GENERAL

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Appleton, Wisconsin

EFFECT OF RELATIVE HUMIDITY ON THE STACKING PERFORMANCE OF BOXES MADE WITH WATER-RESISTANT ADHESIVE AND WITH REGULAR AND WET-STRENGTH COMPONENTS

Project 2695-16

Report One

A Summary Report

to

TECHNICAL DIVISION
FOURDRINIER KRAFT BOARD INSTITUTE, INC.

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SUMMARY

A previous study sponsored by the Fourdrinier Kraft Board Institute, Inc. (FKBI) showed that the stacking (creep) performance of corrugated boxes made with regular starch adhesive and regular components is more adversely affected by exposure to high RH conditions than would be expected on the basis of box compression performance. It appeared that this result was partly due to adhesion failure under long-term loading at high RH levels when regular (nonwater-resistant) starch adhesive is used. Therefore, this study was initiated to study the effect of RH on the top-load box stacking (creep) performance of boxes made using water-resistant starch adhesive and both regular and wet-strength components.

For this study, two 350-lb series C-flute box samples made in the same size as used in the previous study were evaluated. Both samples were made with water-resistant starch adhesive (5% resin). One sample was made using regular linerboard and medium; the other sample was made using wet-strength linerboard and medium. Box compression and stacking (creep) tests were carried out at the following conditions: (1) 50% RH, 73°F (standard conditions); (2) 85% RH, 73°F; (3) 85% RH, 40°F; and (4) 90% RH, 90°F.

The following results were obtained:

1. The boxes made with water-resistant adhesive and either regular or wet-strength components exhibited significantly better (lower) stacking "safety factors" than boxes made with regular components and starch adhesive at high RH (moisture) conditions. The stacking

safety factor is the ratio of the box compression strength required at standard conditions to the stacking load, for example, for a stacking load of 500 lb and a safety factor of 3, the box compression strength at standard conditions would need to be 1,500 lb; for a safety factor of 4, the required box compression strength would be 2,000 lb. The results below show that for equilibrium moisture contents in the 15-20% range (RH levels from 85 to 90%) the percentage improvements in "safety factors" ranged from 15.5 to 21.8% for a 180-day failure life.

		Stacking "Safety Factor"		
Moisture, %	Equivalent Test Condition (Approx.)	Boxes Made with Water-resistant Adhesive	Boxes Made with Regular Starch Adhesive	Diff., %
15.0	85% RH, 73°F	3.8	4.5	15.5
17.5	85% RH, 40°F	4.8	6.0	20.0
20.0	90% RH, 90°F	6.1	7.8	21.8

Thus the results indicate that the use of water-resistant starch adhesive in fabricating the combined board can effect a significant improvement in box stacking performance under humid storage conditions and possibly permit savings in packaging costs.

2. For the boxes made with water-resistant adhesive, the type of components — regular vs. wet-strength — did not appear to significantly affect stacking performance.

3. At a given load ratio the failure times for both box samples made with water-resistant adhesive significantly increased as the combined board moisture content decreased as expected on the basis of previous work.

INTRODUCTION

The moisture content of the board is one of the major factors affecting the stacking (creep) performance of corrugated boxes. It is well known that a corrugated box loses 50-60% or more of its short-term box compression strength when the RH is increased from 50 to 90% RH. Under long-term stacking conditions, Kellicutt (1), in an early study, indicated that long-term stacking performance decreased with increasing moisture in exactly the same way as short-term box compression strength — i.e., laboratory box compression. However, Stott (2), in more recent work, showed that stacking performance is more adversely affected by exposure to high RH conditions than is short-term box compression strength. This result was confirmed in a past study at the Institute for FKBI and in other work carried out at the Institute on the stacking performance of corrugated boxes containing plastic bottles (3,4). A review of the above and other related literature may be found in Ref. (3).

In the previous study (3) carried out at the Institute for FKBI, the boxes which were evaluated were fabricated with regular (nonwater-resistant) adhesive and regular components. During the stacking (creep) tests, it was observed that there was a tendency for the adhesion to fail at 90% RH, 90°F as exposure time increased. It appeared this would not occur if weather-resistant adhesives and components were employed in the box and, hence, that high moisture contents might have a lesser effect on the stacking behavior of such boxes. Accordingly, this study was initiated for the purpose of evaluating the effect of RH on the top-load box stacking (creep) performance of boxes made using water-resistant adhesive and sized or treated components.

MATERIALS

In the previous study (Project 2695-9), 200- and 350-lb series C-flute boxes made with regular kraft liners, 26-lb semichemical medium and regular starch adhesive were evaluated. The box size was 20-1/2 × 13-1/2 × 12-1/2 inches. In order to permit comparison with the previous study, two 350-lb series C-flute box samples were obtained in the same size as follows:

1. Sample No. 790 — 90-lb regular kraft liners, 26-lb semichemical medium, fully water-resistant starch adhesive (5% resin).
2. Sample No. 791 — 90-lb wet-strength kraft liners, 26-lb wet-strength semichemical medium, fully water-resistant starch adhesive (5% resin).

The wet-strength and regular components were fabricated into C-flute boxes by a local box shop. The regular liners and medium were taken from the local company's inventory, whereas the wet-strength liners and mediums were furnished by an FKBI member company.

The results obtained in this study on the above materials were compared to the results obtained in a previous study on C-flute boxes made with regular components and regular (non-water-resistant) starch adhesive (3).

A comparison of the physical characteristics of the combined boards used in this and the previous study is shown in Table I. It should be noted that the pin adhesion strengths of the combined boards made with water-resistant adhesive were considerably higher under all RH and temperature conditions than the

TABLE I

COMBINED BOARD PROPERTIES

Test	Test Condition RH	Test Condition Temp., °F	Sample No. 790 Reg. Comp., W.R. Adhesive Av.	Sample No. 790 % Loss[b]	Sample No. 791 W.S. Comp., W.R. Adhesive Av.	Sample No. 791 % Loss[b]	Sample C-200[a] Reg. Comp., Reg. Adhesive Av.	Sample C-200[a] % Loss[b]	Sample C-350[a] Reg. Comp., Reg. Adhesive Av.	Sample C-350[a] % Loss[b]
Basis Weight, lb/M ft^2	50	73	230	--	221	--	124	--	215	--
Caliper, pt.	50	73	190	--	187	--	159	--	177	--
Pin Adhesion, lb/4 sq in	50	73	64	--	82	--	50	--	52	--
	85	73	54	-15.6	60	-27.7	30	-40.0	34	-34.6
	85	40	48	-25.0	61	-25.6	--	--	--	--
	90	90	42	-34.4	58	-30.1	27	-46.0	30	-42.3
Moisture, % (o.d.)	50	73	7.3	--	7.2	--	7.5	--	7.0	--
	85	73	14.8	--	14.7	--	13.8	--	14.6	--
	85	40	18.3	--	18.0	--	--	--	--	--
	90	90	20.3	--	19.7	--	21.2	--	20.7	--
Edgewise Compression, lb/in	50	73	80.6	--	82.6	--	43.6	--	75.5	--
	85	73	40.9	-49.3	47.2	-42.9	25.1	-42.4	42.5	-43.7
	85	40	38.9	-51.7	40.0	-51.6	--	--	--	--
	90	90	30.0	-62.8	34.9	-57.7	19.2	-56.0	35.5	-53.0

[a] Taken from Report One, Project 2695-9.

[b] Based on 50% RH, 73°F results as reference.

corresponding results for the combined boards made with regular starch adhesive for the previous study.

TEST ATMOSPHERES

1. 50% RH, 73°F — standard conditions.
2. 85% RH, 73°F.
3. 85% RH, 40°F.
4. 90% RH, 90°F.

CONDITIONING

The boxes were preconditioned for at least 24 hours at less than 35% RH and 73°F. For tests at 50% RH, the boxes and combined board were conditioned at least 48 hours prior to test. For the tests in the other atmospheres, the boxes and combined board were conditioned at least 120 hours prior to test.

TEST PROCEDURES

Box Compression Tests

For each sample, ten boxes were evaluated for top-load compression strength after conditioning in the prescribed atmosphere. In the case of the tests on boxes conditioned at 85% RH, 40°F and 90% RH, 90°F, the boxes were inserted in polyethylene bags after conditioning, placed in an insulated enclosure, transported to the box compression tester and tested as quickly as possible after removing the plastic encased box from the insulated enclosure.

Box Stacking (Creep) Tests

In general, four boxes per sample were tested at each of four load levels in each atmosphere using the equipment described in Ref. (5). The load levels were selected in so far as possible to give failure times no longer than 60-90 days.

DISCUSSION OF RESULTS

BOX COMPRESSION RESULTS

The box compression and moisture content results for the box samples made for this study with water-resistant starch adhesive and regular (Sample No. 790) and wet-strength (Sample No. 791) components are shown in Table II. For comparison purposes, results are shown for the two box samples evaluated in the previous study (Project 2695-9) which were made with regular components and nonwater-resistant starch adhesive.

At 85% RH and 73°F, decreases in box compression strength of 41.1 and 39.7% were obtained for Samples 790 and 791, respectively, which were made with water-resistant adhesive. Thus, the reductions in strength were about the same for these two samples as would be expected even though one was made with regular components and the other with wet-strength components. The reductions in strength for these two samples were also about the same as obtained in the previous study for boxes made with regular components and nonwater-resistant adhesive.

At 85% RH and 40°F, Samples 790 and 791 also exhibited approximately equal reductions in box compression strength of 52.4 and 50.1%, respectively. These reductions in strength were greater than at 85% RH and 73°F because of the higher moisture content values obtained in the 85% RH and 40°F atmosphere. In general, the lower the temperature at constant RH, the higher the equilibrium moisture content. It may be noted that the humidity control tolerances could not be maintained as close at 40°F as in the other atmospheres for which a ±2% RH tolerance was employed and may have produced a slightly greater difference in equilibrium moisture content between the 40 and 73°F, 85% RH atmospheres than might be expected on the basis of the temperature alone.

TABLE II

TOP-LOAD COMPRESSION AND MOISTURE CONTENT RESULTS

Sample Code	Liner	Medium	Adhesive[a]	50% RH, 73°F	85% RH, 73°F	Diff., %[a]	85% RH, 40°F	Diff., %[a]	90% RH, 90°F	Diff., %[b]
			Maximum Box Compression Strength, lb							
790	90-lb Reg. Kraft	26-lb Reg. S.C.	W.R.	1412	831	-41.1	672	-52.4	577	-59.1
791	90-lb W.S. Kraft	26-lb W.S. S.C.	W.R.	1782	1074	-39.7	889	-50.1	764	-57.1
C-200[c]	42-lb Reg. Kraft	26-lb Reg. S.C.	Reg.	864	566	-34.5	--	--	289	-66.6
C-350[c]	90-lb Reg. Kraft	26-lb Reg. S.C.	Reg.	1342	824	-38.6	--	--	593	-55.8
			Deflection at Maximum Load, in							
790	90-lb Reg. Kraft	26-lb Reg. S.C.	W.R.	0.58	0.50	-13.8	0.62	+ 6.9	0.53	- 8.6
791	90-lb W.S. Kraft	26-lb W.S. S.C.	W.R.	0.57	0.55	- 3.5	0.58	+ 1.8	0.52	- 8.8
C-200	42-lb Reg. Kraft	26-lb Reg. S.C.	Reg.	0.55	0.51	- 7.3	--	--	0.44	-20.0
C-350	90-lb Reg. Kraft	26-lb Reg. S.C.	Reg.	0.56	0.55	- 1.8	--	--	0.54	- 3.6
			Moisture Content, % (o.d. basis)							
790	90-lb Reg. Kraft	26-lb Reg. S.C.	W.R.	7.3	14.8	--	18.3	--	20.3	--
791	90-lb W.S. Kraft	26-lb W.S. S.C.	W.R.	7.2	14.7	--	18.0	--	19.7	--
C-200[c]	42-lb Reg. Kraft	26-lb Reg. S.C.	Reg.	7.5	13.8	--	--	--	21.2	--
C-350[c]	90-lb Reg. Kraft	26-lb Reg. S.C.	Reg.	7.0	14.6	--	--	--	20.7	--

[a] W.R. denotes water resistant starch adhesive (5% resin content); Reg. denotes regular starch adhesive.

[b] Based on results at standard conditions.

[c] Results taken from previous study (Project 2695-9, Report One, Nov. 10, 1972).

At 90% RH and 90°F, decreases in box compression strength of 59.1 and 57.1% were obtained for Samples 790 and 791 — i.e., approximately the same percentage reduction. These percentage losses in strength were of about the same magnitude as exhibited by the box samples evaluated in the previous study.

It may be noted that the boxes made with the wet-strength components and water-resistant adhesive (Sample No. 791) exhibited higher box compression loads in all test atmospheres than the boxes made with regular components and water-resistant adhesive (Sample No. 790). However, it should be kept in mind that the components in the two samples were made by different mills, hence, the differences in compression are not necessarily due to the wet-strength treatment of the components.

BOX STACKING (CREEP) RESULTS

The average box stacking results are summarized in Table III and graphs of load ratio _vs_. failure time are shown in Fig. 1 and 2 for Samples 790 and 791, respectively. The load ratio is defined as the ratio of the applied load to the box compression strength in the test atmosphere. It may be noted that, at a given load ratio, the failure times markedly increase as the RH in the test atmosphere and, hence, board moisture content decreases. An analysis of covariance indicated that the differences in position of the regression lines due to test atmosphere were highly significant (beyond the 0.01 level) for both samples. Thus, these results confirm the trends observed in the previous study (_3_) and the work of Stott (_2_).

As discussed in Ref. (_3_) the change in "level" of the regression lines in Fig. 1 and 2 are primarily due to the changes in equilibrium moisture content of the board — i.e., apparently creep rates increase as moisture content increases.

TABLE III

AVERAGE BOX STACKING RESULTS

Load Ratio[a]	Sample 790 Regular Comp. Water Res. Adh.		Sample 791 Wet Str. Comp. Water Res. Adh.	
	P_a, lb	t, day	P_a, lb	t, day
	50% RH, 73°F			
0.74	1045	0.50	--	--
0.70	988	5.0	1247	0.52
0.66	932	16.7	1176	1.5
0.62	875	148.2	1105	10.6
0.58	--	--	1034	28.4
	85% RH, 73°F			
0.66	548	0.07	699	0.14
0.58	482	1.9	623	2.7
0.54	449	7.2	580	9.0
0.50	416	21.0	537	34.3
0.46	382	68.0	--	--
	85% RH, 40°F			
0.62	417	0.24	551	0.68
0.58	--	--	516	4.3
0.54	363	3.6	480	5.2
0.50	336	11.6	444	22.0
0.42	282	88.7	373	126.1
	90% RH, 90°F			
0.58	--	--	443	0.45
0.54	312	2.7	413	2.5
0.50	288	4.9	382	5.6
0.42	242	44.5	321	45.3

[a]Ratio of applied load to box compression strength in the test atmosphere.

Note: P_a is the applied load and t is the failure time.

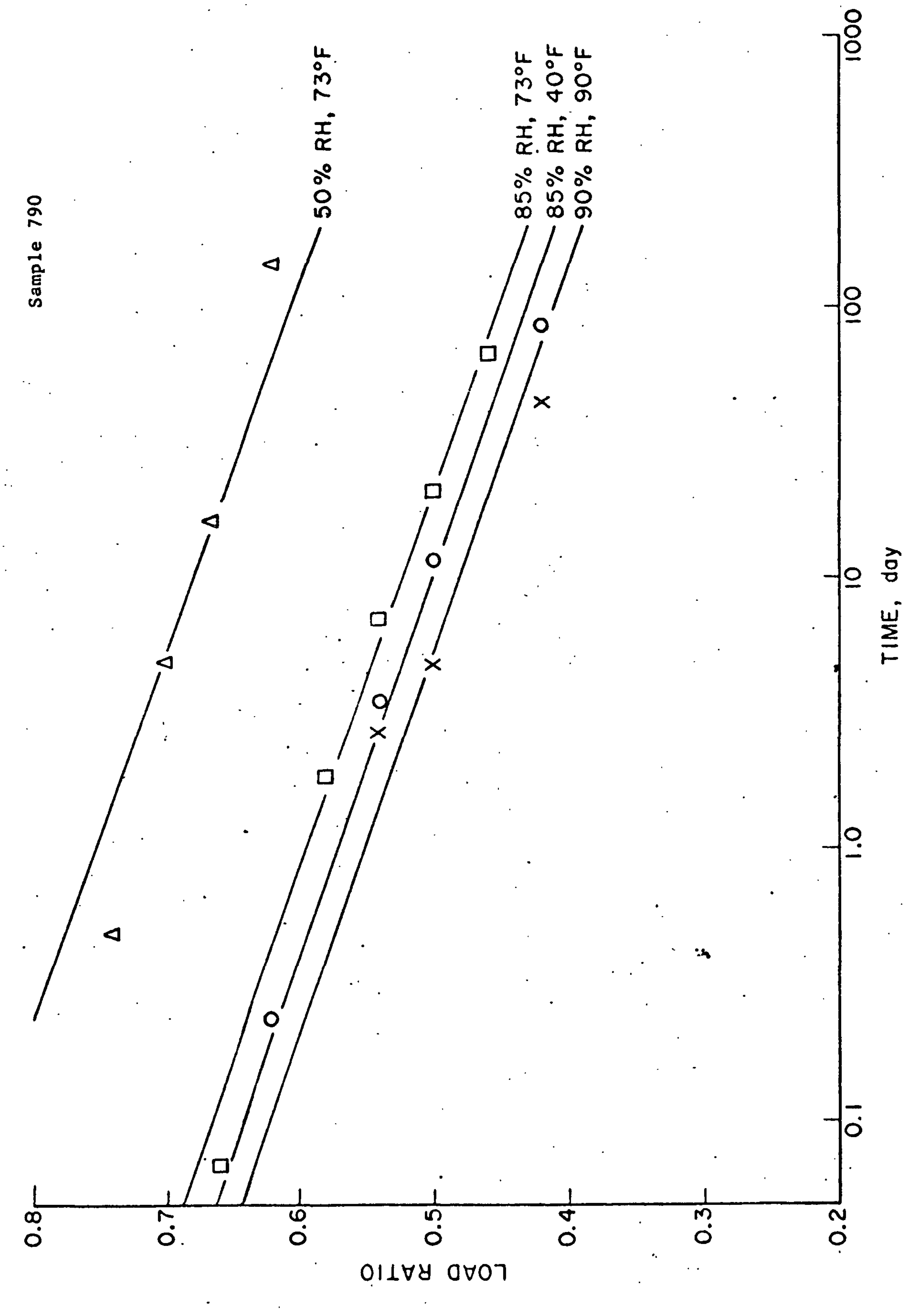

Figure 1. Relationship Between Load Ratio and Failure Time at Different Conditions for Boxes Made with Regular Components and Water-Resistant Starch Adhesive (Sample No. 790)

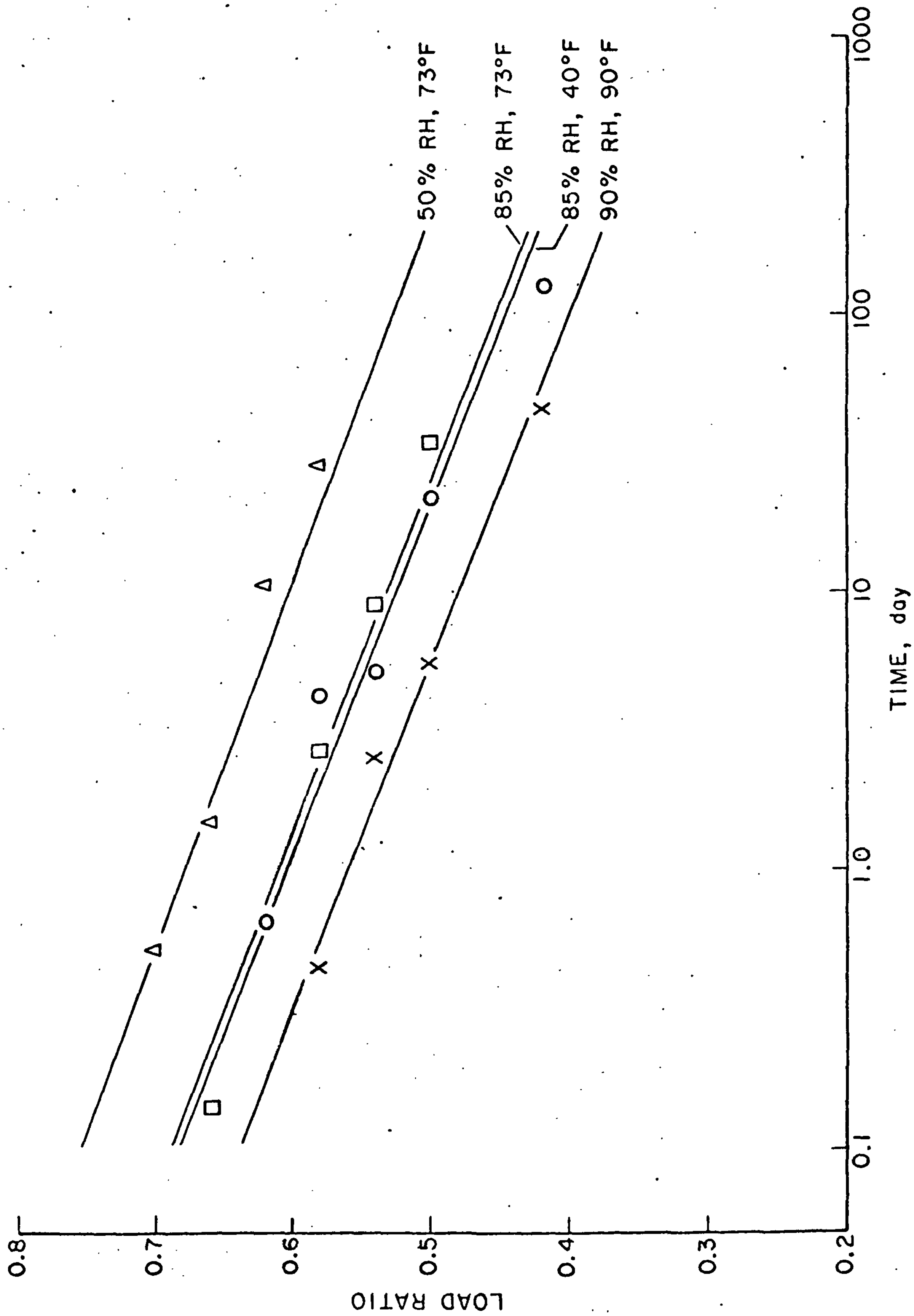

Figure 2. Relationship Between Load Ratio and Failure Time at Different Conditions for Boxes Made with Wet-Strength Components and Water-Resistant Starch Adhesive (Sample No. 791)

Thus the lower position of the 85% RH, 73°F lines relative to standard conditions occurs because of the increase in moisture content from about 7-7.5% at 50% RH to about 14-15% at 85% RH and 73°F. Slightly lower creep performances were obtained at 85% RH and 40°F as compared to 85% RH and 73°F — apparently because of the change in moisture content from about 15 to 18%. The decrease in temperature from 73° to 40°F might be expected to have a reverse effect on the creep curves but it appears that the changes due to temperature are overshadowed in this case by the increase in moisture. It appears that a similar explanation holds for the 90% RH, 90°F results.

The regression constants for the regression lines in Fig. 1 and 2 are tabulated in Table IV. Because of the variability in the test results and the limited number of tests in each atmosphere, parallel lines were fitted to the data in an effort to obtain more reliable estimates of the load ratios required to cause failure in 90, 180 and 360 days. These predicted load ratios are shown in Table III. In general, the predicted load ratios for a given failure time and moisture condition were about the same for the two samples. Thus, the difference in components between the two samples did not appear to have a significant effect on creep performance.

The load ratios in Table III which resulted in box failure in 180 and 360 days are graphed in Fig. 3 as a function of combined board moisture content. Also shown are the corresponding data for the boxes evaluated in the previous study which were made with regular components and regular (nonwater-resistant) adhesive. It may be noted that at a given moisture content, higher load ratios to cause failure in 180 or 360 days were generally obtained with the boxes of this study which were made with water-resistant adhesive. The differences in

TABLE IV

REGRESSION CONSTANTS FOR RELATIONSHIPS BETWEEN LOAD RATIO AND FAILURE TIME

Sample Code	Liner	Medium	Adhesive	Test Condition		Moisture, %	Regression Constants[a]		Predicted Load Ratio		
				RH	Temp., °F		Slope	Intercept, Log a	90 day	180 day	360 day
790	90-lb Reg. Kraft	26-lb Reg. S.C.	W.R.	50	73	7.3	-14.27	10.6510	0.609	0.588	0.567
				85	73	14.8	-14.27	8.4467	0.455	0.434	0.413
				85	40	18.3	-14.27	8.1572	0.435	0.414	0.393
				90	90	20.3	-14.27	7.8677	0.414	0.393	0.372
791	90-lb W.S. Kraft	26-lb W.S. S.C.	W.R.	50	73	7.2	-12.66	8.6951	0.532	0.509	0.485
				85	73	14.7	-12.66	7.7330	0.456	0.433	0.409
				85	40	18.0	-12.66	7.6602	0.451	0.427	0.403
				90	90	19.7	-12.66	7.0705	0.404	0.380	0.357

[a] Differences in regression lines due to test conditions were significant at the 1% level.

Note: Regression equation form Log t = Log a + b R where t is the failure time in days, R is the load ratio and a, b are constants.

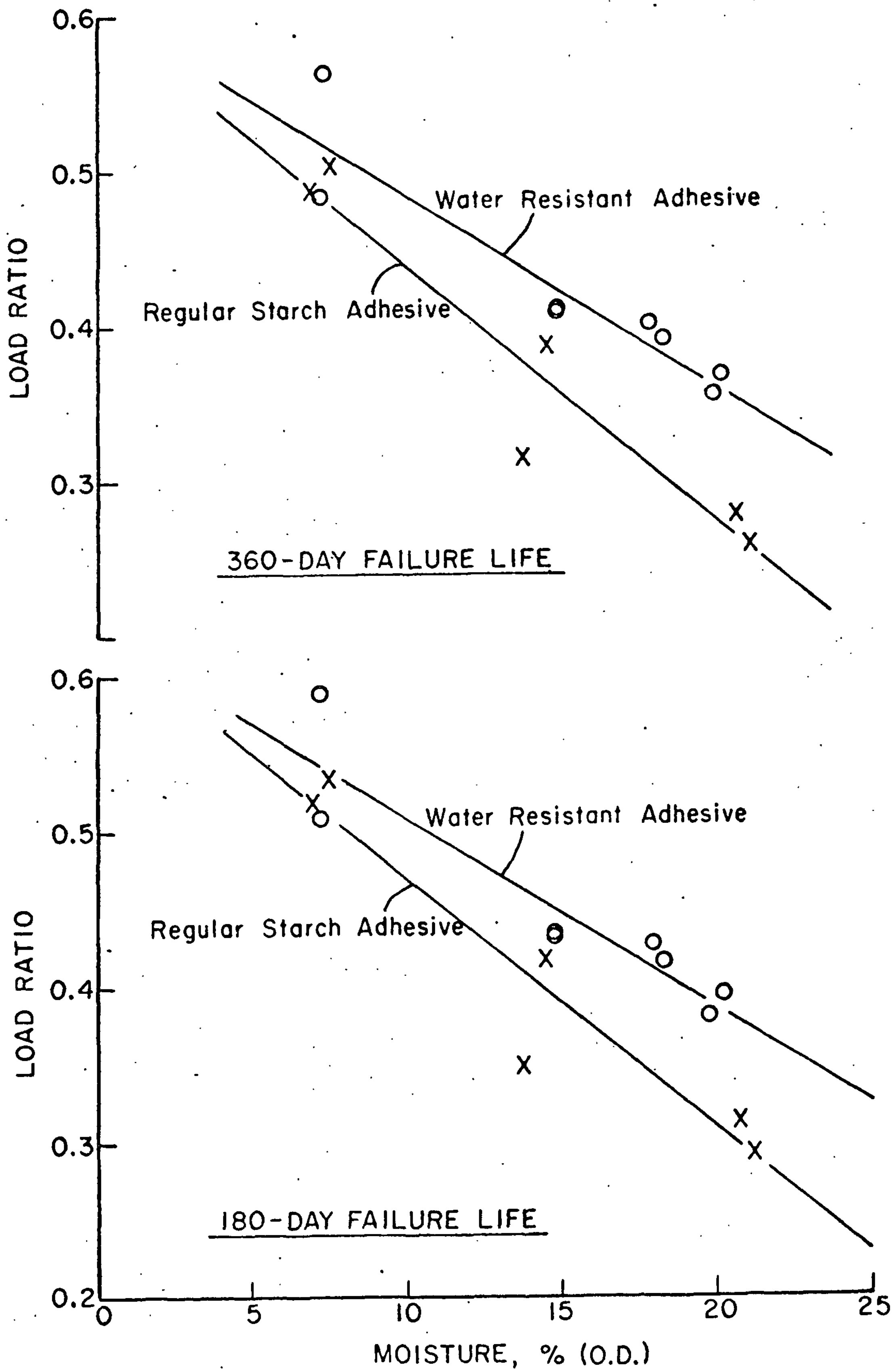

Figure 3. Relationship Between Combined Board Moisture Content and the Load Ratios Causing Failure in 180 and 360 Days

load ratio due to type of adhesive were not very large at standard conditions but appeared to become progressively greater at high moisture (high RH) levels. An analysis of covariance showed that the differences between the regression lines were statistically significant at the 0.01 level. Thus, it appears that boxes made with water-resistant starch adhesive should give better stacking performance in high RH storage atmospheres.

The regression lines are shown below where M is the o.d. moisture content and R is the load ratio for the indicated storage time.

180-Day Storage Life

Water-resistant adhesive: $R = 0.63 - 0.01226\ M$ (1)

Nonwater-resistant adhesive: $R = 0.63 - 0.01632\ M$ (2)

360-Day Storage Life

Water-resistant adhesive: $R = 0.61 - 0.01222\ M$ (3)

Nonwater-resistant adhesive: $R = 0.61 - 0.01636\ M$ (4)

Values of the load ratio for 180 and 360-day storage life were calculated using the above regression equations as shown in Table V. As may be noted for a 180-day life at a moisture content of 20% which approximately corresponds to a 90% RH atmosphere, the load ratio increased from 0.30 for boxes made with regular starch and components to 0.38 for the boxes with water-resistant adhesive — i.e., an improvement of about 27%. At a moisture content of 15%, which approximately corresponds to an 85% RH, 73°F atmosphere, the percentage improvement was about 15%.

In the industry it is common practice to employ stacking "safety factors" in the selection and design of boxes for the trade. The term "safety factor" refers to the ratio of the box compression strength at standard conditions to the maximum stacking load which will be applied to the box in service. For example, for a box strength of 2,000 lb and an expected load of 500 lb, the stacking safety factor would be 4. Various rules of thumb are used in selecting safety factors depending on storage conditions, time, palletizing arrangements, transportation conditions, etc. Thus, depending on experience and the particular requirements in a specific packaging application, it is not uncommon to employ "safety factors" in the range of 3 to 5 or perhaps more.

TABLE V

CALCULATED LOAD RATIOS FOR BOXES MADE WITH NONWATER-RESISTANT AND WATER-RESISTANT STARCH ADHESIVES

	Load Ratio			
	180-Day Life		360-Day Life	
Moisture, % (o.d.)	Water-Res. Adhesive	Nonwater-Res. Adhesive	Water-Res. Adhesive	Nonwater-Res. Adhesive
7.5	0.54	0.51	0.52	0.49
10.0	0.51	0.47	0.49	0.45
12.5	0.48	0.43	0.46	0.41
15.0	0.45	0.39	0.43	0.36
17.5	0.42	0.34	0.40	0.32
20.0	0.38	0.30	0.36	0.28

With the above in mind, the results of this study were converted to stacking "safety factors" for the 180 and 360-day storage periods. The resulting safety factors are plotted vs. moisture content in Fig. 4 and 5 for the 180 and 360-day storage periods, respectively. Table VI shows values of the "safety factor" read from the curves in the figures. In general, the results indicate that lower safety factors may be employed for boxes made with water-resistant adhesive as compared to boxes made with regular starch adhesive. The differences are rather small and probably not of practical significance at moisture contents below 10%.

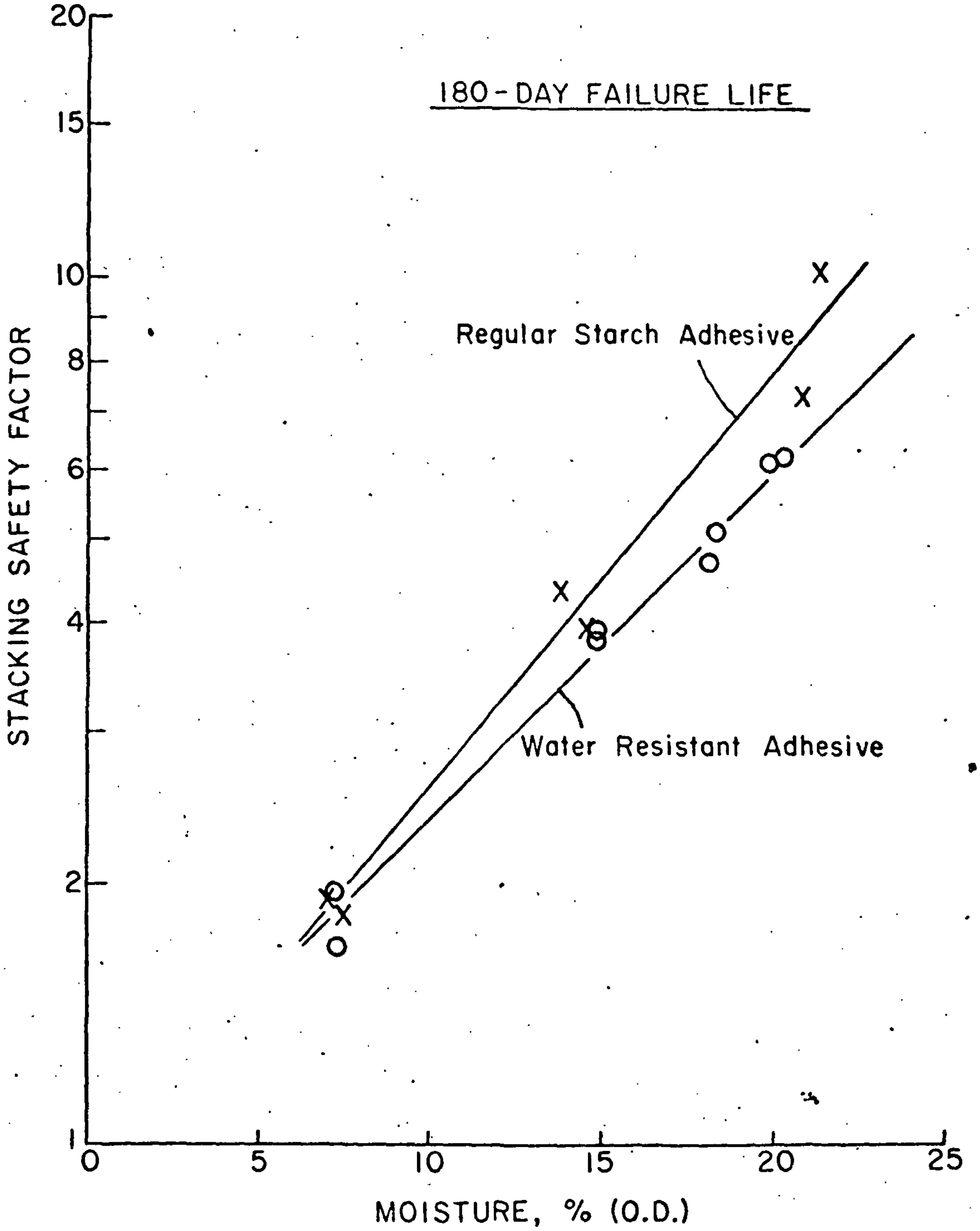

Figure 4. Effect of Combined Board Moisture Content on Stacking "Safety Factors" for 180-Day Failure Life for Boxes Made with Regular and Water-Resistant Starch Adhesive

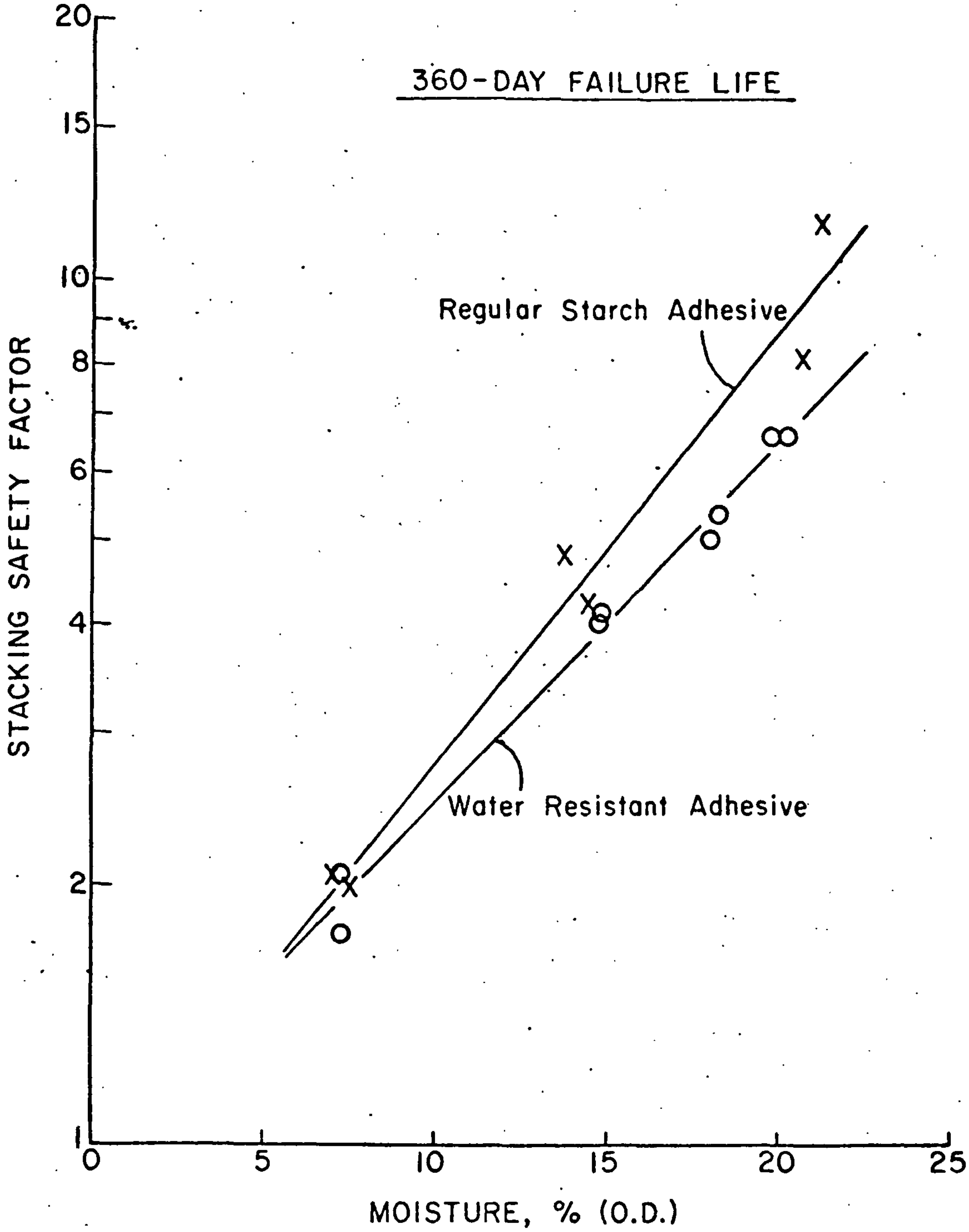

Figure 5. Effect of Combined Board Moisture Content on Stacking "Safety Factors" for 360-Day Failure Life for Boxes Made with Regular and Water-Resistant Starch Adhesive

TABLE VI

EFFECT OF MOISTURE CONTENT ON STACKING "SAFETY FACTORS"

Moisture Content, % (o.d.)	Stacking Safety Factor: 180-Day Failure Life — Boxes Made with Water-Resistant Adhesive	180-Day Failure Life — Boxes Made with Regular Adhesive	180-Day Failure Life — Diff., %[a]	360-Day Failure Life — Boxes Made with Water-Resistant Adhesive	360-Day Failure Life — Boxes Made with Regular Adhesive	360-Day Failure Life — Diff., %[a]
10.0	2.4	2.6	7.7	2.5	2.8	10.7
12.5	3.0	3.4	11.8	3.2	3.7	13.5
15.0	3.8	4.5	15.5	4.0	4.9	18.4
17.5	4.8	6.0	20.0	5.1	6.5	21.5
20.0	6.1	7.8	21.8	6.4	8.6	25.6

[a] Based on results for boxes made with regular starch adhesive as reference.

However, for moisture contents in the 15 to 20% range the improvements in safety factors vary from 15.5 to 21.8% for 180-day failure life and 18.4 to 25.6% for the 360-day failure life data. Even considering the variability in the data the latter improvements seem great enough to be of practical importance. As an example, assume that a package must be capable of supporting 500 lb for at least 180 days under humid conditions where the moisture content may approach 17.5% — roughly equivalent to 85% RH and 40°F in this study. The required box compression strengths at standard conditions are obtained by multiplying the safety factors shown in Table V by 500 lb as shown below:

1. Boxes made with water-resistant adhesive:

   Box compression strength = 4.8 × 500 lb = 2,400 lb

2. Boxes made with regular starch adhesive:

   Box compression strength = 6.0 × 500 = 3,000 lb

Thus, in this example, the required box strength is 600 lb (20%) lower if water-resistant adhesive is employed rather than regular starch adhesive. Therefore, it appears that the use of water-resistant adhesive in fabricating the combined board can improve stacking performance under humid conditions and potentially result in savings in packaging costs.

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