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Western Michigan University

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THE EFFECTS OF FIBER FURNISH ON PHYSICAL PROPERTIES OF PAPER

by

Dennis Havard

A Thesis submitted to the

Faculty of the Department of Paper Technology

in partial fulfillment

of the

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Abstract

This experiment was designed to determine the effects of fiber furnish on the physical properties of paper. To do this various pulps and combinations of these pulps were formed into handsheets and their physical properties determined. The tests performed on the handsheets were tear, fold, tensile, stretch and tensile energy absorption.

The findings of this report indicates possibilities of a linear relationship between percent of pulp in a sheet and the fold and tensile. Stretch values increase by various degrees as more of the higher stretch fiber is added. The TEA follows the stretch values very closely.

Historical Background

The use to which a paper product will be subjected can often determine what manner of characteristics the papermaker should incorporate into his paper. Tensile testing of paper under one load rate cannot always supply the buyer with all the physical information he needs to know. If he is to print the paper on a rotary press, he must know how fast the fibers will respond to the sudden stress of being fed into the press. If he makes wallpaper, where stress occurs very slowly, it is the overall stretch he is interested in. If he is working with paper rolls, flexibility and recovery after long periods of strain is desired, especially on rolls of small diameter. When making food cartons or maps, it is desired to be able to make quick and permanent creases. For this elastic recovery is not desired. In addition to these characteristics, moisture can affect them all. Although much work has already been done in these areas, more work needs to be done to understand the stress-strain properties of paper and what affects them.

Determination of Physical Properties

Three characteristis of fiber networks can be used to

best understand the physical properties of paper. They are tensile strength, stretch, and tensile energy absorption.

Tensile strength is indicative of the serviceability of many papers, such as bags, gummed tapes, and cable wrapping, which are subject to direct tensile stress. Also, the tensile strength of printing papers is thought to be an indication of the potential resistance to breaking during converting operations and during travel through equipment as a web.(1)

Stretch is an indication of the ability of the paper to conform to a desired contour and therefore is important for creped paper, towels, napkins, decorative papers, industrially used paper tape and bags, especially those used for lining cans, barrels, and cartons.(1)

Tensile energy absorption (TEA) is reflective on the durability of paper which will be subjected to repetitive straining or impact.(1) When a sheet does not return to its original length after stretching, the degree of irreversible extensibility is called permanent set. Permanent set is one of the most unique characteristic features of paper and occurs even at very low stress levels. However, this permanent set has been found to be more apparent than real. After a sufficient amount of time all extensibility of paper has been found to be recoverable. Nevertheless, the portion referred to as permanent set requires a great deal more time than the

reversible or elastic extensibility. If water or moisture is added, the stretched paper, once dried, will have recovered all, and in some cases more, of its original dimensions. From this, it would appear that water swelling accelerates permanent set recovery. Practically speaking, permanent set, for a reasonable amount of time, is permanent.(2)

Light scattering can be used to accurately determine the internal bonding characteristics within a sheet without damaging it. Pulps show a decrease in light scattering with increased fiber bonding. Although, the surface area of a pulp in suspension is increased by mechanical action, the new surface will generally be optically inactive in the sheet because of more area used in bonding. The relative bonding area (RBA) is determined from light scattering (S) by the equation $RBA = \frac{S_0 - S}{S_0} \times 100\%$ where S_0 is equal to the scattering coefficient of the unbonded sheet. This is determined by extrapolation of a graph of light scattering vs. modulus of elasticity which is measured in the plane of the sheet.(3) Relative bonding areas are important in that all physical properties depend in some way on the degree of bonding.(4) Many researchers have used this method of studying a sheet before testing the same sheet to eliminate some of the randomness of testing. Light scattering was not used in this experiment due to complications arising from the nature of the test. Large numbers of samples were used to reduce randomness and statistical analysis of the data

reported the degree of its effectiveness.

Variables Affecting Physical Properties

Some research has been done in this area to provide the papermaker with some insight into controlling his product. However, there are many factors affecting the physical properties of paper that are not understood. Some of the properties are the furnish, cooking, bleaching, methods of production, beating, additives, drying, moisture, temperature, and basis weight.

Moisture

Physical tests on paper with a varying moisture via humidity shows that stretchability increases while breaking load decreases. This is illustrated by the tensile which shows a marked increase as relative humidity dropped from 91 to 65%. The mullen stayed about the same, showing its dependence on strength as much as stretchability. The fold showed a dramatic increase indicating its great dependency on relative humidity and moisture content.(2) These three tests, mullen, fold, and tensile, show most easily the physical properties of a sheet under a variety of conditions. For these reasons, the tensile and fold were used in this experiment. Mullen was not used due to the difficulty of separating the results due to stress forces from those due to strain forces.

Examination of paper breaks from a tensile tester shows 15% of the fibers break and 85% are pulled out. Addition of water can result in less bonding and a loss in friction for the bonds which do remain. Knowing this, it is not surprising that water addition to paper causes great loss in strength and also explains how the tensile is dependent on breaking load.(2) Since the tensile does measure breaking load it is almost independent of stretch, lending itself as a test for this one variable.

When unsized paper is exposed to water and becomes wet, its strength can be reduced to less than 10% of the original. Non-crystalline portions of the fibers are noted to swell upon wetting. These dimensional changes in paper are also very important to the stress. While drying, the fibers shrink. Since the fibers vary in size and shape, their shrinkage also varies. This places stress on the fibers, as some are stretched and some compressed. Because of this internal stress, the addition of some water, through vapor, can actually increase the strength of the paper by relaxing some of the internal tensions.(2)

Breaking load vs. logarithm of breaking time results in a straight line relationship when plotted. This illustrates the dependence between fracture load and pre-fracture straining. Breaking strain, at a given humidity, is virtually independent of load and time. A proposed explanation of this is, as the weak spots in the sample stretch, they cumulate until one

gives way completely at which point the fracture occurs. Since the degree of stretch is the only major factor, the load used to achieve this stretch and the time taken, should not greatly affect it.(5) The energy consumed in straining the sheet can be determined from the area of the hysteresis loop of the stress-strain curve.(6)

Previous experiments illustrate the need for great care in the controlling of the humidity in the area of testing and therefore the sheets themselves. Express experimental design did just this to eliminate humidity as a variable from this research.

Effects of Fibers

The stress-strain properties are very dependent on the components of the paper as well as the conditions the sheet has been or is being kept in. Cellulose, the main raw material of paper, is itself a great variable. Its degree of refining, purity and degradation all affect the final properties. With the ever increasing use of additives, even more variables come to play on the fiberous network. It is necessary to understand the basic raw sheet of paper and determine its physical properties, for it is then that one may determine the exact effects of additives on the paper.(2)

The fibers within a sample vary due to the time of year they are formed. A study of springwood and summerwood

showed that refining reduced the breaking load and tensile strength of summerwood fibers but increased the strength of springwood fibers. Tensile strength of unrefined springwood fibers was about half that of summerwood fibers, but refining decreased this difference. The percent elongation at failure was about the same for springwood and summerwood fibers. At the same applied load, elongation of unrefined springwood fibers was about four times that of the unrefined summerwood fibers, however, refining reduced this difference also. The Young's Modulus of unrefined summerwood was about three times that of the springwood fibers. Refining reduced the Young's Modulus of summerwood fibers but increased that of springwood fibers. This suggests a fibrillar reorganization of the wet fiber wall with mechanical treatment.(7)

Effects of Cooks and Bleaching

In a recent study, the breaking load per unit mass increased with decreasing yield for kraft fibers, reflecting a progressive removal of weaker material during pulping. Sulphite type pulping leads to a slight decline in breaking load per unit mass at intermediate (65%) yields, followed by a slight increase at lower yields. This indicates that damage to the fiber walls by sulphite pulping plays a significant role in this type of pulp.(8) The effect of pulping and bleaching on the stress-strain properties of fibers, as several recent studies have shown, is definitely present, but

due to the wide variety of times, temperatures, and concentrations with each type of process, a wide, often overlapping, range of effects usually results.(2) This experiment is basically concerned with the effects of pulping and combinations of pulps on the resulting sheet's physical properties.

Effects of Beating

Beating has a great, varying effect on physical properties of paper. Beating of pulp can be achieved by both cutting and fibrillation to various degrees. By decreasing the clearance in the beater, cutting is favored. Fibrillation results from greater clearance distances. Beating initially increases paper's stress-strain characteristics; however, cutting soon reduces the distance between bonds and therefore reduces stretch. Fibrillation also decreases the distance between bonds but not as much. Though beating helps the final strength of the sheet, too much beating, even at wide clearances, causes a decline in the amount of stretch in a sheet of paper.(9)

In addition to fibrillation and cutting the fibers, beating exposes water accessible portions of the fibers. When a sheet is formed of fibers with high portions of water accessible parts, it would seem, and has been found to be the case, that its physical properties have a great dependency on the moisture content of the sheet. The

dimensional stability of the sheet is greatly decreased as the amount of unordered, water-accessible cellulose is increased.(2)

Increased beating causes increased extensibility but the greatest increase in extensibility for a unit time occurs at about 20 to 30 minutes. The density of a sheet also increases with increased beating but has interesting relations with the stress-strain properties of the sheet. In an experiment with sulphite pulps, the sheet density (d) was found to be related to the modulus of elasticity (E) by the formula $E = k\ (d - d_o)$ where k is a constant and d_o depends on the type of pulp being tested. The greatest post-yield extension of a sheet occurs between .8 and .9 $\frac{g}{cm^3}$. The tearing strength also shows a maximum strength at about .7 $\frac{g}{cm^3}$. However, breaking load constantly increases while the density increases. A proposed theory to explain this, is that beating decreases fiber length and increases fiber bonding. Tearing and post-yield extension result from fiber slippage which is at first helped by fiber bonding. As fibers shorten and bond more, they cannot slip as much and a decrease in strength occurs. The breaking load is almost solely dominated by bonded area which constantly increases with beating and the extent of the bonded area is reflected by the density.(2)

In correlation with beating, the solids concentration at which a sheet is formed also has its effect. At low (1%)

solids, the strength of the paper increases with increased beating. However, at greater concentrations (4-5%), the strength increased much more rapidly. This is explained by the nature of beaten cellulose. It exists as long, hollow, flexible fibers with many small fibers called fibrills. As the solids increase, these fibrills can better intertwine while in solution and result in a stronger sheet.(10)

Effect of Drying

Even the type of drying has an effect on stretch. A recent study of a mill using a flash drying process reported the paper to have a higher stretch. This phenomena is attributed to the fact that the fibers are free to shrink during drying and retain their stretchability.(11) Similar effects are noted when paper is dried with a reduced amount of tension, however, as would be expected, the tensile strength suffered a slight decline.(12,13)

Effect of Basis Weight and Temperature

Load elongation tests show that there is a substantial difference in the percent stretch between a high and low basis weight sample. If the elasticity hypothesis is true, then it can be predicted that when the basis weight is decreasing, stretch of the sheet under constant tension increases. This would have special significance in processes where a web of paper is put under tension as it would cause the paper to elongate.(14) By maintaining a constant basis weight throughout this experiment this variable was eliminated.

Even temperature has an effect on the stress-failure of a sheet. Tensile strain-to-break suffered a 10% drop when the temperature was raised from 15.5° to 48.9°C. This was due to, in part, a difference in moisture content at the higher temperature. When the relative humidity was increased to maintain a constant equilibrium moisture content a drop of 40% was experienced. This shows both the effects of moisture and temperature.(15) Physical properties did not vary due to temperature and moisture in this experiment because they were held constant in the area of testing.

Purpose

The practical aspects of paper properties have been of major concern to the paper making interests for many years. Recent research has shown the complex and omnipresent effects of stretch and strength in almost every characteristic of the fiber network. During manufacturing, testing and usage, paper undergoes many stresses and strains. The ability of the paper to respond properly is of much concern to the user. This reversible and irreversible extension greatly affects the success of the paper in performing its desired function.

A better understanding of the variables that affect the mechanical properties of paper and paperboard and an application of this information to product design could improve the performance of these products. This should allow paper to compete more effectively with other materials in the market place. Those who work with paper and paperboard should be provided with comprehensive data that describes these materials. Data on how variables affect response to an applied stress should be available to enable an engineer to make reliable predictions on expected performance under all usage conditions.(15)

As the literature previously stated illustrates, most variables of paper properties have been inspected to various degrees. However, the actual paper fiber, as supplied to

the papermaker, has not been very well investigated. Therefore, it is the purpose of this study to determine the effects of fiber furnishes on the very important stress-strain relationship within the non-woven fiber network.

This study is designed to analyze specifically the effect of changes in fiber furnish on the stress-strain properties of paper. To accomplish this, several commonly used fibers will be used to make handsheets with no other additives. Handsheets composed of a mixture of the fibers are also to be studied to determine their combined effects.

For reasons previously cited, the tensile, fold and tear will be the primary tests. The Instron will be used to get tensile strength, stretch and TEA. From the information given by these tests, a better understanding of the stress-strain relationships with the fiber furnish should be achieved.

Procedure

Whenever possible, Tappi standards were used in the preparation and testing of the pulps used. The pulps were softwood kraft, hardwood kraft, and softwood sulphite. All were bleached. The "Laboratory Processing of Pulp (Beater Method)" T 200 ts-66 was followed in beating the pulp. A Canadian Standard Freeness of 360 ml was the target. Actual Canadian Standard Freenesses obtained are reported in the data. Identical weights on the beater bedplate were not available. Actual weights used were as close to those called for in the Tappi procedure as possible and are recorded for each run in the data tables.

The pulp was formed into handsheets following the procedure outlined in "Laboratory Handsheets for Physical Tests of Pulp" T 205 m-58. "Conditioning of Paper and Paperboard for Testing" T 402 m-49 was followed prior to any physical tests run on the sheets.

The physical tests were: fold following "Folding Endurance of Paper" T423 m-50, tear following "Internal Tearing Resistance of Paper" T414 ts-65, tensile following "Tensile Breaking Strength of Paper and Paperboard" T 404 ts-66 also measuring the stretch before rupture, and the TEA following "Tensile Energy Absorption of Paper" T 494 su-64. The results of the testing are listed in the data tables on the following pages.

Data

Table I

		HWK	SWK	SWS
1.	Weight on Beater (gm)	5650	5450	5440
2.	Time of Beating (min)	55	105	100
3.	C S Freeness (ml)	360	370	365
4.	Sheet Weight (gm)	1.2048	1.2405	1.2348
5.	Tear (gm-cm)	1373±68	1922±204	1922±274
6.	Fold (MIT double fold)	36±12	880±245	259±114
7.	Tensile (Kg/cm)	8.6±.9	13.6±1.2	9.4±1.3
8.	Stretch (percent)	2.6±.4	3.6±.2	2.9±.5
9.	TEA (gm mm/mm^2)	31654±8031	64094±10079	34803±9921

Table II

HWK SWK	100% 0%	75% 25%	50% 50%	25% 75%	0% 100%
1.	5650	5420	5420	5450	5450
2.	55	55	60	60	105
3.	360	360	350	370	370
4.	1.2048	1.2445	1.2499	1.2459	1.2405
5.	1373±68	995±102	1029±102	1339±160	1922±274
6.	36±12	287±255	357±192	766±246	880±245
7.	8.6±.9	11.7±1.3	11.9±.9	12.5±1.3	13.6±1.2
8.	2.6±.4	3.0±.3	3.0±.3	3.3±.4	3.8±.2
9.	31654±8031	39213±8661	40157±6457	40078±9134	64094±10079

HWK - hardwood kraft
SWK - softwood kraft
SWS - softwood sulfite

Table III

SWS SWK	100% 0%	75% 25%	50% 50%	25% 75%	0% 100%
1.	5440	5450	5450	5450	5450
2.	100	55	55	60	105
3.	365	360	360	380	370
4.	1.2348	1.2188	1.2305	1.2153	1.2405
5.	1922±247	2197±136	2471±136	2265±136	1922±204
6.	259±114	444±167	618±201	566±224	880±245
7.	9.4±1.3	11.2±.8	12.0±1.0	10.2±1.0	13.6±1.2
8.	2.9±.5	2.6±.3	3.0±.2	2.6±.4	3.6±.2
9.	34803±9921	32126±5197	39685±4881	30079±7244	64094±10079

Table IV

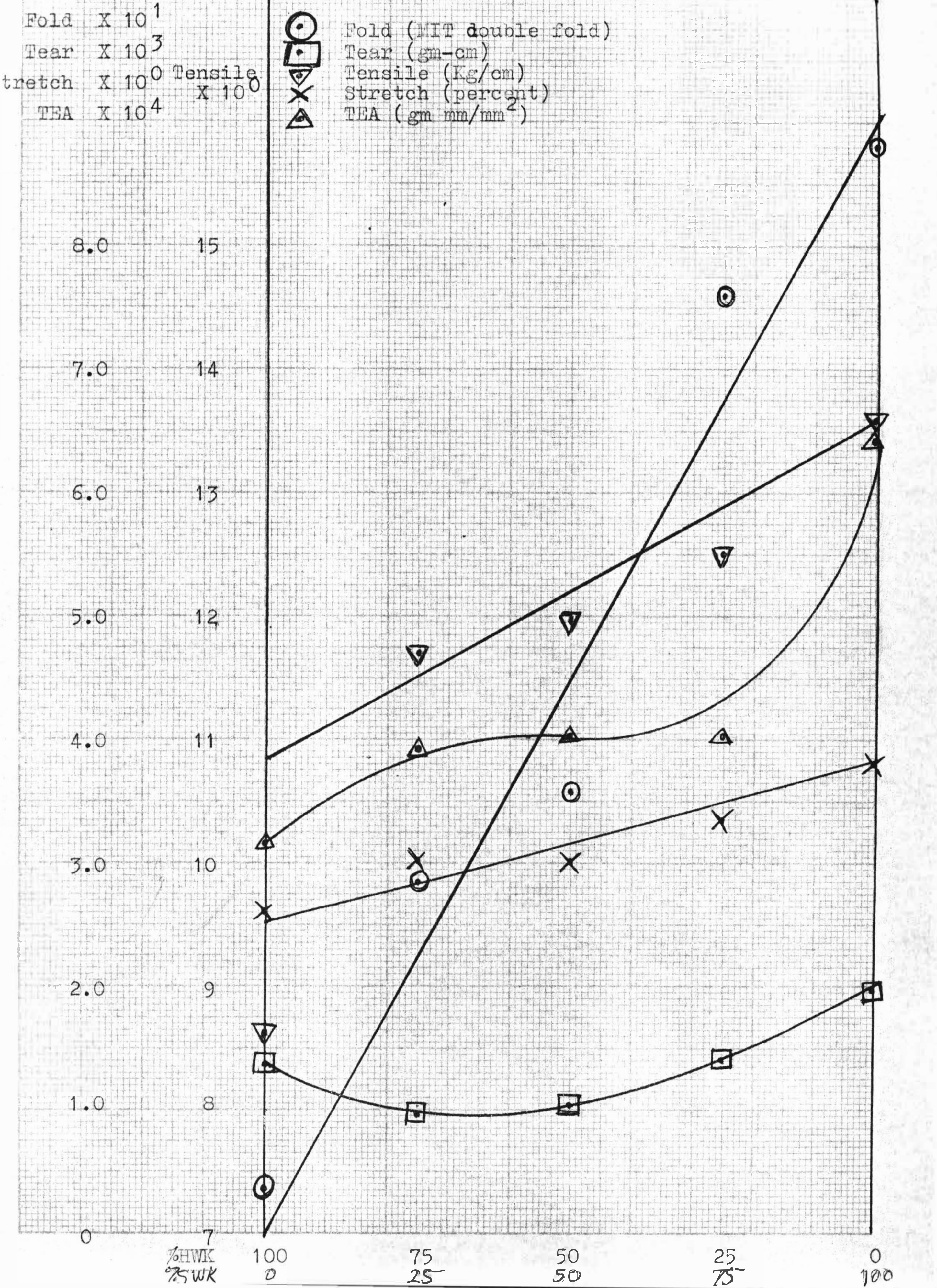
HWK SWS	100% 0%	75% 25%	50% 50%	25% 75%	0% 100%
1.	5650	5450	5450	5450	5440
2.	55	45	45	70	100
3.	360	365	350	360	365
4.	1.2048	1.2299	1.2022	1.2295	1.2348
5.	1373±68	1510±68	1648±68	2883±204	1922±247
6.	36±12	79±24	99±33	839±245	259±114
7.	8.6±.9	9.0±.6	9.1±1.4	13.1±1.2	9.4±1.3
8.	2.6±.4	2.4±.3	2.4±.5	3.4±.3	2.9±.5
9.	31654±8031	23464±4409	24251±9764	49289±9448	34803±9921

HWK - hardwood kraft

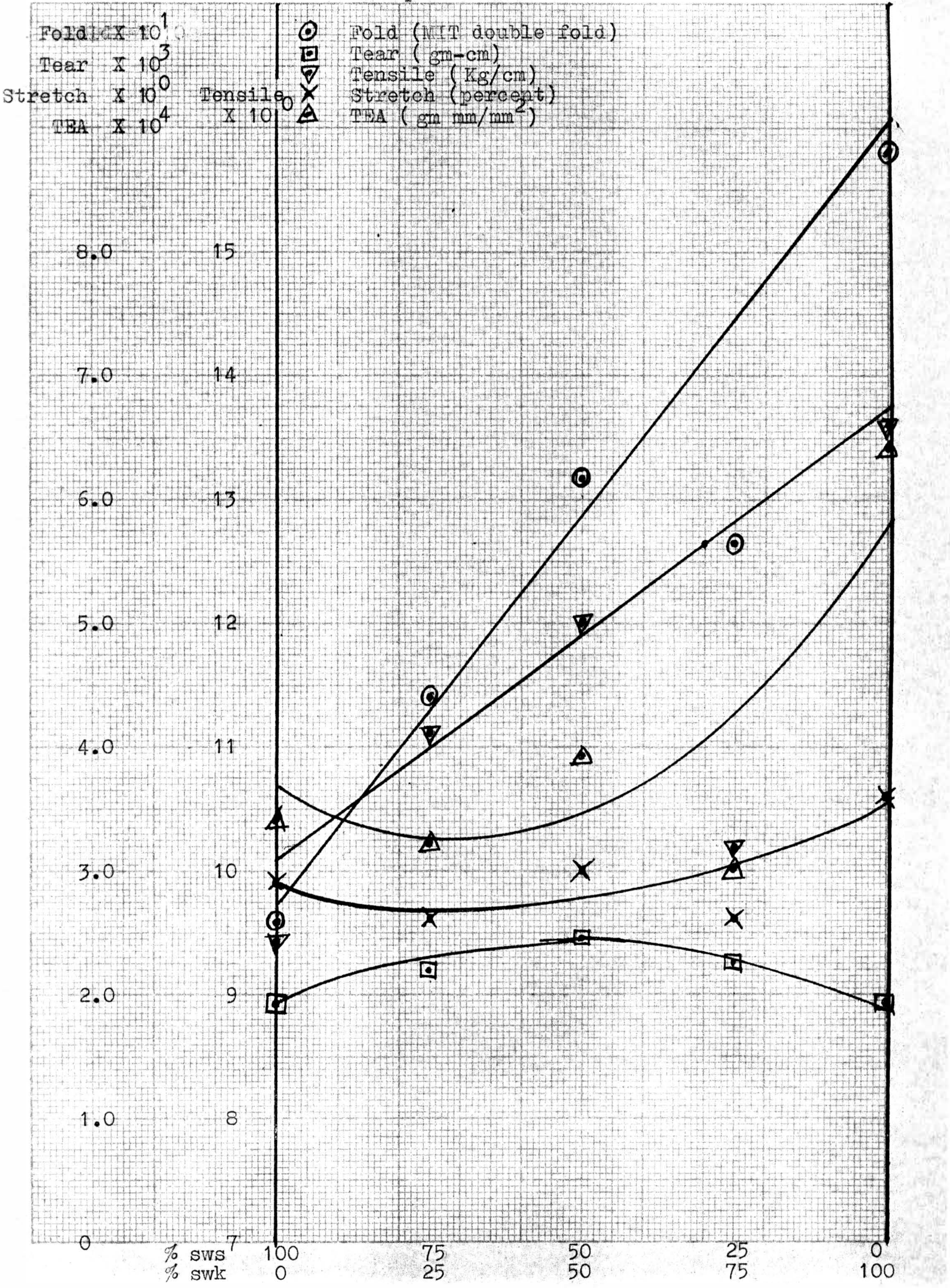
SWK - softwood kraft

SWS - softwood sulfite

Graph I


Fold X 10^1
Tear X 10^3
tretch X 10^0
TEA X 10^4
Tensile X 10^0
Fold (MIT double fold)
Tear (gm-cm)
Tensile (Kg/cm)
Stretch (percent)
TEA (gm mm/mm^2)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
15
14
13
12
11
10
9
8
7
%HWK 100 75 50 25 0
%SWK 0 25 50 75 100

Graph II



Fold X 10^1
Tear X 10^3
Stretch X 10^0
TEA X 10^4
Tensile X 10^0
Fold (MIT double fold)
Tear (gm-cm)
Tensile (Kg/cm)
Stretch (percent)
TEA (gm mm/mm^2)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
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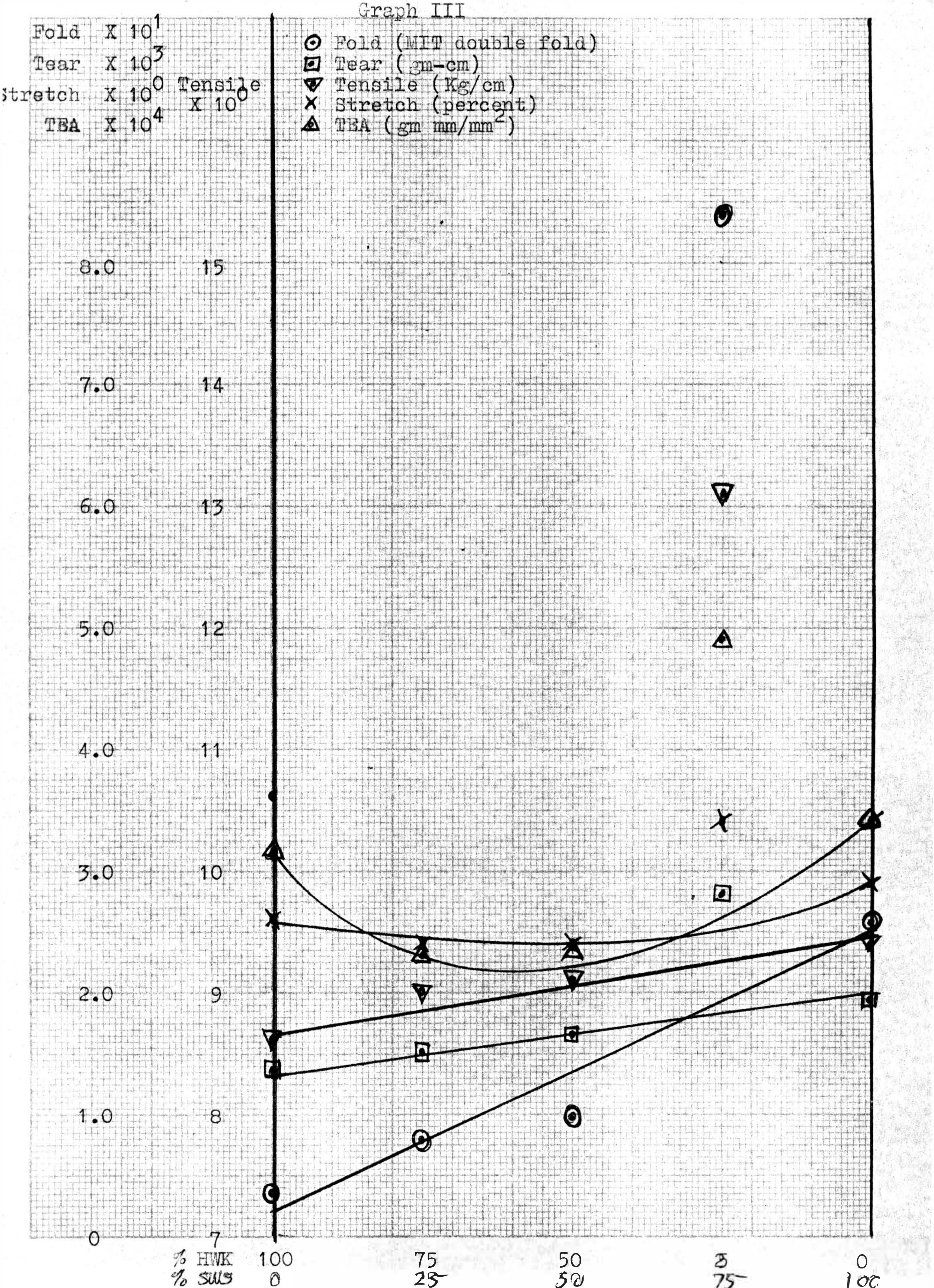
% sws 100 75 50 25 0
% swk 0 25 50 75 100

Graph III



Fold X 10^1
Tear X 10^3
Stretch X 10^0
TBA X 10^4
Tensile X 10^0
Fold (MIT double fold)
Tear (gm-cm)
Tensile (Kg/cm)
Stretch (percent)
TEA (gm mm/mm^2)
8.0 15
7.0 14
6.0 13
5.0 12
4.0 11
3.0 10
2.0 9
1.0 8
0 7
% HWK 100 75 50 25 0
% SWS 0 25 50 75 100

Discussion of Results

In the experimental work, great care was taken to get the freeness and handsheet weights as similar as practically possible. Exact weights and freenesses were impossible but each sample was close enough to give reasonable assurance that data received was due to the fibers themselves rather than variations in the way the pulps were treated. The standard deviations for the tests were reduced by repetition on each sample. The fold is noted to have the largest degree of deviation but this is due to the nature of the test which samples only a small area. Other tests show standard deviations larger than might be desired but time limitations prevented further replications. Trends can still be noted and observations can be made with a fair degree of assurance with the data reported.

In analyzing the data, each physical test is taken separately. Theories and explanations are made relating the tests to varying physical properties the fibers may have possessed. Whenever possible, related work from outside sources is used to reaffirm the data supplied by this study.

Fold

The ability to be folded and wrinkled gives the fiber

its characteristic flexibility which appears to be dependent on the pulp and yield (16). In this study, the yields and the pulps are fixed. The only remaining variables are the fibers themselves. The softwood kraft fibers proved to be more flexible since the fold test is much more dependent on fiber flexibility or enbrittlement, than the strength or number of fiber bonds (17). For this reason, a weighted average of the two pulps used gives the ultimate fold of a sheet. The result is a linear relationship between fold and the composition of a sheet. This is illustrated by the graphs of fold versus sheet composition.

The fold test, as would appear from its linear relationship, is a test of the ability of individual fibers to flex under an applied stress. This is substantiated by recent research which shows softwood fibers to be much more flexible than hardwood partly due to their length. To distinguish between the kraft and sulphite softwood pulps, the sulphite process is known to be more detrimental to the cell wall of the fiber causing it to weaken (18). The physical properties showing the strain for individual fibers should be highest for softwood kraft, followed by softwood sulphite, with hardwood kraft being lowest. This is precisely what the data of this research indicates.

Tear

The tear measures the amount of work necessary to

complete a tear across a given distance. On a local level, the tear is basically a test for the number of fibers pulled from a tear as opposed to being broken. The former results in higher tear values and requires fiber-fiber bonds being broken with fiber slippage occurring. It is the fiber reorientation in the direction of the stress which causes it to be pulled from the sheet. Conversely, a lack of fiber reorientation causes the fibers to break under the stress. Also affecting fiber slippage and breakage is fiber surface. The surface affects bonding and the ultimate strength of the fiber network. Since different cooks and different fibers would result in different extra-cellular matter being removed, the surface of the fibers from different pulps would have a variation in their fibrillar arrangement (16). This theory is substantiated by Hill who has also shown that changes in the mechanical properties of fibers are related to changes in fibrillar organisation (20).

Softwood sulphite and hardwood kraft fibers appear to act similarly with respect to tear. Any increase due to a larger number of bonds with the presence of hardwood fibers must be offset by weaker bonds between the two types of fibers. The linear relationship shown in the data reflects a progressively increasing amount of work needed to tear the sample as the sheet approaches one hundred percent composition of the pulp with the higher tear.

Smaller hardwood fibers fill in the gaps between the softwood fibers in the softwood kraft-hardwood kraft

sheets. The result is a tighter, more dense sheet with a greater degree of bonding. More bonds result in fiber breakage and minimizes fiber pullout. The stress applied in breaking fibers overcomes the strain which the network of fibers is capable of assuming and the tear value drops.

The softwood sulphite-softwood kraft bonds must be fewer in number than when dealing with hardwood fibers due to the nature of the softwood fibers. Softwood fibers are longer and result in a sheet of lower density than sheets with hardwood fibers. Since the fibers are longer, with fewer bonds, they are able to sustain the stress throughout the sheet by distributing the strain. The surface arrangement of the fibers varies due to the cooks. The bond strength must be different when softwood kraft and softwood sulphite are mixed (16). High values of tear are seen from the experimental data as the fibers of each cook approach equal proportions in the sheet. These high tear values would indicate a lower level of bonding between fibers of different cooks allowing for reorientation. This reorientation allows the stress to be distributed, giving way to slippage rather than breaking of fibers. With no new bonds being formed, the condition resulting in the greatest kraft-sulphite fiber contact, versus kraft-kraft or sulphite-sulphite contact, is when each comprises fifty percent of the sheet. At this point, the tear is at its peak.

Tensile

The strength of the fibers, the amount of bonding and the degree of cross linking are the main influences on the stretch and strength of a sheet (20,21). Experimental data obtained througth this study indicates these three variables to be dependent on the amount of each fiber making up the sheet. Thus, the tensile stress strength of a sheet is directly related to the percent of the pulps. The result is a linear dependency between the stress and the weighted averages of the components of the sheet.

Stretch

When a sheet is formed, the fibers are cross linked in randon directions. When a tension is applied to the sheet, the fibers reorientate in the direction of the stress (21). Recent research (19) has shown stretch due to fiber reorientation about the bonds to be much greater than the actual stretch of individual fibers. Similarly, a sheet stretched during drying orients its fibers in the direction of the stress. This results in a lower amount of stretch in the same direction after it is dried (10). Logically, one could expect some fibers to elongate more, such as softwood fibers have been shown to do, but the main influence on a sheet's ability to stretch would be its formation. Since this experiment used controlled methods for handsheet preparation, it would seem reasonable that

only a slight increase in stretch would be noticed. This increased stretch would be due to individual fiber elongation and some advantage in fiber reorientation. Such is the case with all three combinations of pulps.

TEA

The TEA is the area under the stress-strain curve as given by the Instron. It is related to the toughness of the sheet and is dependent on both strength and stretch. The TEA of pulp combinations from different cooks shows lower TEA values than either pulp alone, while the two kraft pulps showed a constant TEA value for all combinations. This pattern was basically set by the stretch values for the pulp since in all cases, the tensile varied very little.

Conclusions

Results of this experiment show the best tear at fifty percent each of softwood sulphite and softwood kraft. However, addition of hardwood kraft to softwood kraft shows a gradual decline in all the softwood kraft's properties. Properties of a hardwood kraft and softwood kraft mixture change very little as long as the ratio of either fiber is no larger than three to one. Stretch and strength of softwood kraft and softwood sulphite differ little from a sheet of all one fiber type to a sheet comprised completely of the other fiber.

In general, trends which may be applicable in other pulp combinations are as follows. A fairly linear relation seems to exist between the percent of a given fiber in a sheet and tensile or fold strength. Stretch values are higher as more of the higher stretch fiber is found in the sheet. The TEA values show characteristics very similar to the stretch, which TEA is known to depend on heavily.

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