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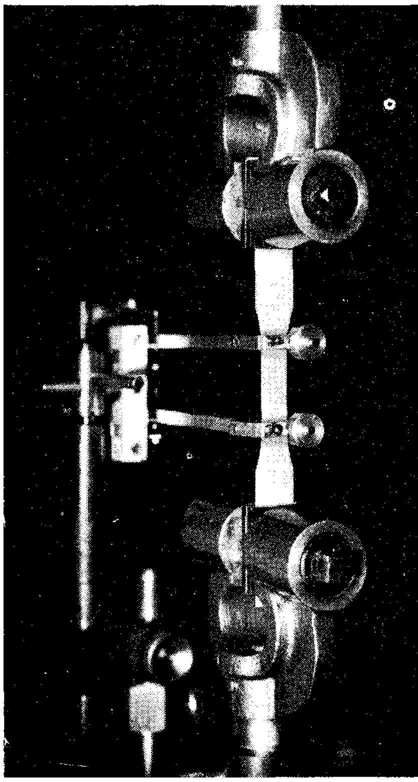

The EFFECT OF RESTRAINT DURING DRYING on Tensile Properties of Handsheets

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SUMMARY

Handsheets of various commercial and experimental papermaking pulps were ovendried in special drying frames that controlled the amount of shrinkage. Unstretched handsheets and those stretched predetermined amounts were dried with various allowances for shrinkage and tested in tension to determine the influence of restraint during drying on the strength, modulus of elasticity, and strain to failure.

The results show that modulus of elasticity is independent of the type of pulp but increases with the degree of restraint during drying, and with the density of the handsheets. Modulus of elasticity in the direction of restraint was found to vary as the cube of density. Tensile strength and strain to failure, on the other hand, were dependent on the type of pulp, as well as on the degree of restraint and density of handsheets. Tensile strength increased with the degree of restraint and appeared to vary as a power function with density changes. Strain to failure decreased as degree of restraint increased; it increased, however, with increasing density.

Handsheets ovendried under frame restraint exhibited different relationships of strength-to-density and modulus-to-density than handsheets of similar pulps pressed to different densities and air dried on polished disks in the manner described in standard method T205 of the Technical Association of the Pulp and Paper Industry (TAPPI). For instance, the tensile modulus of elasticity of handsheets dried in frames varied as the cube of density while modulus of handsheets dried on polished disks varied as the square of density.

Wet pressing was shown to increase the tensile elastic modulus by an amount much greater than could be accounted for by the reduction in thickness. Dry pressing, on the other hand, produced elastic modulus increases directly proportional to the decrease in thickness. The effect of frame restraint on tensile properties was dependent on the moisture content of the wet web before it was placed in the restraining frames. The higher the moisture content, the higher was the modulus of elasticity and tensile strength of the restrained handsheets. Changes in tensile properties as a result of restrained drying are retained to a substantial degree by the sheet, even after high humidity exposure or after being soaked in water for 60 hours andredried without restraint at 73° F. and 50 percent relative humidity.

Stretching within limits before drying improved tensile strength and elastic modulus but reduced the strain to failure. The limits of stretching depended upon the type of pulp used.

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EFFECT OF RESTRAINT DURING DRYING ON THE TENSILE PROPERTIES OF HANDSHEETS

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INTRODUCTION

Adequate carton stiffness is one of the key factors in the production, merchandising, and sale of containers made from multi-ply cylinder board. Stiffness is important, not only to utilize the full strength of a container board, but to minimize carton bulge and permit successful operation of boxmaking equipment. The stiffness of multi-plycylinder board can be predicted if the modulus of elasticity of the separate component plies is known. Work at the Forest Products Laboratory has shown that the temperature and degree of restraint applied during the drying of the wet web will materially affect the strength and modulus of elasticity of the finished sheet (8).[2]

Drying temperature and degree of restraint, however, are not the only important parameters influencing the mechanical properties of pulp handsheets. Pulping process and handsheet density were considered and found to be of basic importance in predicting the behavior of pulp handsheets under tensile stress.

A large variety of pulps are available for the manufacture of multi-plycylinder board. The purpose of this project, undertaken with the cooperation of the Boxboard Research and Development Association at Kalamazoo, Mich., was to determine how restraining sheets prepared from beaten and unbeaten pulps during drying affected the tensile modulus of elasticity. These pulps were 15 of the most widely used, and were selected with the advice of the Stiffness Subcommittee of the Boxboard Research and Development Association.

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[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] Numbers in parentheses refer to "Literature Cited" at the end of the report.

MATERIALS

The pulps and their Canadian Standard freeness values after beating in the standard test beater are shown in the following tabulation:

		Freeness (Ml.)
(1)	Western softwood bleached kraft	700, 650, 530, 355
(2)	Western hemlock bleached sulfite	700, 600, 500, 280
(3)	Southern pine bleached kraft	420
(4)	Sweetgum bleached kraft	430
(5)	Aspen bleached cold soda	320
(6)	Western softwood unbleached kraft	700, 620, 510, 330
(7)	Southern pine unbleached kraft	370
(8)	Manila tabulating card stock	560
(9)	Waste newsprint	170
(10)	Corrugated boxes	520
(11)	Western hemlock unbleached sulfite	350
(12)	Spruce groundwood	50, 100
(13)	Milk carton stock	600
(14)	Eastern softwood bleached sulfite	380
(15)	Mixed hardwood semichemical pulp	450

APPARATUS & PROCEDURES

This study was designed to simulate some of the drying stresses induced in webs on the paper machine and to relate them to the resulting changes in strength and elasticity. Samples of pulp (360 grams, ovendry basis) were beaten in the test beater to the freenesses indicated above. Handsheets weighing approximately 90 grams per square meter (air-dry basis) were formed on a 7- by 9-inch sheet mold and wet pressed between blotters at 60 pounds per square inch for 5 minutes. Two opposite edges of the sheets were dried between heated platens for a distance of approximately five-eighths inch.

These sheets were then clamped to a distance of one-half inch in the frames shown in figure 1, and the tension was adjusted either to provide various degrees of restraint or to stretch the sheet and then provide restraint. A flat supporting plate was placed under the sheet during clamping to provide support for the wet sheet. The drying frame and sheet were then placed on edge in an oven maintained at 150° F. for at least one-half hour (twice the time required to remove all free moisture). After drying, the sheets were conditioned at 73°F. and 50 percent relative humidity for at for at least 48 hours. The sheets were trimmed to 5 by 7-1/2 inches on a paper cutter and weighed on a triple-beam balance to the nearest 0.01 gram.

Two tension specimens were cut from the center of each sheet. These were necked specimens, as shown in figure 2, and were cut from the sheet in the direction in which shrinkage stresses were induced by the applied restraint. Thickness measurements were made at the necked section to the nearest 0.0001 inch, with a dial-type micrometer (TAPPI Method T 411M-44). Tension tests of specimens were made on a test machine that used a mechanical drive and employed a load cell with an electrical resistance-type strain gage for measuring loads.

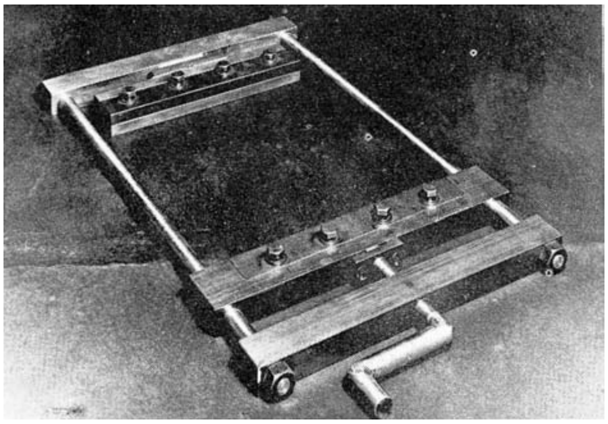

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Figure 1.--Frame used to hold wet handsheets when placed in drying oven. The degree of restraint is controlled by adjusting position of clamp attached to the crank.

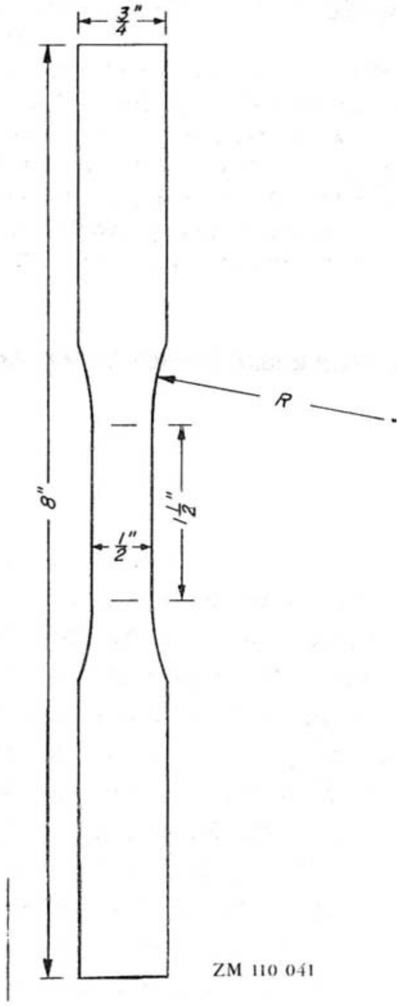

Figure 2.--Paper tension specimen.

The test machine was equipped with an autograph recorder for plotting load and testing machine crosshead movement simultaneously. Six specimens of each type of material were tested with a free length of about 5 inches between the grips. Loads were applied through a constant rate of head movement of 0.02 inch per mi nut e. Because of slippage and the irregular shape of the specimen, the crosshead movement was not used as a measure of strain. An optical, mechanical-type strain gage, described in Forest Products Laboratory Report No. 2066, was used to obtain accurate strain readings (9). Later a mechanical-electrical strain gage was developed to obtain load-strain data (4). This direct-reading strain gage is shown in figure 3. Electrical output from the gage is fed into an amplifier and then directly to the autographic recorder of the testing machine. All tests were made in a room conditioned to 73° F. and 50 percent relative humidity.

An additional investigation was made to determine the change in strength and elastic properties due to humidifying and soaking paper-machine webs previously dried under restraint. For this experiment, paper-machine webs of a western softwood bleached kraft pulp at a freeness of 370 milliliters were taken from the machine wire and ovendried at 150° F. unrestrained and with no allowance for shrinkage. These were then subjected to 50, 65, 80, 90, and 97 percent relative humidity for 60 hours, as well as water soaking for 60 hours. All samples were then returned to a 50 percent relative humidity atmosphere for conditioning and tensile strength determinations.

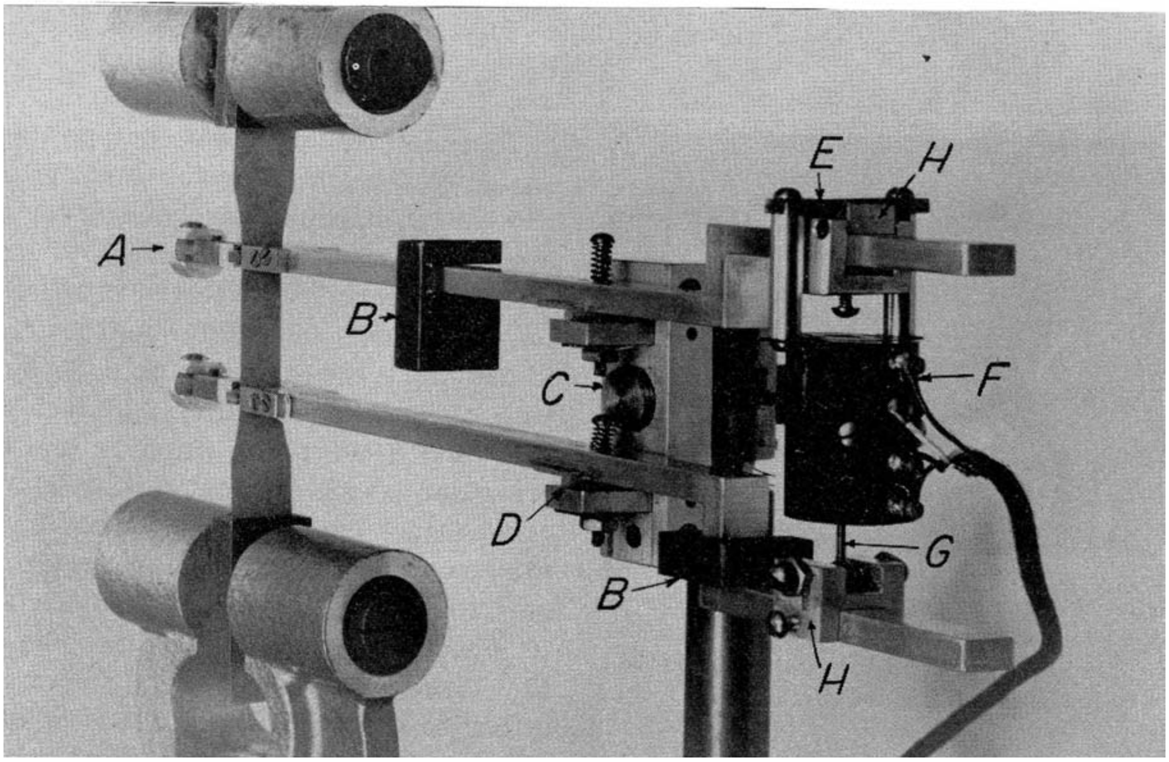

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Figure. 3.--Straingage used to measure lengthwise specimen deformations under tensile load. Spring-loaded, knife-edged clamps (A) attach the gage firmly to the specimen. The weights (B) balance the system. The bearings (C, D, and E) allow the transformer core (G) to move in exact correspondence with the knife-edged clamps (A). The knife-edge bearings (D) are pinned to prevent lateral slippage, and springs are used to hold the knife edges in the grooves. This arrangement allows the lever arm to move freely, yet keeps the gage from flying apart when the specimen fails. The "cradles" (H) for the transformer (F) and core (G) can be moved laterally to provide the desired lever ratio.

PRESENTATION OF DATA

The effect of beating and restraint in frames during drying on 15 different commercial pulps is shown in table 1. This table shows the tensile strength, modulus of elasticity, and strain to failure for each pulp, as well as the pulp freeness, handsheet thickness, density, and conditions imposed during drying. Each of these values is an average of six determinations.

Typical stress-strain curves for handsheets dried at different levels of restraint are shown in figure 4.

The results of a study to determine the influence of density on tensile properties of air-dried handsheets of four different pulps are shown in table 2. Pulps used in the. preparation of these handsheets include: Western hemlock bleached sulfite beaten in the test beater to a Canadian Standard freeness of 305 milliliters, corrugated board waste beaten to a freeness of 510 milliliters, and unbleached western softwood kraft beaten to a freeness of 450 milliliters and to a freeness of 225 milliliters. Handsheets were formed on a British sheet mold, placed on polished disks, and pressed for 5 minutes at several different pressures in a screw press with a capacity of 600 pounds per square inch. The handsheets were then air

Table 1.--Tensile properties[1] of handsheets from various pulps that were dried under varying degrees of restraint

Canadian Standard freeness	Drying conditions[2]	Thickness	Density	Strength	Modulus of elasticity	Strain to failure
Ml.		Mils	Lb. per 1,000 sq. ft. per mil	P.s.i.	1,000 p.s.i.	Pct.
WESTERN SOFTWOOD UNBLEACHED KRAFT						
700	U	7.5	2.26	1,850	139	4.62
700	4	7.1	2.42	2,210	204	4.26
700	2	7.0	2.50	2,330	295	3.34
700	0	6.5	2.56	2,490	425	1.66
620	U	7.2	2.44	2,240	178	4.80
620	4	6.8	2.70	3,180	318	4.60
620	2	6.0	2.72	2,650	358	3.13
620	0	6.3	2.76	3,620	534	1.90
620	S-2	7.3	2.64	3,870	513	2.06
620	S-0	6.2	2.52	4,000	592	1.25
510	U	6.9	2.69	3,390	199	7.20
510	4	5.7	2.99	3,980	384	4.70
510	2	5.9	3.02	5,300	583	3.90
510	0	5.4	3.05	4,940	640	2.25
330	U	7.2	2.76	4,360	186	7.50
330	4	5.5	3.12	4,860	508	5.60
330	2	5.6	3.18	5,300	596	3.50
330	0	5.3	3.25	5,980	931	2.10
BLEACHED WESTERN SOFTWOOD KRAFT						
700	U	7.6	2.28	990	100	3.53
700	4	7.6	2.32	930	183	2.22
700	2	7.6	2.37	1,070	229	1.67
700	0	7.0	2.44	1,220	230	1.10
650	U	6.6	2.67	1,930	159	4.31
650	4	6.8	2.69	2,160	269	4.04
650	2	7.1	2.55	2,190	314	2.96
650	0	6.0	2.77	2,300	521	1.64
650	S-2	7.2	2.43	2,730	457	1.46
650	S-0	6.6	2.42	2,480	494	.a4
530	U	7.0	2.77	2,630	176	5.89
530	4	6.8	2.88	2,860	336	4.08
530	2	5.4	2.98	3,410	495	3.10
530	0	5.5	3.09	4,000	660	1.92
355	U	6.2	2.82	2,440	143	6.58
355	4	6.2	3.05	4,680	527	5.12
355	2	5.0	3.24	5,140	582	4.00
355	0	5.3	3.17	4,590	642	2.44
WESTERN HEMLOCK BLEACHED SULFITE						
700	U	7.2	2.53	970	130	3.10
700	4	6.4	2.63	1,070	160	2.85
700	2	6.2	2.64	1,140	205	1.90
700	0	6.5	2.66	1,350	305	.98
600	U	6.8	2.78	1,910	182	4.88
600	4	5.5	2.96	2,110	314	3.89
600	2	5.4	3.05	2,430	468	1.63
600	0	5.6	3.13	2,820	588	1.40
600	S-2	5.1	3.08	2,560	490	1.38
600	S-0	5.8	3.07	3,080	619	1.00
500	U	6.4	2.87	2,100	187	5.20
500	4	5.0	3.13	2,730	349	4.92
500	2	5.0	3.22	3,080	457	3.22
500	0	4.9	3.21	3,580	587	1.67
280	U	6.3	2.95	3,000	231	7.30
280	4	5.2	3.58	3,670	514	4.70
280	2	5.0	3.58	4.530	738	3.04
280	0	4.7	3.69	4,890	851	1.86
SWEETGUM BLEACHED KRAFT						
430	U	6.6	2.90	2,770	247	7.38
430	4	5.6	3.17	3,520	437	5.74
430	2	5.6	3.20	3,890	567	3.05
430	0	5.1	3.24	4,610	656	2.25
430	S-2	5.4	3.17	4,650	661	2.31
430	S-0	5.6	3.02	4,680	733	1.67
WASTE NEWSPRINT						
170	U	8.4	2.08	1,220	1.37	2.14
170	4	8.2	2.11	1,140	146	2.37
170	0	8.4	2.09	1,000	147	1.90
170	2	8.2	2.01	1,010	156	1.39
170	S-2	8.2	2.02	1,050	160	1.28
170	S-0	8.2	2.05	1,250	235	.85
CORRUGATED BOARD WASTE						
520	U	7.9	2.35	1,900	165	5.02
520	4	7.3	2.36	2,410	224	4.73
520	2	7.5	2.40	2,620	317	2.85
520	0	6.7	2.51	2,960	402	1.81
520	S-2	7.6	2.34	2,760	395	1.65
520	S-0	7.9	2.27	2,890	433	1.02
TABULATING CARD WASTE						
560	U	7.9	2.62	2,230	232	4.21
560	4	6.6	2.60	2,200	213	3.95
560	2	6.7	2.61	2,240	263	3.26
560	0	7.4	2.78	2,800	403	2.04
560	S-2	6.8	2.63	2,600	346	2.01
560	S-0	6.9	2.53	2,580	417	1.12
SOUTHERN PINE UNBLEACHED KRAFT						
370	U	7.1	2.56	3,400	147	8.18
370	4	6.4	3.10	4,730	390	5.82
370	2	6.1	3.11	4,910	479	3.80
370	0	5.5	3.17	5,800	620	2.53
370	S-2	5.3	3.08	5,640	582	2.46
370	S-0	5.7	2.90	5,430	636	1.64
SOUTHERN PINE BLEACHED KRAFT						
420	U	6.5	2.86	4,210	250	8.90
420	4	5.1	3.35	4,860	470	6.24
420	2	5.0	3.48	5,670	674	4.10
420	0	4.8	3.44	5,690	711	3.18
420	S-2	5.5	3.46	5,310	705	2.58
420	S-0	5.3	3.30	5,290	659	1.91
COLE SODA PULP						
320	U	8.8	2.02	1,190	109	3.33
320	4	8.2	2.07	1,250	141	2.42
320	2	8.4	2.10	1,240	173	1.68
320	0	8.2	2.18	1,750	236	1.24
320	S-2	8.5	2.09	1,590	228	1.16
320	S-0	8.9	2.02	1,630	243	1.06
MILK CARTON STOCK						
600	U	7.16	2.64	2,241	170	5.23
600	4	6.72	2.67	2,150	198	4.46
600	2	6.25	2.73	2,390	250	3.91
600	0	6.17	2.72	3,060	351	2.80
600	S-2	6.63	2.62	2,630	302	2.12
600	S-0	6.48	2.52	2,780	371	1.39

Table 1.--Tensile properties[1] of handsheets from varoius pulps that were dried under varying degrees of restraint--Con.

Canadian Standard freeness	Drying [2] conditions	Thickness	Density	Strength	Modulus of elasticity	Strain to failure
Ml.		Mils	Lb. per 1,000 sq. ft. per mil	P.s.i.	1,000 p.s.i.	Pct.
			BLEACHED EASTERN SOFTWOOD SULFITE			
380	U	5.5	3.13	3,010	184	6.73
380	4	5.2	3.41	3,100	246	5.92
380	2	4.7	3.53	3,540	353	3.58
380	0	4.7	3.53	3,690	426	2.34
380	S-2	4.7	3.63	3,920	446	2.11
380	S-0	4.6	3.47	4,510	506	1.61
			UNBLEACHED WESTERN HEMLOCK SULFITE			
350	U	6.4	2.99	2,820	172	6.70
350	4	5.2	3.47	3,740	349	5.40
350	2	5.0	3.52	3,870	412	3.67
350	0	4.9	3.65	4,770	532	2.42
350	S-2	5.0	3.67	4,910	568	2.11
350	S-0	5.0	3.60	5,750	658	1.59
			UNBLEACHED SPRUCE GROUNDWOOD			
50	U	8.1	2.23	1,550	139	3.06
50	4	8.1	2.21	1,630	147	2.94
50	2	8.0	2.24	1,850	194	2.10
50	0	8.1	2.24	1,840	198	1.69
50	S-2	8.0	2.17	1,920	219	1.59
50	S-0	8.1	2.16	1,960	230	1.29
100	U	9.4	1.94	1,020	108	1.96
100	4	8.9	2.05	1,110	112	2.28
100	2	8.9	1.94	1,110	121	2.07
100	0	8.7	1.96	1,270	160	1.43
100	S-2	9.1	2.02	1,180	149	1.44
100	S-0	9.0	2.00	1,220	152	1.23
			MIXED HARDWOOD BLEACHED NEUTRAL SULFITE SEMICHEMICAL			
450	U	5.8	3.16	4,450	341	3.86
450	4	5.6	3.38	3,950	351	4.00
450	2	5.4	3.60	4,500	442	3.22
450	0	5.2	3.71	5,190	632	1.96

[1]Results are average of 6 tests made after conditioning at 75° F. and 50 percent relative humidity.

[2]U--Sample dried unrestrained

4--Sample dried with a 4 percent allowance for shrinkage.

2--Sample dried with a 2 percent allowance for shrinkage.

0--Sample dried with no allowance for shrinkage.

S-2--Sample stretch 3 percent and dried with a 2 percent allowance for shrinkage.

S-0--Sample stretch 3 percent and dried with no allowance for shrinkage.

dried on the disks in a conditioned atmosphere of 73° ± 3-1/2° F. and 50 ± 2 percent relative humidity. Tests were made at these standard conditions to determine the tensile strength, modulus of elasticity, and strain to failure.

Table 3 shows the influence of restraint and stretch on tensile properties when handsheets were partially dried before frame restraint was applied, and the effect of applying restraint and releasing the restraint before drying was com-

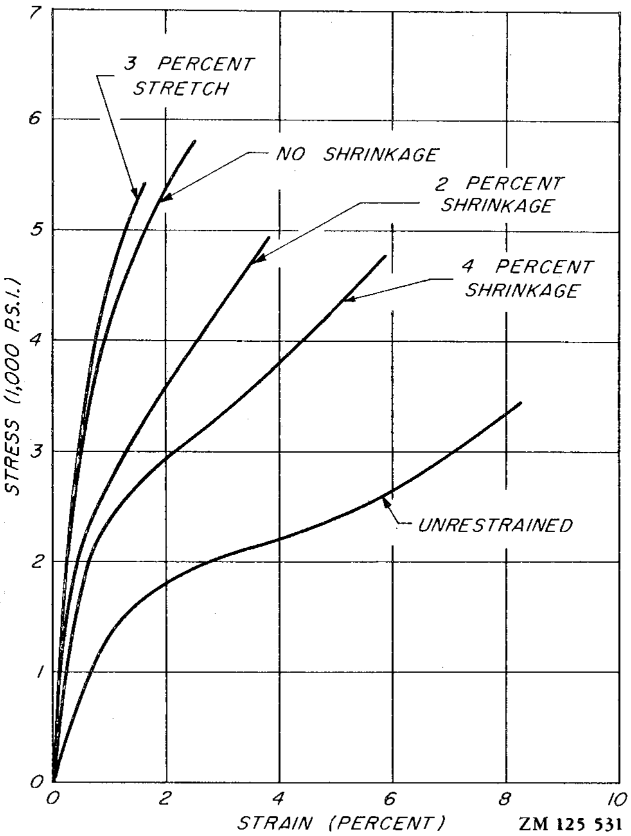


Figure 4. Typical stress-strain curves for handsheet of southern pine kraft pulp (370-milliliter Canadian Standard freeness).

pleted. This work was done on 7- by 9-inch handsheets from a bleached western softwood kraft pulp beaten in the test beater to a freeness of 650 milliliters. Restraint was applied using the drying frame shown in figure 1.

A somewhat related investigation was made to determine how tensile properties were affected when paper-machine webs were dried to higher and higher solids content before restraint was applied. These tests were made on 7- by 9-inch wet webs of a southern pine kraft pulp processed in a beater to a freeness of 450 milliliters.

Results of an additional experiment to determine the permanence of tensile strength, modulus of elasticity, and

Table 2.--Effect of density on tensile properties[1] of handsheets from four pulps wet pressed to different densities

Basis weight	Pressure	Density	Tensile strength	Modulus of elasticity	Strain to failure
Lb. per 1,000 sq. ft.	P.s.i.	Lb. per 1,000 sq. ft. per mil	P.s.i.	1,000 p.s.i.	Pct.
WESTERN HEMLOCK BLEACHED SULFITE: 305 FREENESS					
15.0	12.0	3.65	6,190	687	3.31
15.2	14.5	3.74	6,400	677	3.32
14.8	21.8	3.86	6,120	696	3.03
14.0	28.2	3.88	6,540	792	3.02
13.6	41.0	3.89	6,220	726	3.01
13.6	60.0	4.04	6,480	720	3.09
13.4	115.0	4.26	7,710	770	2.95
15.3	211.0	4.50	7,710	766	2.98
15.2	315.0	4.52	7,940	862	3.02
15.3	440.0	4.62	8,450	868	3.29
CORRUGATED BOARD WASTE: 510 FREENESS					
13.8	12.0	2.28	2,513	276	2.78
14.0	14.5	2.35	2,893	302	2.82
13.8	21.8	2.37	2,666	285	3.09
13.8	28.2	2.45	2,846	295	2.57
14.0	41.0	2.54	2,930	289	2.47
13.8	60.0	2.68	3,160	331	2.72
13.9	115.0	2.83	3,590	398	2.64
14.2	211.0	2.90	3,800	416	2.55
14.2	315.0	3.00	4,180	446	2.60
14.1	440.0	3.10	4,310	499	2.63
WESTERN SOFTWOOD UNBLEACHED KRAFT: 450 FREENESS					
13.9	10.25	2.59	3,800	320	4.32
13.9	20.5	3.00	4,680	408	3.50
13.6	41.0	3.27	5,660	505	3.25
13.2	61.5	3.49	6,270	562	3.42
14.2	62.0	3.65	6,270	630	3.19
13.9	123.0	3.69	6,610	666	3.16
13.6	164.0	3.81	6,350	604	3.41
13.8	246.0	3.97	7,130	671	3.24
14.3	328.0	4.12	7,390	685	3.47
14.0	410.0	4.10	7,710	813	2.94
13.5	513.0	4.09	7,260	766	2.78
13.7	615.0	4.21	7,930	728	3.31
WESTERN SOFTWOOD UNBLEACHED KRAFT: 225 FREENESS					
13.0	9.8	3.65	9,670	671	3.30
13.2	13.7	3.81	10,000	780	2.98
12.9	19.6	3.85	8,920	691	3.31
12.7	29.3	3.94	9,930	733	3.45
	77.8	4.22	10,030	836	3.03
	127.0	4.33	11,030	a15	3.37
	254.0	4.40	10,890	828	2.96
	391.0	4.61	11,620	1,016	3.02
	585.0	4.65	11,290	917	3.02

[1] Results are average of 4 tests made after conditioning at 75° F. and 50 percent relative humidity.

strain to failure are given in table 4. Here handsheets, which had been dried under restraint in two directions, were subsequently humidified or immersed in water for 60 hours and then redried unrestrained at 73° F. and 50 percent relative humidity.

Table 3.--Effect of moisture content at the time restraint was applied on tensile properties[1]

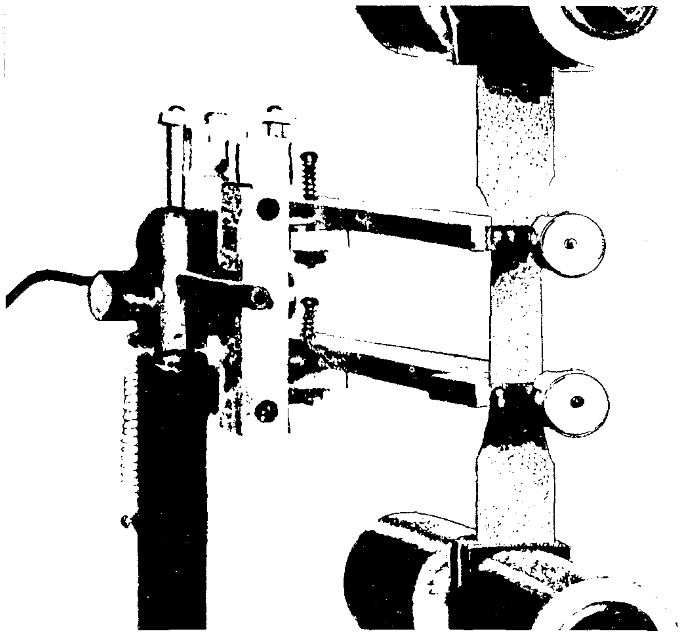
Conditions for drying	Thickness	Density	Tensile strength	Modulus of elasticity	Stretch
	Mils	Lb. per 1,000	P.s.i.	1,000 p.s.i.	Pct.
Unrestrained.	6.6	2.67	1,920	160	4.31
4 pct. shrinkage allowance.	6.8	2.69	2,160	269	4.04
2 pct. shrinkage allowance.	7.1	2.55	2,190	314	2.96
No shrinkage allowance.	6.0	2.77	2,300	523	1.64
Stretch 3 pct., then unrestrained.	6.8	2.45	1,760	183	3.36
Stretch 3 pct., then 2 pct. shrinkage..	1.2	2.43	2,720	455	1.46
Stretch 3 pct., no shrinkage	6.6	2.42	2,480	495	.84
Dried to 50 pct. moisture content, then fully restrained.	6.3	2.73	2,320	380	1.91
Dried to 50 pct. moisture content under restraint, then dried unrestrained.	6.9	2.56	1,840	209	3.27
Dried to 30 pct. moisture content under full restraint, then dried unrestrained.	7.6	2.55	2,000	260	3.51

[1] Average of 6 tests. Specimens conditioned and tested at 75° F. and 50 percent relative humidity.

Table 4.--Effect of humidity and water soaking on strength and elastic properties[1] of restraint-dried webs

Condition	Exposure relative humidity	Thickness	Density	Tensile strength		Modulus of elasticity		Strain to failure	
				Machine direction	Cross-machine direction	Machine direction	Cross-machine direction	machine direction	Cross-machine direction
		Mils	Lb. per 1,000 sq. ft. per mil	P.s.i.	P.s.i.	1,000 p.s.i.	1,000 p.s.i.	Pct.	Pct.
Unrestrained	50 pct.	10.4	2.34	2,750	1,600	145	70	6.9	8.7
Restrained	. . .do. . .	8.1	2.57	4,180	3,190	560	380	2.1	2.4
Do.	65 pct.	8.4	2.52	3,900	2,710	450	365	2.7	2.3
Do.	80 pct.	8.2	2.54	4,080	2,720	430	300	3.0	2.8
Do.	90 pct.	8.4	2.49	4,100	2,650	460	280	3.3	3.1
Do.	97 pct.	8.6	2.45	4,150	3,060	450	300	3.7	3.1
Do.	water soak	8.9	2.37	1,600	2,390	270	140	3.5	4.6

[1] Averago of 6 tests. Specimens conditioned and tested at 75° F. and 50 percent relative humidity after exposure shown in column 2.



DISCUSSION OF RESULTS

Preliminary Evaluations of the Effect of Wet Pressing

The tensile properties of paper are, to a substantial degree, dependent on paper density. The manipulation of paper density is easily accomplished at any of the several stages of paper manufacturing, particularly by variation in wet-web pressure. Highly beaten pulps require less pressure than lightly beaten pulps to achieve the same density. On the other hand, handsheets from lightly beaten pulps are capable of greater variations in density with the same amount of wet pressure. Horio and Onogi (3) show that density variation can have a large effect on modulus of elasticity. In fact, they conclude that the modulus of elasticity varies as the square of density.

These findings, with regard to density and modulus, are corroborated by Luner, Karna, and Donofrio (5), who also showed that modulus varies as the square of density. Further, they found that the bonded area of handsheets was a function of modulus of elasticity.

In this report, which is aimed chiefly at measuring the effects of restraint during drying on the strength and elastic properties of paper, it seemed necessary to take into consideration the differences in pulp that might be attributable to density, as well as to the effects of restraint. The problem was to find what the intrinsic effects of restraint during drying were on the strength and elastic properties of papermaking pulps. If sheetmaking and pressing conditions are held constant, a meas-

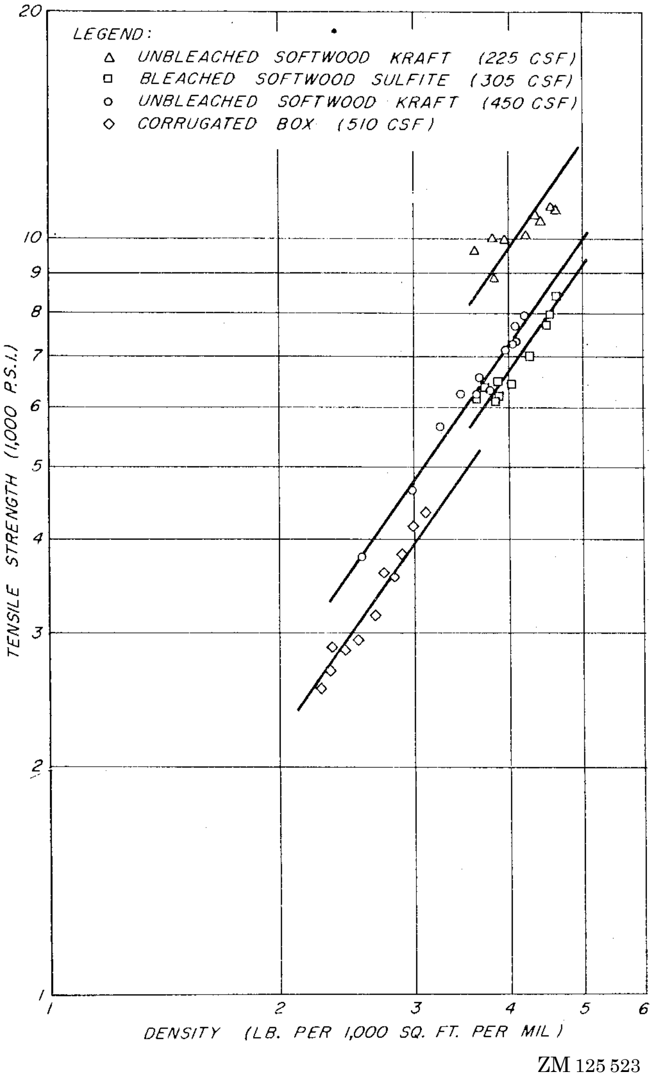


Figure 5. --Relationship between tensile strength and density of handsheets wet pressed to different densities and dried while in contact with polished plates.

ure could be obtained of the practical effects of restraint during drying on the strength and elastic properties of handsheets.

A preliminary study to measure the effect of density was made with four pulps: (1) Unbleached softwood kraft at a 450-milliliter Canadian Standard freeness, (2) unbleached softwood kraft at a 225-milliliter freeness, (3) bleached softwood sulfite at a 305-milliliterfreeness, and (4) waste corrugated box pulp at a 510-milliliter freeness. In general, handsheets were prepared according to TAPPI standard procedures, except that the pressures applied during the pressing operation were varied over a range of 0 to 600 pounds per square inch to produce sheets with a wide range of densities. Densities varied from 2.3 to 4.7 pounds per 1,000 square feet per mil, or 0.444 to 0.906 gram per cubic centimeter.

Since these handsheets were dried on disks, allowing very little shrinkage, they were considered to be fully restrained in all directions during drying.

The results of this study are presented in table 2 and illustrated in figures 5 and 6. These data show that neither the tensile strength nor the elastic modulus can be said to vary directly in proportion to density. The relationship between strength and density (fig. 5) shows that tensile strength increases as a power function with density increase. Tensile strength for these handsheets was dependent on the type of pulp, as well as the degree of beating as shown by lines drawn through the plotted points having the same slope.

The relationship between the tensile modulus of elasticity and density (fig. 6), shows that modulus of elasticity varies as the square of density and is independent of pulp type, as well as thedegree of beating. Based on the data obtained, the elastic modulus of handsheets wet pressed to any density and dried on polished disks can be predicted from the density value. The increase in elastic modulus with density is attributed to an

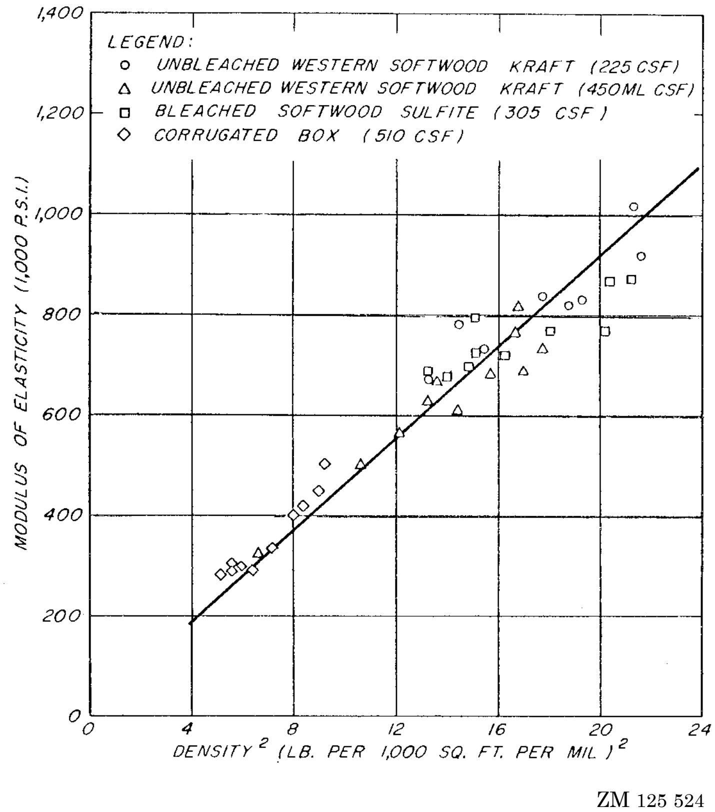


Figure 6.--Effect of handsheet density on modulus of elasticity for handsheets wet pressed to different densities and dried while in contact with polished plates.

increased area of fiber bonds. Whether the increase in elastic modulus can also be attributed to shorter segments between fiber bonds is a matter for speculation. Undoubtedly, both occur. It seems evident that the increase is not due to a change in the microcreping at fiber bonds, since the restraint applied was constant.

Wet pressing is emphasized here in contrast to dry pressing or calendering which is not likely to result in the formation of additional fiber bonding. Experience has shown that dry pressing or calendering will increase modulus of elasticity only in proportion to the reduction in thickness caused by the pressing operations. If, on the other hand, an appreciable amount of moisture (beyond fiber saturation) is present at the time of pressing, the modulus of elasticity of the paper will be increased beyond that which can be attributed to the reduction in thickness.

An illustration of the effect of dry pressing versus wet pressing on the elastic modulus of paper or handsheets is shown in figure 7. Data showing the effect of wet pressing on the elastic modulus-to-density ratio were taken from table 2. Those illustrating the effect of dry pressing on the modulus-to-density ratio were taken from compression tests on 8-, 10-, and 12-mil filter paper. In this instance, the 12-mil filter paper was reduced to thicknesses of 8 and 10 mils by passing the dry paper through the calender stack of the experimental paper machine. These data, though somewhat limited and different in origin, clearly show that the specific elastic modulus is not improved by dry pressing and, further, that wet pressing will increase the modulus of elasticity beyond that which can be attributed to reduction in sheet thickness.

Effect of Restraint on the Modulus of Elasticity

When wet handsheets are restrained from shrinking in a rigid drying frame, the development of drying stresses resulting from surface tension and bond formation imposes a stress on the sheet in the direction of the applied restraint.

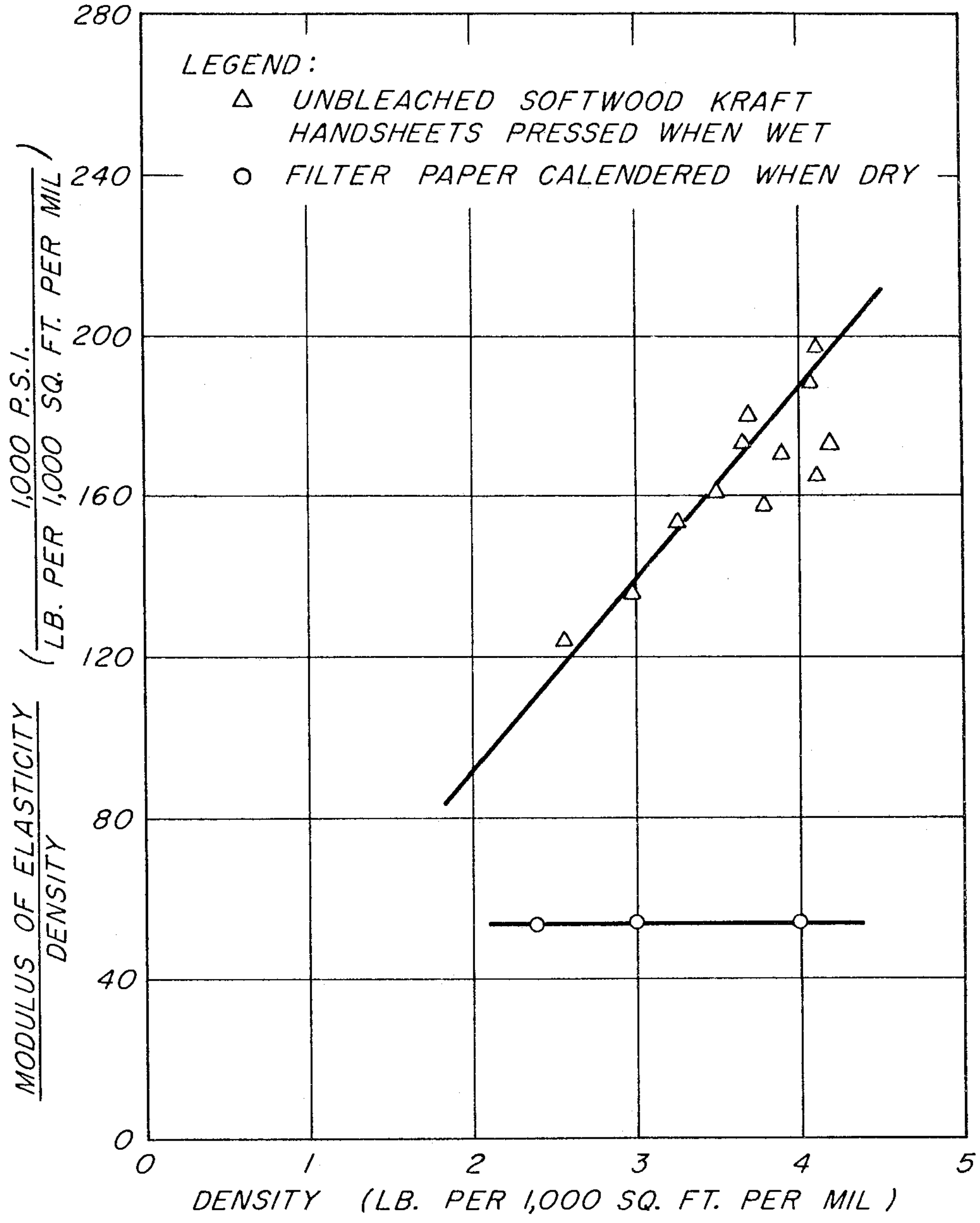


Figure 7.--Relationshipbetween density and modulus of elasticity divided by density for wet-pressed handsheets and dry-pressed papers.

In theory, this results in an improvement in the stress distribution (7), as well as a reduction in the amount of microcreping at the bondsites (6). The application of restraint results in an increase in tensile strength of failing load, an increase in elastic modulus, and a decrease in strain to failure. There is a small increase in density, which is probably caused by an increase in bonding. This increase in density increases with decreased shrinkage allowance and decreases with stretching. The following tabulation is a composite of density data in table 1:

Condition of restraint	Average density of all handsheets
	(lb. per 1,000 sq. ft. per mil)
Unrestrained	2.62
4 percent shrinkage	2.82
2 percent shrinkage	2.87
Restrained	2.92
1 percent stretch	2.74
3 percent stretch	2.66

This is another indication that the increase in density can be accounted for by an increase in the area of the fiber bonds. The decrease in density with stretching would be expected to reduce the modulus of elasticity. Therefore, the increase in elastic modulus with stretching must be due to other factors, such as improved stress distribution and prevention of microcreping at fiber bond-sites.

The data in table 2 showing the relationship between modulus of elasticity and density for handsheets pressed to different densities and dried on disks, are based on different pulps at several different freenesses. Therefore, it is assumed from the general grouping about a single line that the effect of density on modulus of elasticity is independent of pulp type and freeness level.

Data in table 1 for unbleached western softwood kraft, bleached western hemlock sulfite, and bleached western softwood kraft show that the .modulus of elasticity of fully restrained handsheets dried in frames more nearly varies as the cube of density than as the square of density. Handsheets air-dried on disks do not show this relationship. Sheets of similar density ovendried and restrained by drying frames are stiffer than similar sheets air-dried on disks. The difficulty in concluding that disk drying versus "frame drying" is basically different results from the fact that there are other variables such as temperature to which these differences might be attributed.

If handsheet data from three pulps of the same type are examined, there is support for the view that ovendried frame-restrained sheets are stiffer than sheets of the same density that were air-dried on disks. These data are shown in table 5.

Table 5.--Comparisons of modulus of elasticity obtained by two methods of restraining sheets

Pulp	Restraining method	Canadian Standard freeness	Density	Modulus of elasticity	Difference
		Ml.	Lb. per 1,000 sq. ft. per mil	P.s.i.	Pct.
Western hemlock bleached sulfite	Frame Disk	280 305	3.69 3.65	851,000 687,000	24
Waste corrugated board	Frame Disk	510 520	2.51 2.54	402,000 289,000	39
Unbleached western softwood kraft	Frame Disk	510 450	3.05 3.00	640,000 408,000	57

A further examination of the possibility that elastic modulus varied as the cube of density was made using all the data available in table 1. This examination confirmed the supposition, and more interestingly, it showed that the degree of restraint during drying was also of basic importance. The relationships are shown in figures 8, 9, 10, 11, and 12. These graphs show that a straight line passing through the origin will fit most of the points on these curves. Some scatter exists on all of the curves above

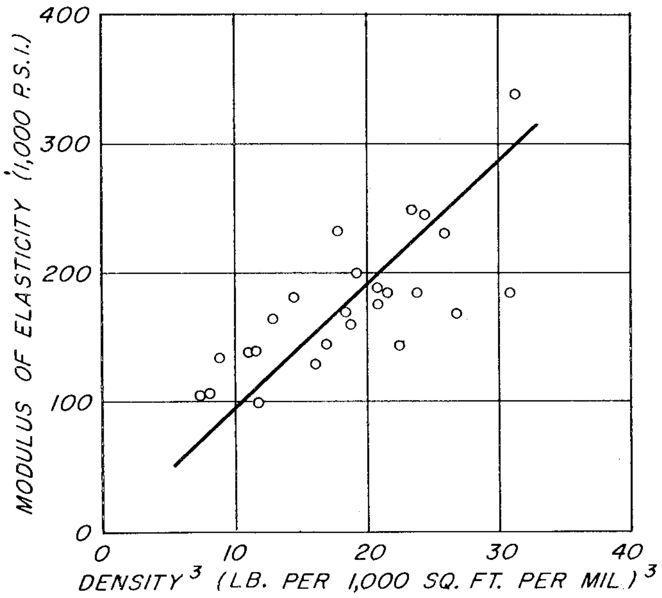


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Figure 8.--Effect of density on modulus of elasticity when handsheets from different pulps are dried in unrestrained condition.

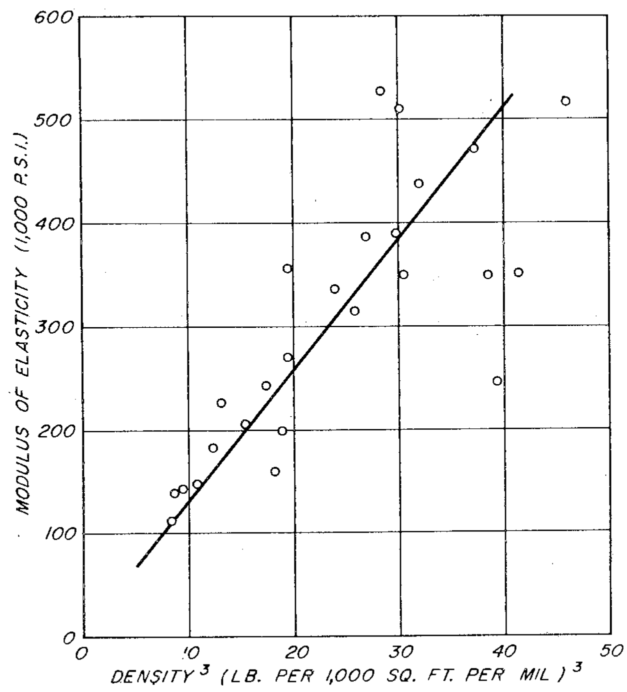

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Figure 9.--Effect of density on the modulus of elasticity when handsheets from different pulps are dried with a 4 percent allowance for shrinkage.

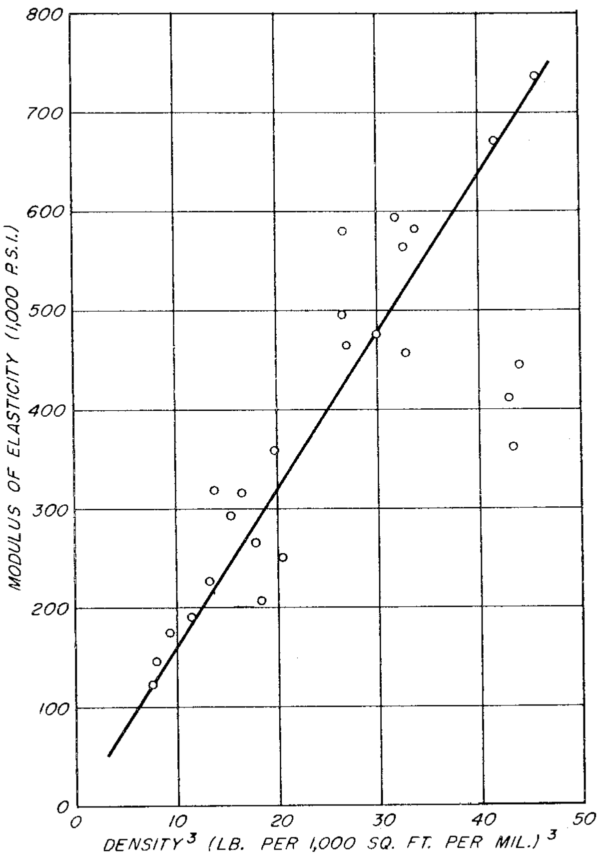

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Figure 10.--Effect of density on the modulus of elasticity when handsheets from different pulps are dried with a 2 percent allowance for shrinkage.

density-cubed values of 37. Most of this scatter is introduced by plotting the data for the eastern bleached and the western unbleached sulfite pulps. Whether the handsheets from these pulps are typical or whether this marks the endpoint of the density-modulus relationship is not certain. More research should be conducted to explore the limit and precision of this relationship.

Curves 8 to 12 are reproduced in composite form in figure 13. This family of curves shows clearly the large effect drying under restraint has on the elastic modulus. As an example, the following tabulation of values was prepared for handsheets with a density of 3 pounds per 1,000 square feet per mil. These data are graphically illustrated in bar chart form in figure 14.

Wet-web treatment before drying	Increase in elastic modulus
	(Pct.)
Unrestrained	--
Allow 4 percent shrinkage	38
Allow 2 percent shrinkage	66
Restrained	106
3 percent stretch	212

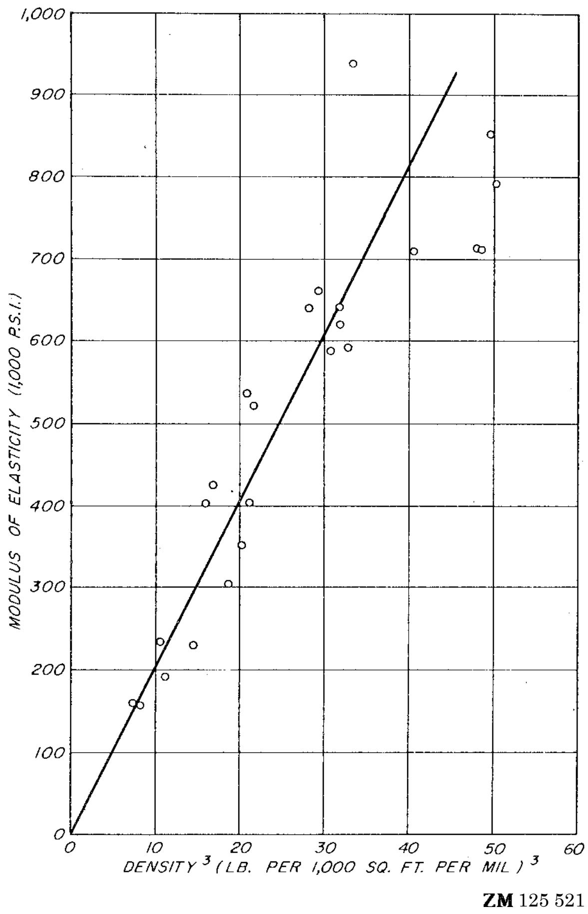

Figure 11.--Effect of density on the modulus of elasticity when handsheets from different pulps are dried with no allowance for shrinkage.

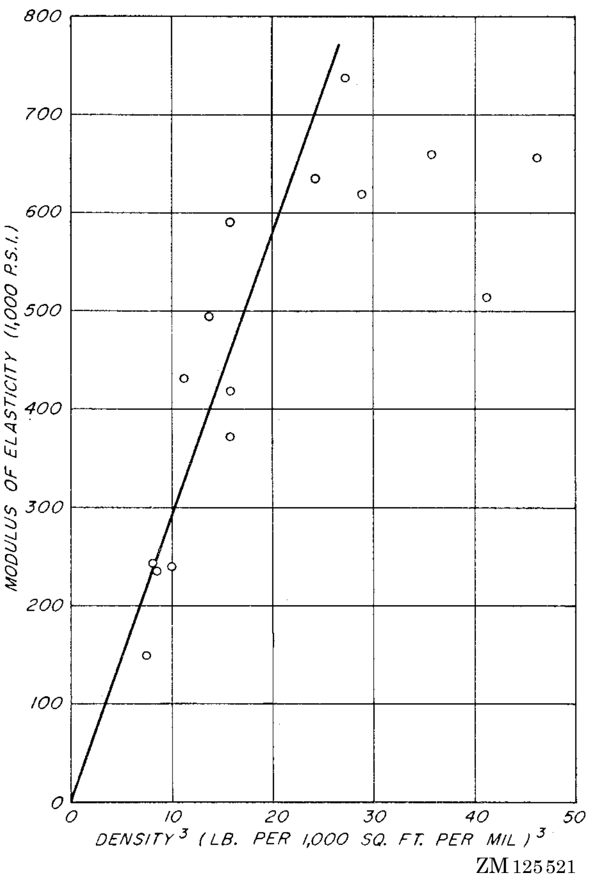

Figure 12.--Effect of density on modulus of elasticity when handsheets from different pulps are stretched 3 percent and not allowed to shrink while drying.

More important, the evidence shows that the relationship between modulus of elasticity and density is not greatly affected by the amount of beating or kind of pulp used in the preparation of handsheets. The modulus of elasticity or stiffness of the handsheets in this study appears to depend primarily on the density of the handsheet and degree of restraint that is applied during the drying of the wet web.

The fact that elastic modulus varies as the cube of density, rather than the square as other researchers have found, is attributed to the drying temperature and the differences in drying in a frame

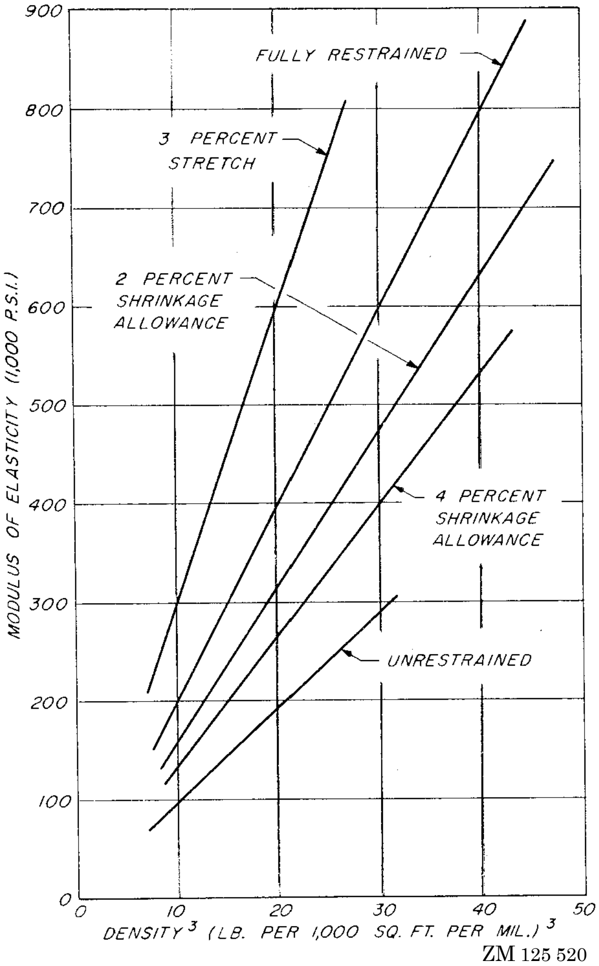

Figure 13.--Compositegraph showing effect of density on modulus of elasticity for different pulps dried under several conditions of restraint.

as opposed to drying on a polished disk. Undoubtedly this is the source of some of the difficulties that arise in relating data obtained from handsheets made according to TAPPI procedures with data obtained from machine-made paper.

Tensile Strength-Density Relationships

The relationship between tensile strength and density for pulps included in table 1 is shown in figure 15. Strength-density data show four distinct classification groups as follows: (Group 1) unbleached softwood kraft pulps; (group 2) bleached softwood kraft pulps; (group 3) bleached and unbleached softwood sulfite, as well as bleached hardwood semichemical pulps; and (group 4) hardwood cold soda, waste news, waste corrugated, and unbleached spruce groundwood pulps. In order to obtain these curves, data for unrestrained handsheets and those that had been stretched 3 percent were omitted. Data for unrestrained pulps were omitted, because accurate thickness

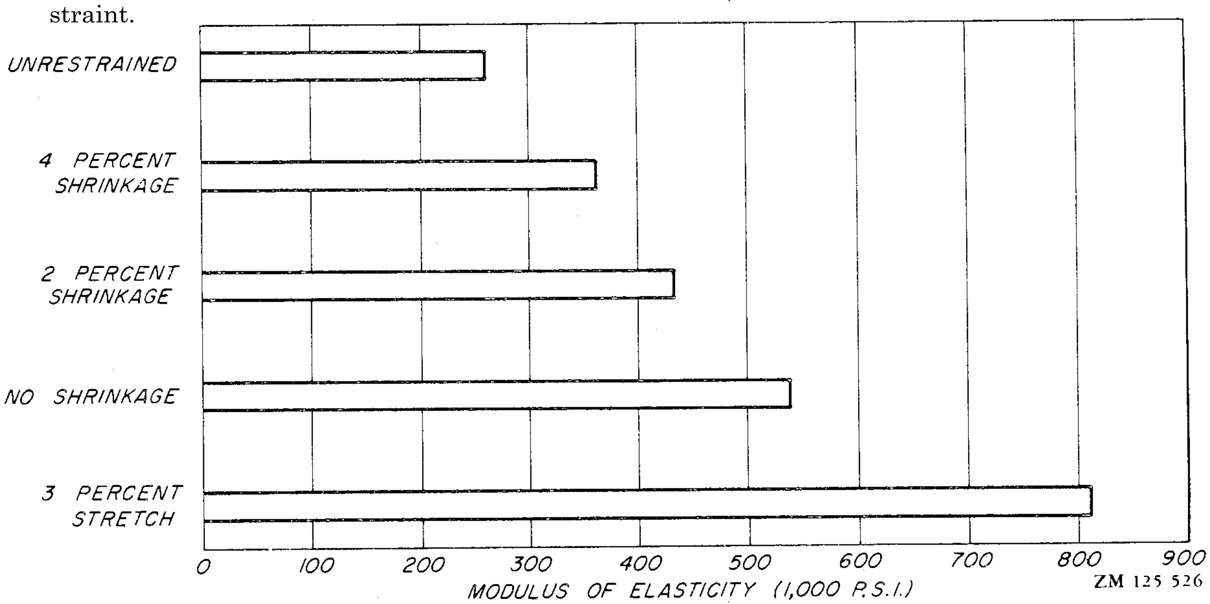

Figure 14.--Effect of restraint during drying on modulus of elasticity at constant density of 3 pounds per 1,000 square feet per mil.

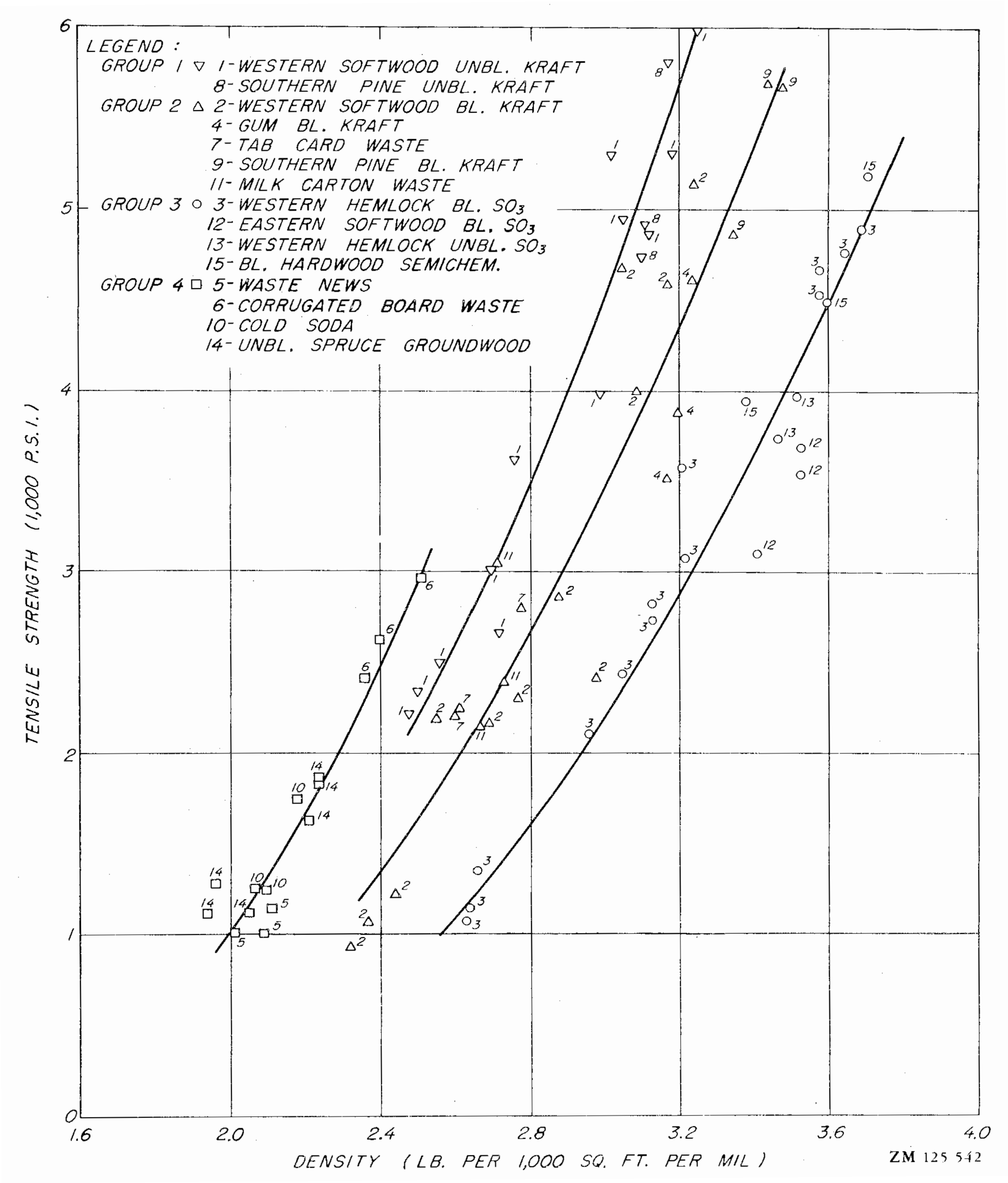

Figure 15.--Effect of density on tensile strength for handsheets from different pulps dried with no allowance for shrinkage, as well as 2 and 4 percent allowance for shrinkage.

measurements could not be made on the more or less cockledunrestrainedhand-sheets. Data for handsheets that had been stretched 3 percent prior to drying were treated separately.

The scatter of data makes it difficult to bring out any distinct differences between the levels of restraint. The four groupings of data about single curves appear to be fairly logical. For example, the data show that at any given density, unbleached softwood kraft has the highest tensile strength.

The data do show that tensile strength is primarily dependent on the pulping and bleaching process and on the density achieved in manufacture of the handsheets. At the same density, tensile strength is independent of freeness. The principal effect of beating on tensile strength is to alter pulp density. This view was also expressed by R. H. Doughty in 1932 (1). One of the basic differences between this study and Doughty's work was the method of drying the handsheets. After pressing wet sheets to a desired density, Doughty dried them between blotters in a vacuum oven, using the blotters to keep the sheets flat. Since no mention was made of the sheets sticking to the blotters, it is assumed that the blotters offered little restraint to the normal shrinking tendencies of his handsheets. The present study shows, as did Doughty, that the most important effect of changing the freeness by beating was to alter the sheet density.

A plot on log scale of tensile strength versus density of handsheets pressed and air-dried to different densities shows a series of straight lines with the same slope (fig. 16). If these data are combined with data for the 15 pulps shown in figure 16, in which handsheets were oven-dried in frames, there are two curve families, each with a distinct and separate slope. The important differences between these two groups arc drying temperatures and the manner in which restraint was applied. In one case, restraint was applied in only one direction in ovendrying with frames, and in the other restraint was applied from all directions in the flatwise plane of the sheet when the webs were air-dried on flat plates. This, in part at least, explains why it is difficult to relate standard handsheet strength values to those obtained on samples made on the paper machine.

The tensile strength-density relationships were studied for unrestrained handsheets to further explore differences in drying conditions. It is fairly certain that thickness measurements on unrestrained handsheets are usually too high because of the wrinkles in the sheets. However, the density and thickness values of sheets with a 4 percent shrinkage allowance very nearly approximate the true values for unrestrained handsheets. Strength values were accordingly adjusted for more realistic thicknesses and the strengths plotted against the adjusted densities. The curves in figure 17 show exactly the same slope as those of the sheets that were restrained in frames. It therefore appears that the difference between the slope of the curves for plate-dried sheets and those for sheets dried in frames is not due to the fact that restraint is applied in one direction only because the lack of restraint does not change the slope. It does indicate, however, that drying temperature is a primary factor in the strength-to-density relationships.

The effect of stretching wet webs 3 percent and then restraining them is shown in figure 18. Results of stretching wet webs 3 percent followed by 2 percent relaxation are shown in figure 19. These curves, along with figures 15 and 17 were used to prepare figures 20 to 23, which are strength-density curves showing the effect of restraint on the tensile

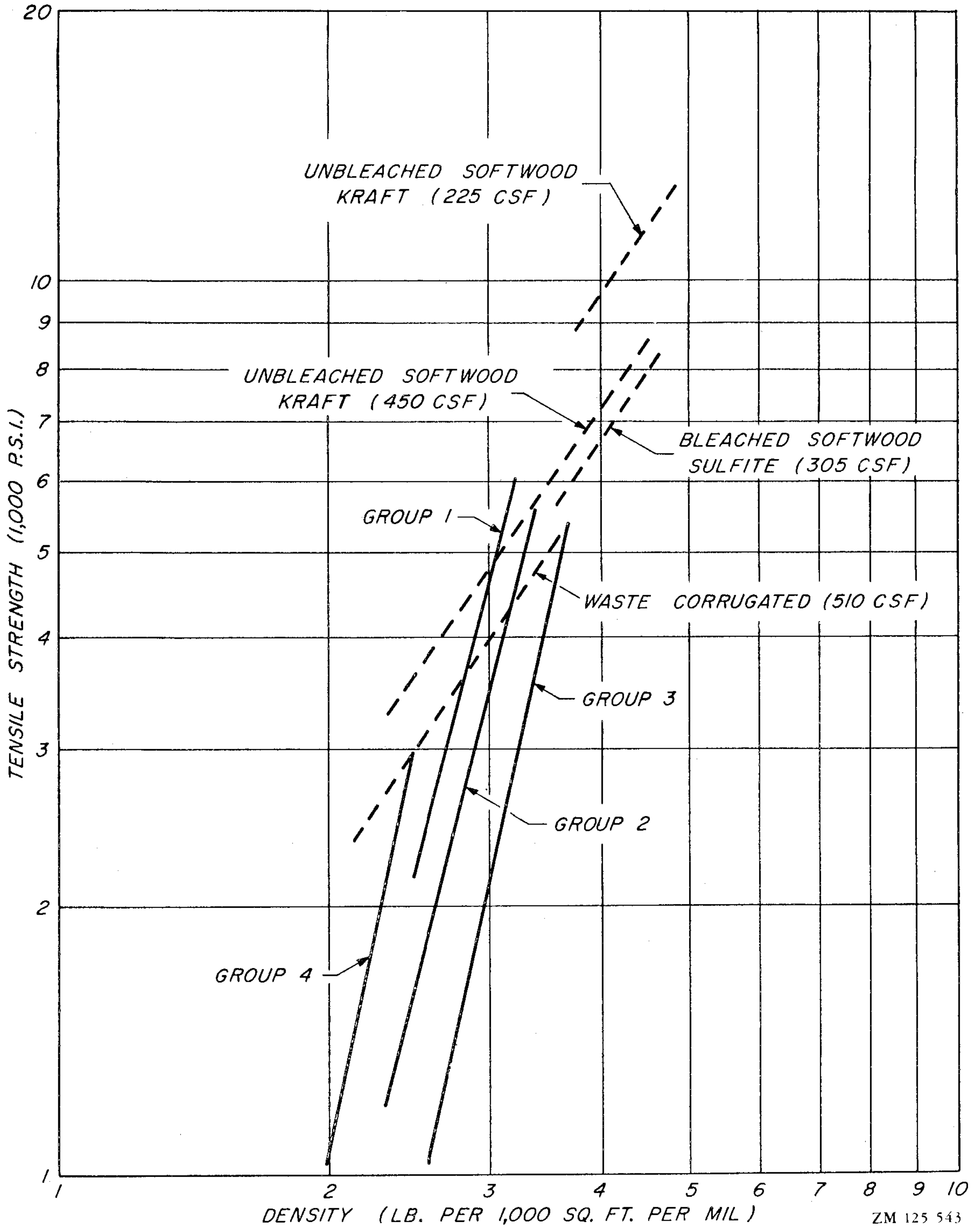

Figure 16.--Relationship between tensile strength and density for handsheets dried under restraint in drying frames and sheets pressed to different densities and dried on polished disks.

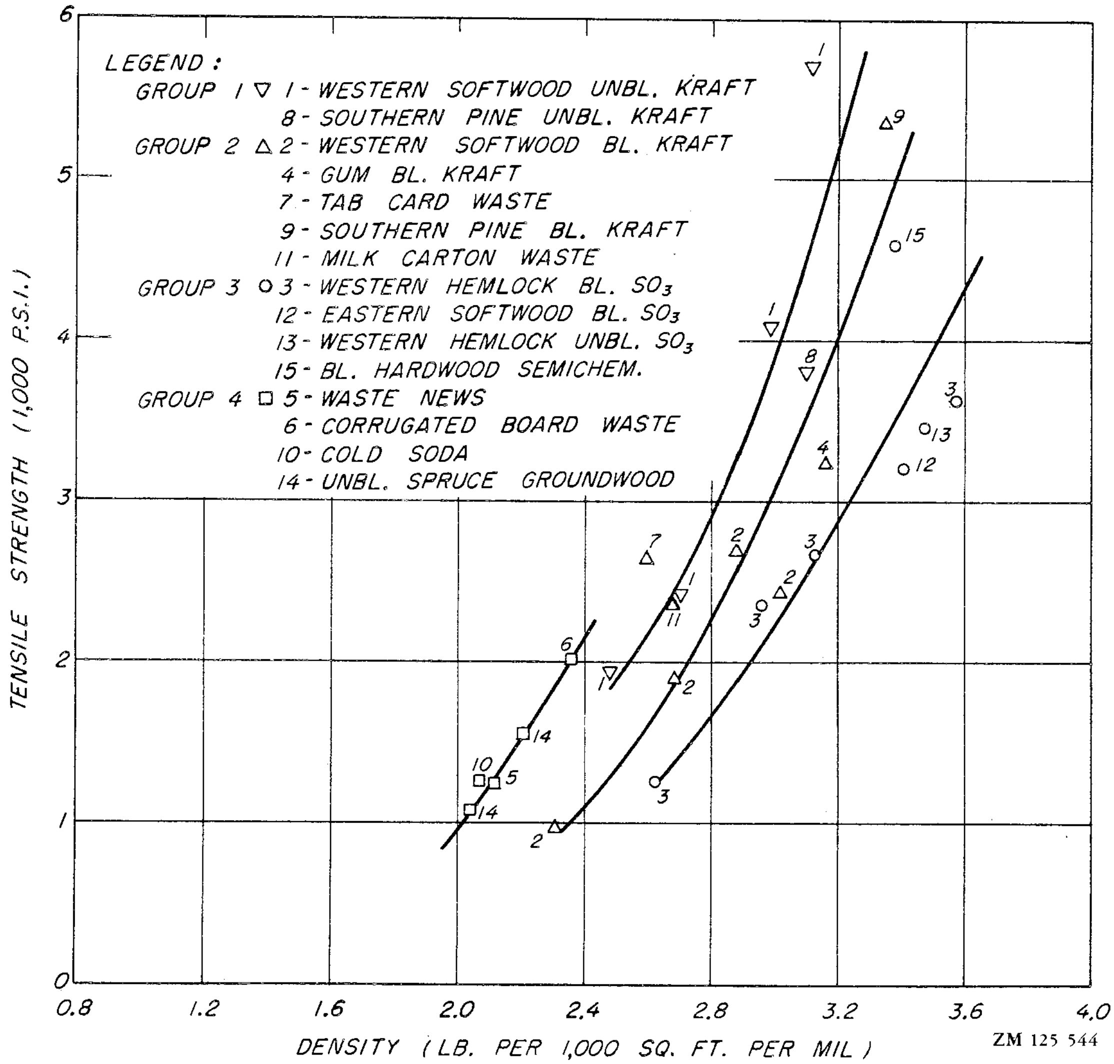

Figure 17.--Showing effect of density on tensile strength for handsheets from different pulps dried in unrestrained condition.

strength of the four groups of pulps.

As previously shown, increasing the amount of restraint during drying will result in subsequent increases in density of the dried sheet. While these changes are not large, they are fairly consistent. Density increases and then decreases along a scale of decreasing shrinkage allowance and beyond to one of stretching and restraining the wet sheet. While tensile strength normally (under constant restraint) would be expected to increase and decrease with density changes, applying restraint increases the tensile strength above that which can be accounted for by changes in density. In fact, tensile strength may even increase while density decreases. It is easy to attribute these effects of drying restraint to improvements in the stress distribution but, while reduction of the microcreping may improve the elastic modulus, it is difficult to visualize how it will benefit tensile strength.

One of the most interesting aspects of the influence of restraint during dry-

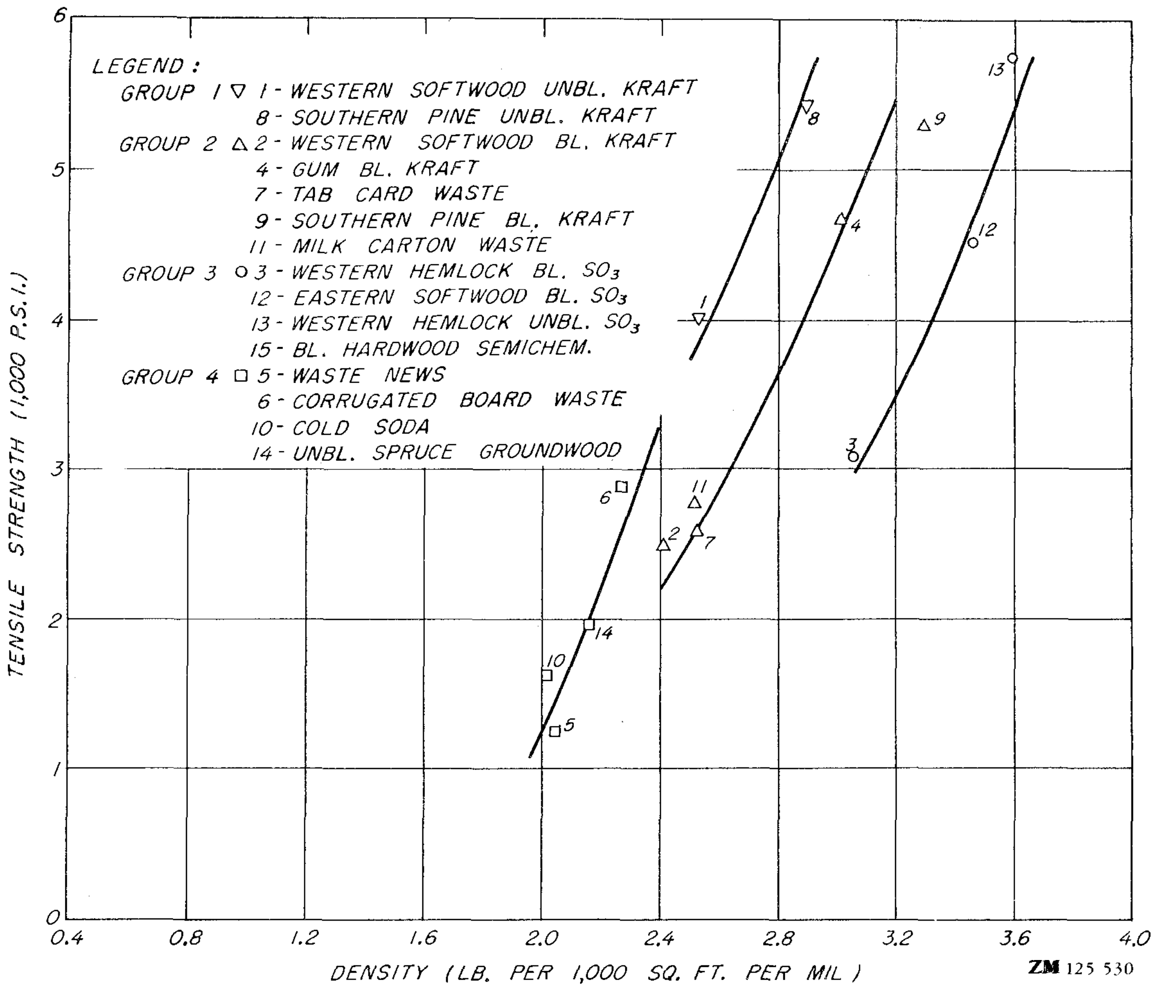

Figure 18.--Effect of density on tensile strength for handsheets from different pulps that have been stretched 3 percent and then dried with no allowance for shrinkage.

ing on tensile strength is the way in which the different pulp groups respond to variations in the restraint and stretching during drying. The kraft pulps (bleached or unbleached, figs. 20 and 21) are more influenced by restraint than are the sulfite pulps. This is illustrated by greater spread between the 3 percent stretch and unrestrained handsheet tensile values. These differences probably reflect basic differences in the ability of the sulfite and kraft pulps to form fiber-to-fiber bonds or intrinsic differences in fiber properties. Similarly, bleaching reduces the ability of kraft pulps to benefit in tensile strength from the effects of drying under restraint. Reworked pulps (fig. 23) such as newsprint or pulps containing a high percentage of groundwood benefit in tensile strength by drying under restraint but not to as great a degree as chemical pulps.

The increase in tensile strength at a constant density (3 pounds per 1,000 square feet per mil), which results from frame restraining during drying stretched and unstretched handsheets of pulp groups 1, 2, and 3, is shown in figure 24. This composite figure illus-

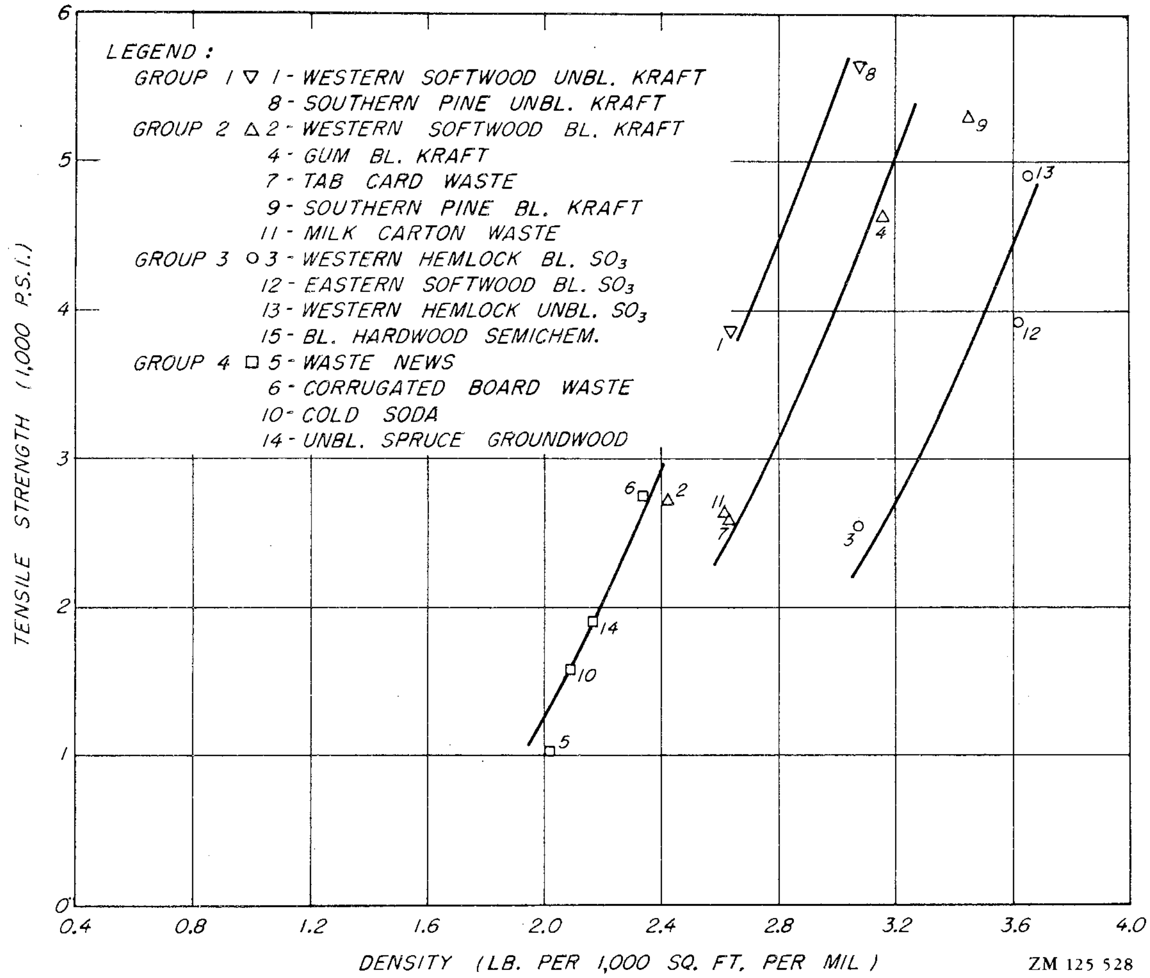

Figure 19--Showingeffect of density on tensile strength of handsheets from different pulps that have been stretched 3 percent and allowed to shrink 2 percent in length during drying.

trates that the type of pulp is an important factor in improving tensile strength.

Effect of Restraint on the Strain at Failure

Much has been said in this report about the improvements in tensile strength and elastic modulus that are achieved as a consequence of drying handsheets under restraint. In addition, there are noticeable improvements in dimensional stability (2) that result from restrained drying. These benefits, however, are obtained at the expense of stretch or toughness of the dried paper. While the loss in strain to failure is immediately evident by examining table 1, the graphical presentation in figures 25 through 28 shows additional comparisons. The figures show strain at failure versus density curves at different levels of restraint for the same pulp grouping that was obtained in the analysis of strength and density data. For these curves the density values shown for unrestrained handsheets were those obtained on handsheets where the shrinkage allowance was 4 percent.

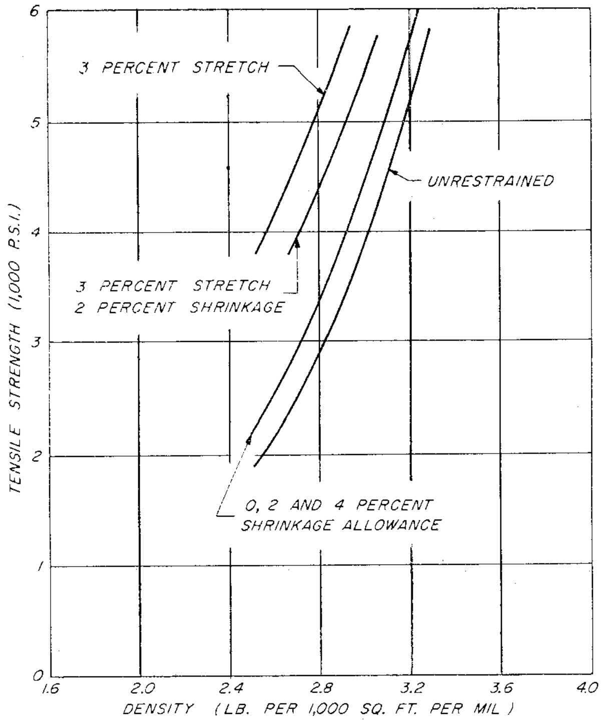

Figure 20.--Composite graph for handsheets from pulps in group 1 showing effect of density on tensile strength at all levels of restraint during drying.

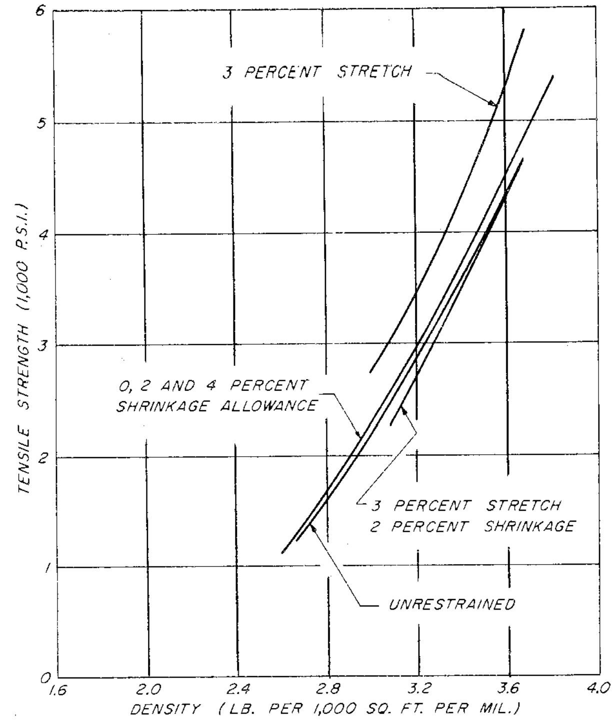

Figure 22.--Composite graph for handsheets from pulps in group 3 showing effect of density on tensile strength at all levels of restraint during drying.

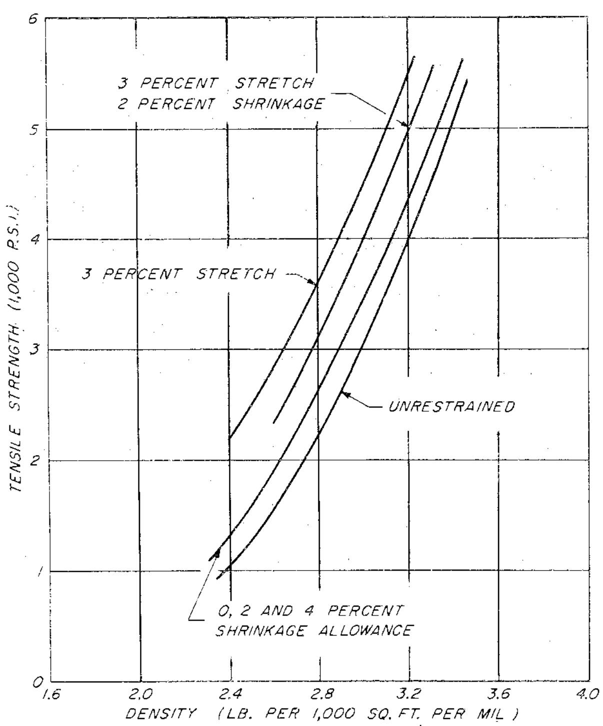

Figure 21.--Composite graph for handsheets from pulps in group 2 showing effect of density on tensile strength at all levels of restraint during drying.

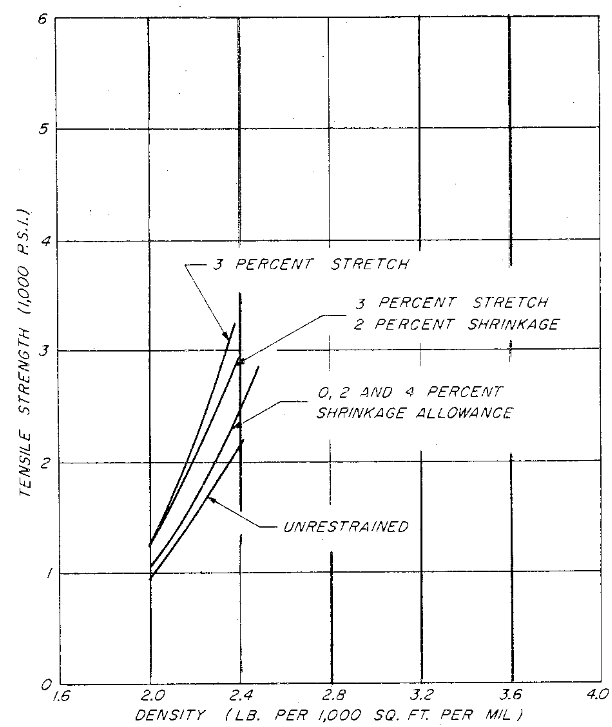

Figure 23.--Compositegraph for handsheets from pulps in group 4 showing effect of density on tensile strength at all levels of restraint during drying.

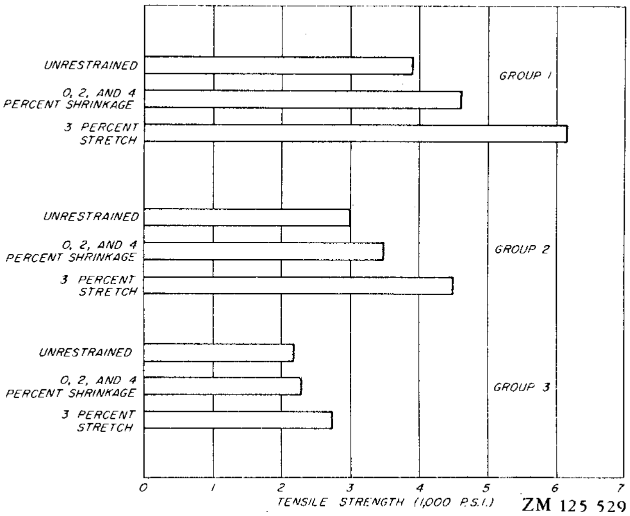

Figure 24.--Effect of restraint during drying on tensile strength at constant density of 3 pounds per 1,000 square feet per mil.

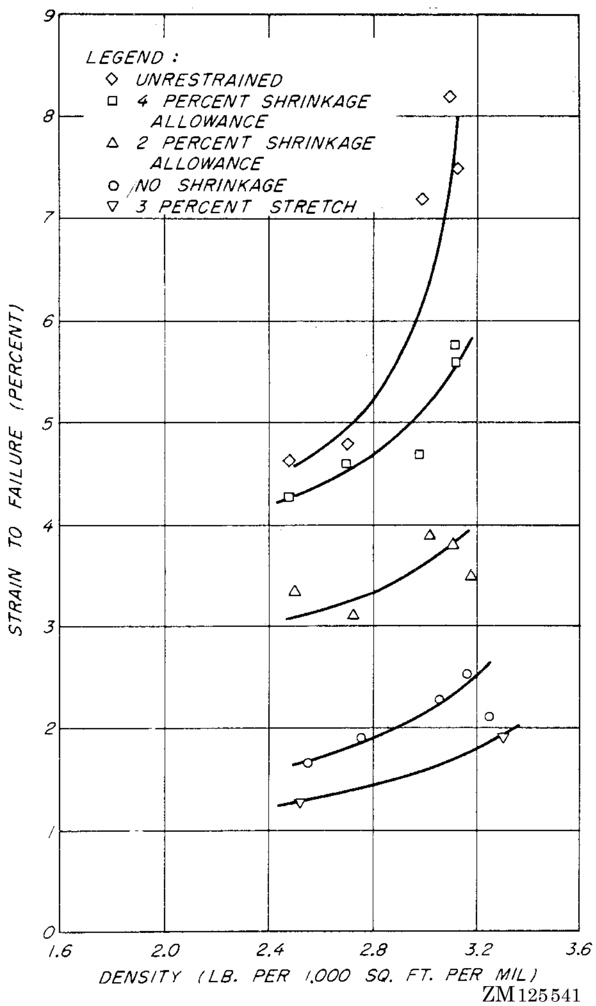

Figure 25.--Effect of density on tensile strain to failure for handsheets from pulps in group 1 at five levels of restraint of stretching.

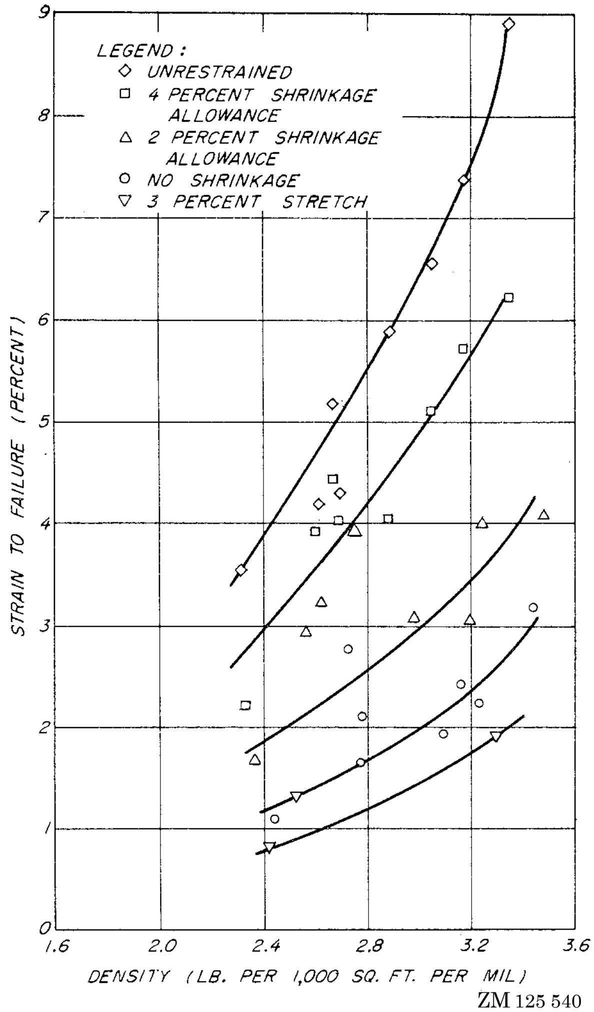

Figure 26.--Effect of density on tensile strain to failure for handsheets from pulps in group 2 at five levels of restraint or stretching.

For most of the pulps, the over all percent reduction in strain to failure from the unrestrained to fully restrained condition was about 70 percent. Stretching the wet webs 3 percent resulted in an additional loss of stretch of about 7 percent. At any given density, the unbleached kraft pulps (fig. 25) showed greater stretch than the bleached kraft pulps (fig. 26). The bleached kraft pulps, in turn, showed greater stretch than the sulfite pulps (fig. 26).

For unrestrained sheets, the stretch is controlled by the degree of beating. As greater restraint is applied during drying, the influence of processing becomes less. Thus, in a general way, stretch is influenced more by restraint than it is by refining in the test beater. However, the more beating and the higher the density of handsheets, the greater will be the effect of restraint on stretch.

Effect of Moisture Content at the Time of Restraint

Results show that, within the moisture limits of the experiment (20 to 60 percent), the higher the moisture content at the time the restraining is accomplished, the higher the strength and modulus of elasticity of the dried sheet. This point is illustrated in figure 29.

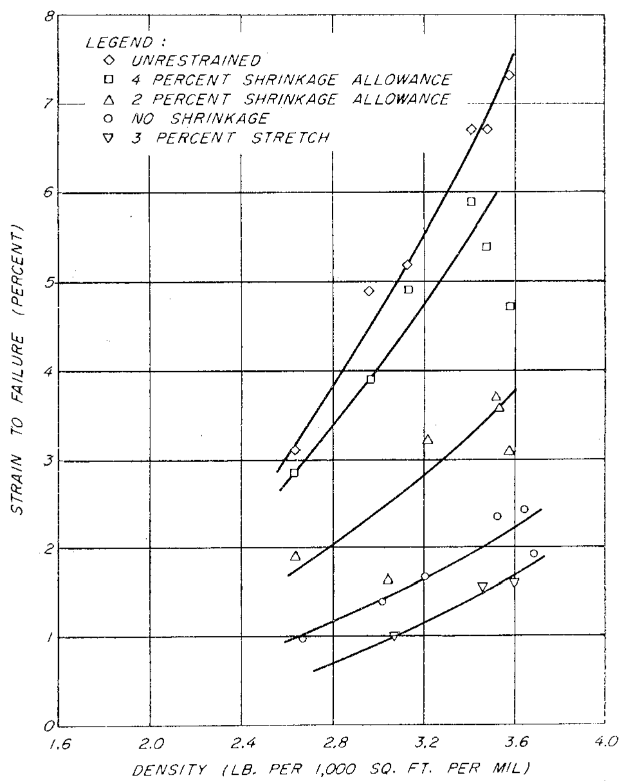

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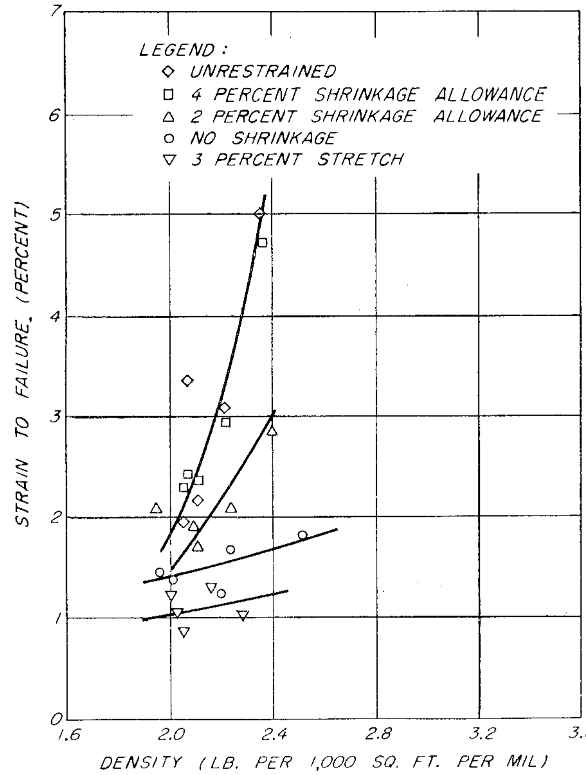
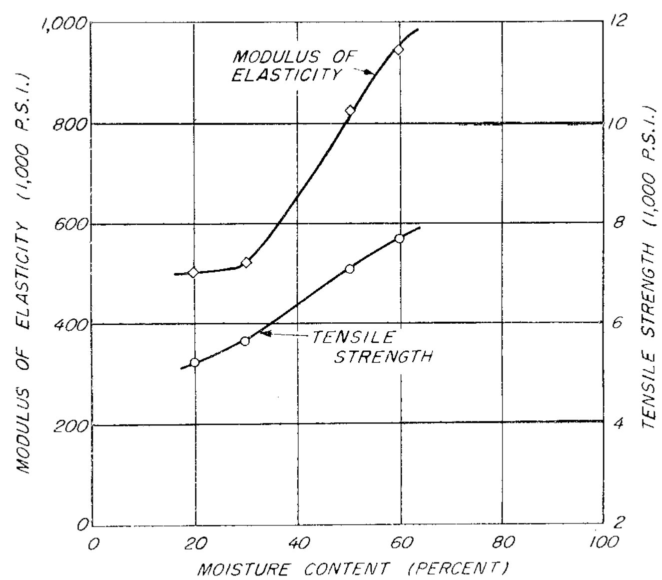
Figure 27.--Effect of density on tensile strain to failure for handsheets from pulps in group 3 at five Bevels of restraint or stretching.



ZM 125 536

Figure 28.--Effect of density on tensile strain to failure for handsheets from pulps in group 4 at five levels of restraint or stretching.



ZM 125 538

Figure 29. Tensile properties of paper as affected by moisture content at time of restraint.

Permanence of Effects of Restraint

Data obtained in this additional experiment show that much of the improvement in strength and elastic modulus induced by drying under restraint are not seriously reduced by a subsequent high-humidity exposure (table 4). Although water soaking reduced the elastic modulus greatly, neither the elastic modulus nor the strength curve returned to the original unrestrained levels.

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