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The Effect of Moisture on Ply-Bond Strength of Paperboard

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THE EFFECT OF
MOISTURE ON PLY-BOND
STRENGTH OF PAPERBOARD

by

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ABSTRACT

This study was carried out to evaluate the effect on the ply-bond strength of the moisture content of the plies of a multi-ply sheet at the time of joining.

Two-ply sheets were formed with the plies at various moisture contents at joining. The resulting ply-bonds were evaluated by three methods, viz. Instron peel, Mullen ply-bond, and z-direction tensile. Each method showed the same trend of ply-bond strength dependence on moisture and within the range of experimental error the average values of the three techniques correlated well.

This study showed that the moisture content of the plies at joining is extremely cririical in the ply-bond strength of paperboard. The practical minimum moisture content at which a ply-bond was possible was 20%. There was a gradual increase of ply-bond strength with increasing moisture content of the plies until a critical moisture range of 85 to 90% was reached. In this narrow range of moisture content the ply-bond strength increased two to fourfold. Once the critical range of moisture content was exceeded, no further increase in ply-bond strength occurred because the failure of the two-ply assembly occurred within one of the plies. This was confirmed by experiments which showed that the single ply (intraply) strength was of the same magnitude as the two-ply bond strength.

INTRODUCTION

The interply bonding strength of paper is the force or energy which is required to separate the layers of a multi-ply sheet of paper or paperboard. This adhesion of plies is developed by pressing (couching) newly formed plies together while still wet. The nature of the forces involved in ply-bonding are very likely the same as those within the individual plies (i.e. hydrogen bonding between fibers) (1).

Interply bonding is of major importance to the paperboard industry. In the manufacture of cylinder-machine multi-ply paperboards it is economically necessary to use low cost filler furnishes sandwiched between higher grade, stronger, brighter furnishes which may or may not be the same. These stocks are formed on individual cylinders and couched onto a pick-up felt in sequence to form a multi-ply web usually of seven layers. It is important that the outer layers (top and backliners) be bonded well to the internal layers. If the topliner adheres poorly to the layer below, it will often "pucker" when the layered sheet is drawn over a small radius roll. Poor ply-bonding can also cause topliner lift from the rest of the sheet when it is subjected to the high speeds and high tack inks of modern printing presses.

The ply-bond also plays a major roll in stiffness. If the plies in a sheet of paperboard are well bonded to each other they will resist relative movement when the sheet is subjected to a bending force (2).

HISTORICAL BACKGROUND

TERMINOLOGY

The interply bond strength, ply-bond strength, or inter-web strength is the effective adhesion of one ply to another in a multi-ply sheet.

Intraweb strength or intraply strength is the strength of an individual ply as evaluated by bursting strength or tensile strength.

Joining pressure is the pressure with which the plies of a multi-ply sheet are couched together.

PREVIOUS STUDIES

PLY-BOND STRENGTH TESTING METHODS

Perpendicular Bonding Force

Sutermeister and Porter (3) reported a method of measuring the force required to pull a single-ply sheet of paper apart by applying a force normal to the surface of the sheet. Two blocks with a surface area of one inch square are used. One block is glued to each side of the sample and the force required to pull the blocks apart, rupturing the sample, is measured. Abrams (4) introduced the use of the perpendicular bonding test for the evaluation of ply-bond strength. This method was modified by Wink and van Eperen (5) by using 1-inch diameter by 1¼ inch long cylinders in the place of the blocks used by Sutermeister and Porter and by using a v-grooved alignment jig to sandwich the sample between the cylinders.

Standardized waxes have also been used to measure a sheets resistance to picking (6).

The burst tester can also be adapted to evaluate the force, applied perpendicular to the surface of a sheet, required to rupture a multi-ply sheet of paper or paperboard. This method is discussed in the experimental portion of this report.

Peel Strength

Doughty and Baird (7) measured the force required to continue the separation of the plies in a multi-ply sheet by peeling. When the multi-ply sheet is being formed a small piece of waxed paper is placed between the plies along one edge to facilitate separation for testing. A 15 millimeter wide sample is cut from the sheet so that the end of the sample is separated. One of the plies is attached to a triple beam balance pan and the other ply is held between the thumb and forefinger of the tester. The amount of weight required to continue the separation is measured and is assumed to be a function of the ply-bond strength.

Sisalkraft Method

The Sisalkraft method consists of gluing a one-inch square sample of multi-ply paper between a metal block and an aluminum angle. The block is then bolted to the frame of the instrument so that the pendulum strikes the aluminum angle, splitting the sample. The strength is measured as excessive angular swing (8).

Shear Force

The force necessary to destroy a ply-bond may be evaluated by subjecting the multi-ply sheet to a shearing force. Brecht and Knittweis (9) studied the effect of shear by two methods. The first method consisted of applying a direct shear to the ply-bond by forming a two-ply sheet with the bottom ply extending beyond the top ply at one end and the top ply extending beyond the bottom ply at the other end of the sheet. The extended end of each ply is clamped in the opposing clamps on a tensile tester and the force required to break the ply-bond is measured. The resistance of the ply-bond to a shearing force was also measured by subjecting the multi-ply sheet to a bending force which causes relative moevment between the plies.

EVALUATION OF PLY-BOND STRENGTH

The first investigation into some of the factors affecting interply bonding was reported by Doughty and Baird (7) Brown (1), in a rather thorough investigation, studied many of the effects of interply bonding as well as the factors affecting interply bonding strength. Other investigators in the field were, Jeitelles (10), Brax (11), and Brecht and Knittweis (9).

The conclusions of the literature as to the effects of ply-bonding are:

1. For a given basis weight and fiber type, the more plies in the sheet the stronger the sheet became to an optimum number of plies for a given system (strength evaluated as Mullen Burst) (10) (1).
2. The total strength (burst, tensile and tear) of a

multi-ply sheet was greater than the combined strength of the plies.

3. The stiffness of a multi-ply sheet increased in proportion to the interply bond strength (1).

The conclusions of the literature concerning the factors affecting interply bonding are:

1. The degree of refining, as evaluated by pulp freeness was a very important factor. Brown (1) found that as the stock was refined the interply bonding strength increased.
2. Doughty and Baird (7) showed that as the joining pressure was increased the interply bonding was increased.
3. Pressing the plies before joining decreased the ply-bonding (7).
4. To achieve good ply-bonding the joining pressure had to be greater than the wet pressing pressure the plies were subjected to before joining (7).
5. As the amount of machine calendering given a multi-ply sheet is increased the ply-bond strength decreased (1).
6. The moisture content was found to be a critical factor in ply-bonding. Brax (11) reported that the moisture content of the plies at joining should be between 70% and 90%. Figure 1 summarizes the findings of Brecht and Knittweis (9) which shows that the ply-bond strength decreased about 40% from 95 to 60% moisture when ground

wood multi-ply sheets were studied.

7. Clark (12) found that. when forming singly-ply sheets, intraweb strength was a maximum when the percent moisture before forming was near 100%. The intraweb strength decreased as the percent moisture decreased. The most rapid area of strength decrease was found to be between 85 and 70% moisture.

8. Brown (1) found the strength of a multi-ply sheet was partially dependent upon the ply-bond strength.

9. The interweb strenth approaches the intra web strength as a limit (1).

10. The mechanism for bonding between plies is the same as the mechanism for bonding within the plies (1).

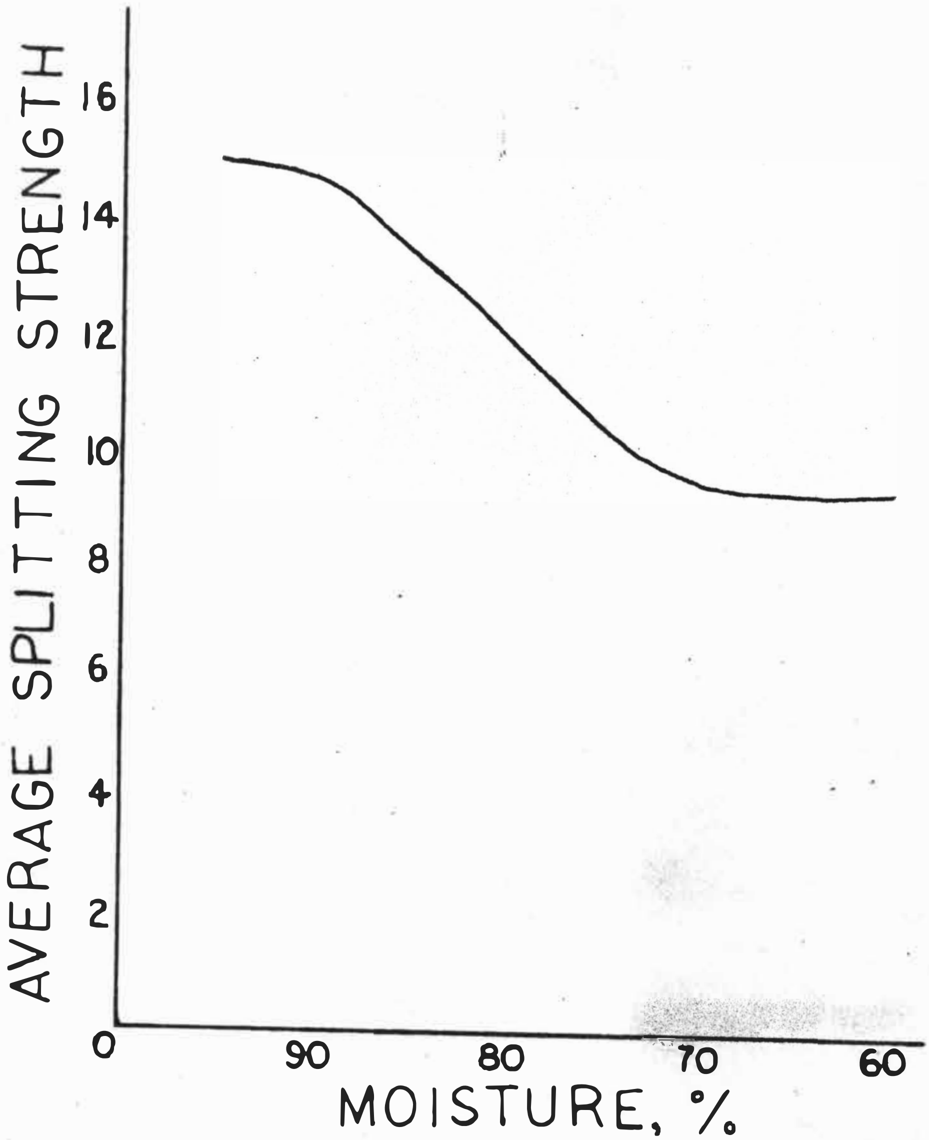


FIGURE 1 AVERAGE PLY-BOND STRENGTH AS A FUNCTION OF MOISTURE OF PLIES BEFORE COUCHING (9)

STATEMENT OF THE PROBLEM

The literature has shown two sets of findings on the effect of moisture content of the plies before couching on ply-bond strength (9) (11). Both indicate that moisture content is probably the most critical factor affecting ply-bonding within a given system.

Brecht and Knittweis (9) found a relatively small drop in ply-bond strength of plies joined at moisture contents between 60 and 95%, using groundwood pulp. Brax reports (11) that bonding between plies does not occur outside the limits of 90 and 70% moisture. However it is believed that moistures of greater than 90% were unattainable by the method of sheet-making used.

It appeared that there was a need for a study of the effect of moisture content on the strength of the ply-bond using a common and consistent reproducable stock and using more analytical methods than were available at the time of the investigation by Brax.

EXPERIMENTAL

EXPERIMENTAL DESIGN

The scope of this investigation will be to analyze the effect of moisture content of plies prior to couching on the ply-bond strength of a two-ply sheet of paper.

A bleached kraft pulp will be used, the webs will be formed and the moisture content determined just prior to joining. The moisture content will be varied by allowing the sheets to air-dry for various time intervals before joining.

Three methods of testing the ply-bond strength will be used in order that the results be more universal and not depend upon a single testing prodedure.

EXPERIMENTAL PROCEDURE

SHEET PREPARATION

The pulp used was Weyerhausser bleached softwood kraft beaten in a 1½-pound Valley laboratory beater to a freeness of 400 CSF.

The individual plies were formed on a Noble and Wood sheet machine at a weight of 2.5 grams per ply (60 g/m^2). The plies were taken from the mold without wet pressing and allowed to air-dry in pairs to the desired moisture, at which point a moisture sample was taken from a corner of each ply and a 1½-inch by 2-inch piece of muslin cloth placed between a portion of the sheet at the edge. The plies, each still on the forming wire, were placed face to face and joined by pressing and drying normally (pressed between steel rollers at 35 p.l.i. between press felts and dried at 225° F against a steam heated dryer). The two-ply sheet was then removed from between the wires and sent through the dryer a second time.

The sheet was then placed in a standard humidity room (73° F, 50% R.H.) for at least 24 hours prior to testing.

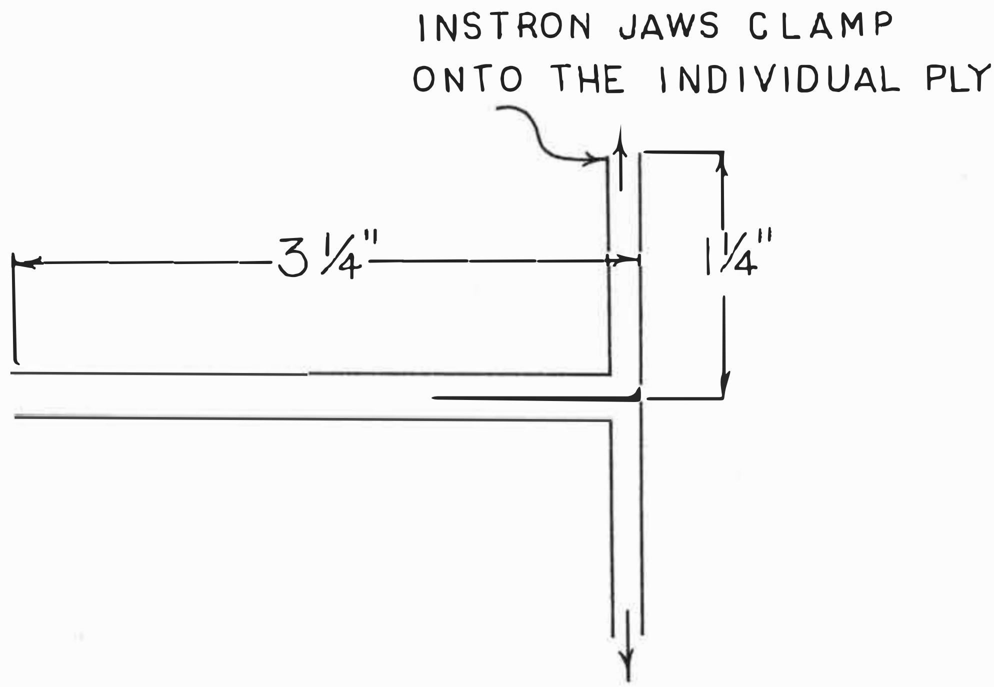
TESTING METHODS

The sheets were tested for ply-bond strength by three different techniques.

Instron Peel

The first method of ply-bond strength evaluation was an improved version of a method introduced by Doughty and Baird (7). In this method a multi-ply sheet was partially separated at the plies and one ply attached to the pan on a triple beam balance and the other held between the thumb and forefinger of the tester. The balance was then adjusted until the weight required to continue the peel was reached.

The geometry used in this report was similar in that the ply was split prior to the test and the plies were pulled apart at a 180° angle, as seen in Figure 2. In this procedure the plies were each clamped into the opposing jaws of an Instron tensile tester and the total energy required to peel a 1-inch by 3-inch surface area peeled along the 3-inch axis was calculated by using the Instron integrator reading and calulating the Tensile Energy Absorption (TEA) according to TAPPI TS 494,



INSTRON PEEL SPLIT

FIGURE 2

giving a work per unit area (Kg-cm/cm^2). If this value is multiplied by the width of the sample (2.54 cm) the average force required to continue peel separation is obtained.

The Instron was set at a 2-inch initial head separation and a 6-inch testing distance (allowing a 3-inch ply separation). The cross-head speed was 50 cm/min. and the chart speed was 30 cm/min. The sample was cut to 4½-inches long by 1-inch wide with a 1¼-inch separation between the plies to facilitate clamping into the Instron. The total surface area peeled was 1-inch by 3-inch or 19.5148 sq. cm.

Z-Direction Tensile

The next method used was a modification of the z-direction tensile evaluation as modified and improved by Wink and van Eperen (5). The method consisted of the testing of an ordinary single-ply sheet of paper in the z-direction (perpendicular to the surface of the sheet). It was readily adaptable to application on two-ply sheets.

Two pieces of double-coated pressure sensitive tape were applied to the test sheet, one to each side. The outer protective backings were not removed. From this double-taped sample 1 3/8-inch diameter samples were cut with a cylinder punch die. The tape backing from one side of the sample was removed and the sample was centered on a 1-inch diameter by 1¼-inch high test cylinder (Figure 3). The tape backing of the other side of the sheet was then removed and the sample placed in a z-direction tensile v-grooved alignment jig (Figure 3). A second test cylinder was pressed against the side of the sheet opposing the first cylinder. The cylinders were then connected to the opposing heads of the Instron tensile tester by means of 5/16-inch by 1½-inch bolts threaded into each cylinder and wires connected between the bolts and the Instron (Figure 4). The testing surface area was 0.784 sq. inches and the results were expressed as Kg/cm^2.

Mullen Ply-Bond

A Mullen burst tester can be adapted to test for ply-bond strength as described in TAPPI RC 273. A three inch strip of double coated pressure sensitive adhesive tape is placed on each side of a three inch wide sample. By means of a special sample cutter, samples are cut from this strip. The sample is 2.645 inches in diameter with a 1.375 inch diameter hole in the center. This gives a surface area of three inches square. The protective liners are then removed from the other side of the tape and the sample is placed between two metal disks. The bottom disk is about three inches in diameter with a 1.375 inch hole corresponding to the hole in the sample. The top disk has the same diameter as the sample and has no hole in it. This apparatus is placed on the sample platform of a Mullen tester with the annular disk down. Another annular disk is placed on top of the first annular disk but has an inside diameter large enough that the top disk is not touched(Figure 5).

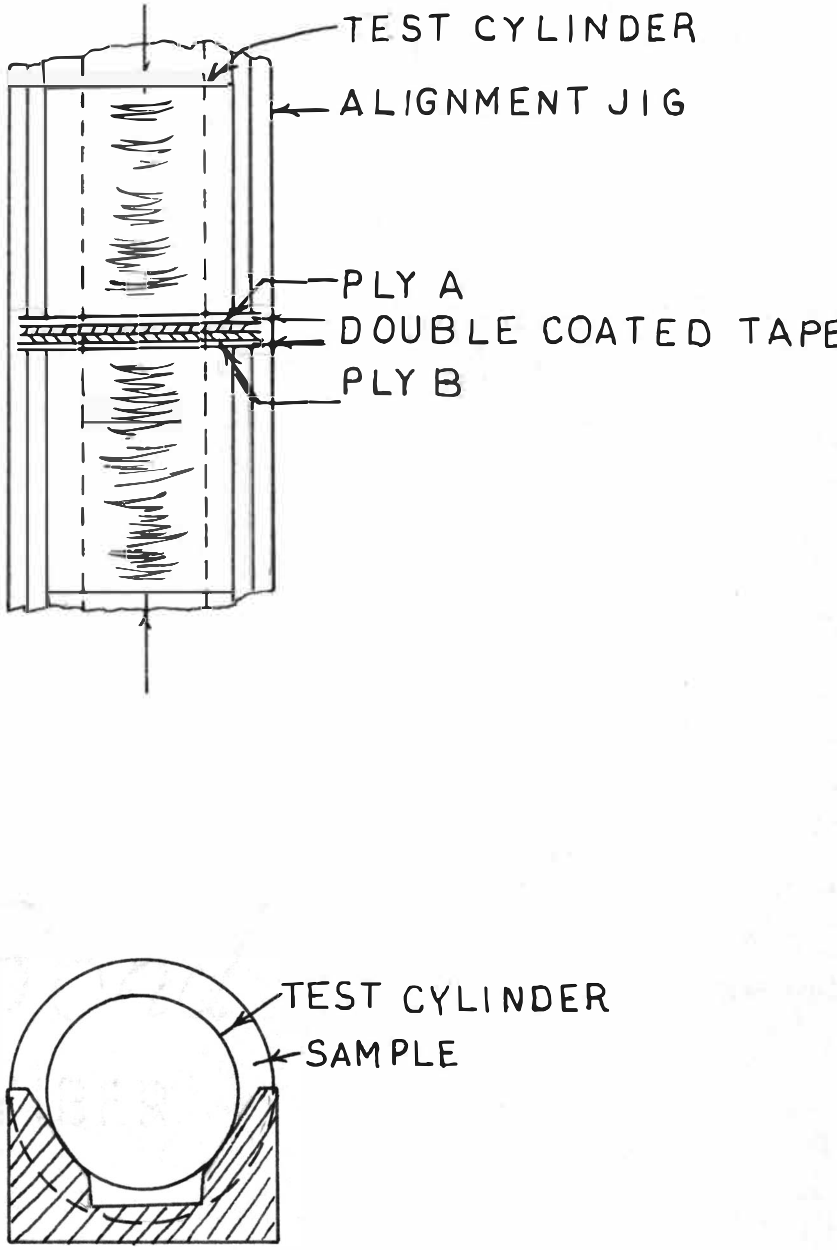


FIGURE 3 PORTION OF Z-DIRECTION TENSILE ALIGNMENT EQUIPMENT

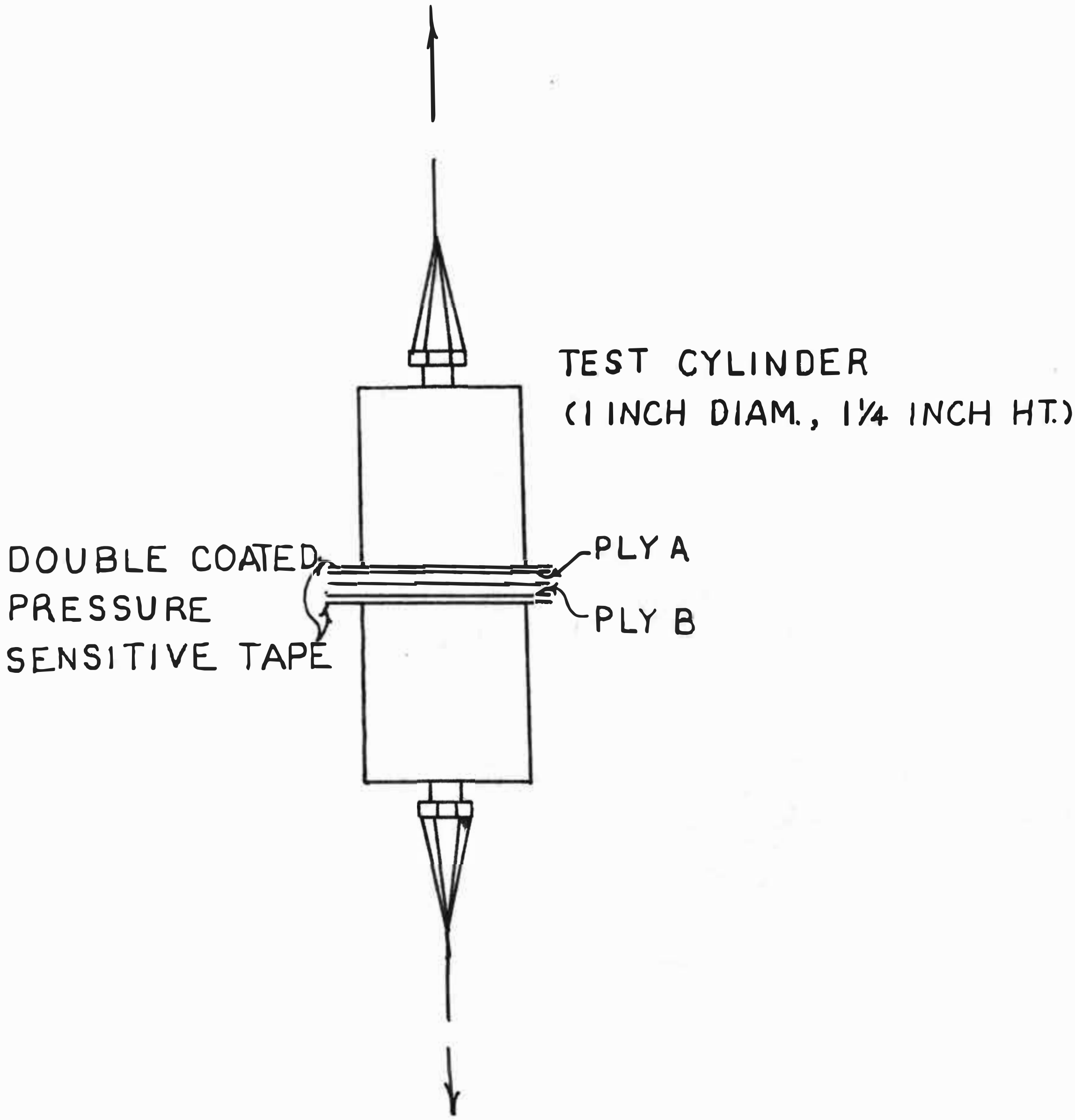


FIGURE 4
Z-DIRECTION TENSILE

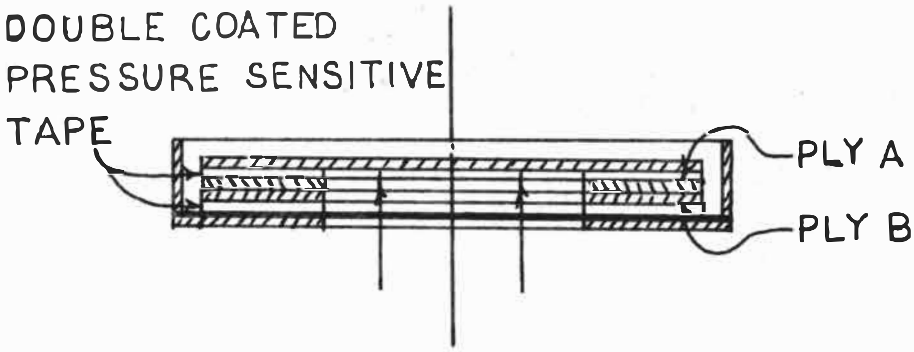


FIGURE 5

MULLEN PLY-BOND

This second annular disk is sufficiently thick so that the Mullen sample clamp can be brought down and the top disk of the adaptation can move up about ½-inch. The hole in the bottom disk and sample allow the Mullen rupturing bulb to pass through and put pressure on the top plate, which is free to rise as much as is necessary. This pressure will pull the sample up, but the annular disks will hold it down. The sample will rupture at its weakest plane which is normally the ply interface (2) (8) (13) (14). Ply-bond strength was expressed as Kg/cm^2.

RESULTS AND DISCUSSION

The effect of moisture content at the time of joining of the plies of a two-ply sheet at moistures ranging from 9.3 to 94% was studied. It was found that measurable ply-bond strength could not be obtained by the methods used at moisture contents below 20%. Furthermore, it was not possible to prepare plies having greater than 94% moisture.

Data of all experiments are summarized in Table I. Figures 6, 7, and 8 show that between 9.3 and 85% moisture the strength of the ply-bonds increased gradually as the moisture content of the plies before joining was increased. There was a sudden inflection between 85.0 and 90% moisture where small increases in moisture content yielded very large increases in ply-bond strength.

The three methods all showed this sharp inflection between 85 and 90% moisture. Between 90 and 94% moisture the ply-bond strength is consistently high with considerable scatter in the data points showing no definite trend. The data indicate that the scatter is due to factors other than the moisture content and that a limit for ply-bonding has been reached.

In Figures 6, 7, and 8 it is shown that the limit reached was the intraply strength. The intraply strength is the internal strength of an individual ply and was evaluated by the z-direction tensile method. Because the ply-bond strength was approximately the intraply strength, between 90 and 94% moisture, the two-ply sheets were probably not always failing

TABLE I

	Percent Moisture			Instron Peel Kg-cm/cm^2			Mullen Ply-Bond Kg/cm^2			Z-Direction Tensile Kg/cm^2		
	Ply 1	Ply 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average
1	91.42	91.89	91.66	5.82	7.30	6.56	1.88	1.75	1.81	1.62	2.25	1.94
2	93.09	93.57	93.33	7.38	8.00	7.69	2.56	---	2.56	2.33	---	2.33
3	91.32	91.31	91.31	6.50	6.54	6.52	2.11	2.36	2.23	2.09	---	2.09
4	95.09	92.85	93.97	5.76	6.22	5.98	2.57	2.32	2.44	2.61	2.55	2.58
5	91.97	91.71	91.81	6.43	6.40	6.41	2.24	1.99	2.12	2.47	2.09	2.28
6	49.99	54.61	52.30	2.04	0.69	1.36	1.08	1.00	1.04	0.24	0.71	0.47
7	49.05	55.75	52.40	1.44	1.68	1.06	0.44	---	0.44	1.33	1.39	1.36
8	30.40	20.30	25.35	0.49	0.41	0.45	0.12	---	0.12	0	0	0
9	7.85	10.70	9.27	0	0	0	0	0	0	0	0	0
10	57.86	57.90	57.88	0.39	0.98	0.69	0.20	0.27	0.23	0	0	0
11	62.54	63.60	63.07	1.20	---	1.20	0.32	0.44	0.38	1.38	0.45	0.93
12	68.01	72.83	70.42	1.77	1.43	1.60	0.76	1.13	0.94	0.57	1.01	0.79
13	91.93	91.78	91.50	6.20	6.02	6.11	1.46	2.06	1.76	2.56	2.50	2.54
14	91.85	90.87	91.36	6.29	5.34	5.82	2.25	3.00	2.62	2.55	2.26	2.40
15	91.94	91.95	91.94	7.52	7.40	7.46	2.50	2.20	2.35	2.43	---	2.43

TABLE I (cont')

	Percent Moisture			Instron Peel Kg-cm/cm^2			Mullen Ply-Bond Kg/cm^2			Z-Direction Tensile Kg/cm^2		
	Ply 1	Ply 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average
16	91.97	91.65	91.81	6.45	7.11	6.78	2.38	3.00	2.67	2.02	2.17	2.09
17	91.10	91.12	91.11	7.40	8.24	7.82	3.13	3.58	2.86	2.11	2.40	2.25
18	90.90	90.23	90.52	7.69	6.67	7.14	2.83	2.33	2.58	2.71	---	2.71
19	91.29	91.82	91.56	6.55	6.45	6.50	2.62	2.81	2.72	2.59	2.33	2.46
20	91.25	91.41	91.33	6.40	6.72	6.56	2.14	2.13	2.14	2.77	---	2.77
21	91.57	90.18	90.82	6.09	6.58	6.34	2.43	2.41	2.42	2.15	---	2.15
22	90.80	91.08	90.94	6.65	5.63	6.14	1.88	2.11	2.00	2.25	2.05	2.15
23	91.43	92.43	91.93	5.57	6.44	6.00	1.81	1.93	1.87	2.51	1.80	2.15
24	90.32	90.32	90.32	5.60	5.67	5.64	1.57	1.28	1.42	1.72	1.83	1.78
25	87.18	87.58	87.38	3.99	3.57	3.78	1.64	1.65	1.65	1.07	0.99	1.03
26	91.02	91.22	91.12	6.39	6.88	6.63	2.76	2.55	2.65	2.41	---	2.41
27	91.64	92.05	91.85	6.41	6.35	6.38	2.16	2.22	2.19	2.27	---	2.27
28	88.93	88.65	88.19	4.64	2.94	3.78	0.68	0.68	0.68	1.05	0.96	1.00
29	88.32	86.92	87.62	2.37	1.27	1.82	0.32	0.41	0.37	0.83	0.78	0.81
30	74.90	78.62	76.76	1.44	2.19	1.76	0.33	0.37	0.35	0.73	0.99	0.86

TABLE I (cont')

	Percent Moisture			Instron Peel Kg-cm/cm^2			Mullen Ply-Bond Kg/cm^2			Z-Direction Tensile Kg/cm^2		
	Ply 1	Ply 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average
31	39.86	42.50	41.18	0.80	0.89	0.85	0	0	0	0	0	0
32	29.31	36.47	32.89	0.38	---	0.38	0	0	0	0	0	0
33	24.72	17.42	21.07	0	0	0	0	0	0	0	0	0

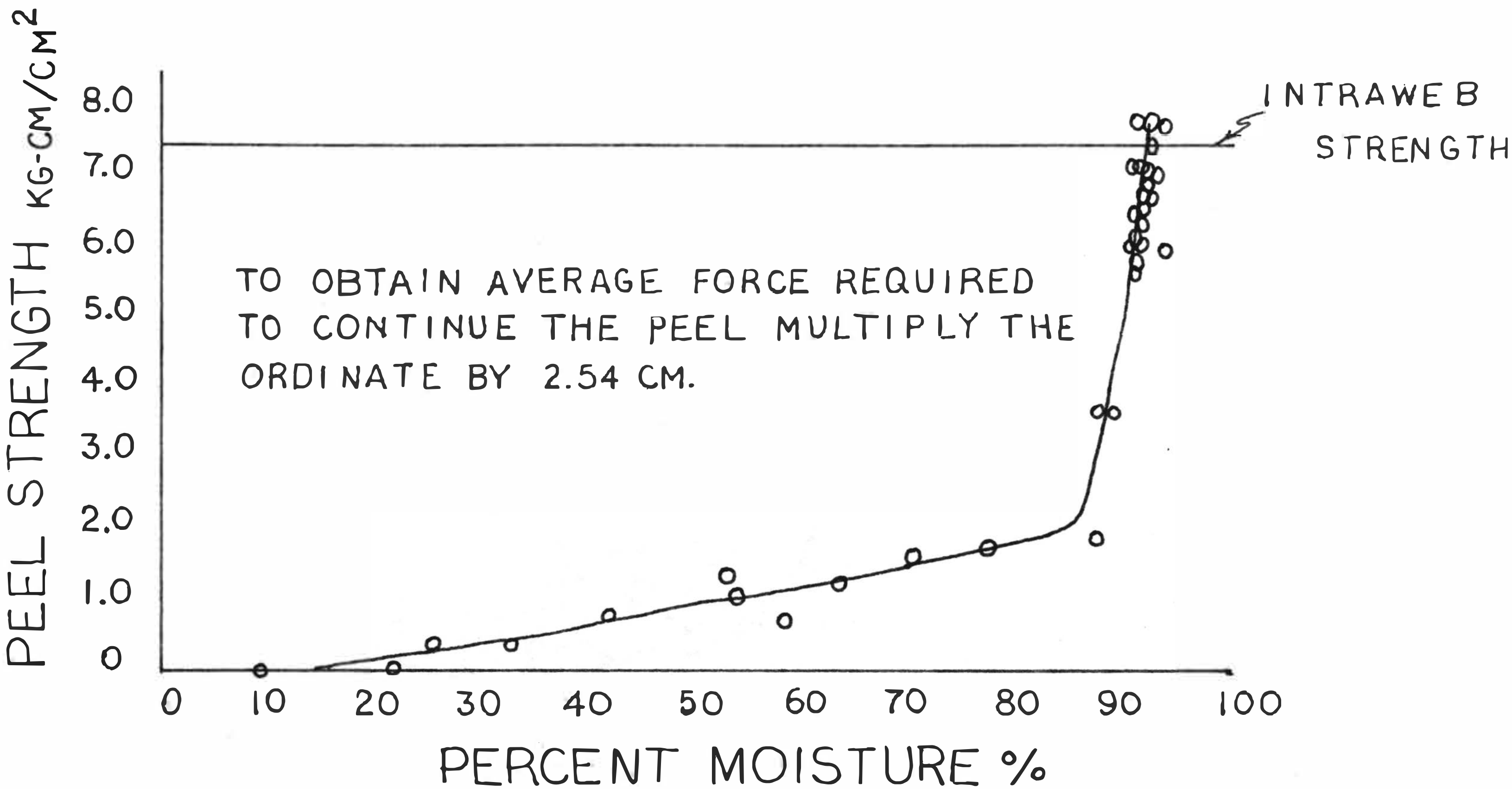


FIGURE 6 PEEL STRENGTH AS A FUNCTION OF MOISTURE

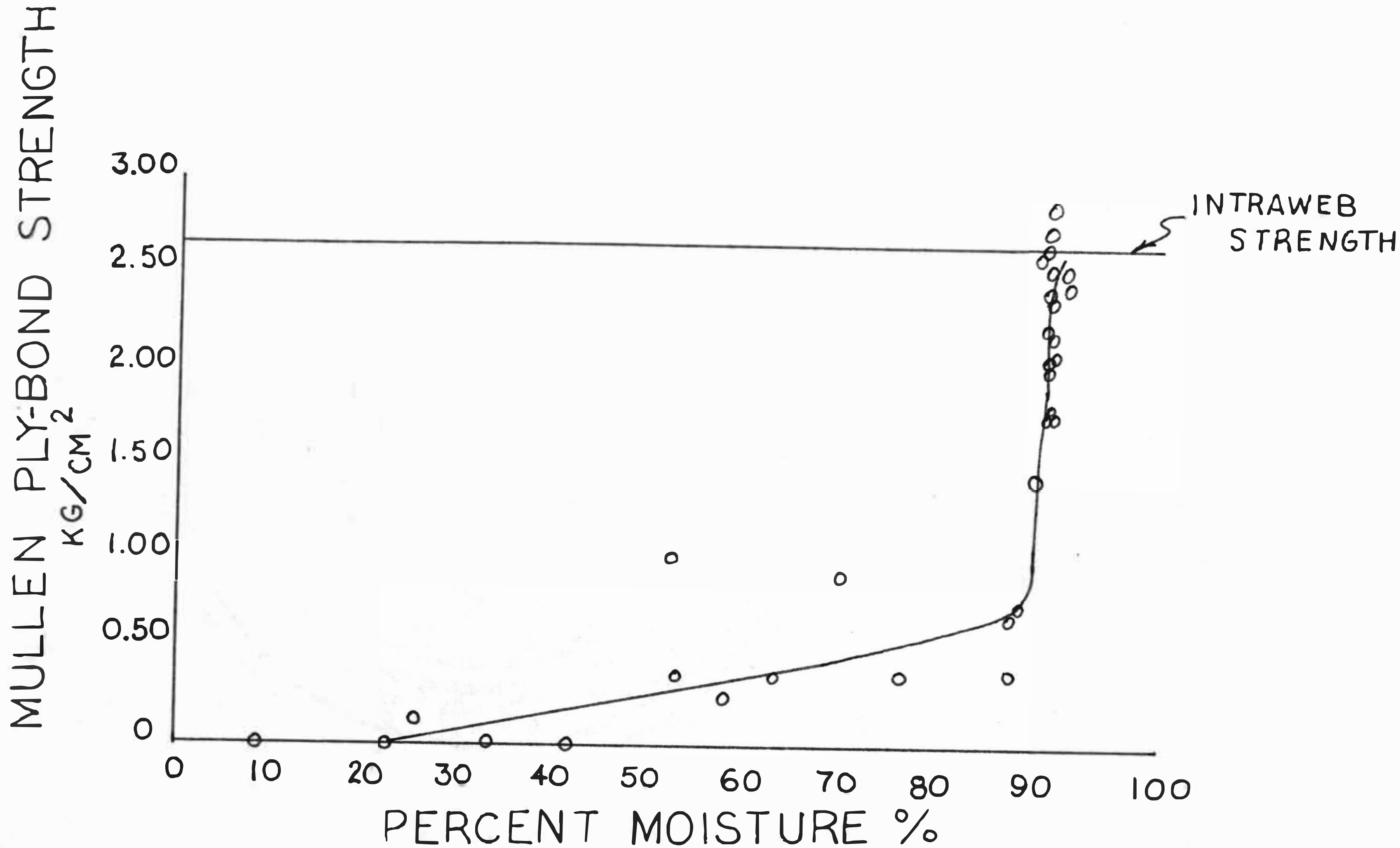


FIGURE 7 MULLEN PLY-BOND STRENGTH TEST AS A FUNCTION OF MOISTURE

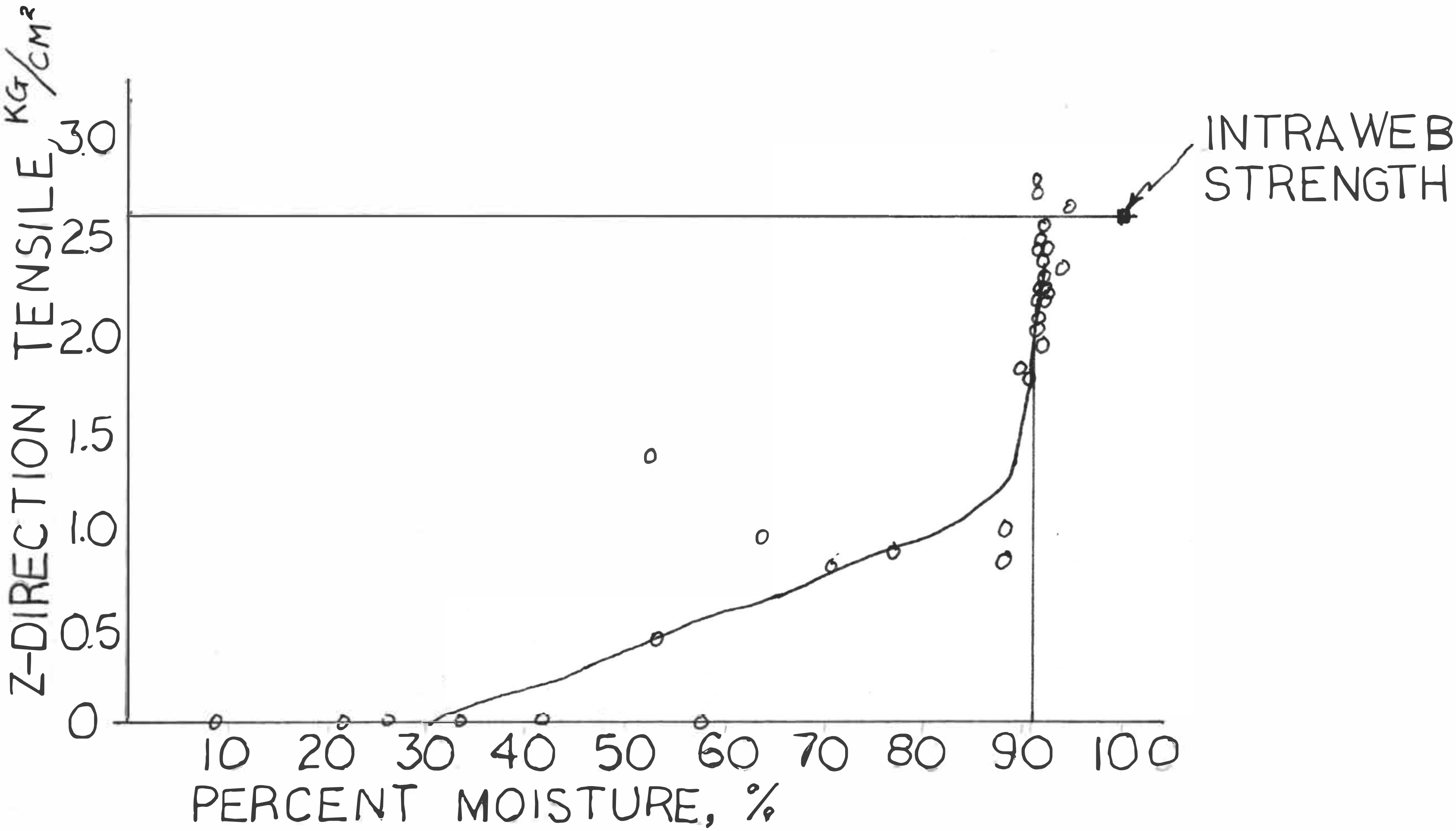


FIGURE 8 Z-DIRECTION TENSILE STRENGTH AS A FUNCTION OF MOISTURE.

at the ply interface but at the weakest plane within the sheets.

The results of this study show that there is a very critical point for ply-bonding at about 90% moisture. This critical point has been recognized by the paperboard industry for many years. The usual moisture content of webs at the point of joining on a typical cylinder machine is 92% (2). The date of Brecht and Knittweis (9) show that, when groundwood multi-ply sheets were used, this severe drop in ply-bond strength with small decreases in moisture did not occur. Brax (11) stated that significant bonding did not occur outside the limits of 70 and 90% moisture. This study has shown that moisture content of above 90% is necessary to achieve a good ply-bond and that some ply-bonding can be realized at as low as 25% moisture.

Ply-bond strength evaluated by the Instron peel method proved to be more sensitive than either the z-direction tensile or the Mullen ply-bond methods. Because the load to failure was obtained over the entire area of the ply-bonds the values were believed to be quite representative of the average ply-bond strength of the two-ply sheet.

The Instron peel method was also applicable to low strength ply-bonds. However, the process of peeling the double coated tape from the Mullen ply-bond and z-direction tensile methods was enough to destroy the ply-bonds of the low moisture content sample sheets. During Instron testing of ply-bonds, the strongest ply-bond sheets separated at a very definite interface which was directly in line between the clamps of the Instron. As the plies became weaker the stiffness of the plies, coupled with the force of the Instron, caused interface separation to move faster than in the stronger ply-bonds, causing the plies to fall apart before the Instron head had traveled the full testing distance. This occurred only on the very low strength bonds and may have caused a slightly high ply-bond strength value due to the Instron head travel after the separation had occurred with the weight of the ply still in the jaw.

The correlation coefficient between the Instron peel and the z-direction tensile methods was .916 (Figure 9). Figure 10 shows that the correlation coefficient between the Instron peel and the Mullen ply-bond was slightly lower at .902. The best agreement between data occurred between the z-direction tensile and the Mullen ply-bond methods. The correlation coefficient was .947 (Figure 11). The high degree of correlation between the z-direction tensile and the Mullen ply-bond methods probably occurred because both methods were evaluating the ply-bond strength in the same manner (i.e. applying force normal to the surface of the sheet). The very good correlation coefficients between all three methods of ply-bond testing, in spite of the scatter which is apparent in Figures 9, 10, and 11, is due to the nature of the correlation coefficient. The correlation coefficient compares the correlation between the two sets of data to the correlation within each set of data. Therefore, although there is considerable scatter in the points when any two of the testing methods are compared the correlation coefficient is quite good due to the scatter of points when the ply-bond strength values of one of the methods is plotted against the moisture content.

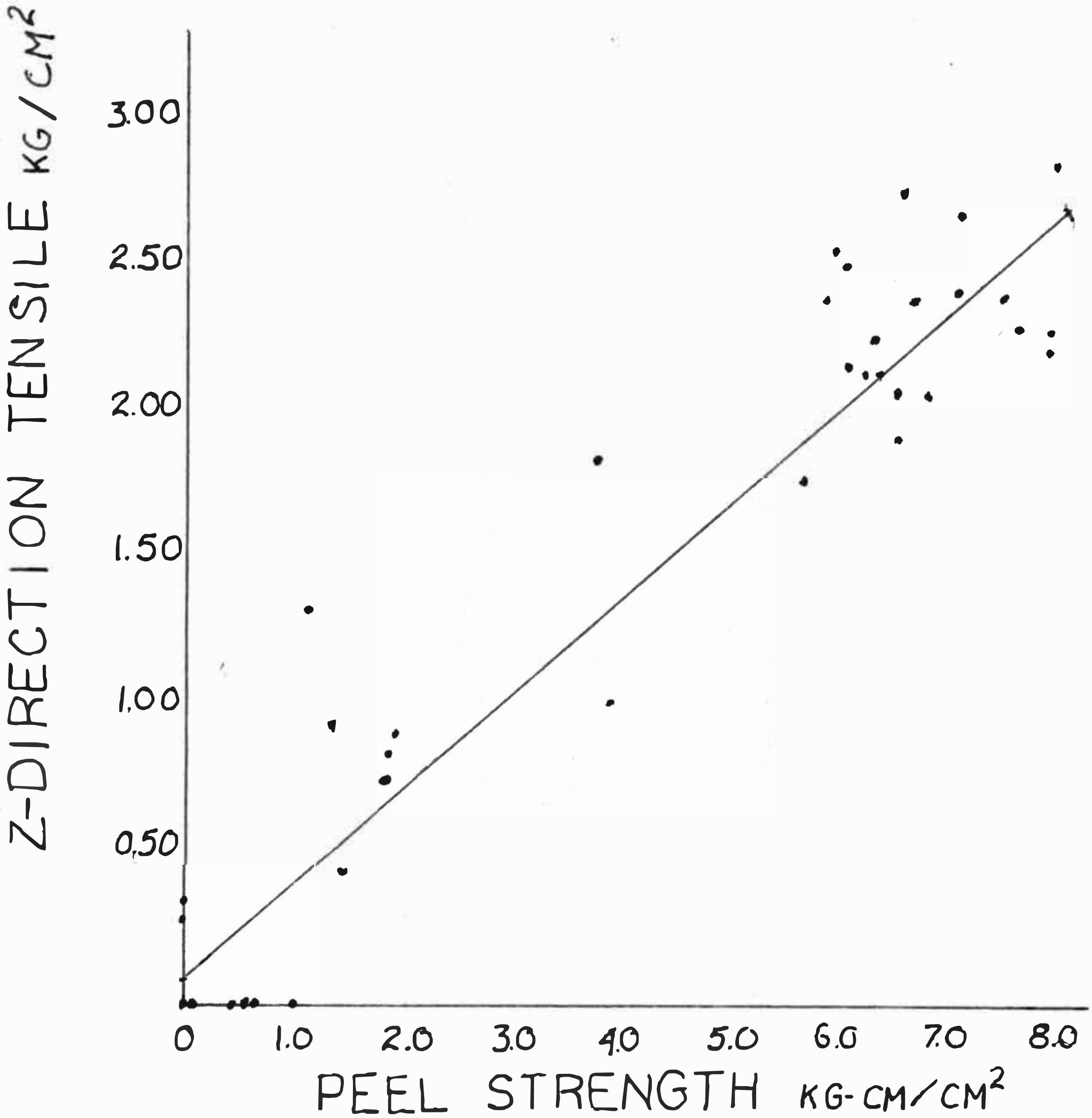


FIGURE 9 Z-DIRECTION TENSILE VS. PEEL STRENGTH
LEAST SQUARES DATA $Y = .129 + .297X$
CORRELATION COEFFICIENT = .916

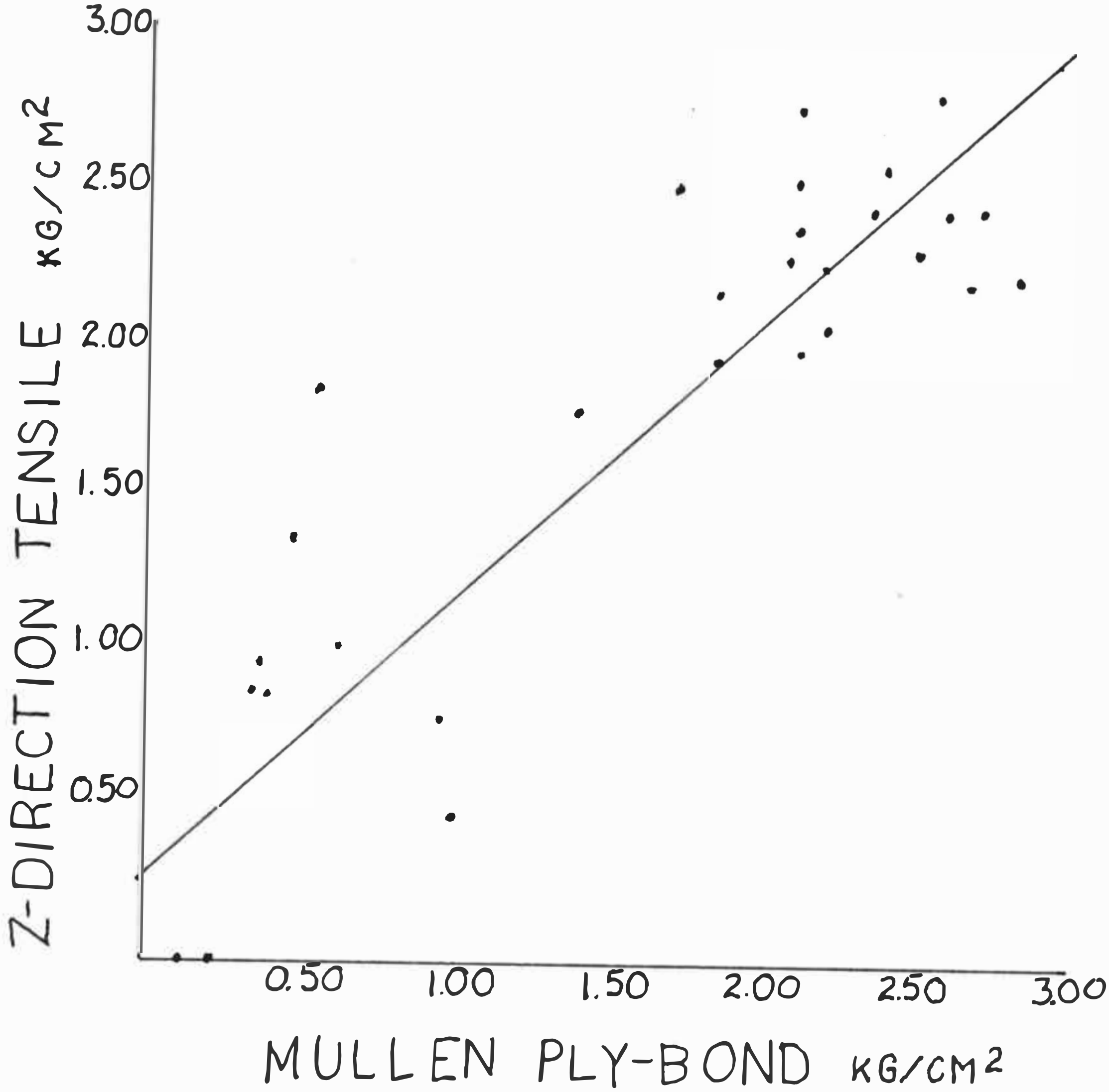


FIGURE 10 Z-DIRECTION TENSILE VS. MULLEN PLY-BOND
LEAST SQUARES DATA $Y = .227 + .878X$

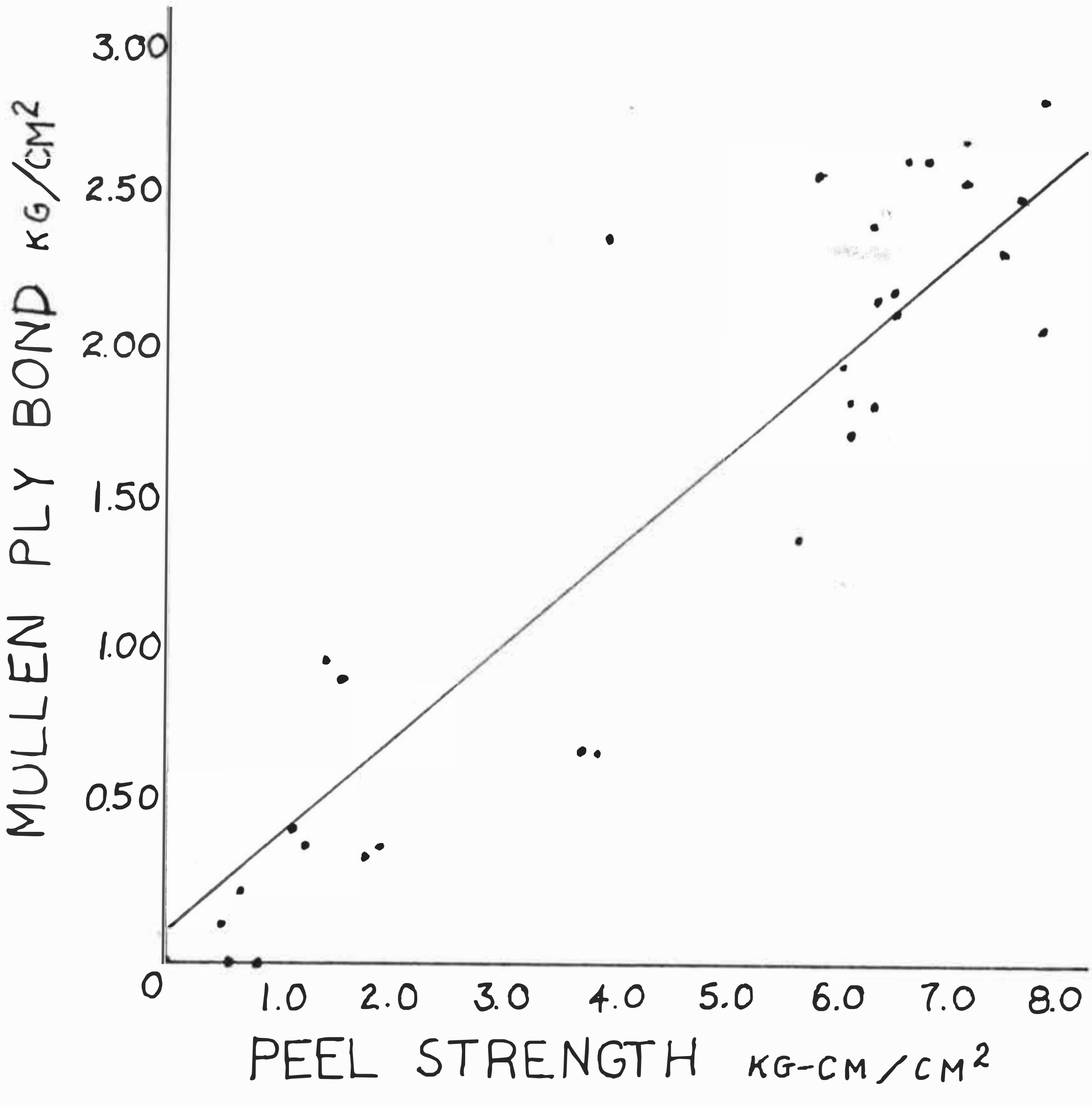


FIGURE 11 MULLEN PLY-BOND VS. PEEL STRENGTH
LEAST SQUARES DATA Y = .130+.317X
CORRELATION COEFFICIENT = .902

CONCLUSIONS

This research showed that moisture content of the webs which form the plies of a multi-ply sheet was a critical factor in the strength of the ply-bond of the sheet. It was shown that a bleached kraft softwood pulp at 400 CSF and formed using the Noble and Wood sheet machine had a critical moisture content for strong ply-bonding. Above 90% moisture at joining, the ply-bond strength was much greater than the ply-bond strength developed at below 85% moisture.

The increase in ply-bond strength with increase in moisture leveled off between 90 and 94% moisture. This was showed to be the result of the fact that the ply-bond strength had reached the internal strength of the individual plies and the ply interface was not necessarily the weakest plane.

The correlation between the three testing methods (Instron peel, z-direction tensile and Mullen ply-bond) was quite good on the average, although the reproducibility of the strength at a given moisture content was poor. The z-direction tensile and Mullen ply-bond correlated best (correlation coefficient was .947) due to the fact that they both evaluated the ply-bond strength by applying a force normal to the surface of the sheet. The correlation coefficient for the Instron peel and Mullen ply-bond was .902 and for the Instron peel and the z-direction tensile it was .916.

Further studies pertaining to the effect of moisture content of the plies of a multi-ply sheet at the time of joining could evaluate the effect of the difference in the moisture content between the two plies. The critical moisture content of ply-bonding should be evaluated using different types of fiber with different degrees and types of mechanical treatments or with different additives.

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