper, when bent to a particular radius of curvature, increase with increasing paper thickness. As a consequence, the magnitude of structural degradation should increase with increasing thickness. An excellent measure of structural change as a consequence of flexing is the increase in air permeability. A plot of the increase in air permeability after flexing against the thickness of the paper is shown in Fig. 1. An excellent correlation exists between the thickness of paper and the increase in air permeability after flexing.

The increase in air permeability for a given thickness is greater for the calendered papers which indicates the tensile and compressive stress are greater in calendered than in uncalendered paper. This is to be expected as the initial modulus of the calendered paper is greater than the initial modulus of the uncalendered paper. Furthermore, the data suggest that there is a maximum thickness for calendered paper which should not be exceeded because of extensive structural degradation when bent to a small radius of curvature. The maximum thickness, however, is probably substantially greater than the thickness which would be acceptable for currency.

The increase in air permeability as a consequence of flexing is probably due to degradation of the matrix. It has been shown previously that the degradation of the matrix is probably the greatest factor in the decline of paper stiffness [2]. Therefore, the retention of bending stiffness should decrease with increase of air permeability. A plot of retention of stiffness against increase in air permeability is shown in Fig. 2. A good correlation exists between these two variables.

Even though retention of stiffness is lower for the thicker papers (higher basis weight) the final stiffness of the thicker papers is much greater than that of the thinner papers (Fig. 3).

Retention of bending stiffness is greater for handsheets wet pressed at the higher pressure whether calendered or not. This would be expected as higher wet pressing produces a higher density and it has been shown previously that stiffness retention is greater the higher the density [1]. Thickness is only one important factor in the bending stiffness of paper. The density is also critical as the importance of matrix to the modulus and stiffness of paper declines with increasing density.

The results of this study indicate once again that currency should have maximum density for greatest retention of stiffness. Wet pressing appears to be a very important manufacturing variable from the standpoint of achieving the greatest density for currency. Furthermore, there is the possibility that wet pressing might affect the uniformity of mass distribution in paper which is of importance to the printability of currency paper. Some studies should be made on the effect of wet-pressing pressures on the formation, density and printability of manufactured currency paper.

3. The Effect of Refining Consistency on the Morphological Changes of Wood Pulp Fibers

3.1 Background

Results reported previously [1] and in Section 2.3 of this report indicate currency paper should have a high density for optimum stiffness retention during circulation. Generally pulp is highly mechanically refined whenever a high density paper is desired. Refining results in greater wet fiber flexibility which in turn eventuates in a more compact fiber network. The more compact the network the greater the density.

As fiber compactness increases, the interstices between the fibers become smaller and smaller and the effect of fines on the mechanical properties of paper declines since there is less opportunity for lateral fiber movement during straining in a compact fiber network. Increased mechanical refining, which produces greater wet fiber flexibility, also results in the production of greater amount of fines and a decrease in fiber length. The increased number of fines causes water drainage to slow down resulting in a decline in the rate of paper production. A point is reached in papermaking where the fines become more of a liability than an asset.

It would be ideal for a refining process to be capable of producing fibers having high wet flexibility without reducing the fiber length or producing undesirable quantities of fines. As mechanical refining progresses, fibers imbibe more water and become more swollen. Increased swelling makes fibers more susceptible to damage when subjected to compressive and shear forces during beating.

One possible means for reducing fiber damage and preserving their integrity is by reducing available water for swelling in the beating process. High consistency refining is becoming increasingly more important in paper manufacture not only because of the smaller amounts of water used but because high consistency refining produces desirable morphological changes in fibers. The morphological changes occurring in high consistency refining are undoubtedly different from those in low consistency refining.

As there is interest in developing an all wood currency paper it was decided to determine the effect of high density refining of wood pulp on the rheological properties for wood pulp paper. Hopefully, morphological changes similar to those occurring with cotton and linen pulps (fiber splitting and fibrillation), will occur with wood pulps under certain specific conditions.

3.2 Experimental

Forty grams of wood pulp was beaten in a PFI laboratory mill at 3.4 kgf/cm at a relative velocity of roll to bedplate of 6 m/sec with no clearance between bedplate and roll for 5 or 10 thousand revolutions at 5, 10, 20 or 40 percent consistency. Also some beatings involved 5 thousand revolutions at either 20, 30, or 40 percent consistency followed by the addition of sufficient water to decrease the consistency to 10 percent and beaten for an additional 5 thousand revolutions.

Six handsheets were made from each of the pulp beatings and wet pressing was done at the maximum pressure possible on the handsheet press. The physical properties of the handsheets were determined and are listed in Table 5.

3.3 Results and Discussion

As could be expected, the reduction of water in the entire mechanical refining process results in a decline of paper strength. As mechanical refining increased paper strength as well as many other physical properties improved regardless of the consistency. The ease of water drainage (Canadian Standard Freeness) increases with increased refining consistency which demonstrates that high consistency refining does indeed reduce the amount of debris generated.

The refining done at two different consistencies produced the most interesting results. The tensile properties of the handsheets beaten for 5 thousand revolutions at either 20, 30 or 40 percent consistency followed by an additional beating of 5 thousand revolutions at 10 percent consistency were essentially equivalent to those of handsheets beaten at either 5 or 10 percent consistency for 10 thousand revolutions. However, the folding endurance of the handsheets beaten at 40 and 10 percent consistencies was significantly higher than that of handsheets beaten at 5 or 10 percent consistency for 10 thousand revolutions (two sided t test). It is also noteworthy that the densities of the paper from the two consistency refining were appreciably higher than the handsheets obtained from the single consistency refining.

Evidently significant differences in morphological changes occur in the two consistency refining resulting in increased density and folding endurance and a decrease in thickness. There also appears to be a trend towards a higher elongation to break in the handsheets from two consistency refining.

The results are encouraging in that morphological changes can be affected by varying the consistency in mechanical refining. Microscopic investigations are needed to identify the changes. However, microscopy is long and tedious work and frequently relies on subjective rather than objective measurements.

Work is commencing in the Applied Mathematics Division on the image analysis of fibers. When completed, the image analysis system should permit rapid, quantitative measurement of such fiber properties as fiber length distribution, coarseness, fibrillation and curl. It was decided to discontinue further work on the effect of consistency in refining on the morphological changes of wood pulp fibers until the image analysis technique is developed.

4. The Physical Properties of Handsheets Made from Classified Currency Paper Furnish

4.1 Background

Paper pulp consists of a wide distribution of fiber lengths and sizes. When filtered on the endless wire section of a paper machine they form a fiber network which determines the eventual paper properties. Different papers rely on different fiber fractions for a particular paper property. To achieve good formation in paper a short fiber furnish is favored over long fiber furnish. Folding endurance is enhanced by long fibers.

Regardless of the importance of a single fiber fraction on a particular paper property the remaining fractions have a strong influence on the final property in question. It has been postulated numerous times in previous reports [1,2,5,6,7] that the fines of currency paper are extremely important to the modulus and bending stiffness of paper. The degradation of that portion of currency paper, consisting primarily of fines, results in a substantial decline in modulus and cantilever stiffness.

One method of demonstrating the importance of the various fiber fractions of paper is to separate the beaten pulp into individual fractions and to make handsheets from the various fractions. This was done with a quantity of currency paper furnish obtained from the manufacturer of currency paper. The stock was sampled just after the final mechanical treatment and prior to final dilution for the headbox. The furnish was at approximately 2.3 percent consistency and contained no wet strength resin.

4.2 Experimental

The currency paper furnish received from the currency paper manufacturer was filtered to remove excess water. The final consistency was approximately 20 percent. Aliquots of the concentrated furnish containing approximately 5 grams of dry fiber, were fractionated on a commercial fiber classifier. Only 3 screens were used in the classification, 14, 35 and 65 mesh as the 150 mesh screen constantly plugged causing water overflow. Approximately 75g of dry fiber were fractionated. Handsheets were then made from the various fractions. The physical properties of the handsheets are given in Table 6.

4.3 Results and Discussion

It was surprising that the long fiber fraction consisted of only about 16 percent of the total furnish. This is less than half the amount usually found in a moderately beaten softwood pulp. The second fraction (35 mesh screen) consisted of approximately 37 percent of the furnish while the third fraction consisted of about 15 percent of the total. This means that approximately 32 percent of currency stock consists of very short fibers and fines.

Despite the low percentage of long fibers in currency paper it nevertheless has excellent physical properties. Apparently there are an appreciable number of very long fibers in the long fiber fraction which have a great effect on the physical properties of currency paper. A fiber length distribution of this fraction will be determined in the future as the information may be very important in the design of a wood pulp paper for currency.

Handsheets made from the first fraction are very porous and have a low density. The handsheets made from the other two fractions are less porous and denser. The initial modulus increases with increasing density demonstrating once again the importance of fiber compaction on the modulus of paper. The handsheets made from the unfractionated stock had the highest modulus, strength, extensibility, folding endurance, and cantilever stiffness.

While the thickness of paper greatly influences its bending stiffness it is nevertheless only one factor of importance to that property. This is demonstrated very nicely when the bending stiffness of the handsheets from fraction one and the unfractionated stock are compared. The thickness of the handsheets from fraction one are 24 percent higher while the cantilever stiffness is 15 percent lower than the handsheets made from unfractionated stock. Apparently, the higher density of the unfractionated handsheets is the primary cause for the higher bending stiffness.

Much could be learned from an in depth study of currency stock. The information obtained from such a study would greatly assist in the design of a wood pulp paper for currency. However, much of the work would involve microscopic investigations of the fibers. As this work is lengthy and tedious with the available microscope techniques further work on this problem will be deferred until fibers can be analyzed automatically (see image analysis in section 3.3).

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APPENDIX

CONVERSION TABLE TO SI UNITS

Property	Convert from	Symbol	To	Multiply by
Modulus	giganewton/meter^2	GN/m^2	kilogram force/cemtimeter^2	10,197
Breaking Strength	kilonewton/meter	kN/m	kilogram force/15 millimeters	1.53
Energy to Break Cantilever Stiffness	millinewton·meter	mN·m	gram-centimeters	10.2×10^{-2}

Table 1. The Effect of Wet Pressing and Calendering on the Tensile Properties of Unflexed Handsheets Having Various Weights per Unit Area

Wet Pressing[1] Pressure	No. of Specimens		Initial Modulus GN/m^2				Breaking Strength kN/m				Elongation to Break %				Energy to Break mN·m				Weight per Unit Area g/m^2	Apparent Density g/cm^3			
	W	L	W[2]	s[3]	L	s	W	s	L	s	W	s	L	s	W	s	L	s		W	s	L	s
Uncalendered																							
L	8	11	3.5	.24	3.8	.23	4.0	.22	4.0	.31	3.6	0.3	3.4	0.3	94.1	11.8	91.5	13.1	52	.524	.006	.523	.009
H	9	10	3.6	.22	3.9	.45	4.3	.22	4.5	.33	4.1	0.2	3.7	0.4	113.7	8.5	107.8	13.1	53	.545	.008	.542	.001
L	10	9	3.6	.20	3.7	.30	5.8	.41	5.8	.24	4.1	0.4	4.0	0.3	156.2	21.6	152.3	13.7	75	.561	.018	.553	.012
H	9	9	3.8	.29	3.9	.28	6.1	.30	6.3	.35	4.8	0.3	4.2	0.3	187.6	17.6	169.3	17.6	75	.606	.008	.584	.014
L	9	9	3.5	.25	3.5	.24	7.3	.51	7.3	.77	4.5	0.4	4.3	0.5	213.7	24.2	205.2	37.9	98	.581	.018	.569	.020
H	10	9	3.6	.23	3.6	.30	7.8	.57	8.0	.70	5.4	0.3	4.8	0.4	257.3	26.8	242.4	35.0	98	.624	.016	.608	.015
Calendered																							
L	10	9	4.5	.52	4.6	.31	4.0	.46	4.0	.24	3.4	0.4	3.3	0.3	90.2	19.6	85.6	11.1	52	.674	.030	.720	.016
H	10	6	4.4	.29	5.0	.51	4.3	.14	4.5	.24	4.1	0.3	3.8	0.2	115.0	8.5	107.2	7.8	54	.662	.019	.736	.014
L	9	10	4.3	.27	4.8	.15	5.9	.44	5.8	.43	4.2	0.3	3.7	0.5	159.5	18.3	142.5	24.2	74	.679	.016	.754	.015
H	9	8	4.3	.23	5.0	.20	5.9	.48	6.1	.25	4.6	0.5	4.1	0.3	177.1	28.8	159.5	14.4	75	.705	.010	.782	.012
L	10	10	4.2	.44	4.4	.28	6.5	.48	7.3	.49	3.7	0.7	4.0	0.4	160.1	36.6	192.1	28.1	97	.696	.064	.730	.018
H	10	7	4.0	.42	4.7	.37	7.6	.33	8.4	.86	5.4	0.3	4.5	0.4	260.1	17.0	232.0	36.6	99	.759	.069	.777	.013

[1] L = lowest possible pressure, H = highest possible pressure on handsheet machine press.

[2] W = width, L = length of 15 x 30 cm flex specimens

[3] $s = \sqrt{\frac{n\Sigma X^2 - (\Sigma X)^2}{n(n-1)}}$

Table 2. The Effect of Wet Pressing and Calendering on the Tensile Properties of Flexed Handsheets having Various Weights per Unit Area

Wet Pressing[1] Pressure	No. of Specimens		Initial Modulus GN/m²				Breaking Strength kN/m				Elongation to Break %				Energy to Break mN·m				Weight per Unit Area g/m²	Density g/m²			
	W	L	W[2]	s[3]	L	s	W	s	L	s	W	s	L	s	W	s	L	s		W	s	L	s
Uncalendered																							
L	10	8	3.1	.28	2.4	.28	4.2	0.2	4.0	0.2	3.7	0.3	3.6	0.2	49.0	5.0	87.6	7.8	53	.526	.009	.532	.013
H	9	10	3.1	.39	2.9	.30	4.1	0.2	4.3	0.2	4.2	0.3	3.7	0.2	104.5	10.5	98.0	7.8	54	.550	.013	.555	.014
L	10	8	2.8	.30	2.0	.25	5.2	0.3	5.5	0.3	4.3	0.2	4.0	0.3	143.1	14.4	129.4	13.7	75	.551	.012	.561	.017
H	10	10	3.2	.22	2.7	.30	5.6	0.4	6.2	0.4	4.8	0.3	4.2	0.3	169.3	17.6	152.9	12.4	76	.605	.017	.601	.035
L	9	9	3.0	.21	1.6	.25	6.8	0.4	6.6	0.8	4.6	0.5	4.3	0.7	199.3	24.8	166.6	41.8	99	.586	.014	.578	.021
H	7	10	2.9	.24	2.6	.30	6.9	0.6	7.3	0.5	5.3	0.4	4.4	0.4	227.4	26.1	189.5	25.5	99	.639	.012	.641	.019
Calendered																							
L	10	7	4.3	.47	3.6	.29	3.6	0.4	3.8	0.2	3.4	0.6	3.4	0.2	80.4	20.9	80.4	7.2	52	.738	.025	.703	.029
H	7	10	4.0	.39	3.6	.57	4.0	0.2	4.2	0.3	4.0	0.5	3.4	0.3	101.3	16.3	88.2	13.7	53	.712	.042	.707	.039
L	7	9	3.7	.35	2.4	.20	5.5	0.4	5.3	0.3	4.0	0.2	3.9	0.3	139.2	14.3	122.2	13.1	74	.730	.041	.714	.014
H	9	10	3.8	.36	3.3	.32	5.8	0.2	6.0	0.4	4.9	0.3	4.0	0.2	175.8	13.1	145.7	14.4	75	.747	.038	.756	.009
L	8	9	3.5	.43	2.1	.36	6.1	0.7	6.5	0.5	3.8	0.5	4.2	0.5	149.7	31.4	163.4	28.8	97	.704	.045	.709	.017
H	5	9	3.2	.38	3.0	.31	7.1	0.3	7.3	0.9	5.5	0.3	4.3	0.5	239.2	16.3	186.9	40.0	98	.760	.047	.767	.011

1 L = minimum, H = maximum pressure of press on handsheet machine.

2 W = width, L = length of 15 x 30 cm flex specimens

3 $s = \sqrt{\frac{n\Sigma X^2 - (\Sigma X)^2}{n - (n-1)}}$

Table 3. The Effect of Wet Pressing and Calendering on the Physical Properties of Unflexed Handsheets having Various Weights per Unit Area

Wet Pressing[1] Pressure	No. of Specimens		Elmendorf Tear g				MIT Fold Endurance 1000 g double folds				Cantilever Stiffness mN·m				Sonic Modulus[4] GN/m^2				Air Permeability cm^3/min (10 cm)		Thickness μM				Weight per Unit Area g/m^2
	W	L	W[2]	s[3]	L	s	W	s	L	s	W	s	L	s	W	s	L	s		s	W	s	L	s	
											Uncalendered														
L	11	11	52	5	56	6	1350	409	1260	276	10.8	0.6	10.4	1.3	51.8	2.1	50.6	1.3	739	198	98.8	3.9	99.1	4.4	52
H	10	10	48	7	49	6	1760	306	1890	502	9.3	0.4	8.7	0.5	53.6	1.8	53.0	2.2	276	13	96.4	1.3	98.1	1.8	53
L	10	10	87	14	80	5	1850	406	1820	265	27.4	1.8	24.5	1.7	54.1	2.0	51.1	2.2	299	37	133.4	4.3	134.1	5.1	75
H	10	10	84	14	70	10	2190	538	2440	312	20.9	1.7	21.4	1.6	56.1	1.9	55.6	3.2	114	6	123.7	3.8	127.6	3.6	75
L	10	10	128	17	127	11	2430	407	2790	347	53.6	4.7	60.0	4.6	50.6	2.0	50.7	1.9	194	18	167.6	5.5	172.4	6.8	98
H	10	10	105	10	123	17	3120	606	3020	288	41.2	3.9	46.8	5.8	57.3	3.5	55.0	2.5	80	6	155.4	3.9	160.9	5.2	98
											Calendered														
L	11	11	49	8	50	7	1250	207	1380	439	8.8	1.0	7.6	1.3	66.1	4.1	73.5	3.5	568	146	76.0	4.0	70.8	3.0	52
H	10	10	40	4	47	6	1540	160	1710	208	8.6	0.6	7.0	0.8	63.9	4.0	70.8	2.2	206	13	80.1	2.0	71.8	1.0	54
L	10	10	79	9	85	9	1890	430	1870	318	24.4	1.3	18.9	1.8	66.2	3.5	70.5	2.5	228	24	107.3	4.0	97.8	2.0	74
H	10	10	84	20	76	6	2760	467	2380	587	20.4	1.7	16.7	1.3	65.9	4.4	72.9	2.6	99	5	104.9	2.0	95.7	2.0	75
L	10	10	114	17	128	15	2300	443	2380	387	44.8	4.6	45.2	5.7	63.8	3.4	67.7	2.8	143	9	137.2	11.0	131.0	4.0	97
H	10	10	115	18	120	18	2970	626	3034	447	37.1	3.5	39.4	4.0	65.6	3.2	74.4	4.0	60	5	129.5	11.0	127.0	4.0	99

[1] L = minimum, H = maximum pressure of press on handsheet machine

[2] W = width, L = length of 15 x 3 cm flex specimens

[3] $s = \sqrt{\frac{n\Sigma X^2 - (\Sigma X)^2}{n(n-1)}}$

[4] Sonic modulus based on apparent density

Table 4. The Effect of Wet Pressing and Calendering on the Physical Properties of Flexed Handsheets having Various Weights per Unit Area

Wet Pressing[1] Pressure	No. of Specimens		Elmendorf Tear g				MIT Fold Endurance 1000 g double folds				Cantilever Stiffness mN·m				Sonic Modulus[4] GN/m^2				Air Permeability cm^3/min (10 cm)		Thickness µm				Weight per Unit Area g/m^2
	W	L	W[2]	s[3]	L	s	W	s	L	s	W	s	L	s	W	s	L	s		s	W	s	L	s	
											Uncalendered														
L	4	9	53	10	49	7	1510	214	1290	387	7.4	0.8	5.4	0.5	44.1	2.9	38.7	2.6	771	193	98.4	3.0	97.3	2.8	53
H	9	10	48	6	44	4	1690	335	1710	404	7.9	1.3	5.3	0.4	46.9	4.9	44.8	2.8	283	14	96.5	2.1	94.9	3.2	54
L	10	10	72	5	82	14	2220	554	2010	341	21.1	7.7	9.8	0.6	42.7	3.5	32.4	2.8	343	43	135.5	3.5	133.8	5.1	75
H	10	10	71	13	77	15	2710	444	2690	525	16.0	2.7	10.7	0.5	47.9	3.0	42.7	3.3	127	6	124.6	4.1	125.0	7.8	76
L	10	10	112	15	119	11	2750	436	2950	388	38.2	3.2	16.5	1.4	44.9	4.1	27.9	2.3	248	24	166.5	5.8	171.5	7.5	99
H	10	10	104	14	113	17	3440	693	3100	658	29.1	3.6	18.4	2.0	46.1	3.0	39.7	2.2	92	6	152.9	4.5	152.3	6.1	99
											Calendered														
L	11	11	48	4	45	6	1160	254	1240	464	6.2	1.0	4.9	0.4	47.8	10.1	53.5	2.4	588	135	69.8	3.0	72.2	4.0	52
H	10	10	46	5	44	5	1500	401	1690	699	6.7	1.3	5.2	0.6	62.6	4.3	57.4	2.6	215	15	74.9	4.0	75.5	5.0	53
L	10	10	76	11	76	9	1910	392	2040	345	18.9	2.6	9.7	0.6	58.3	5.4	41.9	2.8	269	29	105.4	6.0	103.5	3.0	74
H	10	10	69	11	72	3	2530	444	2320	413	15.9	1.6	10.2	0.8	57.4	4.0	53.2	2.2	113	7	100.7	6.0	99.6	2.0	75
L	10	10	112	10	109	9	2700	390	2750	530	33.9	5.2	18.6	2.4	55.4	3.4	34.7	1.3	187	12	133.2	15.0	137.3	3.0	97
H	10	10	96	8	110	17	2950	653	3320	754	28.0	3.2	20.8	1.9	54.2	4.9	50.4	2.8	78	4	128.9	10.0	127.0	2.0	98

[1] L = minimum, H = maximum pressure of press on handsheet machine

[2] W = width, L = length of 15 x 30 cm flex specimens

[3] $s = \sqrt{\frac{n\Sigma X^2 - (\Sigma X)^2}{n(n-1)}}$

[4] Sonic modulus based on apparent density

Table 5. The Effect of Refining Consistency on the Physical Properties of Handsheets

Pulp Consistency %	PFI Rev. 1000	No. of Specimens	Initial Modulus GN/m^2		Breaking Strength kN/m		Elongation to break %		Energy to break µN·m		Elmendorf tear g		MIT Fold Endurance 1000g double folds		Cantilever Stiffness mN·m		Air Permeability cm^3/min ($10\ cm^2$)		Weight per Unit Area g/m^2	Canadian Standard Freeness cm^3	Thickness µm		Density g/cm^3	
				s[1]		s		s		s		s		s		s		s				s		s
Control	0	16	1.28	.31	0.86	.10	0.94	.13	0.7	0.2	30	2.8	1.0	0.5	11.4	2.3	>3000	--	65	695	153.5	2.3	.420	.004
5	5	14	3.53	.49	5.05	.29	3.60	.43	17.2	2.5	74	11.5	1590	259	19.8	2.7	278	3.8	68	505	121.8	2.3	.552	.009
5	10	10	3.75	.67	5.83	.34	4.11	.63	22.8	2.8	66	9.8	1950	449	19.5	2.9	107	7.9	69	380	119.5	2.0	.576	.008
10	5	10	3.20	.33	4.74	.25	3.88	.28	18.2	2.0	82	9.3	1400	182	18.6	1.2	340	12.5	69	507	126.1	1.7	.547	.002
10	10	8	3.68	.23	5.60	.16	4.39	.31	23.9	1.8	74	9.5	2020	279	16.6	1.6	128	5.2	70	398	120.0	2.5	.580	.007
20	5	11	2.85	.22	4.06	.25	4.08	.56	17.0	2.6	95	8.4	820	218	16.0	0.8	602	28.6	69	546	125.2	1.8	.549	.005
20	10	11	3.29	.28	4.66	.43	4.29	.44	20.1	3.0	86	8.9	1480	296	16.4	1.4	300	7.2	70	434	120.6	1.0	.577	.006
20 10	5 5	10	3.72	.31	5.68	.46	4.67	.30	25.6	2.4	71	11.2	2230	449	16.6	0.6	121	9.7	70	376	116.7	2.4	.597	.008
30	5	10	2.34	.29	3.25	.16	3.74	.38	12.6	1.3	97	3.5	270	69	16.5	0.9	1707	79.7	69	630	133.0	1.5	.515	.006
30	10	11	3.18	.26	4.29	.33	4.39	.47	19.3	2.9	96	9.5	1020	225	16.7	0.8	712	28.9	69	511	123.3	1.1	.562	.002
30 10	5 5	16	3.41	.32	5.73	.40	4.79	.24	26.4	2.4	81	13.7	2240	280	16.4	1.0	170	2.3	70	385	119.9	1.6	.586	.010
40	5	11	2.32	.19	3.29	.29	3.53	.49	12.2	2.1	98	5.6	410	189	16.8	1.2	1919	64.4	69	661	132.5	1.0	.523	.006
40	10	11	2.89	.23	3.90	.21	3.87	.33	15.6	1.9	93	6.3	600	126	15.5	0.7	1371	38.3	69	603	124.2	1.7	.554	.005
40 10	5 5	11	3.74	.24	5.77	.30	4.66	.40	26.0	2.5	73	6	2790	546	16.6	1.7	126	5.5	70	379	114.4	1.3	.614	.006

[1] $s = \frac{n\Sigma X^2 - (\Sigma X)^2}{n - (n - 1)}$

Table 6. The Physical Properties of Handsheets made from Fractionated and Unfractionated Currency Paper Furnish

Fraction Screen[1] mesh	Initial Modulus GN/m^2	Breaking Strength kN/m	Elongation to break %	Energy to break μN·m	Elmendorf tear g	MIT Fold Endurance 1000 g double folds	Cantilever Stiffness mN·m	Air Permeability cm^3/min (10 cm^2)	Weight per Unit Area g/m^2	Thickness μm	Density g/cm^3
14	1.42	1.57	0.93	1.37	~200	17	46.1	2750	103	234	0.440
35	1.94	1.75	1.06	1.86	77	7	40.2	2250	96	195	0.491
65	2.49	1.53	1.44	2.45	28	6	10.7	844	60	117	0.491
Unclassified	3.06	4.88	3.74	20.40	172	1350	53.9	41	107	179	0.602

[1] indicate screen mesh size on which fibers were retained in a fiber classification.

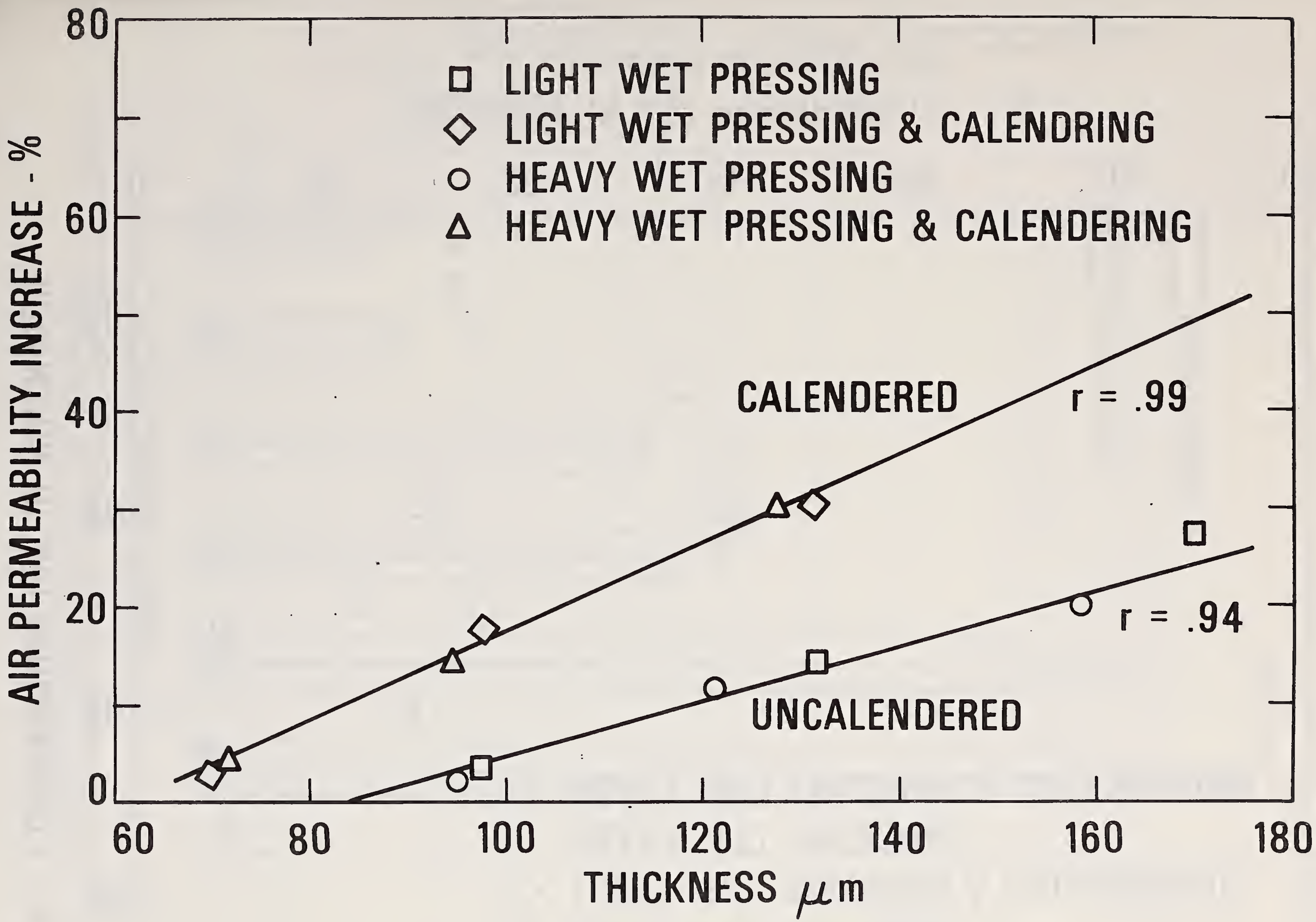

Figure 1: Increase of air permeability with flexing.

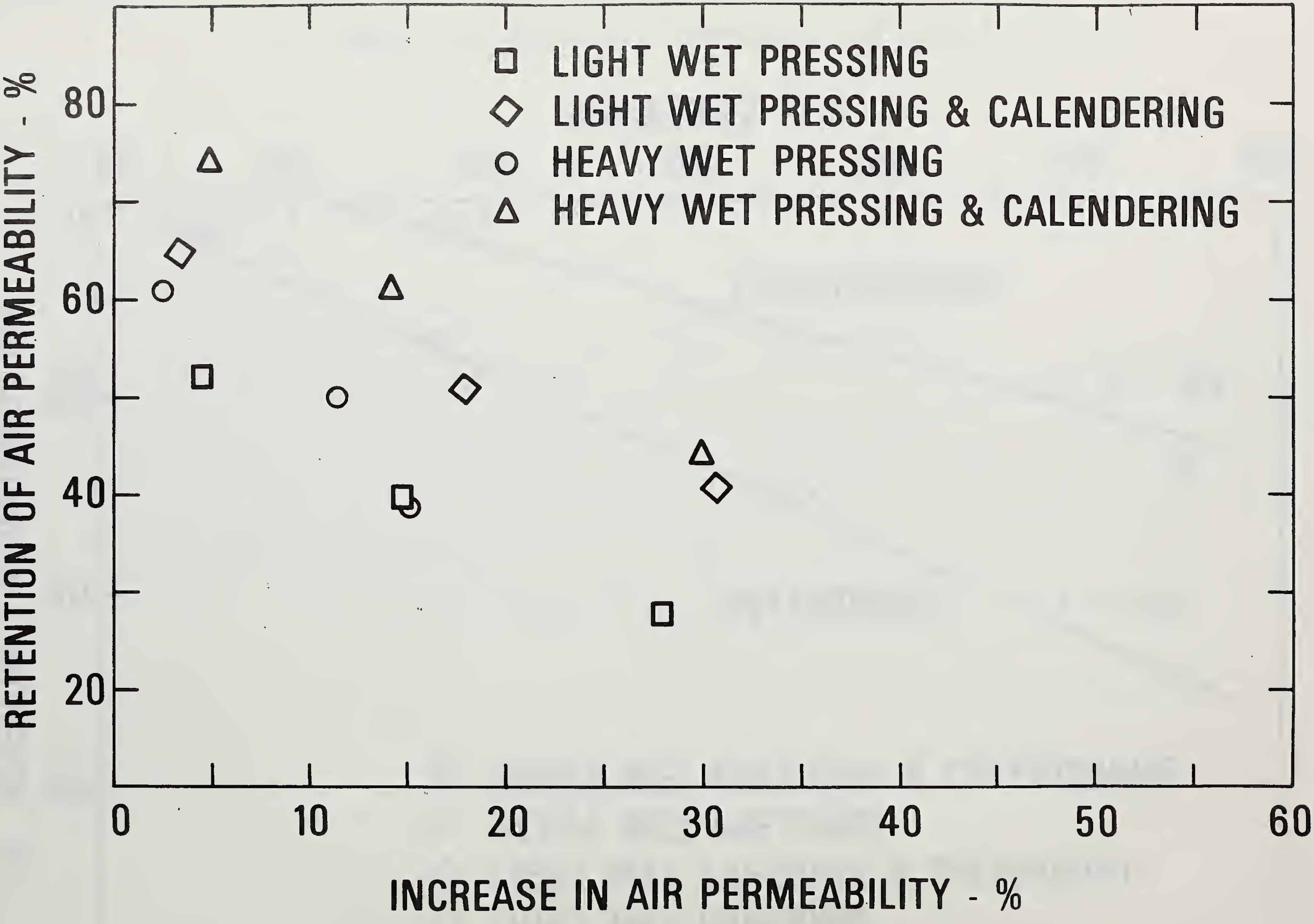

Figure 2: Relationship between the increase in air permeability during flexing and the retention of cantilever stiffness of handsheets.

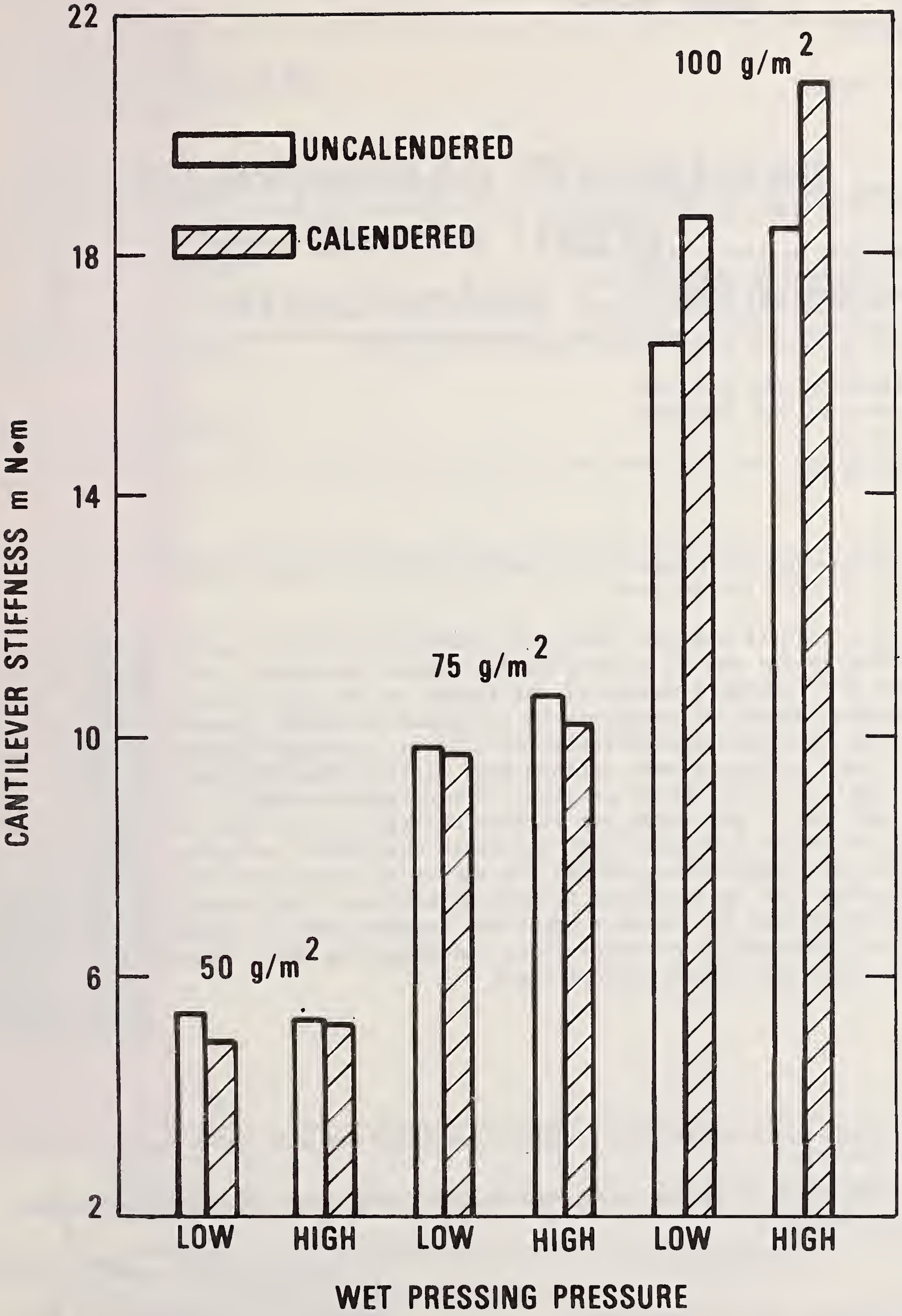

Figure 3: Bending stiffness of flexed handsheets having various weights per unit area.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Experimental results indicate that wet pressing of the wet paper web results in greater densities as the amount of mass being pressed increases. This may be due to greater freedom for lateral movement of the fibers as the thickness of the wet mat increases. Greater densities eventuate in increased stiffness retention during flexing and should result in an improved circulation life of currency. Higher densities with increasing wet mass indicates more uniform mass distribution which should result in improved printability. The debris generated during pulp refining is beneficial to the mechanical properties of paper but its utility decreases as to wet fiber flexibility and the amount of debris increases with increased mechanical refining. High consistency refining of wood pulp apparently reduces the amount of fines produced but other disadvantages arise such as decreased interfiber bonding. The importance of fines to the mechanical properties of currency paper was demonstrated by forming handsheets from the various fractions of currency stock and comparing their mechanical properties with those made from the unfractionated stock.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Calendering; mechanical refining; paper durability; pulp classification; stiffness retention; wet pressing

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