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Evaluation of Currency and Stamp Papers

E. L. Graminski and E. E. Toth

Paper Evaluation Section
Product Evaluation Technology Division
Institute for Applied Technology

January 30, 1973

Progress Report covering the period
July 1 – December 31, 1972

Prepared for
Bureau of Engraving and Printing
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Note

The results contained and the conclusions reached in this progress report are preliminary. Final results and conclusions will be presented in the final report.

U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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1. SUMMARY

As part of a continuing study for the Bureau of Engraving and Printing of the U.S. Department of Treasury, the disparity in the edge tear* of flexed currency paper and redeemed currency and the possibility of improving the stiffness retention of paper by treatment with acrylic resins was studied.

The edge tear of currency increases substantially as the condition of a note deteriorates during circulation. Conversely, the edge tear of currency paper increases only slightly at first then decreases during laboratory flexing. An investigation was conducted to determine if this disparity in edge tear behavior was due to significant differences in the structural changes of currency paper occurring during flexing and circulation or whether the disparity was due to the sampling procedure used to test redeemed currency and flexed currency paper. An investigation also was conducted to determine whether modification of paper with acrylic latexes could improve the stiffness retention of paper and whether the method of modification affected the results.

In determining the edge tear of redeemed currency, the actual edges of notes are tested. In determining the edge tear of flexed currency paper, the edges of the flexed paper are purposely avoided. The edge tear specimens of redeemed currency were retested on the edge opposite to the first test. This simulated sampling for edge tear testing of laboratory flexed paper since the edge used in the retest came from the interior of the note.

The edge tear of redeemed currency in the interior of a note is significantly lower than on the actual edge of the note and is essentially the same as it is for moderately flexed currency paper. Apparently, the increase in edge tear of currency during circulation is caused by edge wear and is not due to the flexing a note receives during circulation. These results further indicate that there is good agreement in the changes that occur in the properties of currency paper during currency circulation and laboratory flexing.

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*Edge tear is the resistance offered by paper to the onset of tearing at the edge of a sheet.

Handsheets were modified with acrylic polymers by beater addition and paper saturation techniques. The effect of polymer concentration on the extent of change in paper properties was also investigated. The handsheets were prepared from a kraft wood pulp beaten in a PFI laboratory mill.

The investigation of acrylic latexes demonstrated that modification of paper with acrylics can result in marked improvement in stiffness retention with flexing and that the best results are obtained when the modification is produced by paper saturation. There is a possibility that wood pulp paper, modified with polymer latexes, could be superior to currency paper manufactured from rag pulps.

The effect of acrylic polymer modification of paper on the retention of cantilever stiffness during flexing will be continued during the next reporting period.

2. EDGE TEAR OF REDEEMED CURRENCY

The edge tear of redeemed currency is appreciably higher than that of uncirculated currency [1]. The edge tear of printed currency paper increases during the early stages of flexing but then decreases as flexing continues [1]. In any event, the average edge tear of flexed printed currency paper is never as high as the edge tear of redeemed currency. The difference in edge tear between flexed currency paper and redeemed currency may be due to significant differences in the structural changes of paper occurring during flexing and currency circulation.

In determining the edge tear of currency, care was taken in cutting the specimens to include the actual edge of the redeemed note [2]. In obtaining specimens for testing from flexed currency paper, care is taken not to include the actual edge of the flexed sample so as to avoid edge effects in testing. Therefore, the disparity in edge tear between redeemed currency and flexed currency paper could also be due to sampling procedures.

In determining the edge tear of redeemed currency or flexed currency paper, only one edge is tested per specimen and not both edges as suggested in TAPPI Method T 470 os-66. Photographs of the edge tear device used at NBS are shown in Figure 3.

The same specimens used in determining the edge tear of redeemed currency [2] were tested a second time but on the opposite edge. This edge came from the interior of the note and would be free of edge effects. The second edge tear determination was made in the area directly opposite the first determination as shown in Figure 1. The results are given in Table 1.

The edge tear of redeemed currency is significantly lower in the interior of the note than on the actual edge of the note. However, it could be argued that the edge tear should be lower by virtue of the specimens being subjected to tensile forces during the first edge tear test. Therefore, the remainder of the untested portion of each redeemed bill was cut (as shown in Figure 1) into two specimens for additional edge tear testing. The previously untested specimens were tested on the side adjacent to the outer specimens and in approximately the same area (see Figure 1). The results are given in Table 1 under the column heading, Top and/or Bottom Control.

The average edge tear for the control specimens was the same as the average for the original specimens tested on the side from the interior of the note. This indicates that the first edge tear test had no effect on the edge tear of the opposite side of the specimen.

The average edge tear of the interior of redeemed currency is essentially the same as it is for uncirculated currency. The higher edge tear for the actual edge of redeemed currency is apparently due to the wear such as abrasion, etc., received during circulation and not due to the flexing it receives. The edge tear data from the interior of redeemed currency are also in good agreement with the edge tear data obtained from flexed, printed currency paper, giving further indication that laboratory flexing is an excellent method for evaluating the durability of paper.

3. MODIFICATION OF PAPER BY TREATMENT WITH ACRYLIC LATEXES

There are two methods for modifying paper with polymer latexes. One is the so-called beater addition which actually does not take place in a beater but in a mixing chest where the beaten pulp can be agitated gently in the presence of a latex. The second method is called paper saturation which involves saturating dry paper with a latex, squeezing out the excess, followed by drying. In beater addition, the fibers are completely coated with polymer prior to sheet formation. In paper saturation, the polymer is deposited only on the exposed portion of the fibers. It is apparent that the effect of polymer on the physical properties of paper will be dependent on the method of polymer application to the paper. The object of this investigation was to determine the effect of acrylic polymers on the retention of stiffness when applied to paper by beater addition and paper saturation.

Four acrylic latexes (designated E-631, P-339, E-610, and AC-61) were chosen for this investigation. The polymer stiffness was estimated by the manufacturer from the torsional modulus of an air-dried film. E-631 was the softest polymer, P-339 and E-610 were intermediate, and AC-61 was the stiffest of the four polymers evaluated.

3.1 Beater Addition of Acrylic Polymers

A. Experimental Details

A bleached kraft wood pulp was beaten in a PFI laboratory mill at a 10 percent consistency with no clearance between bedplate and roll for 5,000 revolutions at 3.4 kilograms force and a relative velocity of roll to bedplate of 6 m/sec. The beating was done in distilled water. Aliquots of this pulp, sufficient to make a 12" x 12" handsheet of 70 g/m^2 basis weight, were diluted with 1.5 liters of distilled water and disintegrated for 7,500 revolutions in a British disintegrator. The pH is adjusted to pH 9 with 1N NaOH. A retention aid is added to the pulp slurry in the amount of 2 percent based on latex solids to be deposited on the fibers. The retention aid is added from a sufficient quantity of a 1 percent solution, diluted with 50 cm^3 of distilled water. Only two-thirds of the retention aid was added at the start. The mixture of pulp suspension and retention aid was stirred 5 minutes prior to latex addition to exhaust the retention aid from solution. The pH of the mixture was then decreased to 4.0 with 0.5 N H_2SO_4.

The acrylic emulsion was diluted with approximately 50 cm^3 distilled water and added to the pulp suspension in three equal portions with moderate stirring. Five minutes was allowed between each addition to exhaust the acrylic latex. Only moderate stirring was used in order not to remove any adsorbed polymer by shearing. After all of the latex was added, the remainder of retention aid was added and the mixture stirred for an additional 5 minutes. Handsheets were then prepared by placing the mixture in the deckle box of the handsheet machine and forming the sheet in the usual way using tap water. The sheets were dried at 95°C for approximately 3 minutes on a drum dryer.

The effect of the acrylics on the retention of cantilever stiffness was evaluated by determining the decline in cantilever stiffness after 1,000 double flexes over 1/8" rollers on the NBS paper flexer. All of the tensile properties and other physical properties were determined in addition to the cantilever stiffness. The results are given in Tables 2-5 and the standard deviation of the results are given in Tables 6-9.

B. Results and Discussion

The extensional stiffness of the handsheets decreased as the amount of polymer deposited on the fibers increased. The decrease in extensional stiffness was greatest with E-631, the softest acrylic evaluated, and least with AC-61, the stiffest of the four acrylics. Breaking strength was affected most by the stiffest polymer (AC-61), while improvement in elongation to break was greatest with P-339, an acrylic with moderate stiffness. The effect of acrylic polymer on the energy to break, yield load, and elongation to break was not very great. Plastic stiffness decreased extensively with handsheets containing E-631, while the remaining three polymers had somewhat less effect on this property.

None of the acrylic polymers evaluated appeared to have any great effect on the initial cantilever stiffness of paper. Their effect on folding endurance ranged from a significant decrease with E-631 (two sided t-test at 95 percent confidence interval) to a significant increase with P-339 and E-610. With the exception of AC-61, each of the acrylic latexes caused the air permeability to increase with increasing amounts of polymer treatment.

Of the tensile properties, only initial stiffness and elongation to yield are affected substantially after 1,000 flexes. There is a large decrease in the initial stiffness and a large increase in elongation to yield. Small but significant increases in elongation to break occurred with all handsheets investigated. The remaining tensile properties exhibited little or no change after 1,000 flexes.

Cantilever stiffness declined extensively after 1,000 flexes. The only real significant improvement in stiffness retention over the controls occurred with handsheets containing 5 and 10 percent AC-61. However, the improvement in stiffness retention was not as great as observed in handsheets treated with wet strength resin.

It is apparent from the above results that none of the acrylics evaluated when deposited in paper by beater addition improve stiffness retention of papers adequately.

3.2 Paper Saturation with Acrylic Latexes

A. Experimental Details

The same wood pulp was used in this investigation as was used in the beater addition investigation, and the beating was done as described in section 3.1A. A total of 600 g pulp was beaten in 15 separate charges then combined in a large stainless steel container. The pulp was diluted with sufficient distilled water to make a 1 percent suspension and was stirred vigorously for 1 hour prior to handsheet preparation. Aliquots of the 1 percent suspension were treated in the British disintegrator for 7,500 revolutions, transferred to the deckle box of the handsheet mold, and sheets were made in the usual way. Each sheet was weighed after drying and only those sheets whose basis weight was 70 $g/m^2 \pm 5$ percent were retained. The sheets were then separated into ten groups of six sheets each by a random selection.

The paper saturation was performed as follows: The felts which are used in wet pressing of handsheets were saturated with either a 5 or 10 percent emulsion of the acrylic. A handsheet was placed in the felt and passed through the calender rolls on the sheet machine. As the felt passed through the calendar rolls, the excess latex was squeezed out, saturating the paper with latex. As the felt and paper proceeded through the rolls, the excess latex in the paper was squeezed out. The wet sheet saturated with acrylic was lifted from the felt and dried on the drying drum at 95°C for approximately 3 minutes. The weight of the sheet was determined after drying and by difference, the percent of polymer in the sheet was determined.

The effect of acrylic on the retention of physical properties was evaluated by determining the decline in physical properties after 1,000 double flexes over 1/8 inch rollers on the NBS paper flexer. The results are given in Tables 10-13, and the standard deviation of the results are given in Tables 14-17.

B. Results and Discussion

It is quite apparent from the results that more and greater changes occurred in tensile properties when the handsheets were modified with acrylics by saturation than by beater addition. Extensional stiffness, breaking strength, elongation to break, energy to break, and plastic stiffness all exhibited significant increases (two sided t-test) over the controls for all of the latexes except E-631. Overall, the greatest increase in tensile properties occurred with sheets modified with AC-61.

With the exception of sheets modified with E-631, Elmendorf tear decreased as a result of saturation with acrylic latexes. Fold endurance either remained essentially unchanged or increased, and in practically every case, air permeability decreased after modification. Cantilever stiffness decreased in all instances except for sheets containing AC-61.

The decline in extensional stiffness with flexing is less with the handsheets modified by the saturation technique than with those treated by beater addition, while the increase in elongation to yield is lower for the saturated sheets. The only other tensile property exhibiting a significant change after flexing is the increase in elongation to break. All other tensile properties were virtually unchanged after 1,000 flexes.

Of greatest importance is the retention of stiffness of the sheets modified by saturation. Stiffness retention for all the modified handsheets was greater than the controls as shown in Figure 2. There is no doubt about the superiority of paper saturation over beater addition with respect to stiffness retention. In fact, stiffness retention was greater for handsheets modified with 8.5 percent AC-61 than for any paper evaluated to date, which includes currency paper. This is significant, as the pulp used in this evaluation was a wood pulp and not a rag pulp. Rag pulp is considerably more expensive and considered to be superior to wood pulp.

These investigations indicate that paper can be modified with acrylic resins resulting in a significant improvement in cantilever stiffness retention. The magnitude of the improvement in stiffness retention apparently depends to a degree on the rheology of the polymer as indicated by the results and quite probably on paper structure and pulp fiber rheology. The great improvement in stiffness retention of a wood pulp paper might result in a superior currency paper which is less expensive than currency paper made from rag pulps.

4. PREPARATION OF THE NIAGARA BEATER

The Niagara beater closely resembles the type of beater generally used in rag paper manufacture. It enables rag pulp to be fibrillated extensively without reduction of fiber length which up to now has been an important requirement for currency paper and for durable papers in general.

A newly acquired Niagara beater must first be "ground in" (a time-consuming operation) before reproducible results can be obtained. During this reporting period, the beater was "ground in," and it is anticipated that a schedule for beating cotton and linen will be worked out during the next reporting period.

5. PLANS FOR FUTURE WORK

1. Continue the investigation on the improvement of stiffness retention by paper saturation of polymeric latexes.

2. Develop beater schedules for rag pulps on the Niagara beater for producing a currency type paper in the laboratory.

6. BIBLIOGRAPHY

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2. Graminski, E. L. and Forshee, B. W., NBS Report 9597, Evaluation of Currency and Stamp Papers, July 31, 1967.

3. Wilson, W. K. and Forshee, B. W., NBS Report 7198, Evaluation of Currency and Stamp Papers, July 15, 1961.

Table 1. Edge tear of redeemed currency at various positions in a note.

Serial No. of Note	Top Edge	Top Interior Edge	Top Control	Bottom Edge	Bottom Interior Edge	Bottom Control
			force, kilograms			
C13322220A	1.43	0.95	0.52	0.93	0.68	0.50
E48965305B	0.85	1.09	1.15	2.03	0.74	0.33
L70573237B	0.80	0.36	0.84	1.16	0.62	0.81
F03214779A	1.04	0.72	0.56	1.10	0.69	0.43
B44442898A	0.56	0.58	0.58	0.71	0.68	0.82
C12248091A	1.34	0.90	1.46	1.40	0.87	0.50
E54593181B	1.92	0.68	0.60	1.36	0.65	0.58
F87500623B	0.89	0.89	0.59	1.12	0.53	1.01
A51449725A	0.60	0.66	0.46	0.92	0.66	0.93
I01112392A	1.93	1.01	0.81	0.80	1.14	0.69
B45657992A	1.34	0.56	0.84	0.52	0.38	0.66
E30313683A	1.81	0.46	0.65	1.18	0.66	0.85
E27910176A	1.62	1.49	0.79	0.68	1.05	1.36
B53207398B	1.19	0.83	0.73	0.60	0.62	0.53
E49645561B	0.92	0.92	0.66	0.54	0.61	0.97
H62119580A	0.90	0.68	0.57	1.05	0.34	0.61
F62862627A	1.22	0.73	0.92	1.48	1.12	0.92
J21513136A	0.76	0.39	0.65	0.85	0.89	0.36
L11257762B	0.77	0.58	0.69	1.58	1.82	0.78
B21823744A	2.00	0.47	0.85	0.84	0.66	0.95
Average	1.19	0.75	0.75	1.04	0.77	0.71
Std. Dev.	0.46	0.27	0.23	0.39	0.33	0.25
95% confidence interval for true mean	1.19±.22	0.75±.13	0.75±.11	1.04±.18	0.77±.15	0.71±.12

Table 2. Tensile properties of unflexed wood pulp handsheets treated with various acrylic resins by beater addition.

Acrylic Resin Type	Acrylic Resin %	Extensional Stiffness kg W	Extensional Stiffness kg L	Breaking Strength kg W	Breaking Strength kg L	Elongation to Break % W	Elongation to Break % L	Energy to Break kg-cm W	Energy to Break kg-cm L	Load at Yield kg W	Load at Yield kg L	Elongation at Yield % W	Elongation at Yield % L	Plastic Stiffness kg W	Plastic Stiffness kg L
E-631	1	592	609	6.3	6.1	3.3	2.8	1.5	1.2	4.1	4.1	0.7	0.7	87	96
	5	519	497	5.9	5.7	3.5	3.4	1.4	1.4	3.9	3.8	0.8	0.8	78	79
	10	428	415	4.9	5.0	3.9	4.0	1.4	1.5	3.4	3.6	0.8	0.9	54	53
P-339	1	659	634	7.1	6.8	3.5	3.3	1.7	1.6	4.4	4.3	0.7	0.7	99	99
	5	535	540	6.4	7.0	3.6	3.9	1.5	1.8	4.0	4.2	0.8	0.8	88	95
	10	484	491	7.0	7.3	4.3	4.2	2.0	2.0	4.0	4.2	0.8	0.9	91	96
E-610	1	624	657	6.8	7.3	3.2	3.6	1.5	1.8	4.5	4.7	0.8	0.7	97	94
	5	557	529	7.4	7.5	3.8	3.8	1.8	1.9	4.5	4.6	0.8	0.9	101	99
	10	446	443	7.0	7.6	4.0	4.4	1.8	2.2	4.2	4.5	0.9	1.0	97	95
AC-61	1	657	681	7.2	6.8	3.5	2.9	1.7	1.4	4.6	4.5	0.8	0.7	98	108
	5	656	629	8.0	7.6	3.8	3.5	2.1	1.8	4.7	4.9	0.7	0.8	103	103
	10	594	620	8.0	7.8	3.7	3.3	1.9	1.7	4.7	4.8	0.8	0.8	116	114
controls	aid[1]	677	690	7.8	7.4	3.6	3.3	1.9	1.7	4.6	4.9	0.7	0.7	107	99
	water	629	676	7.0	7.1	3.5	3.3	1.7	1.6	4.4	4.6	0.8	0.7	94	100

[1]Handsheets made from water containing same amount of retention aid used in beater addition of acrylics.

Table 3. Tensile properties of wood pulp handsheets treated with various acrylic resins by beater addition after flexing 1000 times over 1/8 inch rollers.

Acrylic Resin Type	Acrylic Resin %	Extensional Stiffness kg W	Extensional Stiffness kg L	Breaking Strength kg W	Breaking Strength kg L	Elongation to Break % W	Elongation to Break % L	Energy to Break kg-cm W	Energy to Break kg-cm L	Load at Yield kg W	Load at Yield kg L	Elongation at Yield % W	Elongation at Yield % L	Plastic Stiffness kg W	Plastic Stiffness kg L
E-631	1	444	260	6.1	6.1	3.5	3.7	1.4	1.4	4.0	4.4	0.9	1.7	84	92
	5	338	194	5.4	5.7	3.7	4.2	1.3	1.4	3.8	4.4	1.1	2.3	70	79
	10	284	184	4.7	4.9	4.1	4.6	1.3	1.4	3.4	3.8	1.2	2.1	54	55
P-339	1	486	264	6.7	6.6	3.4	3.7	1.5	1.4	4.2	4.8	0.9	1.8	103	100
	5	405	234	6.6	6.9	3.9	4.4	1.6	1.8	4.1	4.8	1.0	2.1	89	91
	10	374	240	7.3	6.9	4.4	4.4	2.0	1.8	4.4	4.6	1.2	2.0	93	97
E-610	1	496	298	6.3	6.8	3.1	3.8	1.3	1.5	4.1	4.7	0.9	1.6	99	101
	5	428	284	7.1	7.1	3.8	4.0	1.7	1.7	4.3	4.5	1.0	1.6	101	116
	10	355	229	6.7	7.4	4.1	4.8	1.7	2.0	4.0	4.9	1.2	2.2	100	101
AC-61	1	526	361	7.0	6.5	3.6	3.5	1.6	1.4	4.2	4.3	0.8	1.2	104	105
	5	520	334	7.7	7.6	3.8	4.0	1.9	1.8	4.4	4.5	0.9	1.4	110	116
	10	451	364	7.6	7.8	3.7	3.7	1.8	1.7	4.5	4.3	1.1	1.0	116	147
controls	aid[1]	475	287	6.6	7.1	3.6	3.8	1.5	1.6	4.1	4.4	0.9	1.6	100	130
	water	477	336	6.7	6.9	3.7	3.8	1.6	1.6	4.0	4.1	0.9	1.3	99	113

[1]Handsheets made from water containing same amount of retention aid used in beater addition of acrylics.

Table 4. Physical properties of unflexed wood pulp handsheets treated with various acrylic resins by beater addition.

Acrylic Resin		Sonic[1] Modulus $kg/cm^2 x10^{-3}$		Elmendorf Tear g		MIT Fold Endurance 1000 g double folds		Cantilever Stiffness g-cm		Air Permeability csm[2]	Basis Weight g/m^2
Type	%	W	L	W	L	W	L	W	L		
E-631	1	13.0	13.1	97	103	930	920	2.3	2.4	958	70
	5	11.4	11.1	97	93	1100	1170	2.3	2.2	1313	74
	10	9.6	10.1	102	100	880	890	2.2	2.3	1992	78
P-339	1	13.6	13.8	101	96	1400	1600	2.4	2.2	659	70
	5	11.7	11.5	97	100	2140	2300	2.5	2.3	1363	75
	10	11.1	11.1	83	85	2860	2880	2.2	2.1	1517	78
E-610	1	13.7	13.4	97	91	1300	1460	2.3	2.2	800	70
	5	12.3	12.5	87	94	2810	2660	2.3	2.1	978	74
	10	11.5	11.1	81	82	3320	3680	2.2	2.0	1366	78
AC-61	1	13.5	14.0	77	90	1560	1500	2.3	2.3	641	70
	5	13.7	13.1	85	91	2070	2020	2.5	2.4	810	74
	10	12.8	13.3	88	87	2070	2120	2.5	2.4	740	76
controls	aid[3]	14.5	14.0	95	90	1690	1500	2.5	2.2	866	71
	water	13.9	14.1	93	108	1240	1520	2.4	2.3	606	70

[1] Sonic modulus calculations were based on cellulose density of 1.54.
[2] csm = 1 cm^3 of air per second through an area of 1 m^2 when impelled by a pressure difference of 1g force/cm^2.
[3] Handsheets made from water containing same amount of retention aid used in beater addition of acrylics.

Table 5. Physical properties of wood pulp handsheets treated with various acrylic resins by beater addition after flexing 1000 times over 1/8 inch rollers.

Acrylic Resin		Sonic[1] Modulus $kg/cm^2 x10^{-3}$		Elmendorf Tear g		MIT Fold Endurance 1000 g double folds		Cantilever Stiffness g-cm		Air Permeability csm^2
Type	%	W	L	W	L	W	L	W	L	
E-631	1	10.2	6.9	85	84	1020	760	1.3	0.7	918
	5	9.5	6.2	81	85	1120	970	1.3	0.6	1358
	10	8.4	6.0	88	87	860	820	1.3	0.6	2040
P-339	1	11.3	7.5	81	79	1420	1070	1.3	0.8	686
	5	10.4	7.1	82	81	2010	2020	1.5	0.8	1376
	10	10.7	7.7	78	76	2950	2560	1.4	0.9	1440
E-610	1	11.1	7.4	86	77	1280	1250	1.4	0.8	822
	5	10.9	8.2	76	71	2370	1820	1.5	0.8	874
	10	10.3	8.2	75	74	3080	2760	1.5	0.8	1400
AC-61	1	11.8	8.1	82	81	1580	1080	1.5	0.8	626
	5	12.2	8.5	74	78	2130	1650	1.7	1.0	752
	10	11.9	9.1	80	77	1890	1970	1.8	1.2	682
controls	aid[3]	11.5	7.7	78	73	1390	1440	1.5	0.8	1032
	water	12.7	8.0	87	83	1520	1350	1.8	0.8	647

[1] Density used in calculating sonic modulus was 1.54 (density of cellulose).
[2] csm = 1 cm^3 of air per second through an area of 1 m^2 when impelled by a pressure difference of 1 g force/cm^2.
[3] Handsheets were made from water containing same amount of retention aid used in 10 percent beater addition of acrylic.

Table 6. Standard deviation for tensile properties given in Table 2 of unflexed wood pulp handsheets treated with various acrylic resins by beater addition.

Acrylic Resin Type	Acrylic Resin %	No. of Specimens W	No. of Specimens L	Extensional Stiffness kg W	Extensional Stiffness kg L	Breaking Strength kg W	Breaking Strength kg L	Elongation to Break % W	Elongation to Break % L	Energy to Break kg-cm W	Energy to Break kg-cm L	Load at Yield kg W	Load at Yield kg L	Elongation at Yield % W	Elongation at Yield % L	Plastic Stiffness kg W	Plastic Stiffness kg L
E-631	1	6	6	67.3	47.6	0.83	0.69	0.32	0.48	0.32	0.31	0.40	0.35	0.04	0.06	10.2	4.6
	5	6	6	38.5	40.3	0.45	0.55	0.23	0.44	0.16	0.27	0.32	0.31	0.03	0.07	6.0	7.3
	10	6	6	47.2	48.4	0.26	0.21	0.30	0.34	0.15	0.10	0.19	0.17	0.11	0.08	6.6	5.5
P-339	1	6	6	60.3	21.0	0.67	0.54	0.25	0.46	0.26	0.35	0.45	0.30	0.08	0.35	5.5	7.3
	5	6	6	32.6	78.6	0.34	0.37	0.32	0.21	0.21	0.07	0.28	0.33	0.06	0.07	4.7	5.5
	10	6	5	31.5	36.6	0.38	0.35	0.41	0.40	0.22	0.24	0.27	0.24	0.03	0.12	9.8	12.9
E-610	1	5	5	49.9	51.7	0.37	0.36	0.21	0.19	0.12	0.12	0.34	0.11	0.05	0.04	13.0	10.6
	5	6	6	57.9	39.8	0.36	0.77	0.14	0.37	0.05	0.35	0.31	0.49	0.06	0.05	10.0	6.4
	10	6	6	25.1	39.8	0.48	0.42	0.27	0.21	0.19	0.19	0.46	0.21	0 09	0.06	7.9	3.9
AC-61	1	5	5	79.8	39.7	0.91	0.83	0.46	0.58	0.41	0.39	0.32	0.30	0.07	0.04	10.7	7.8
	5	5	5	13.1	30.0	0.20	0.41	0.17	0.20	0.12	0.14	0.36	0.34	0.05	0.05	7.1	6.8
	10	5	5	30.3	44.6	0.41	0.82	0.37	0.47	0.29	0.38	0.27	0.48	0.08	0.05	7.6	16.2
controls	aid	6	6	30.3	49.4	0.60	0.73	0.23	0.47	0.23	0.34	0.30	0.41	0.04	0.05	9.0	10.1
	water	5	5	12.1	39.0	0.56	0.50	0.37	0.23	0.25	0.20	0.42	0.42	0.11	0.05	15.3	6.0

Table 7. Standard deviation for tensile properties given in Table 3 of wood pulp handsheets treated with various acrylic resins by beater addition after flexing 1000 times over 1/8 inch rollers.

Acrylic Resin Type	Acrylic Resin %	No. of Specimens W	No. of Specimens L	Extensional Stiffness kg W	Extensional Stiffness kg L	Breaking Strength kg W	Breaking Strength kg L	Elongation to Break % W	Elongation to Break % L	Energy to Break kg-cm W	Energy to Break kg-cm L	Load at Yield kg W	Load at Yield kg L	Elongation at Yield % W	Elongation at Yield % L	Plastic Stiffness kg W	Plastic Stiffness kg L
E-631	1	6	6	38.4	26.0	0.44	0.60	0.26	0.16	0.20	0.18	0.42	0.55	0.08	0.30	8.1	9.3
	5	6	6	32.6	10.2	0.40	0.39	0.19	0.22	0.16	0.13	0.40	0.43	0.09	0.22	6.3	10.2
	10	6	6	24.0	15.9	0.27	0.24	0.30	0.20	0.14	0.08	0.13	0.39	0.09	0.31	4.5	4.4
P-339	1	6	6	30.9	13.3	0.62	0.35	0.21	0.19	0.16	0.15	0.50	0.41	0.46	0.18	8.6	10.4
	5	6	6	58.8	24.4	0.58	0.40	0.22	0.24	0.22	0.09	0.48	0.44	0.11	0.30	46.1	10.0
	10	6	6	26.2	17.6	0.69	0.81	0.20	0.52	0.27	0.37	0.73	0.82	0.13	0.45	7.0	7.3
E-610	1	6	6	42.7	27.5	0.53	0.41	0.27	0.17	0.19	0.15	0.35	0.68	0.06	0.31	6.2	8.4
	5	6	6	38.3	25.2	0.36	0.44	0.21	0.26	0.14	0.20	0.57	0.46	0.18	0.35	13.9	8.0
	10	6	6	31.5	35.0	0.45	0.35	0.50	0.31	0.38	0.21	0.44	0.57	0.14	0.49	8.7	9.2
AC-61	1	5	5	38.6	62.1	0.42	0.84	0.15	0.64	0.11	0.43	0.25	0.60	0.06	0.32	9.3	11.3
	5	5	5	37.2	45.9	0.50	0.21	0.08	0.16	0.16	0.14	0.32	0.59	0.07	0.32	5.0	9.2
	10	5	5	70.0	31.8	0.52	0.37	0.33	0.36	0.29	0.24	0.47	0.73	0.21	0.27	7.7	17.0
controls	aid	6	6	39.2	31.6	0.54	0.53	0.34	0.21	0.26	0.22	0.16	0.33	0.13	0.22	6.1	16.6
	water	5	5	16.9	51.0	0.45	0.48	0.39	0.36	0.32	0.25	0.12	0.50	0.08	0.31	6.2	5.7

Table 8. Standard deviation for physical properties given in Table 4 of unflexed wood pulp handsheets treated with various acrylic resins by beater addition.

Acrylic Resin		No. of Specimens		Elmendorf Tear g		MIT Fold Endurance 1000 g double flexes		Cantilever Stiffness g-cm		Air Permeability csm
Type	%	W	L	W	L	W	L	W	L	
E-631	1	6	6	11.0	12.1	376.5	344.8	0.31	0.37	131.4
	5	6	6	8.6	8.6	277.7	294.3	0.10	0.10	213.3
	10	6	6	11.2	3.7	213.5	140.1	0.15	0.37	200.4
P-339	1	6	6	13.5	12.7	515.8	201.7	0.16	0.08	63.6
	5	6	6	19.9	22.8	281.3	429.7	0.32	0.30	145.9
	10	6	6	8.5	5.4	436.6	368.0	0.17	0.20	181.3
E-610	1	5	5	13.5	15.3	148.1	324.5	0.21	0.20	47.8
	5	6	6	11.9	14.3	412.1	717.8	0.12	0.28	150.6
	10	6	6	10.9	6.2	475.4	557.8	0.22	0.24	145.5
AC-61	1	5	5	1.6	10.3	323.4	245.3	0.23	0.19	69.2
	5	5	5	8.2	11.2	340.3	230.1	0.29	0.36	72.9
	10	5	5	18.4	10.6	400.1	260.1	0.12	0.13	53.6
controls	aid	6	6	16.1	7.9	284.2	249.5	0.15	0.20	96.6
	water	5	5	18.9	21.7	469.3	214.1	0.20	0.09	56.0

Table 9. Standard deviation for physical properties given in Table 5 of wood pulp handsheets treated with various acrylic resins by beater addition after flexing 1000 times over 1/8 inch rollers.

Acrylic Resin		No. of Specimens		Elmendorf Tear g		MIT Fold Endurance 1000 g double flexes		Cantilever Stiffness g-cm		Air Permeability csm
Type	%	W	L	W	L	W	L	W	L	
E-631	1	6	6	7.6	4.8	286.1	373.2	0.16	0.07	155.5
	5	6	6	8.6	10.2	297.3	484.0	0.16	0.08	226.2
	10	6	6	4.8	17.8	354.4	257.4	0.07	0.05	290.4
P-339	1	6	6	9.3	6.3	395.2	414.3	0.17	0.06	56.6
	5	6	6	6.9	15.5	327.2	244.6	0.13	0.04	274.3
	10	6	6	4.3	11.7	779.8	471.9	0.12	0.08	177.3
E-610	1	6	6	12.1	5.5	276.8	263.0	0.14	0.10	85.8
	5	6	6	5.3	3.3	519.9	392.3	0.20	0.05	104.1
	10	6	6	5.8	6.4	302.9	434.6	0.11	0.04	222.0
AC-61	1	5	5	8.9	6.7	226.4	207.5	0.13	0.09	67.9
	5	5	5	4.7	10.7	445.6	188.1	0.17	0.10	90.1
	10	5	5	15.7	7.9	206.5	162.1	0.19	0.06	52.9
controls	aid	6	6	14.4	13.5	299.7	319.0	0.18	0.04	73.9
	water	5	5	12.1	9.1	291.0	438.6	0.09	0.07	61.9

Table 10. Tensile properties of unflexed wood pulp handsheets treated with various acrylic resins by paper saturation.

Acrylic Resin		Extensional Stiffness kg		Breaking Strength kg		Elongation to Break %		Energy to Break kg-cm		Load at Yield kg		Elongation at Yield %		Plastic Stiffness kg	
Type	%	W	L	W	L	W	L	W	L	W	L	W	L	W	L
E-631	6.3	572	646	6.5	7.0	3.5	2.9	1.5	1.4	4.0	4.5	0.7	0.7	100	120
	10.5	557	681	7.0	7.8	4.1	3.5	2.0	1.9	4.2	5.0	0.7	0.7	95	117
P-339	2.7	653	730	8.4	8.9	3.8	3.4	2.1	2.0	4.5	5.3	0.7	0.7	124	140
	4.9	633	695	9.4	9.4	4.3	3.8	2.6	2.3	4.8	5.1	0.8	0.7	134	146
E-610	4.5	636	664	8.7	8.9	3.8	3.5	2.1	2.0	4.8	5.2	0.8	0.8	133	139
	7.0	745	747	9.4	9.8	4.1	3.7	2.5	2.3	4.7	5.3	0.7	0.7	138	152
AC-61	4.5	708	841	8.7	9.8	3.5	3.2	2.0	2.1	4.8	5.7	0.7	0.7	139	165
	8.5	786	799	10.4	10.5	4.0	3.6	2.7	2.4	5.3	5.6	0.7	0.7	151	168
controls	water[1]	714	736	6.9	7.1	3.2	3.0	1.5	1.5	4.3	4.7	0.6	0.7	103	105
	reg.[2]	761	755	7.6	8.0	3.4	3.6	1.7	1.9	4.9	4.7	0.7	0.7	101	108

[1]Post treatment was done with water only.
[2]Handsheets made in conventional manner with no post treatment

Table 11. Tensile properties of wood pulp handsheets treated with various acrylic resins by paper saturation after flexing 1000 times over 1/8 inch rollers.

Acrylic Resin		Extensional Stiffness kg		Breaking Strength kg		Elongation to Break %		Energy to Break kg-cm		Load at Yield kg		Elongation at Yield %		Plastic Stiffness kg	
Type	%	W	L	W	L	W	L	W	L	W	L	W	L	W	L
E-631	6.3	426	294	6.1	6.9	3.7	3.6	1.5	1.5	4.0	5.5	1.0	1.9	81	101
	10.5	421	330	6.4	7.3	4.2	4.0	1.8	1.8	4.3	5.5	1.0	1.7	76	93
P-339	2.7	493	375	7.4	8.7	3.7	3.9	1.8	2.0	4.0	5.1	0.8	1.1	123	151
	4.9	531	400	8.4	8.6	4.2	3.9	2.2	2.0	3.9	4.8	0.8	1.3	138	150
E-610	4.5	513	397	7.8	8.7	3.7	3.9	1.8	2.0	3.9	4.8	0.8	1.3	135	148
	7.0	542	414	9.5	9.1	4.5	4.0	2.6	2.1	4.6	4.9	0.9	1.2	136	154
AC-61	4.5	665	492	8.8	9.2	3.9	3.5	2.2	1.9	4.7	4.6	0.7	0.9	128	176
	8.5	627	532	10.0	9.6	4.2	3.8	2.6	2.1	4.6	5.1	0.8	1.0	144	159
control	water[1]	456	302	5.8	6.6	3.2	3.6	1.2	1.4	3.6	4.4	0.8	1.5	94	105
	reg.[2]	617	343	6.5	7.5	2.9	4.0	1.3	1.8	4.2	4.5	0.7	1.3	111	109

[1] Post treatment was done with water only.
[2] Handsheets were made in conventional manner with no post treatment.

Table 12. Physical properties of unflexed wood pulp handsheets treated with various acrylic resins by paper saturation.

Acrylic Resin Type	Acrylic Resin %	Sonic Modulus[1] $kg/cm^2 x10^{-3}$ W	Sonic Modulus[1] L	Elmendorf Tear g W	Elmendorf Tear g L	MIT Fold Endurance 1000 g double folds W	MIT Fold Endurance L	Cantilever Stiffness g-cm W	Cantilever Stiffness L	Air Permeability csm[2]	Basis Weight g/m^2
E-631	6.3	12.9	14.2	95	94	2290	1610	2.1	2.0	562	80
	10.5	12.4	14.0	76	78	2810	2530	2.1	2.0	391	83
P-339	2.7	14.7	14.2	88	82	1910	1850	2.2	2.2	504	78
	4.9	15.9	15.3	77	74	2980	2810	2.2	2.3	380	80
E-610	4.5	14.3	14.9	74	78	2440	2070	2.2	2.1	460	79
	7.0	14.6	15.7	77	74	2820	2750	2.3	2.2	296	82
AC-61	4.5	14.7	16.6	80	83	1480	1620	2.6	2.5	539	78
	8.5	15.5	15.7	75	72	2020	2140	2.7	2.6	366	82
controls	water[3]	14.6	14.1	100	104	1280	1350	2.4	2.3	642	75
	reg.[4]	14.7	14.7	89	89	1700	1670	2.9	2.6	544	76

[1] Sonic modulus calculations were based on cellulose density of 1.54.
[2] csm = 1 cm^3 of air per second through an area of 1 m^2 when impelled by a pressure difference of 1 g force/cm^2.
[3] Post treatment was done with water only.
[4] Handhseets made in conventional manner with no post treatment.

Table 13. Physical properties of wood pulp handsheets treated with various acrylic resins by paper saturation after flexing 1000 times over 1/8 inch rollers.

Acrylic Resin Type	Acrylic Resin %	Sonic[1] Modulus $kg/cm^2 x10^{-3}$ W	Sonic[1] Modulus $kg/cm^2 x10^{-3}$ L	Elmendorf Tear g W	Elmendorf Tear g L	MIT Fold Endurance 1000 g double folds W	MIT Fold Endurance 1000 g double folds L	Cantilever Stiffness g-cm W	Cantilever Stiffness g-cm L	Air Permeability csm^2
E-631	6.3	10.5	8.4	81	88	1960	1480	1.3	0.8	742
	10.5	10.7	9.4	74	75	3070	2580	1.3	0.9	491
P-339	2.7	11.8	10.0	78	83	2480	2060	1.5	1.0	584
	4.9	12.4	10.8	70	84	3490	2900	1.6	1.1	468
E-610	4.5	12.1	10.3	77	85	2800	2490	1.6	1.0	517
	7.0	13.0	11.6	69	73	3890	3010	1.6	1.2	330
AC-61	4.5	12.9	10.7	76	79	1970	1790	2.0	1.4	580
	8.5	13.3	11.6	70	72	2320	1760	2.3	1.7	385
controls	water[3]	9.6	6.8	99	90	1840	1330	1.3	0.7	899
	reg.[4]	11.6	7.4	85	90	1830	1950	1.9	0.9	758

[1] Sonic modulus calculations were based on cellulose density of 1.54.
[2] csm = 1 cm^3 of air per second through an area of 1 m^2 when impelled by a pressure difference of 1 g force/cm^2.
[3] Post treatment was done with water only.
[4] Handsheets made in conventional manner with no post treatment.

Table 14. Standard deviation of tensile properties given in Table 10 for unflexed wood pulp handsheets treated with various acrylic resins by paper saturation

Acrylic Resin Type	Acrylic Resin %	No. of Specimens		Extensional Stiffness kg		Breaking Strength kg		Elongation to Break %		Energy to Break kg-cm		Load at Yield kg		Elongation at Yield %		Plastic Stiffness kg	
		W	L	W	L	W	L	W	L	W	L	W	L	W	L	W	L
E-631	6.3	6	5	21.0	79.3	0.2	0.5	0.3	0.2	0.2	0.2	0.2	0.4	0.05	0.08	7.3	3.9
	10.5	6	6	42.4	35.0	0.4	0.4	0.2	0.2	0.2	0.1	0.4	0.3	0.09	0.05	7.6	10.7
P-339	2.7	6	6	50.1	61.8	0.3	0.5	0.2	0.2	0.1	0.2	0.2	0.5	0.06	0.11	2.4	7.2
	4.9	6	6	34.0	47.5	0.5	0.7	0.1	0.2	0.2	0.3	0.2	0.5	0.05	0.08	9.6	8.3
E-610	4.5	5	6	85.1	76.1	0.6	0.6	0.2	0.6	0.2	0.3	0.5	0.7	0.09	0.03	16.5	16.9
	7.0	6	6	118.4	49.9	0.3	0.4	0.3	0.3	0.2	0.3	0.4	0.4	0.13	0.06	15.6	8.0
AC-61	4.5	5	6	40.7	46.6	0.4	0.3	0.3	0.1	0.3	0.1	0.1	0.3	0.06	0.05	12.9	5.6
	8.5	6	6	54.0	64.2	0.6	0.3	0.3	0.3	0.3	0.2	0.3	0.4	0.07	0.06	7.8	13.4
controls	water	6	6	41.5	36.7	0.6	0.5	0.3	0.3	0.2	0.2	0.2	0.2	0.06	0.07	11.7	11.4
	reg.	6	6	77.4	45.9	0.5	0.4	0.4	0.1	0.3	0.01	0.2	0.4	0.12	0.05	5.7	5.6

Table 15. Standard deviation of tensile properties given in Table 11 for wood pulp handsheets treated with various acrylic resins by paper saturation after flexing 1000 times over 1/8 inch rollers.

Acrylic Resin		No. of Specimens		Extensional Stiffness kg		Breaking Strength kg		Elongation to Break %		Energy to Break kg-cm		Load at Yield kg		Elongation at Yield %		Plastic Stiffness kg	
Type	%	W	L	W	L	W	L	W	L	W	L	W	L	W	L	W	L
E-631	6.3	6	6	32.3	38.5	0.3	0.6	0.2	0.2	0.1	0.2	0.3	0.7	0.11	0.40	11.2	14.4
	10.5	6	6	28.3	35.2	0.4	0.3	0.2	0.3	0.2	0.2	0.5	0.2	0.18	0.20	5.2	13.0
P-339	2.7	6	6	32.4	52.0	0.3	0.4	0.2	0.2	0.2	0.1	0.3	0.5	0.11	0.28	5.8	14.6
	4.9	6	6	31.0	63.6	0.7	0.4	0.4	0.2	0.4	0.1	0.6	0.6	0.12	0.35	7.4	15.4
E-610	4.5	6	6	52.6	48.0	0.7	0.5	0.3	0.4	0.2	0.3	0.4	0.8	0.12	0.30	13.7	23.2
	7.0	6	5	24.6	47.8	0.3	0.3	0.2	0.2	0.1	0.2	0.5	0.6	0.17	0.26	15.2	13.4
AC-61	4.5	6	6	90.7	27.1	0.5	0.6	0.3	0.2	0.2	0.2	0.4	0.6	0.14	0.11	12.6	10.2
	8.5	6	6	52.0	71.6	0.9	0.4	0.4	0.3	0.4	0.2	0.6	0.5	0.09	0.22	7.4	8.9
controls	water	5	5	26.8	49.8	0.2	0.5	0.4	0.3	0.2	0.2	0.09	0.6	0.04	0.36	4.7	11.3
	reg.	6	6	59.6	27.5	0.8	0.3	0.5	0.1	0.4	0.1	0.3	0.2	0.06	0.13	4.6	10.2

Table 16. Standard deviation for physical properties given in Table 12 of unflexed wood pulp handsheets treated wtih various acrylic resins by paper saturation.

Acrylic Resin		No. of Specimens		Elmendorf Tear		MIT Fold Endurance 1000 g		Cantilever Stiffness		Air Permeability
Type	%			g		double flexes		g-cm		csm
		W	L	W	L	W	L	W	L	
E-631	6.3	6	5	15.4	10.2	474.0	222.0	0.11	0.18	39.7
	10.5	6	6	6.8	8.2	690.2	527.7	0.16	0.16	36.6
P-339	2.7	6	6	14.2	7.2	288.7	146.6	0.11	0.16	21.3
	4.9	6	6	10.1	6.6	980.1	302.0	0.18	0.16	32.3
E-610	4.5	6	6	2.8	15.0	399.7	422.3	0.17	0.26	32.9
	7.0	6	6	9.8	7.3	529.1	323.1	0.15	0.14	22.8
AC-61	4.5	6	6	3.6	9.4	174.2	273.5	0.22	0.20	43.9
	8.5	6	6	8.0	5.8	291.2	442.3	0.09	0.24	42.6
controls	water	6	6	14.5	16.0	204.5	277.1	0.24	0.15	45.6
	reg.	6	6	11.6	9.1	207.0	260.6	0.13	0.16	11.2

Table 17. Standard deviation for physical properties given in Table 13 of wood pulp handsheets treated with various acrylic resins by paper saturation after flexing 1000 times over 1/8 inch rollers.

Acrylic Resin		No. of Specimens		Elmendorf Tear		MIT Fold Endurance 1000 g		Cantilever Stiffness		Air Permeability
Type	%			g		double flexes		g-cm		csm
		W	L	W	L	W	L	W	L	
E-631	6.3	6	6	13.1	12.3	778.5	341.0	0.17	0.05	69.6
	10.5	6	6	8.2	8.6	488.4	471.0	0.09	0.07	42.7
P-339	2.7	6	6	4.6	7.2	436.2	212.9	0.16	0.06	16.8
	4.9	6	6	6.3	23.4	628.1	358.0	0.14	0.07	42.0
E-610	4.5	6	6	7.8	7.9	333.9	616.3	0.29	0.10	32.6
	7.0	6	6	6.4	6.9	357.6	565.6	0.18	0.09	32.7
AC-61	4.5	6	6	10.4	8.9	413.9	237.3	0.24	0.09	37.7
	8.5	6	6	7.4	7.8	388.3	473.9	0.13	0.16	42.1
controls	water	6	6	6.4	6.9	357.6	565.6	0.18	0.09	32.7
	reg.	5	5	7.8	7.9	333.9	616.3	0.29	0.10	32.6

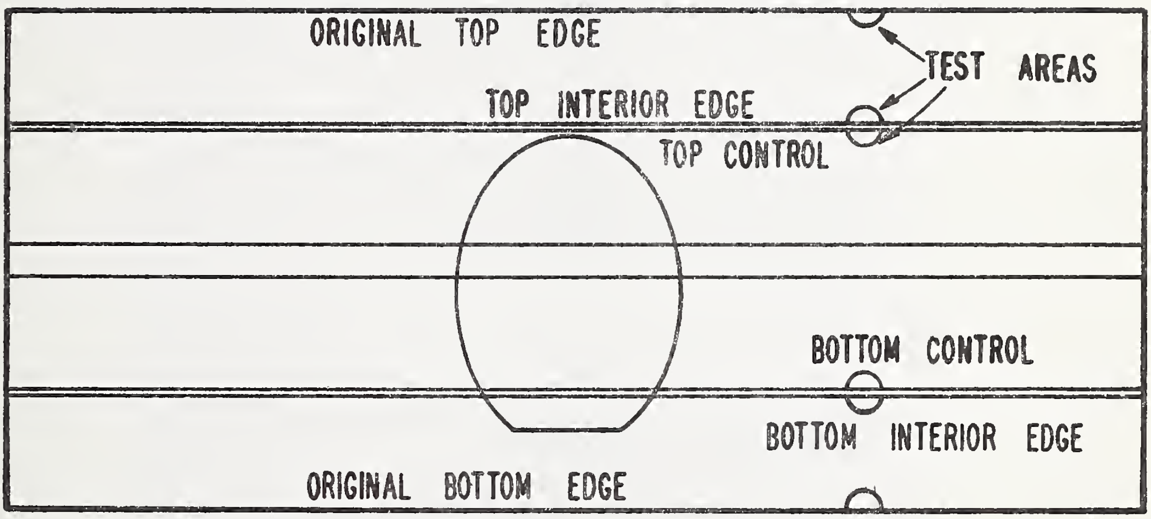

Figure 1. Specimen layout for redeemed currency for edge tear specimens.

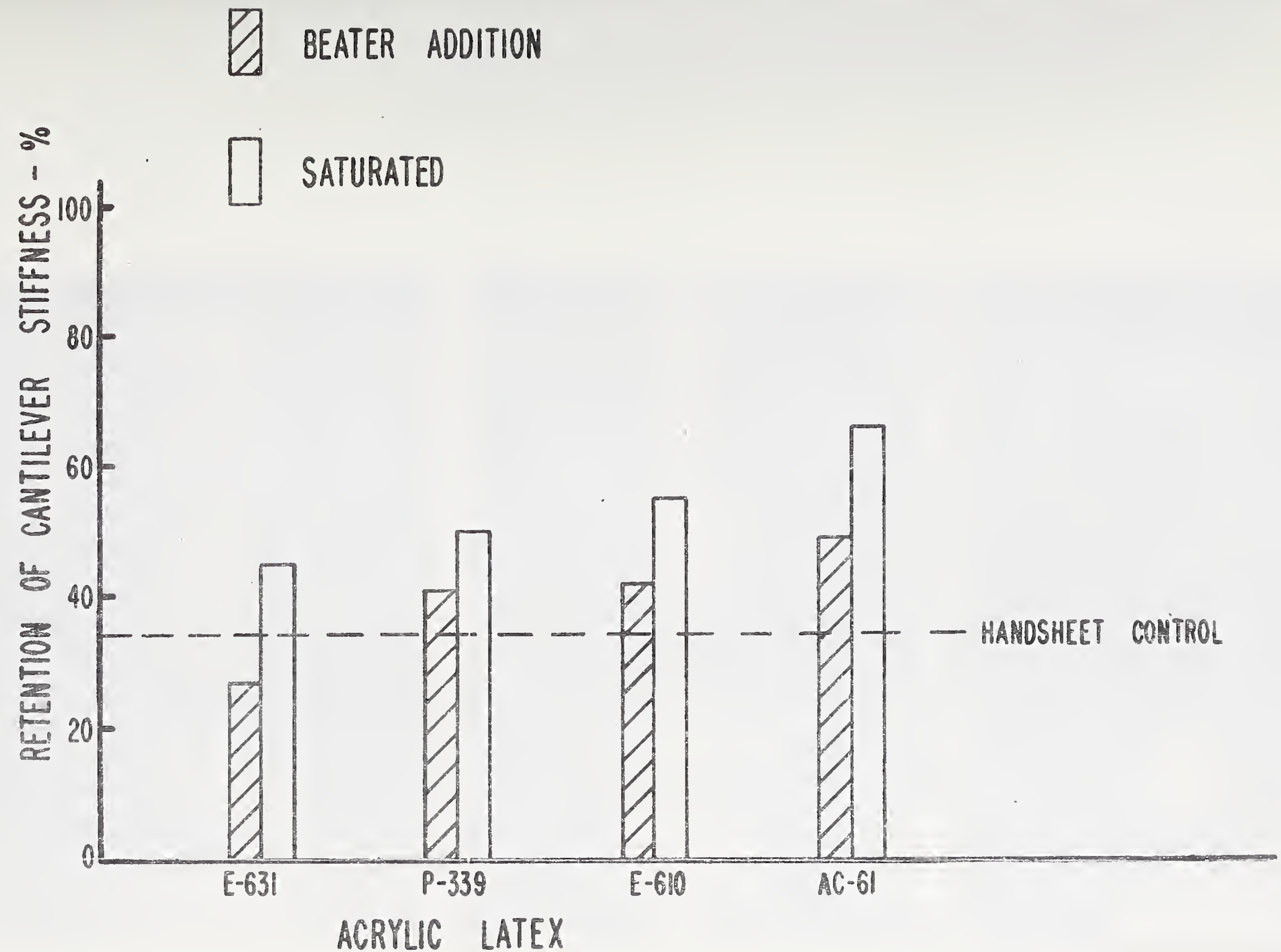

Figure 2. Retention of cantilever stiffness during flexing of handsheets modified with acrylic resins.

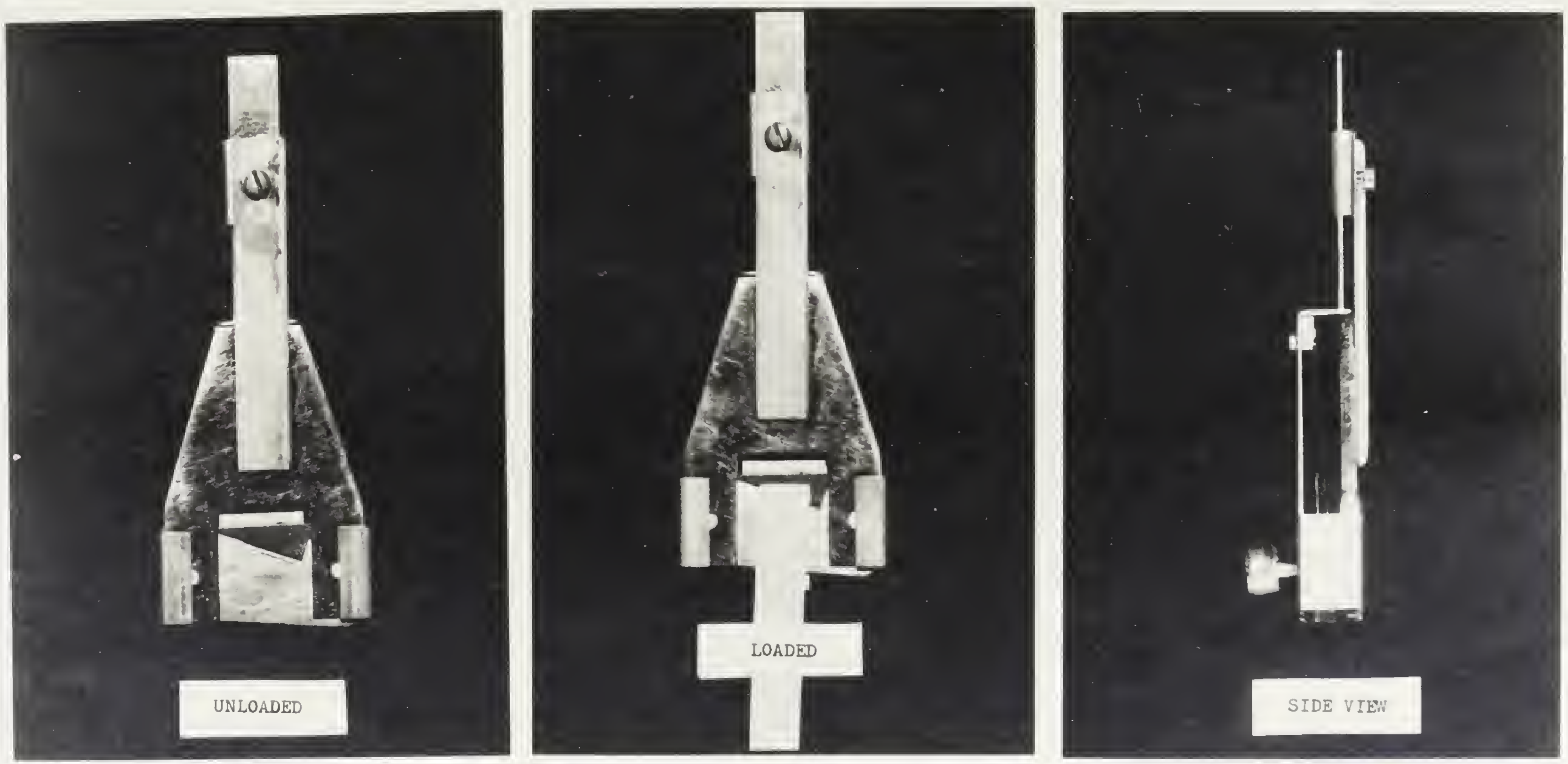

FIGURE 3. SPECIAL EDGE TEAR DEVICE FOR USE IN TENSILE TESTING MACHINES

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15. SUPPLEMENTARY NOTES

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.)

As part of a continuing study for the Bureau of Engraving and Printing of the U.S. Department of Treasury, the disparity in the edge tear of flexed currency paper and redeemed currency and the possibility of improving the stiffness retention of paper by treatment with acrylic resins was studied. It was shown that the increase in edge tear of currency during circulation is caused by wear and is not due to the flexing a note receives during circulation. Also, paper can be modified with acrylic latexes by a paper saturation technique with the result that the paper has a marked improvement in stiffness retention with flexing.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Acrylic latexes; edge tear; paper; paper durability; stiffness retention.

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