8-1974

The Effect of Sheet Moisture on the Anisotropy of Paper Subjected to Various Degrees of Restraint during Drying

Ivan T. Mascarenhas

THE EFFECT OF SHEET MOISTURE ON THE ANISOTROPY OF PAPER SUBJECTED TO VARIOUS DEGREES OF RESTRAINT DURING DRYING

by

Ivan T. Mascarenhas

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment
of the
Degree of Master of Science

Western Michigan University
Kalamazoo, Michigan
August 1974

ACKNOWLEDGEMENTS

I wish to express my tremendous debt to Thomas Rumsey for his patience and assistance in the experimental program of this study. My sincere appreciation is due to my Advisory Committee members, Dr. R. L. Janes, Mr. J. Kline, Mr. J. Fisher, for their valuable advice. I would like to acknowledge the financial aid in the form of a graduate assistantship given by the Department of Paper Science and Engineering which made this study possible. A special debt of gratitude is due to my colleagues, Chinu Dalal, Ramachandran Ambady and George Paulose without whose suggestions and constructive criticism this work would not have been possible. Finally, I am grateful to Charlotte O'Connell for devoting much time and effort in compiling the graphical representation of the results.

Ivan T. Mascarenhas

MASTERS THESIS M-5871

MASCARENHAS, Ivan Thomas
THE EFFECT OF SHEET MOISTURE ON THE ANISOTROPY OF PAPER SUBJECTED TO VARIOUS DEGREES OF RESTRAINT DURING DRYING.

Western Michigan University, M.S., 1974
Chemistry, physical

University Microfilms, A XEROX Company, Ann Arbor, Michigan

KEY WORDS

Stress - The force exerted upon a body that tends to deform its shape.

Strain - The response of a body to an external force exerted upon it.

Degree of wet straining, DWS - The amount the sheet is strained during drying divided by the original length of the sheet after wet pressing, expressed as a percentage.

Relative Humidity, RH - Measure of the degree of saturation based on unit volume of air-water vapor mixture.

Anisotropy - Lack of 'squareness' of a sheet i.e. the machine direction properties of the sheet are different from those of the cross machine direction.

Angle of wet straining or angle of restraint - The angle to that of the direction of wet straining. 0° is designated as the direction of wet straining or strain direction (SD) and 90° as cross strain direction (CD) or perpendicular to the wet straining operation.

TABLE OF CONTENTS

CHAPTER PAGE

FIGURES

PAGE

TABLES

INTRODUCTION

Paper, in the course of its manufacture, is subjected to various stresses and strains imposed by the paper machine. The sheet may be stressed off the couch roll and in the press section. More significant is the stretching of the sheet in the drier section while it is still wet. It has long been recognized that the application of stress to paper before it is fully dried imparts to the sheet considerable directional anisotropy.

The paper maker may increase his control over the properties of his final product by intelligent manipulation of the mechanical history of the sheet during manufacture or by careful conditioning of the paper after its manufacture. It is a well known fact that humidity and temperature exert a pronounced influence on sheet properties. Cellulose is extremely hygroscopic, especially the less well-ordered regions of the fibers and interfiber bonds. Moisture absorption reduces interfiber bonding strength and increases plasticity and flexibility of the fibers.

The increase in plasticity and flexibility of the fibers with increase in moisture content may undo some of the stresses developed in the sheet during its drying and, consequently, decrease the degree of anisotropy in the sheet. The effects of restraint during drying on paper properties have been thoroughly investigated. However, there is need for a better understanding of sheet moisture interaction history with tension induced effects caused by drying.

This investigation was a dual study. First, the effect of wet straining on sheet properties were examined. Second, the influence of sheet moisture, at testing conditions, on the anisotropy induced by wet straining was determined. Consideration was given to strength properties of the sheet at various angles to the application of the stress.

HISTORICAL BACKGROUND OF THE PROBLEM

Influence of Tension During Drying Upon Paper Properties

Changes in tensile breaking stress, ultimate elongation and work-to-rupture of paper have been identified for some time now with stress applied to a sheet during the course of its manufacture. Related to this phenomena are changes in dimensional stability and moisture expansivity of paper.

Cottral and Gartshore (1), Carter (2) and Ivarrson (3) established that tight draws and felts reduce the extensibility of the sheet in the machine direction. Schulz (4) proposed a reduction in the extent of interfiber bonding with increased wet straining by increase in the light scattering power of the handsheets. He also concluded that there was no marked fiber reorientation since no change in the zero-span tensile strength was noted. The increase in tensile breaking stress, ultimate elongation and work-to-rupture of paper was attributed to changes in the distribution of stress in the sheet due to wet straining.

Sapp and Gillespie (5) obtained load-elongation curves for paper dried under various constant loads. It was found that tensile strength in the direction in which tension is applied at first increases, reaches a maximum value of 5% to 10% greater than that of the unstretched sheet, then decreases. They also showed that the bursting strength decreases with increased tension. The bursting strength at the reel was only 64% of the potential bursting strength at the wet end.

Fujiwara (6) concluded that the effect of tension during drying upon mechanical properties of paper depended upon the degree of wet pressing, the degree of beating and the method of beating. He found that the amount of tension in the cross machine direction influenced the effect of tension applied simultaneously in the machine direction during drying, but that the influence was not strong and that the essential nature of the machine direction was not altered.

Robertson and Bailey (7) showed that the mechanical isotropy ratios altered sharply during the drying sequence. The MD:CD ratio for tensile strength rose from 1.36 to 1.66 between the second press and the reel, while the MD:CD ratio for elongation at tensile break fell from 0.79 to 0.36 between the same sections.

In addition to stretching handsheets, Setterholm (8) allowed them to shrink various percentages during drying and found the tensile modulus of elasticity to increase with the degree of restraint during drying and with density. He also showed that tensile strength and strain to failure were dependent upon pulp type, degree of restraint during drying and handsheet density. There are conflicting reports on the effect of drying stress on the ultimate strength of the dry sheet. Sapp and Gillespie (5) found that as the stress was increased the ultimate strength of the dry sheet was increased but that there was an optimum drying stress beyond which the sheet was weakened by additional loading. Ivarrson's (3) work refutes this and no change in strength was produced during drying.

Carter (9) found that high tensions decrease tensile strength but it is suspected a stretch was involved which brought about a

substantial amount of breakage in inter-fiber bonds. This is similar to that obtained in the explanation of the plastic region of the stress-elongation curve on dry paper, according to the theory of Rance (10).

Corte and Schaschek (11) and also Broens (12) found that fewer inter-fiber bonds originate from drier tensions. According to Pritchard (13) the inter-fiber shrinkage is wholly irreversible, in which case the recoverable shrinkage will depend on the ratio of intra-fiber to inter-fiber shrinkage which occured on drying.

Lyne and Gallay (14) related the tensile strength of paper to the shrinkage tensions involved during drying of the wet web. The tensions required to just balance the shrinkage forces and maintain the same length in the web were measured during a drying cycle. The tensile strength developed at stages along the drying cycle from about 25% to 95% dryness was also measured. It was shown that the curve relating developed shrinkage tension to wet web dry contents is of almost exactly the same shape as the curve relating the tensile strength of the web to its dry content. The shrinkage tension during drying must thus be important in determining the wet expansion and elongation of the paper, and also in the ultimate tensile strength.

Robertson and Bailey (15) using tensile strength anisotropy as a measure of fiber orientation, noted that anisotropy developed primarily in the drier section and, hence, concluded that most of the fibers were oriented in the drier section. However, Danielson and Steenberg (16) using tagged fibers found that the combing action of the wire was the chief cause of fiber alignment.

The recent surge in understanding of the response of paper to an applied stress has initiated the proponement of several theories (17-19) which relate the response of the sheet to that of the component fibers. Van den Akker (17) postulates that the fibers in a sheet restrained in one direction during drying are dried under different axial loads which are dependent upon the fibers' angular orientation; the fibers oriented in the direction of straining are subjected to the largest axial tensile stress while those oriented in the y-direction are dried under axial compressive stresses. Rance (20) argues that tension reduces bonding between adjacent transverse fibers. On this view, fibers are forcibly held apart while correspondingly, the fibers lying in the direction of tension are prevented from bending and crimping under the influence of the transverse shrinking fibers.

Effect of Drying Tension on Paper Fibers

Negishi (21, 22) found that drying cotton yarn under tension caused the largest increase in Young's modulus and increased tensile strength and decreased ultimate elongation. X-ray patterns of the fibers showed that drying under tension increased the crystallization and molecular alignment.

Jentzen (23) dried individual fibers under various axial tensile loads and used x-ray techniques to determine the effect of drying under tensile load on the mechanical properties and on the fiber structure. Elongation measurements during drying showed that the fibers underwent a sudden extension at the commencement of drying which was independent of the drying load. This is related to the

reduction in the fiber diameter and to the initial fibril orientation. An increase was observed in Young's modulus, tensile strength, work-to-rupture and crystallite orientation, with a decrease in ultimate elongation. The total crystallinity remained the same. He also observed statistically significant changes in fibrillar orientation in springwood fibers on comparing fibers dried with and without tensions. It seems reasonable to conclude that the main effect of tension drying was to cause the swollen, plastic fiber to undergo slight internal slippage probably between microfibrils in the helical structures of the secondary wall in such a manner that in subsequent straining of the dry fiber, the fibrils would more equally share the load. In other words, the effect of tension during drying of paper, at the level of the sheet structure, is, to a certain extent, presumably found within the individual fiber. Although Jentzen did not have an opportunity to study the effect of axial compression, it is logical to suppose that the negative effects exist. Page and Tydeman (24) theorize that restraint during drying will hold individual fibers in tension and prevent the development of kinks in the free areas of the fibers and of microcreping at the bond sites. However, in the cross tension direction, the fibers are subjected to an axial compression and microcompressions occur at the bond sites and kinks develop in the free segments of the fibers. Hence axial compression induces into the sheet the opposite effects of tension.

Sorption of Water Vapor by Paper

Gallay (25) has classified the water take-up by cellulose into essentially three parts, (a) adsorption or bound water, (b) absorption or imbibed water, and (c) capillary water.

He defined adsorption as the fixation of water molecules on the surface of the solid. It is an exothermic reaction and therefore, decreases with higher temperature. Following adsorption, further take-up of water by cellulose is essentially thermodynamically neutral. This absorption or imbibition involves occlusion or 'solution' of water among the molecular chains.

Figure 1 represents a typical sorption curve for cellulose over the whole range of relative humidities. The relationship shows two inflections, the first concave to the horizontal axis and the second,

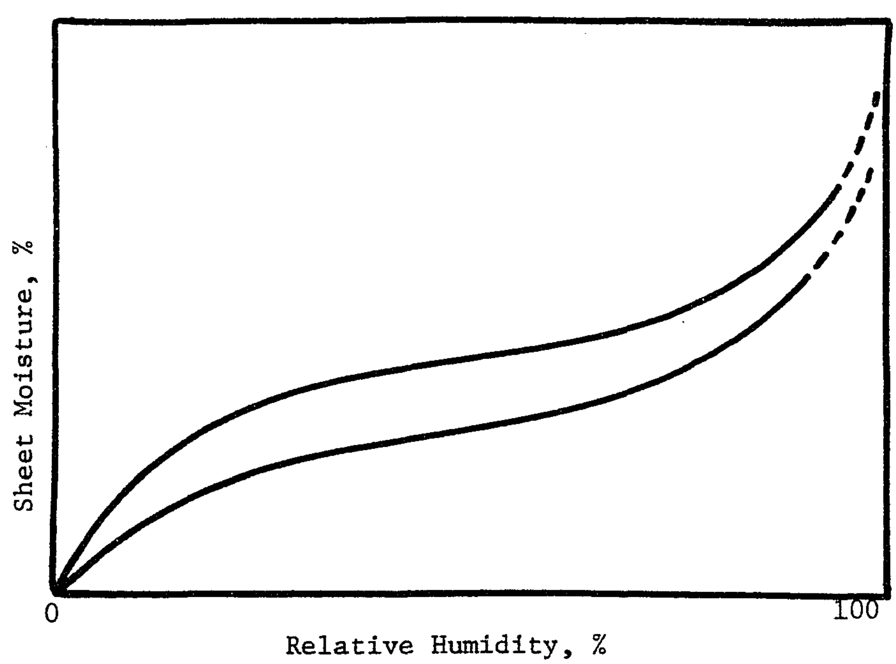


Fig. 1. Sorption curve for cellulose.

convex. The first portion of the sorption isotherm represents adsorption. A relatively straight portion follows which represents imbibition together with adsorption on new surfaces created by swelling. The two processes are regarded as occuring simultaneously following initial adsorption, with imbibition or absorption being the major factor toward the higher relative humidities.

When cellulose fibers take on or give up moisture, an equilibrium is reached with the surrounding atmosphere. The value of this equilibrium moisture content of the fiber depends on two factors, (a) the condition of the fiber resulting from previous chemical or physical treatment and (b) the previous history of the fiber with respect to cycling of sorption and desorption. The second of these depends on the phenomenon of hysteresis.

The hysteresis effect is shown in Fig. 1. The sorption isotherm representing the take-up of water vapor is lower throughout the whole range than the desorption isotherm with decreasing relative humidities. Gallay (25) explains hysteresis by the concept of the mechanism of sorption. Initially, when the cellulose is in contact with liquid water, as in the case when it is in nature, adsorption has taken place on every available hydroxyl group and further take-up beyond this maximum is blocked by a highly ordered network residue. On desorption, adsorbed and absorbed water evaporate from the fiber. Previously separated cellulose hydroxyls now become increasingly hydrogen bonded to neighboring hydroxyls. Thus, on desorption, numerous secondary bonds are inserted into the system reaching a maximum at the lowest RH. On resubmission to an atmosphere of higher RH

some of these hydrogen bonds between cellulose hydroxyls remain inaccessible to water as a result of the formation of well ordered regions. The amount of water absorbed is therefore less at any given RH than that for the desorption curve.

X-ray analysis of wood fibers has shown that the constituent cellulose molecules exist in well ordered regions of the fiber. In these regions the cellulose molecules are packed closely together, thus providing maximum opportunity for hydrogen bonding between adjacent cellulose chains. In other regions, however, the molecular arrangement is more random and less compact and this is referred to as the less well-ordered regions. These regions in native fibers are composed partly of cellulose and hemicelluloses.

Cellulose and hemicellulose are extremely hygroscopic. Water is strongly polar in nature. Hydrogen bonding is effective between water and any substance containing strongly electronegative groups eg. -OH, -CO, -CHO. If such molecules are small, they dissolve in water. Large molecules containing a sufficiency of such groups swell in water and in some instances proceed to solution through unlimited swelling. Cellulose shows a very limited swelling as a result of its high degree of orderliness with the units bonded together by hydrogen bonding. The degree of swelling is increased by the presence of hemicelluloses as in papermaking fibers. The degree of swelling has a pronounced effect on the physical properties of the fiber when wet and eventually on the structure and properties of the web made from these fibers.

Several investigations (26-29) have revealed that an interaction of wood with changes in moisture content produces far greater deformation than creep under constant high relative humidity conditions. Humidity cycling reduced rupture life (28) and performance under stress without any apparent change in Young's modulus (27).

Stamm (30) has showed that the swelling of paper is not only dependent upon the reversible swelling of the fibers themselves but also upon accompanying separation or dispersion of the fibers. Paper is a web of cellulose fibers, inter-bonded and inter-woven to form a structure. Expansion and contraction of the individual fibers with changes in moisture content will bring about expansion and contraction of the whole web because of the interweaving and bonding among the individual units of the structure. The dimensional changes of the paper web will be governed by the orientation of the fibers in the web. If, for example, such orientation were completely in the machine direction of the paper expansion and contraction of the web with changes in relative humidity would be almost completely in the cross direction. Fiber orientation is not uniform through the cross section of the sheet, and it is apparent that the expansion or contraction following sorption or desorption would not be uniform through the sheet. The suspension of pulp fibers is released from the slice onto the wire under pressure, and it is altogether likely that there will be a high degree of orientation of the fibers in the direction of flow or machine direction (31). Rance (20) notes that increasing sheet moisture might be expected to undo some part of the effect of the original tension. Any fibers with deformed cross sections

should revert, in part at least, to the shape they would have assumed in the absence of that tension, and fibers forcibly kept apart by that tension should be liable to revert to a condition of bonding approaching that which they would have assumed in the absence of tension.

Such reversion is in fact one of the most striking hygroscopic characteristics of paper dried under restraint. Larocque (31) subjected machine made paper to adsorption-desorption humidity cycles. He found that the paper contracted on desorption and that the strains present in the paper as a result of the manufacturing processes are gradually released when the moisture content of the sheets is increased. As a result, a permanent alteration in dimension takes place when paper goes through an adsorption-desorption humidity cycle for the first time. When the paper was thus "humidity-conditioned" he found that during subsequent humidity cycles smaller expansion and contraction effects occured than before, and the hysteresis effects were less.

Smith (33) argues that inhibited shrinkage is equivalent to a dried-in strain. Most of this dried-in strain is permanent, but Smith gives figures showing that a certain proportion of it can manifest itself as a subsequent shrinkage, if the dried sheet is wetted with water vapor and redried. For example, a certain paper which would have shrunk 4.8 per cent was constrained during drying so that it shrank only 0.7 per cent. The dried-in strain was thus 4.1 per cent. After wetting and redrying the paper shrank by 0.9 per cent. Thus, 3.2 per cent of the dried-in strain was permanent and only this small amount, 0.9 per cent was capable of showing itself again. Fur-

ther rewettings and redryings lead to small, successively diminishing increments of strain recovery, but the first cycle was predominant. Smith suggests that the major part of the dried-in strain, as represented by the 4.1 per cent in the above example, is irrecoverable, either because the fiber-fiber bonds have shifted during the period of shrinkage inhibited drying or because there has been plastic deformation of the fibers. He goes on to show that the recoverable dried-in strain is related quantitatively to the total dried-in strain. The greater the degree of inhibition of shrinkage, the greater is the amount of recoverable dried-in strain.

Rance (34) allowed a drying web to shrink and found that nearly one-half of that shrinkage showed in the dried paper as an expansion on wetting.

Brezinski (35) demonstrated the humidification recovery of creep. Relative humidity cycling between 97.8% and 50% RH yielded an almost complete recovery of the creep deformation. He suggested that the deformation which is recoverable by humidification is largely retarded configurational elastic response, whose recovery was inhibited at the test conditions by the formation of a metastable molecular structure. Humidification recovery occured most readily following tests at low relative humidities where strong inter-molecular bonding was present. Humidification is less effective in providing for increased recovery in tests at higher relative humidities.

Moisture content has a marked effect upon many paper properties. Water has the effect of plasticizing the cellulose fiber and of relaxing and weakening the interfiber bonding. Such properties as

folding endurance, tearing strength and stretch reach maximum values at relatively high humidities (80 to 90% RH) and decrease at low humidities when the fibers become more stiff and brittle. Tensile strength reaches a maximum value in the region of low humidity and steadily decreases with increasing moisture content, presumably because of the weakening effect on the interfiber bonding (36).

PRESENTATION OF THE PROBLEM

The purpose of the present work is to study the effect of sheet moisture on the anisotropy of paper which has been previously subjected to restraint during drying. It is hypothesised that increasing the sheet moisture will weaken the bonds and enable the fibers and fibrils to revert, at least in part, to their original configurations before they were locked into position under the influence of wet straining. Secondly, it is suggested that the fiber structure will partially return to its unstrained state in response to the swelling of the less well ordered regions in the fibers. This relaxation of tensions or dried-in strains will tend to reduce the anisotropy of the sheet.

The experimental part of this study involved examination of the effects of sheet moisture on the mechanical properties of paper which included tearing strength, tensile strength, ultimate elongation, elastic modulus and work-to-rupture, on sheets previously wet strained during drying.

The experimental program was focused on four major areas:

1. The preparation of handsheets with various degrees of wet straining.

2. The conditioning of these handsheets to various relative humidities at a constant temperature.

3. The determination of the mechanical properties of these handsheets using the Instron Universal Tester and the Elmendorf Tear Tester.

4. The determination of the zero-span tensile strength and degree of fiber orientation by the Pulmac Zero Span Tensile Tester.

EXPERIMENTAL

Handsheets were made from Rayonier bleached, softwood, kraft pulp and subjected to four different degrees of wet straining; 0.0%, 1.5%, 3.0% and 3.57%. Under restraint, they were dried in a 112°F oven for 5 minutes. After drying, the handsheets were conditioned to various relative humidities. The tearing strength, tensile strength, elongation, tensile energy absorption and modulus of elasticity of the handsheets were determined and compared at relative humidities of 30%, 50%, 70% and 90%.

Preparation of Pulp

The pulp used in this study was a commercial Rayonier bleached, softwood, kraft pulp. It was received as dry lap and was stored in a constant humidity room for 7 days. The pulp was refined in a Valley Laboratory beater according to TAPPI Standard T200 ts-66. Before beating, the pulp was soaked in 10 liters of water for 5 hours and then defibered in a TAPPI disintegrator. The pulp was beaten to approximately 500 cc. Canadian Standard Freeness with 5500 gm. on the bedplate.

Several beater loads of pulp were prepared. After beating, the pulp was mixed in a barrel for 30 minutes to insure uniformity. A final series of freeness checks showed a CSF of 530 ml. A small amount of formaldehyde was added to the pulp, which was stored in a cold room, to prevent bacterial degradation.

Sheet Forming and Pressing

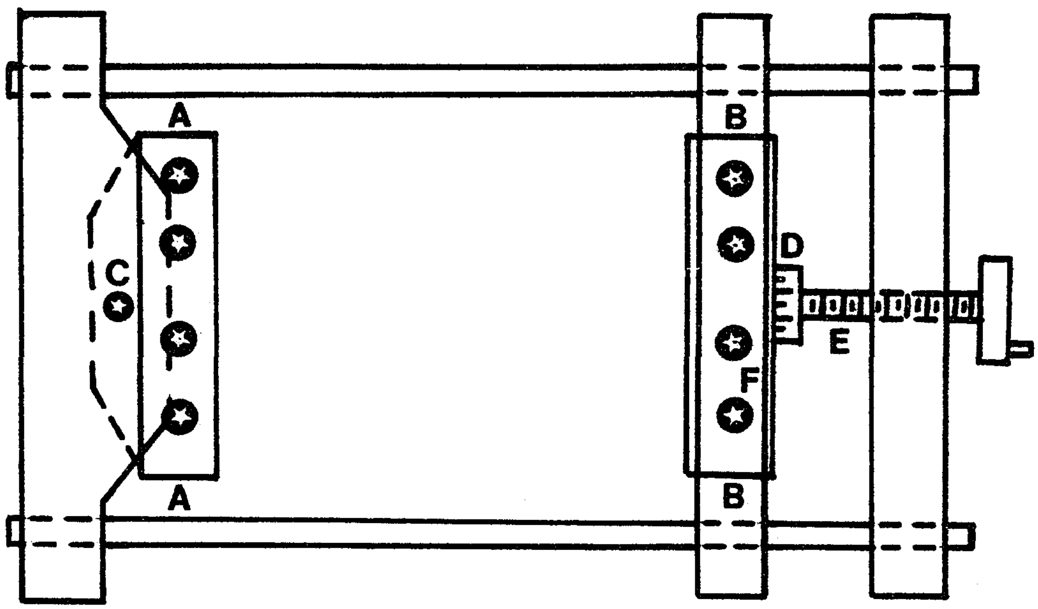
All sheets were formed on a Noble and Wood Handsheet machine. The final consistency in the sheet mold was 0.021% and this effectively eliminated flocculation, promoting good formation.

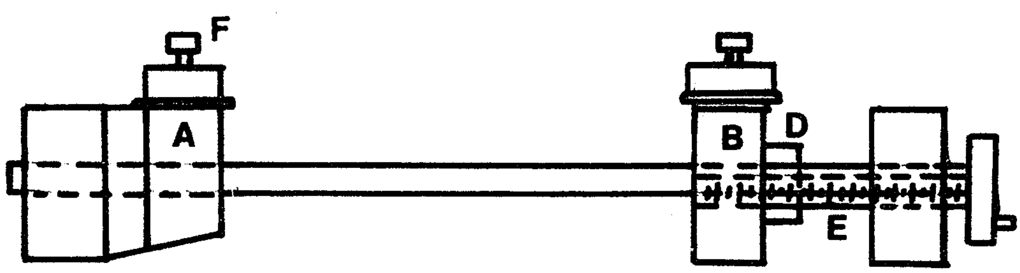
After the water drained and the wet web was formed, the sheet and wire were transferred to a Noble and Wood press. The press felt was carefully conditioned before each sheet was pressed by thoroughly soaking it in water and pressing twice with maximum weight on the lever arms. The sheet and wire were then introduced into the felt and the trio was subjected to two pressings. This pressing schedule insured a solids content in the pressed sheet of 35.5%. Preliminary tests showed that the solids content varied by ± 0.5% through two days of handsheet making. The variation of solids content within the sheet also was investigated. Several handsheets were cut into 8 parts and the moisture content of each portion was determined. An average deviation of ± 0.4% was detected. Similarly, a basis weight profile of several handsheets deviated by ± 0.5%.

Sheet Drying Techniques

The purpose of the sheet drying equipment was to prepare handsheets subjected to controlled unidirectional strain during drying.

The equipment used was devised by the Boxboard Research and Development Association of Kalamazoo, Michigan and is shown in Fig. 2. It consists essentially of a frame with two parallel clamping blocks, A and B. Block A is stationary but free to pivot around point C.





A Stationary block

B Movable block

C Pivot for stationary block

D Graduated collar

E Micrometer type screw

F Clamping screws

Fig. 2. Sheet Drying Equipment

Block B is hooked to a micrometer type screw with a graduated collar affixed to the latter. The collar was an excellent indicator of the amount of tension applied to the handsheet. However, the final measurement of the degree of wet straining was done by two methods. One, by the collar and the second by a method which is described at the end of this section.

An average of 2 minutes was taken for the introduction of the sheet into the drying unit. During this period, evaporation could take place from the surface of the sheet. To compensate for this and maintain uniformity throughout, the bulk of the operation was conducted with the sheet in the felt. This reduced evaporation to a minimum. A check on the amount of evaporation occuring indicated a value of 3.0%. Therefore, all wet straining was done at essentially 38.5% solids since wet pressing produced a sheet of 35.5% solids.

The handsheet edges to be clamped were ironed dry to avoid rupture at the clamp as drying stresses were developed. Two reference marks were made on the wet sheet to be used later for calculating the degree of wet straining. The marks were made with a felt tipped pen 5 inches apart, measured with a steel ruler, and parallel to the direction of wet straining. Immediately after placing the wet sheet in the frame, the distance between the clamps was adjusted to give the desired amount of restraint during drying. The assembly was placed in a drying oven maintained at 112°F for 5 minutes, with the sheet held in a vertical plane to minimize the tendency to sag that could occur if the sheet were held in a horizontal position. This drying schedule produced a sheet of 91.5% solids. Such a solids level eliminated the possibility

of hornification (37) of the fibers which may interfere with their reabsorptive properties. It has been shown (38) that moisture gradients due to uneven drying, create curl and cockle in the sheet. Therefore the sheets were dried very slowly to allow the diffusion of water through the fibrous system and effectively reduce cockling.

After removal from the drying unit, the sheets were hung to equiliberate in a temperature and humidity controlled room. At no time were the fully dried sheets exposed to any but the prescribed conditions.

The degree of wet straining was measured by two methods. The first, using the micrometer type screw on the frame. A more accurate measurement was obtained by measuring, with a ruler, the distance between two reference marks on the sheets before and after the straining operation. From this, the degree of wet straining was calculated. There was good correlation between the two methods. The degree of wet straining was accurate to ± 0.05%.

Humidity Conditioning

Immediately after removal from the drying unit, the sheets were introduced into a temperature and humidity controlled room. The humidity and temperature in this specially constructed room was regulated by an Aminco-Aire system. The desired conditions were simply dialed in on the front panel of this unit. Very precise control of temperature and humidity is possible with this equipment and fluctuations in temperature were ± 0.5°F and variations in humidity ± 0.2%. The temperature and humidity in the room were recorded on a chart. A daily

check on the measuring and recording system was made with the aid of a thermometer and the Bendix Psychron which measures the relative humidity. The handsheets were conditioned for 48 hours before any tests were conducted on them.

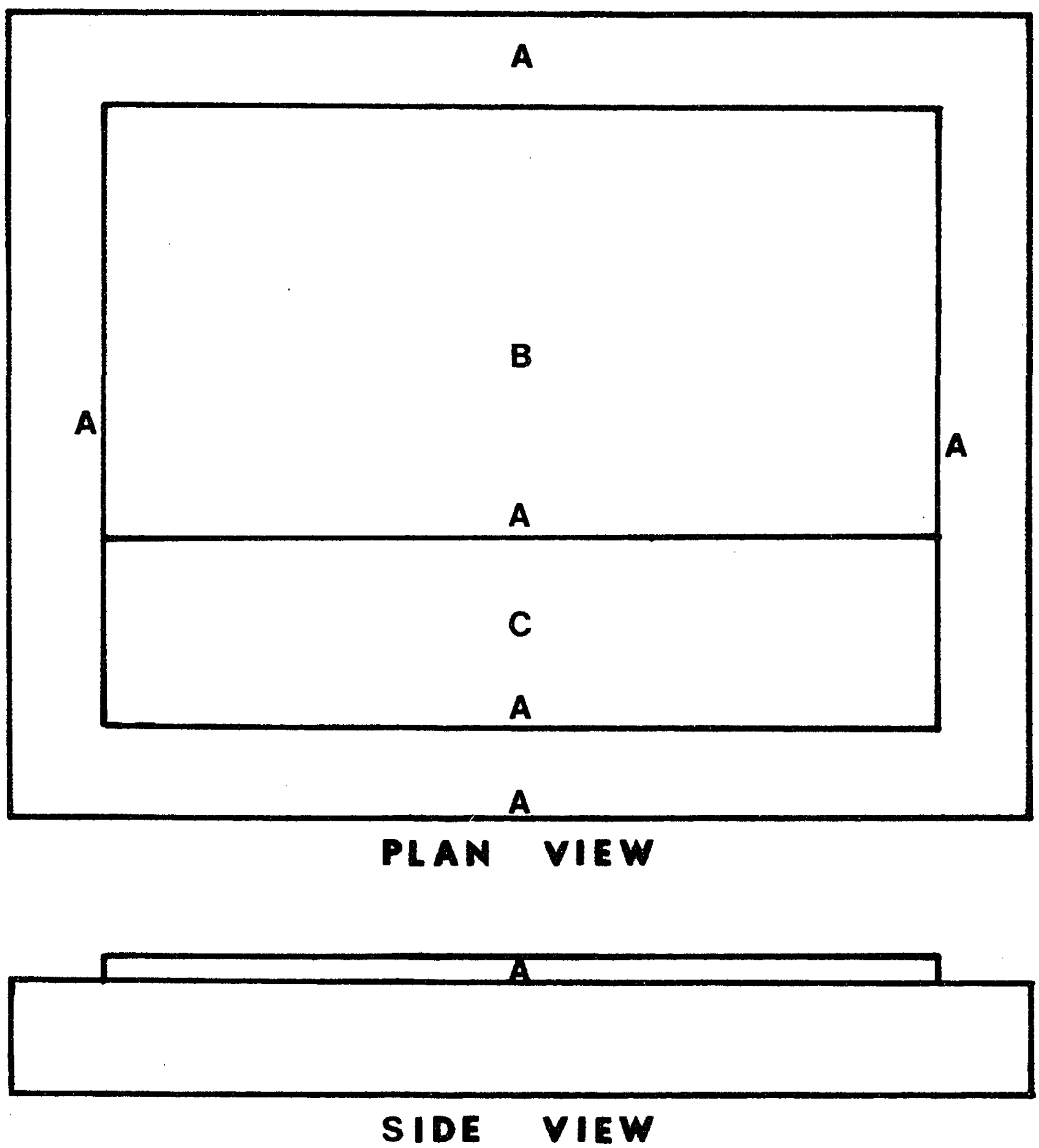
Handsheet Sampling

While drying, the sheets were in a vertical position and hence the upper portions of the sheets were subjected to greater stresses than the lower portions because of the cummulative weight of the web itself. The dimensions of the wet web used were 8" by 8". This sheet was clamped at the ends and free to shrink laterally. When the sheet was dry, it was wider at the ends than in the middle since the area under the clamps was prevented from shrinking.

In order to obtain the most consistent and representative sample of the effect due to wet straining, all test samples were confined to a 5" by 5" square in the center of each sheet. Tests indicated no significant variations in mechanical properties of samples taken from this central portion. Test samples were cut at five angles; 0.0°, 22.5°, 45.0°, 67.5° and 90.0°, with the aid of a die (Fig. 3) manufactured by J. A. Richards Die Company, Kalamazoo, Michigan. Each cut provided a 1" test strip for the Instron Tester and a 63 mm. wide strip for the tear tester.

Tear Measurements

The tearing strength of the handsheets prepared was measured using the Elmendorf Tear Tester. It measures the average force in



A Cutting knife edge

B Test sample for Elmendorf Tear Test

C Test strip for Instron Tensile Test

Fig. 3. Test Sample Cutting Die

grams required to tear a single sheet of paper after the tear has been started.

The Elmendorf Tear Tester comprises a stationary clamp and, suitably aligned therewith, a second movable clamp carried on a pendulum that is free to swing on a substantially frictionless bearing. The sample, 63 mm. wide, is clamped in the jaws and a 20 mm. wide tear started. A lever is released and the retardation of the pendulum swing is a measure of the work done in tearing the rest of the sample. The tests were conducted at 73.4°F and at four relative humidities; 30.0%, 50.0%, 70.0% and 90.0%.

The values reported are tear factors as determined from the equation:

$$\text{Tear factor} = 100\ e/r$$

where e is the force in grams to tear a single sheet and r is the basis weight in grams per square meter.

Basis Weight Determinations

The area cut out by the die was carefully measured by cutting commercial paper samples of known basis weight. From the weights of these pieces, the area was calculated by the following equation:

$$\text{Area of die} = \frac{\text{Weight of paper cut out by die}}{\text{Basis weight of commercial paper}}$$

Before the handsheet samples were tested, they were weighed individually and the basis weight of each handsheet was determined using the above equation.

Instron Load-Elongation Measurements

The Instron Universal Testing Instrument was used to determine the mechanical properties such as tensile strength, ultimate elongation, the tensile energy absorption or amount of work necessary to cause rupture and the modulus of elasticity.

Van den Akker and Hardacker (39) have examined the ability of this instrument to determine these paper properties. The Instron is designed to apply a constant rate of straining to the specimen held between its jaws. While the upper jaw remains in a fixed position, the lower jaw moves down at an adjustable, fixed speed. The upper jaw is connected to any one of several load cells; the amplified electrical signal from which permits the recording of the load-elongation behaviour of the test specimen.

Air-pressurized, line-contact clamps set for a guage length of 10 cm. were utilized to test 1" wide sample strips.

All Instron tests were carried out at 73.4°F and four relative humidities; 30.0%, 50.0%, 70.0% and 90.0%. In all cases, the rate of straining was 2 cm/min. The tensile factor reported was determined from the equation:

$$\text{Tensile factor} = 100\ k/r$$

where k is the force in kilograms to rupture the sheet and r is the basis weight in grams per square meter.

The modulus of elasticity was calculated by measuring the initial slope of the load-elongation curves. Values are reported in dynes/cm^2. A sample calculation is included in Appendix I. This

procedure is based on the assumption that during the early part of the load-elongation test, the rate of elongation is small compared to the rate of creep.

The values of work-to-rupture or tensile energy absorption reported in this investigation are measures of the work necessary to rupture the paper specimen and are calculated by measuring the area under the load-elongation curves. This was performed automatically by the Instron Integrator. A sample calculation is presented in Appendix II, with values expressed in Kg-m/m^2.

The ultimate elongation was obtained directly from the load-elongation curves. Since a cross-head speed of 2 cm/min and a chart speed of 20 cm/min was used, 1 cm. in the y-direction represented 1% elongation.

Zero Span Tensile Strength Analysis

The zero span tensile strengths of the handsheets were obtained with the use of the Pulmac Zero Span Tensile Tester. With this instrument it is possible to obtain tensile data for samples over a span range from nominal zero (clamping jaws in contact) to several millimeters. Since a finite distance is required to develop adequate clamping pressure, it is not physically possible to obtain tensile data at true zero span. When the clamping jaws are in mechanical contact, a span of about 0.2 mm. exists where fiber pull-out can occur (40). This distance from nominal zero to true zero is called the 'residual span'. However, it is possible to obtain true zero span tensile strength by extrapolation.

Zero span tensile tests were conducted on both the dry (bonded) and wet (unbonded) paper samples that were subjected to 3.0% and 3.5% degree of wet straining. Only the strain and cross strain directions were investigated. It was felt that if any significant fiber orientation occured during wet straining, the maximum effect would be observed at this degree of wet straining.

From the data obtained, the fiber length index, fiber strength index, fiber orientation index and bonding index can be calculated. The ability of the Pulmac Zero Span Tensile Tester to measure these paper properties have been demonstrated by Cowan and Cowdrey (41).

The instrument readout was converted into Kg. per 25.4 mm. by the equation:

$$\text{Zero span tensile strength in kg. per 25.4 mm.} = \frac{(P-1.4)(0.739\text{x } 454\text{x } 10\text{x } 2.54)}{15\text{x } 1000}$$

where P is the pressure guage readout.

PRESENTATION OF RESULTS AND DISCUSSION

Introduction

Data analysis was conducted by utilization of STAT PACK, (Statistical Package), Library Program #1.1.4. STAT PACK is an integrated, interactive package compiled by the Computer Center, Western Michigan University. It allows the user to issue simple commands for the complete statistical analysis of data. Statistical tests include T tests, Linear Regression, Partial Correlations, Correlation Matrices and Analysis of Variances. The reader is referred to a summary on STAT PACK which is available from the Computer Center.

Effect of Relative Humidity on Sheet Moisture

It is generally accepted that the adsorption of water by cellulose occurs essentially in the less well-ordered regions of the fiber with subsequent decreased intermolecular bonding and increased spacing between molecules.

The relationship between sheet moisture and relative humidity is nonlinear. The moisture content versus relative humidity data is presented in Table I and Fig. 4. The amount of water absorbed by cellulose depends upon the relative humidity and the temperature of the air in contact with the paper. Further, under the same humidity and temperature conditions, a sample of paper may have different moisture contents depending on whether the sample approached these conditions from a more dry state or from a more moist state.

Table I

Specimen Moisture Content Versus Relative Humidity at 73°F.

Relative Humidity	Specimen Moisture Content, %
30	5.04
50	7.43
70	9.99
90	14.6

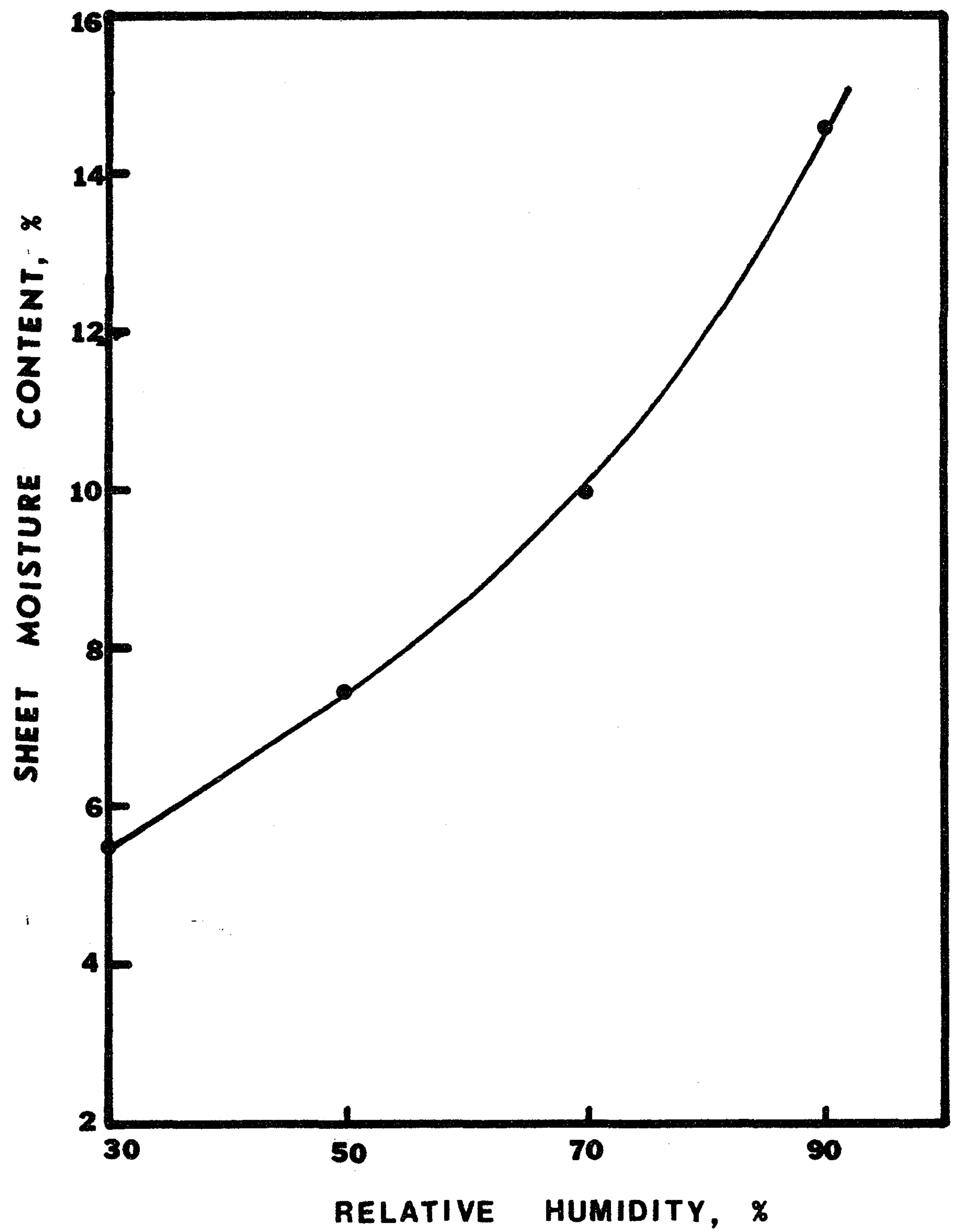


Fig. 4. The Effect of Relative Humidity on Sheet Moisture

The relative humidities of 30%, 50%, 70% and 90% were reached by adsorption from 5% RH. This study, therefore essentially represents tests at relative humidities reached by adsorption.

Load-Elongation Measurements

The stress-strain characteristics of the handsheets measured by the Instron Universal Testing Instrument are shown in Figures 5-8. Each figure represents one relative humidity and each curve represents a certain degree of wet straining and the direction at which testing was conducted, strain direction (SD) or cross strain direction (CD). The reader should be cautioned in that these curves are reproductions of the ones obtained from the Instron and have not been corrected for basis weight variations. Therefore, although the curves at 90% relative humidity demonstrate high tensile strengths, they represent handsheets of high basis weight. The figures indicate the gradual increase in ultimate elongation with sheet moisture and a corresponding decrease in tensile strength. A detailed analysis of the effects of wet straining and sheet moisture on these paper properties follows this section.

The Instron curves were used to detect changes in tensile strength, ultimate elongation, modulus of elasticity and the amount of work necessary to cause rupture, brought about by wet straining. This information is assembled in Tables II through V.

The tensile strength, modulus of elasticity and work-to-rupture have been corrected for basis weight. Since ultimate elongation is independent of basis weight, no correction has been made for this paper property.

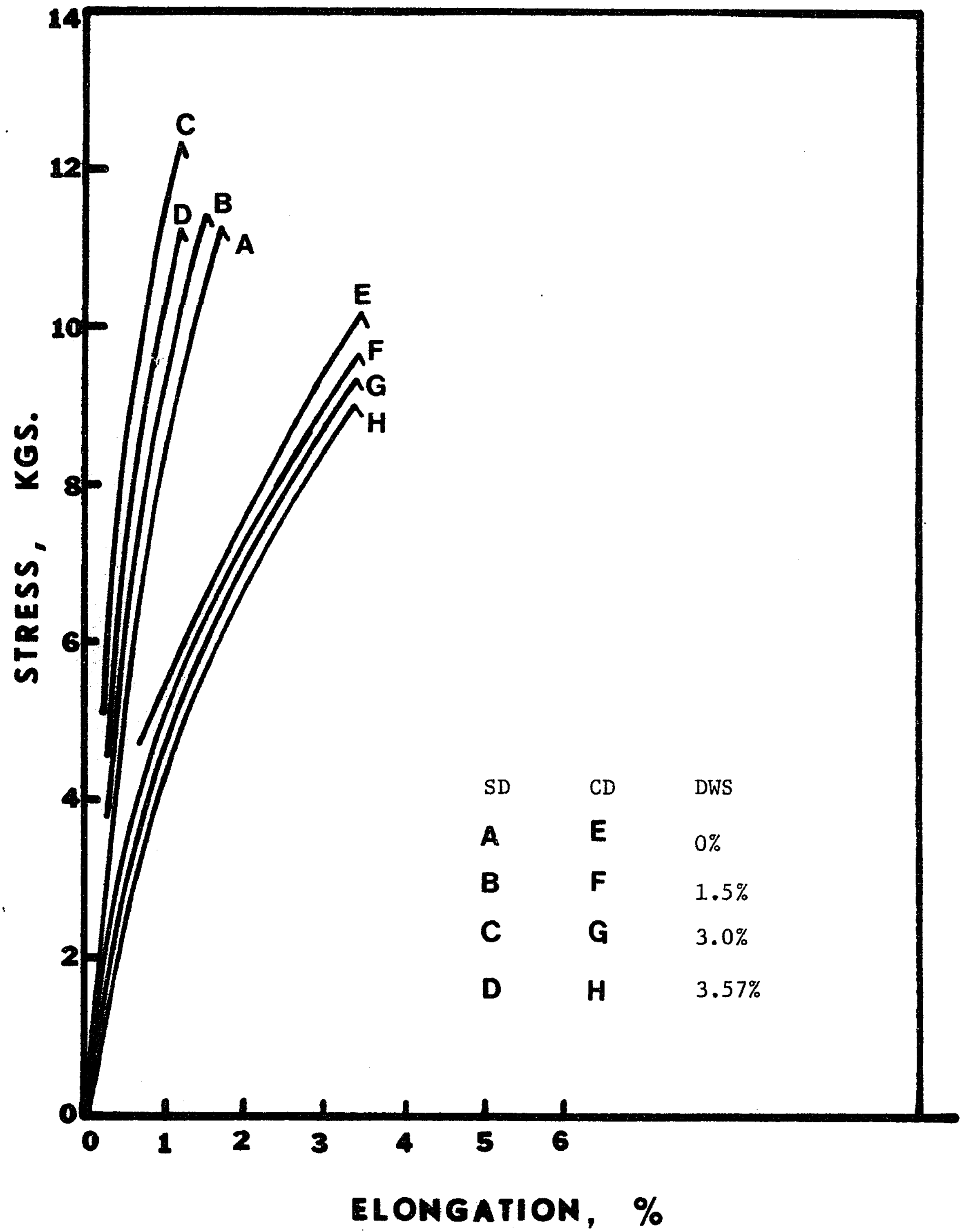


Fig. 5. Stress-Strain Curves at 30% Relative Humidity

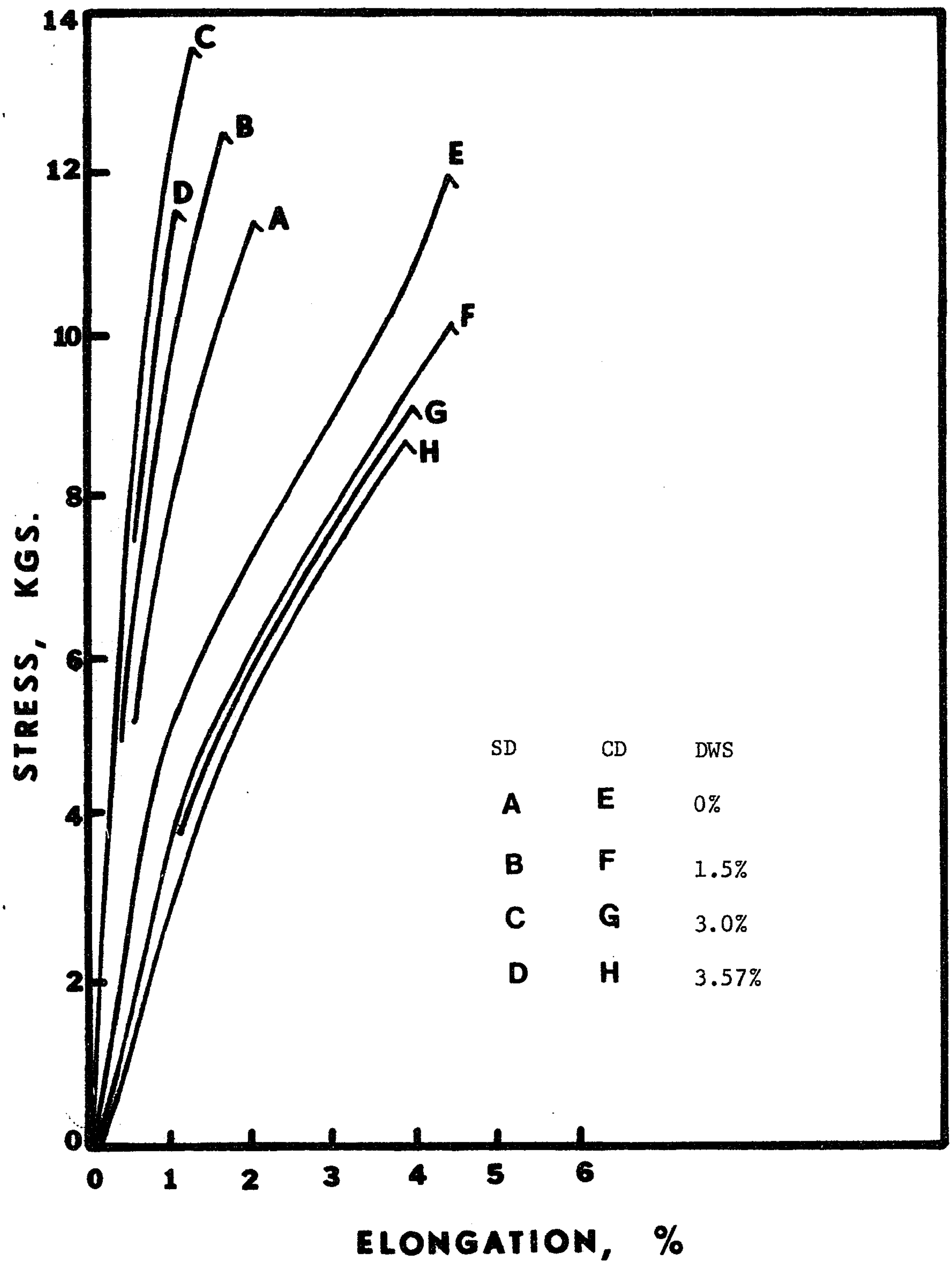


Fig. 6. Stress-Strain Curves at 50% Relative Humidities

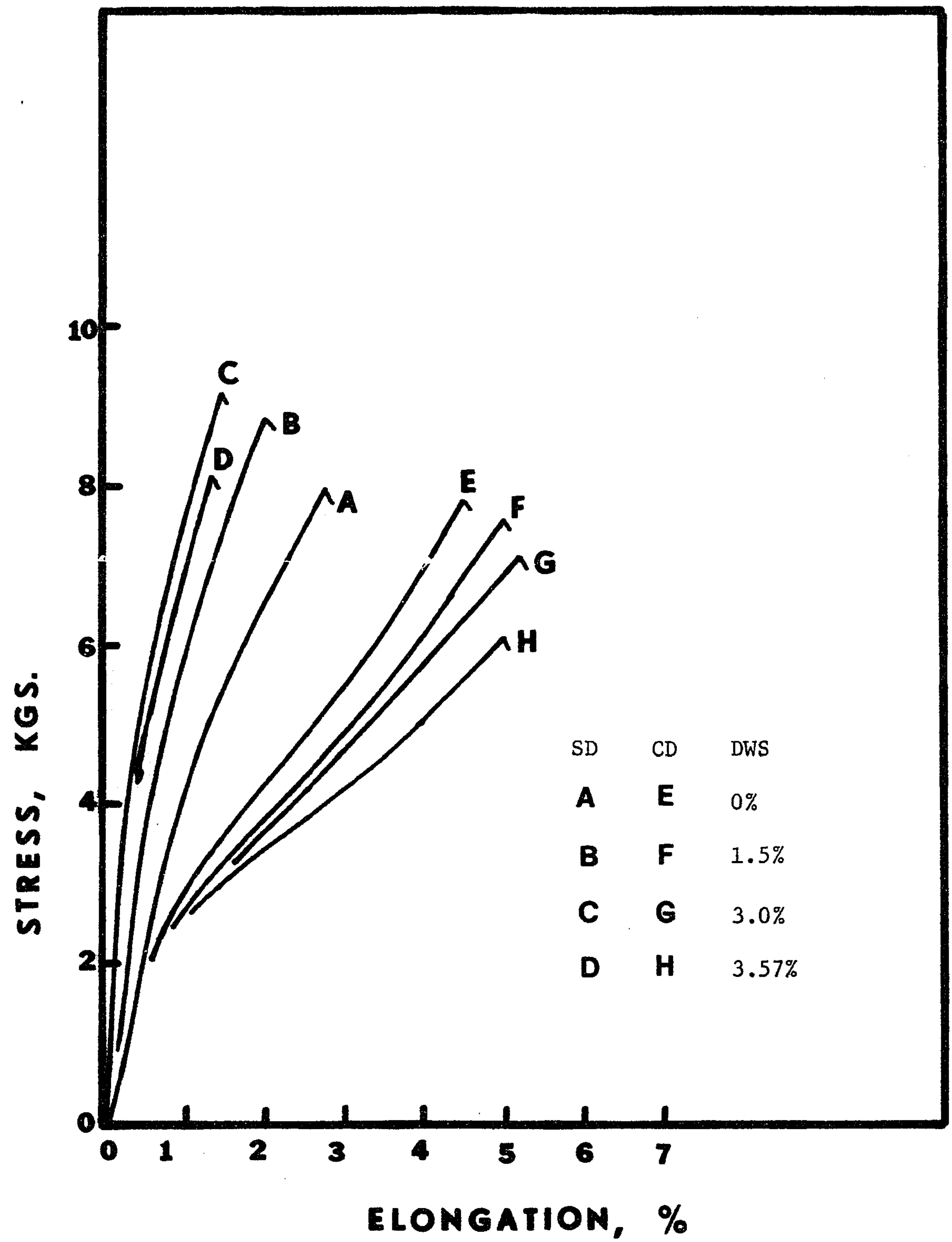


Fig. 7. Stress-Strain Curves at 70% Relative Humidity

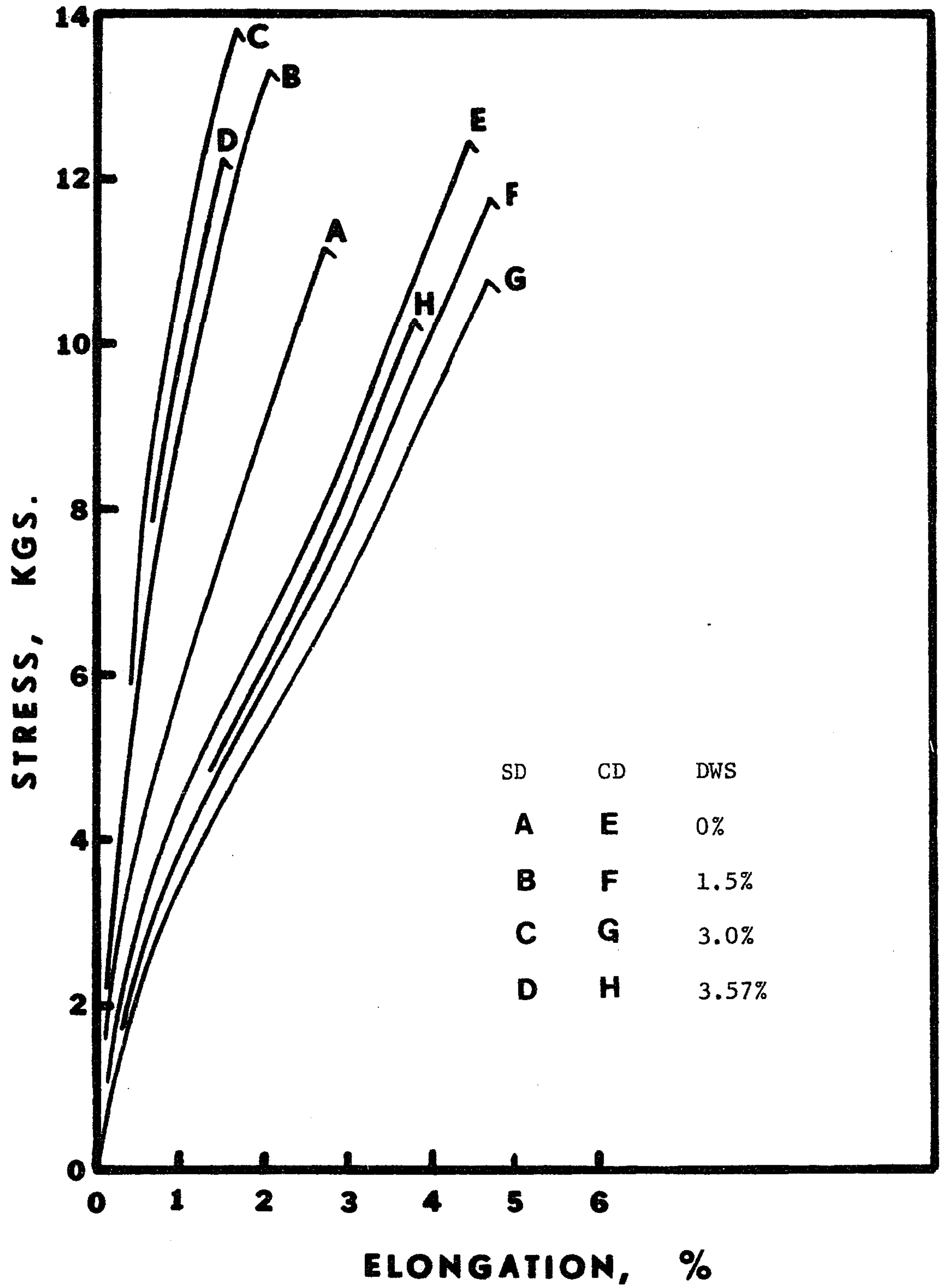


Fig. 8. Stress-Strain Curves at 90% Relative Humidity

Table II

Mechanical Properties of Handsheets at
30% Relative Humidity

Degree of Restraint	Angle	Basis Weight	Tear Factor	Tensile Factor	Elong-ation	TEA Factor	Modulus of Elasticity Factor
%	degrees	gm/m^2			%		$X10^{-7}$
0	0	64.24	122.9	18.34	2.25	10.21	35.54
0	22.5	66.39	122.4	17.77	2.82	13.00	31.47
0	45	63.01	120.9	15.28	3.30	15.35	26.77
0	67.5	68.56	131.6	15.21	4.00	16.96	25.54
0	90	62.39	137.2	15.68	4.06	17.92	23.10
1.5	0	65.28	119.4	18.38	1.30	6.31	43.10
1.5	22.5	71.33	113.9	19.34	1.90	10.68	39.84
1.5	45	69.13	125.9	16.92	3.00	14.96	32.09
1.5	67.5	70.63	126.9	16.80	4.28	20.02	24.84
1.5	90	68.51	129.8	15.65	4.15	19.00	24.24
3.0	0	64.84	127.10	19.80	1.12	5.55	44.40
3.0	22.5	65.72	127.1	18.50	1.46	7.94	40.11
3.0	45	65.24	125.6	17.98	2.54	12.51	26.89
3.0	67.5	64.82	134.3	16.82	3.27	16.06	25.78
3.0	90	69.63	146.1	14.61	4.08	17.28	22.74
3.57	0	64.70	124.1	17.81	1.00	4.45	45.57
3.57	22.5	66.16	122.9	17.49	1.45	6.51	40.68
3.57	45	63.51	127.0	14.75	2.25	9.32	30.62
3.57	67.5	66.63	135.0	14.25	3.35	14.87	27.58
3.57	90	64.53	143.8	13.29	4.00	16.92	22.13

Table III

Mechanical Properties of Handsheets at
50% Relative Humidity

Degree of Restraint	Angle	Basis Weight	Tear Factor	Tensile Factor	Elongation	TEA Factor	Modulus of Elasticity Factor
%	degrees	gm/m^2			%		X10^{-7}
0	0	69.54	124.2	15.10	2.20	8.89	29.67
0	22.5	68.17	126.8	15.77	3.08	12.92	27.31
0	45	56.66	136.0	16.06	3.93	15.46	20.87
0	67.5	61.32	133.0	14.95	4.83	21.74	19.17
0	90	64.45	139.5	13.72	5.55	26.17	18.99
1.5	0	66.44	122.9	19.16	2.03	10.17	38.27
1.5	22.5	64.90	127.6	18.03	2.48	11.79	33.34
1.5	45	63.83	110.3	17.50	3.23	10.12	22.80
1.5	67.5	63.04	123.1	15.15	4.65	18.62	19.42
1.5	90	67.55	135.0	15.47	4.93	19.56	20.15
3.0	0	67.44	127.4	18.76	1.48	7.06	45.58
3.0	22.5	67.32	128.3	16.68	1.90	7.78	37.53
3.0	45	65.00	138.5	15.00	2.78	11.05	25.86
3.0	67.5	67.63	131.9	14.12	4.05	14.82	21.09
3.0	90	71.84	143.1	13.92	4.90	17.71	18.89
3.57	0	65.53	129.8	18.28	1.18	5.28	45.13
3.57	22.5	68.93	134.6	16.25	1.53	6.50	37.19
3.57	45	67.73	133.5	15.40	2.68	11.07	27.90
3.57	67.5	65.64	149.9	13.61	4.38	18.03	19.87
3.57	90	69.80	147.8	13.74	4.50	18.02	17.97

Table IV

Mechanical Properties of Handsheets at
70% Relative Humidity

Degree of Restraint	Angle	Basis Weight	Tear Factor	Tensile Factor	Elong- ation	TEA Factor	Modulus of Elas- ticity Factor
%	degrees	gm/m^2			%		X10^{-7}
0	0	68.73	149.9	12.32	3.28	10.17	17.83
0	22.5	69.44	153.4	12.37	3.60	11.49	22.16
0	45	67.66	156.7	12.16	4.48	13.83	16.34
0	67.5	65.90	159.3	10.43	4.93	12.68	12.14
0	90	70.23	160.9	11.50	6.10	16.56	13.49
1.5	0	70.37	149.2	13.32	2.50	8.51	27.40
1.5	22.5	70.84	156.0	13.38	2.75	9.23	27.22
1.5	45	70.00	156.4	12.33	4.30	13.40	18.49
1.5	67.5	70.13	153.3	10.29	5.13	13.13	14.86
1.5	90	70.83	158.1	10.92	5.68	15.69	15.64
3.0	0	69.53	151.8	14.29	1.88	6.53	31.67
3.0	22.5	72.31	161.3	14.25	2.15	7.74	28.56
3.0	45	70.05	157.8	11.86	3.28	9.98	20.56
3.0	67.5	70.23	162.3	11.13	4.90	13.53	15.25
3.0	90	69.84	162.9	10.77	5.75	15.03	13.52
3.57	0	65.21	148.0	13.44	1.60	5.09	30.84
3.57	22.5	66.23	164.6	13.35	2.08	6.87	27.88
3.57	45	65.48	170.3	10.54	2.90	8.00	18.58
3.57	67.5	66.63	171.8	10.66	5.23	13.96	13.42
3.57	90	65.32	163.8	10.46	5.73	14.30	13.41

Table V

Mechanical Properties of Handsheets at
90% Relative Humidity

Degree of Restraint	Angle	Basis Weight	Tear Factor	Tensile Factor	Elong-ation	TEA Factor	Modulus of Elas-ticity Factor
%	degrees	gm/m^2			%		$X10^{-7}$
0	0	75.28	178.0	7.82	3.74	7.49	12.79
0	22.5	78.97	176.9	8.65	4.38	9.45	11.08
0	95	77.07	177.8	9.02	4.83	10.22	9.11
0	67.5	77.11	176.4	8.35	5.48	10.74	8.60
0	90	77.12	173.1	8.44	6.00	11.49	8.68
1.5	0	82.84	173.8	9.56	2.78	6.58	17.47
1.5	22.5	80.74	166.3	9.38	3.26	7.81	14.60
1.5	45	81.09	159.1	8.63	4.28	9.23	13.16
1.5	67.5	78.24	180.9	8.27	5.05	10.2	11.05
1.5	90	81.49	170.6	8.05	5.63	10.55	10.60
3.0	0	75.29	176.7	9.21	1.93	4.73	19.36
3.0	22.5	79.34	160.0	8.72	2.33	5.33	18.47
3.0	45	77.36	168.7	8.21	3.83	7.96	11.92
3.0	67.5	77.36	179.4	7.22	5.40	9.60	8.99
3.0	90	76.04	173.6	7.34	5.33	9.14	9.50
3.57	0	75.61	159.4	8.91	1.91	4.34	20.95
3.57	22.5	76.92	158.0	8.60	2.00	4.34	19.66
3.57	45	75.73	180.3	7.10	3.13	5.65	13.55
3.57	67.5	75.35	160.6	7.22	5.25	9.28	9.55
3.57	90	77.73	167.9	7.45	5.73	9.98	9.05

Tensile Strength

The effect of wet straining on the tensile strength of paper at four relative humidities, 30%, 50%, 70% and 90% is shown in Figures 9-12. Each figure is labeled with the angle of wet straining to which the paper was subjected. 0° is designated parallel or strain direction and 90° is perpendicular or cross strain direction to the wet straining operation.

It is seen that wet straining, initially, increases tensile strength in the 0°, 22.5° and 45° direction but as it is continued a maximum strength is attained, around 3% wet straining, after which further wet straining brings about a reduction. The cross direction tensile strength does not rise initially but decreases, at first slowly, then at an increasing rate as the sheet is stretched by larger amounts. An estimate can be made of the percent increase in tensile strength due to wet straining by the strength values at 0% wet straining and the values at the peak of the curves. Results are presented in Table VI. Percent increases varied from 0% to 27%. The largest increase was observed in the strain direction with no increase, except at 50% RH, in the cross direction tensile.

Fig. 13 illustrates the effect of sheet moisture and the angle of wet straining on the mean tensile strength. It is seen that tensile strength decreases with increase in sheet moisture and the angle of wet straining. This is in accordance with other work which has appeared in the literature (42). The decrease in tensile strength

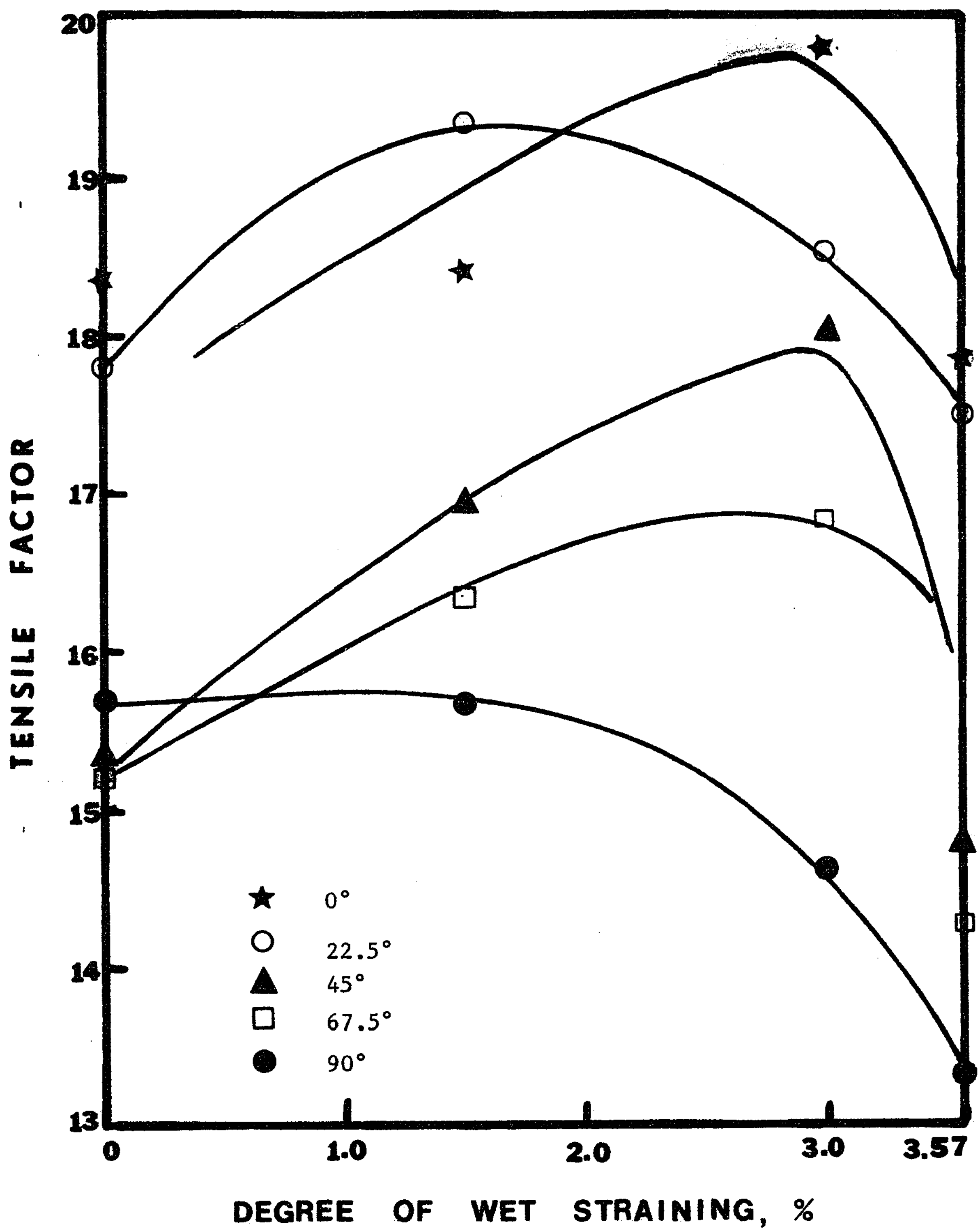


Fig. 9. The Effect of Wet Straining on the Tensile Strength of Paper at 30% RH

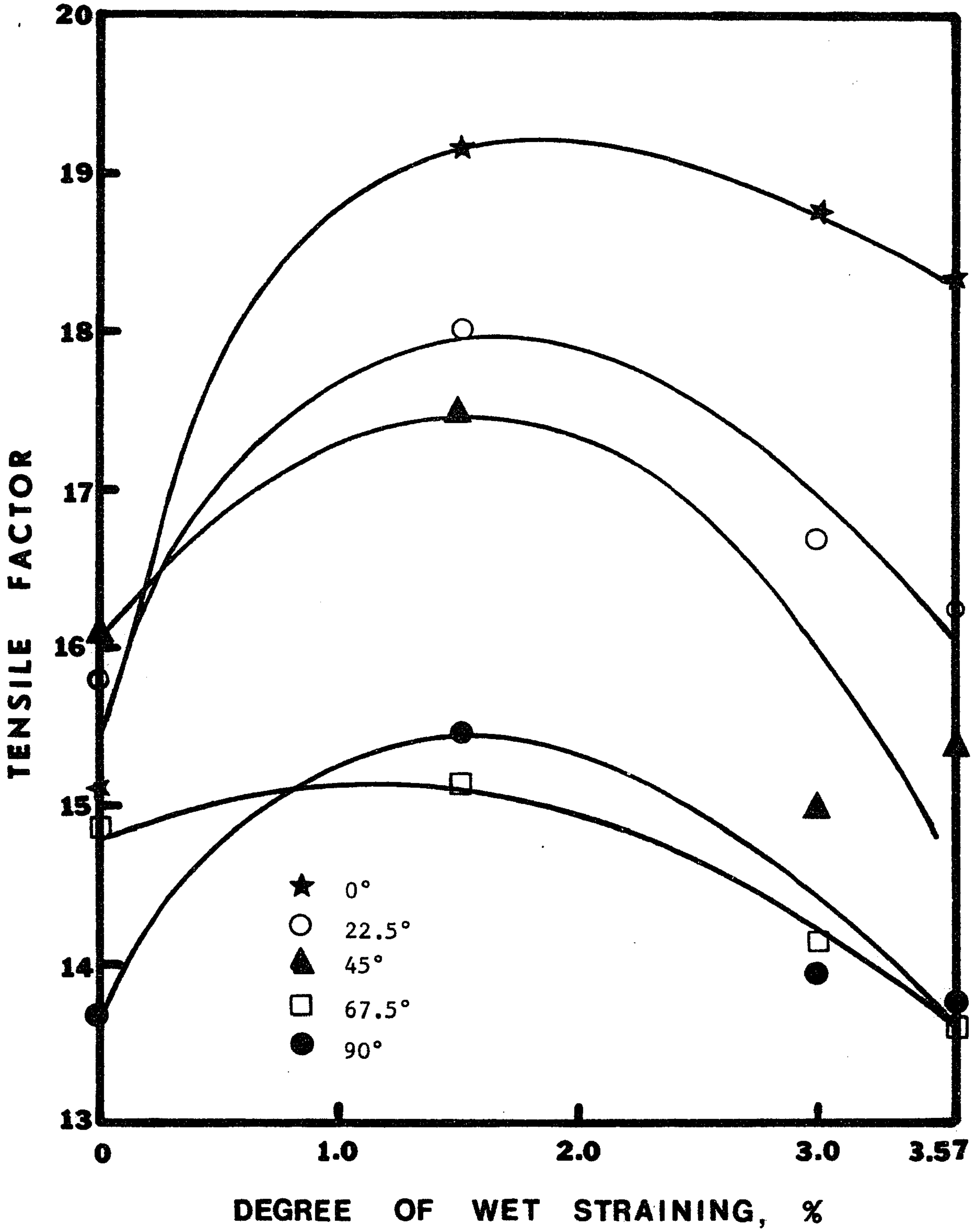


Fig. 10. The Effect of Wet Straining on the Tensile Strength of Paper at 50% RH

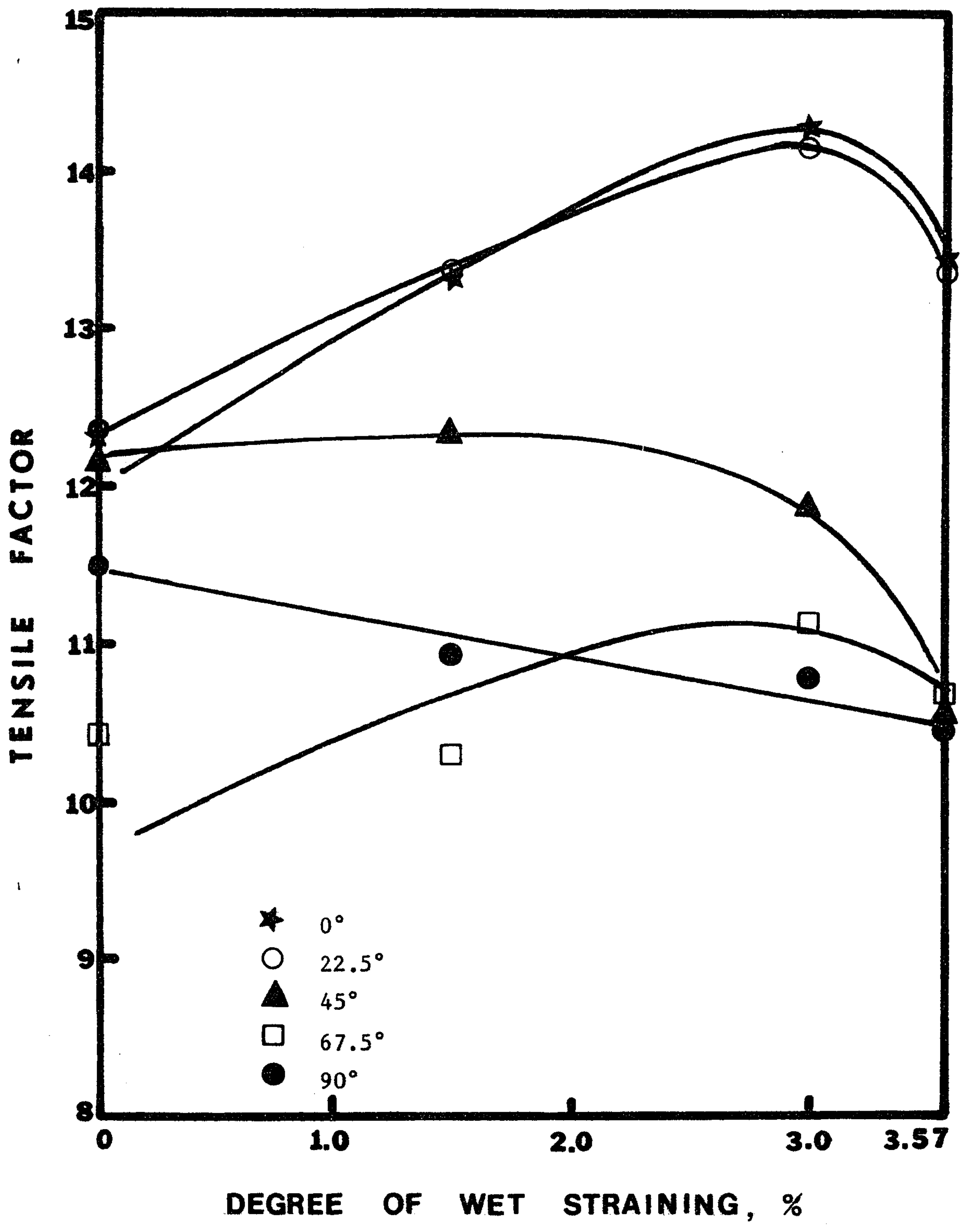


Fig. 11. The Effect of Wet Straining on the Tensile Strength of Paper at 70% RH

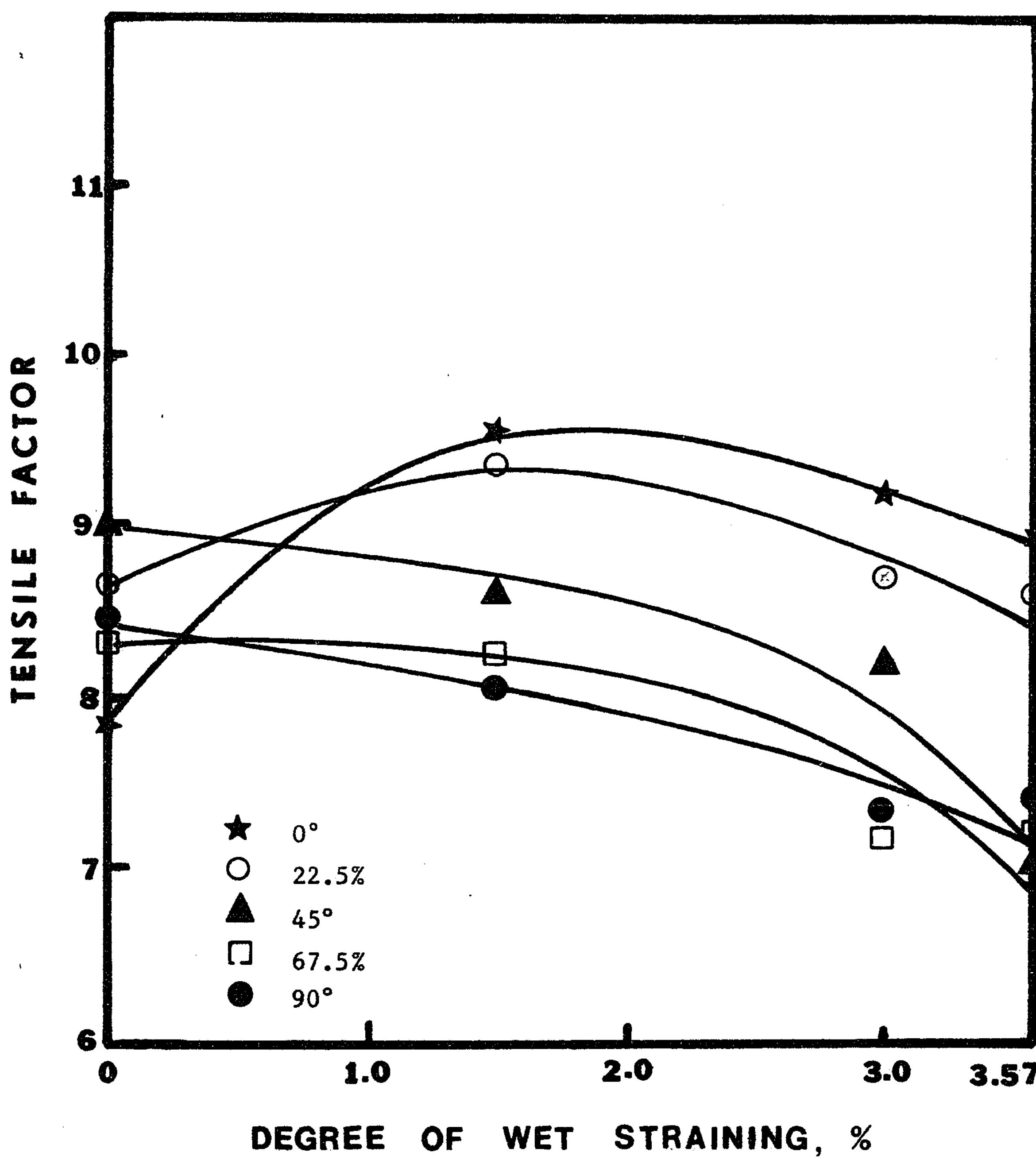


Fig. 12. The Effect of Wet Straining on the Tensile Strength of Paper at 90% RH

Table VI

Maximum Percent Increase in Tensile Strength
due to Wet Straining

Sheet Moisture	Angle of Tensile Test	Increase in Tensile Strength
%	degrees	%
5.46	0	12.9
5.46	22.5	8.7
5.46	45	17.0
5.46	67.5	15.1
5.46	90	0
7.43	0	27.0
7.43	22.5	14.6
7.43	45	8.4
7.43	67.5	2.37
7.43	90	5.1
9.99	0	19.2
9.99	22.5	15.0
9.99	45	1.2
9.99	67.5	15.0
9.99	90	0
14.6	0	22.3
14.6	22.5	8.1
14.6	45	0
14.6	67.5	0
14.6	90	0

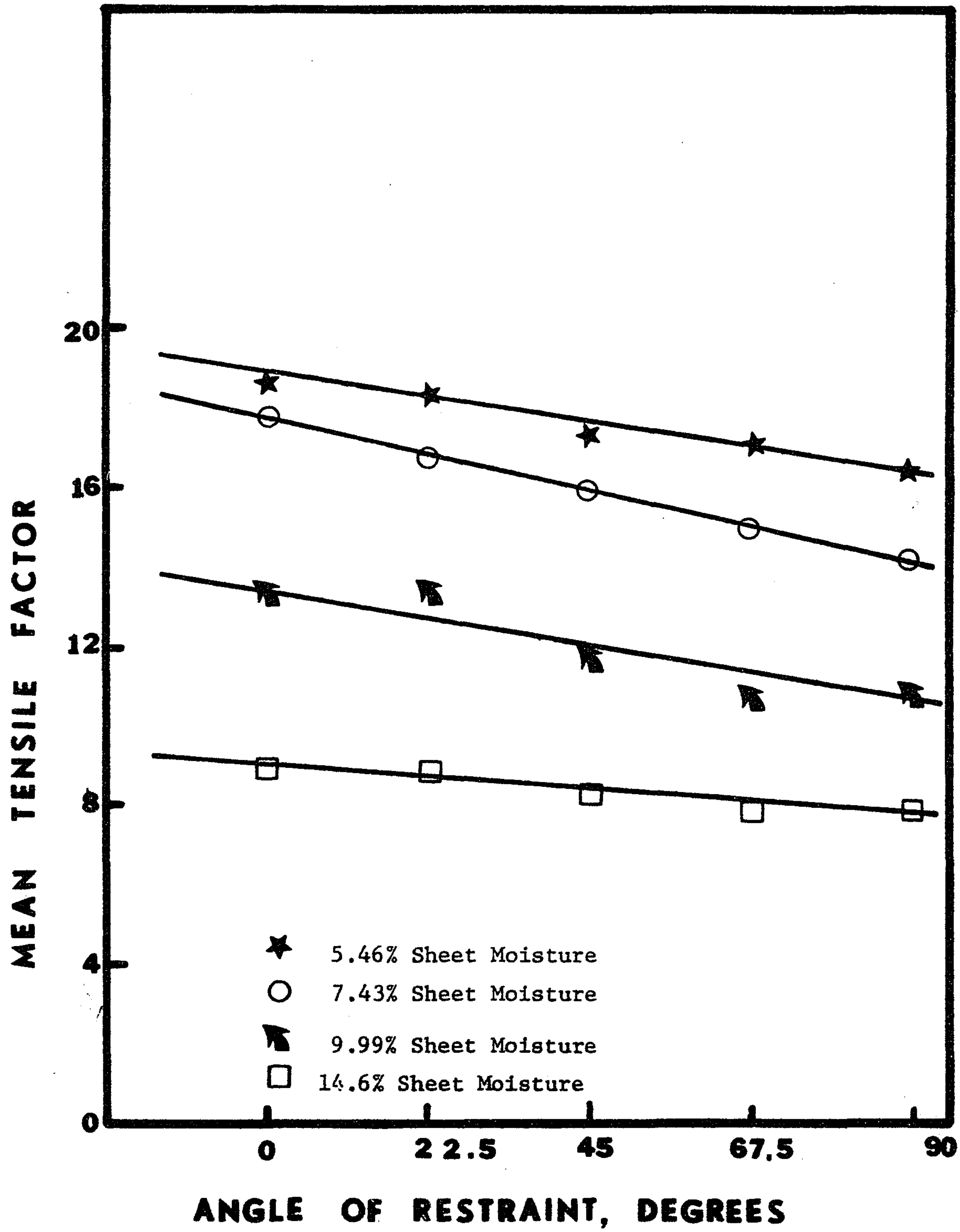


Fig. 13. The Effect of Angle of Restraint During Drying on the Mean Tensile Strength Factor

with increase in moisture content is presumably due to the weakening effect on interfiber bonding. The cross strain direction tensile is significantly lower than the strain direction tensile.

In Table VII, the mean strain direction and cross strain direction tensile strengths and the ratio of the two are tabulated. It is observed that the SD:CD ratio increases to a maximum around 3% wet straining, causing the sheet to become more directional in its properties. Further wet straining results in a decrease of the SD:CD ratio. This observation is similar to the effect of wet straining on the tensile strength previously discussed. As the sheet moisture is increased the SD:CD ratio approaches unity indicating a decrease in tensile strength anisotropy, Fig. 14. This can be attributed to two factors. First, the softening of the interfiber bonds will enable the fibers and fibrils to flex and contribute strength in all directions. Secondly, the microfibrils and crystallites will tend to return to their original states due to adsorption of moisture by the less well-ordered regions of the fiber and in the process tend to revert the fiber to its original, unstrained condition.

Table VII

Effect of Sheet Moisture on Tensile Anisotropy

Sheet Moisture %	Degree of Wet Straining	Machine Direction Tensile	Cross Direction Tensile	SD/CD
	%			
5.46	0	18.34	15.68	1.17
5.46	1.5	18.38	15.65	1.26
5.46	3.0	19.80	14.61	1.36
5.46	3.57	17.81	13.29	1.34
7.43	0	15.10	13.72	1.10
7.43	1.5	19.16	15.47	1.24
7.43	3.0	18.76	13.92	1.35
7.43	3.57	18.28	13.74	1.33
9.99	0	12.32	11.50	1.07
9.99	1.5	13.32	10.92	1.22
9.99	3.0	14.29	10.77	1.33
9.99	3.57	13.44	10.46	1.28
14.6	0	7.82	8.44	0.93
14.6	1.5	9.56	8.05	1.19
14.6	3.0	9.21	7.34	1.25
14.6	3.57	8.91	7.45	1.20

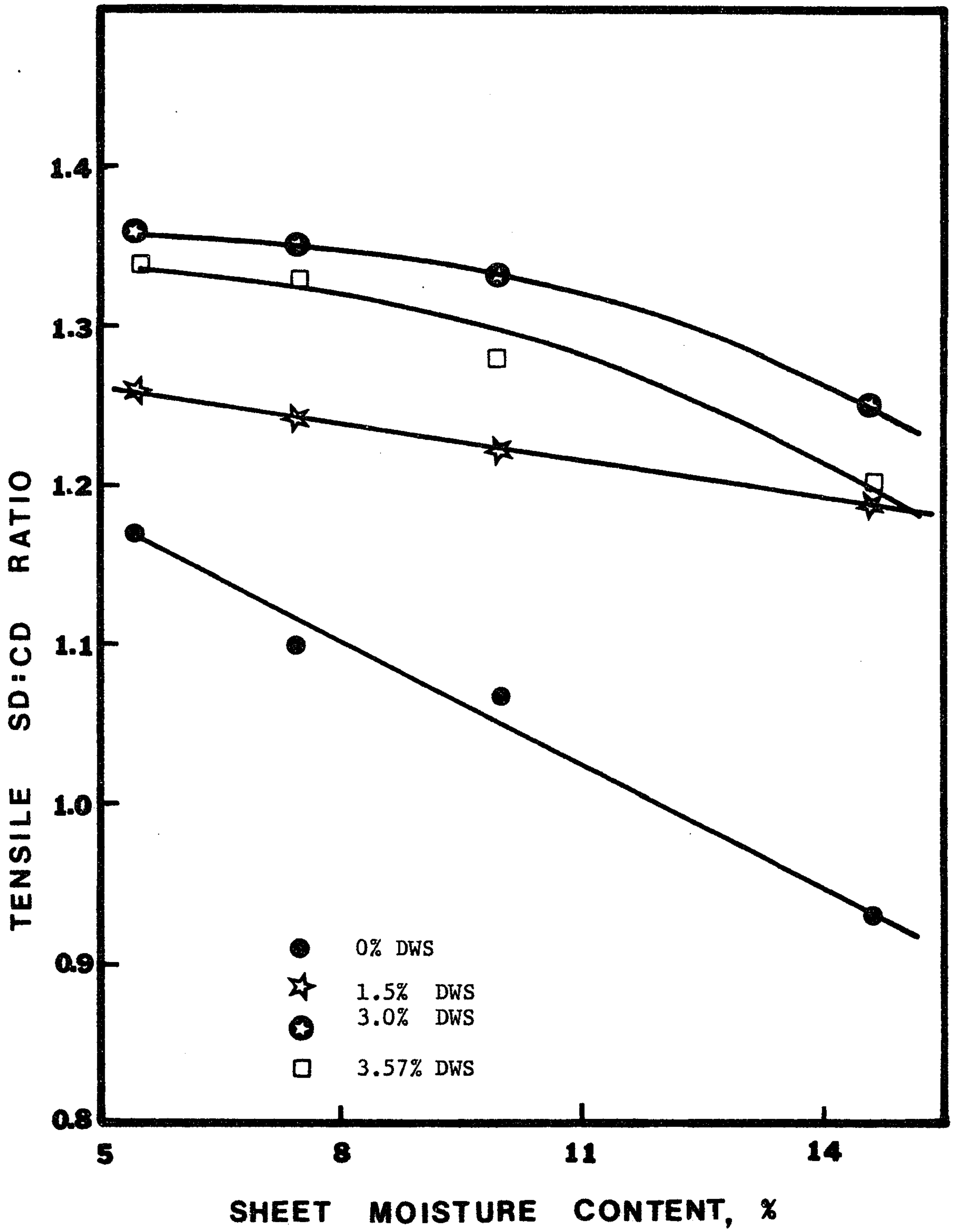


Fig. 14. The Effect of Sheet Moisture Content on Tensile Strength SD:CD Ratio

Tearing Strength

Wet straining effects on tearing strength at each of the four relative humidities is presented in Tables II-V. An examination of Figs. 15-18 reveals that, in the majority of cases, the effect of wet straining is to initially decrease tearing strength to a minimum and upon further wet straining to increase it. At 90% RH, only the cross strain direction tearing strength increases with increase in wet straining whereas the 22.5°, 45° and 67.5° tearing strengths decrease steadily throughout.

The effect of wet straining on tearing strength can be explained by the theory proposed by Van den Akker (43). The initial decrease in tearing strength/degree of wet straining curve may be due to a decrease in the 'frictional drag work' by virtue of looser enmeshment caused by slightly decreased bonding (4) during which time a large number of fibers fail in tensile rupture. As straining is continued, less fibers fail in tensile rupture and therefore, more fibers are pulled intact from the mesh. Since the frictional drag work per fiber is very much greater than the rupture work, this increase in the number of fibers pulled intact from the mesh causes the tearing strength to increase.

Fig. 19 shows the effect of the angle of restraint during drying and sheet moisture on the mean tearing strength. There is a general increase in tearing strength in the cross strain direction. Again, this can be attributed to an increase in frictional drag work caused by more fibers being pulled out intact than being ruptured in the

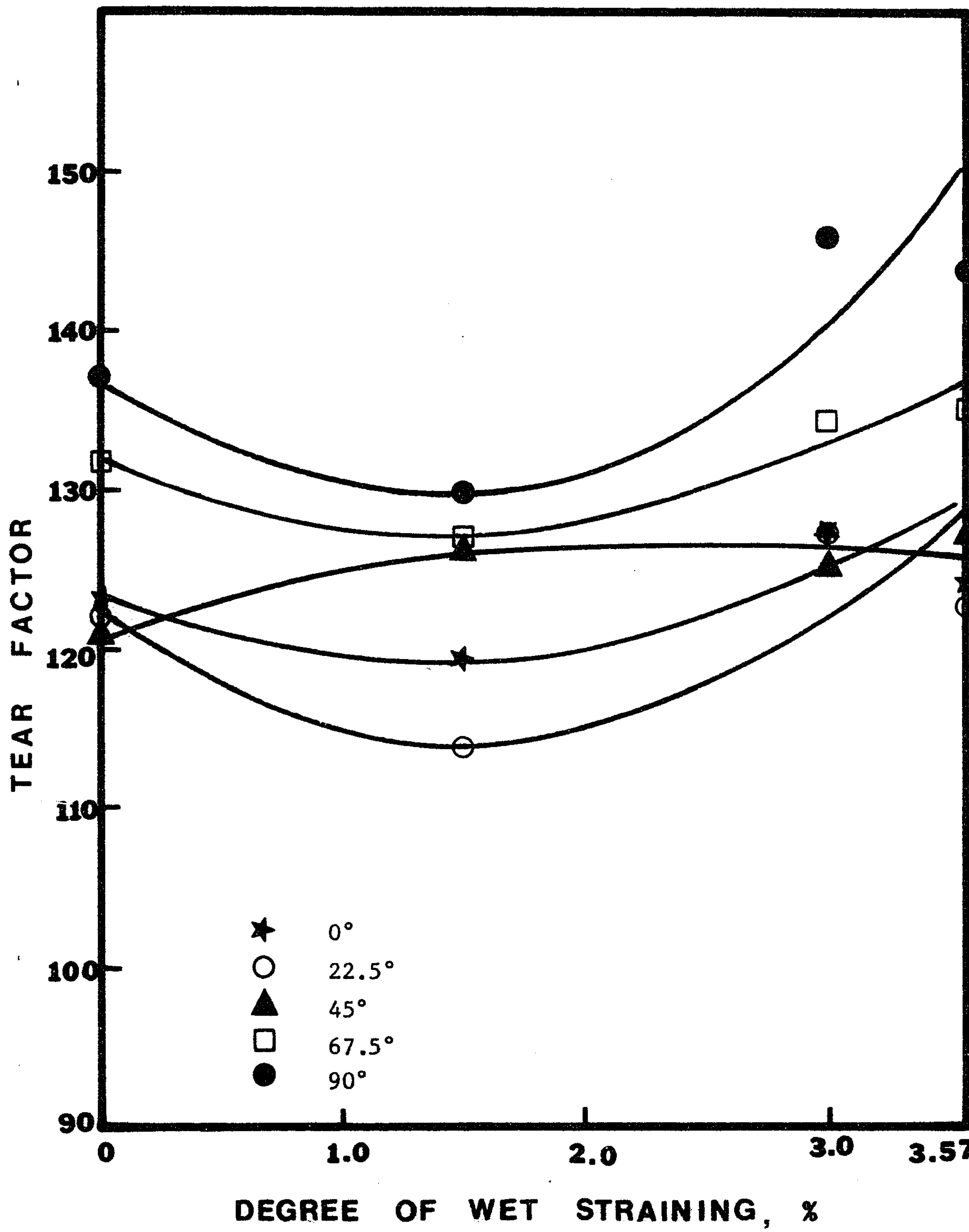


Fig. 15. The Effect of Wet Straining on the Tearing Strength of Paper at 30% RH

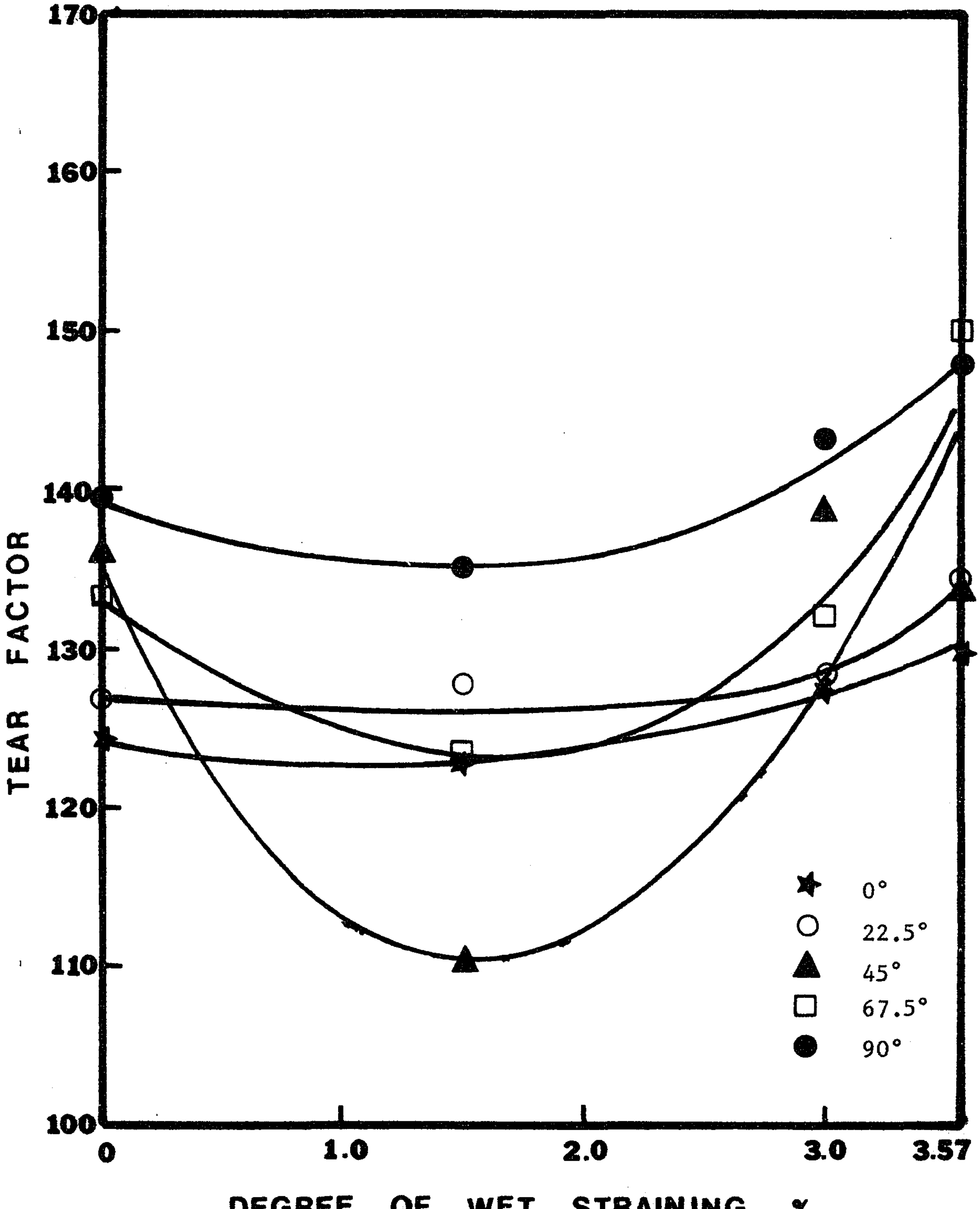


Fig. 16. The Effect of Wet Straining on the Tearing Strength of Paper at 50% RH

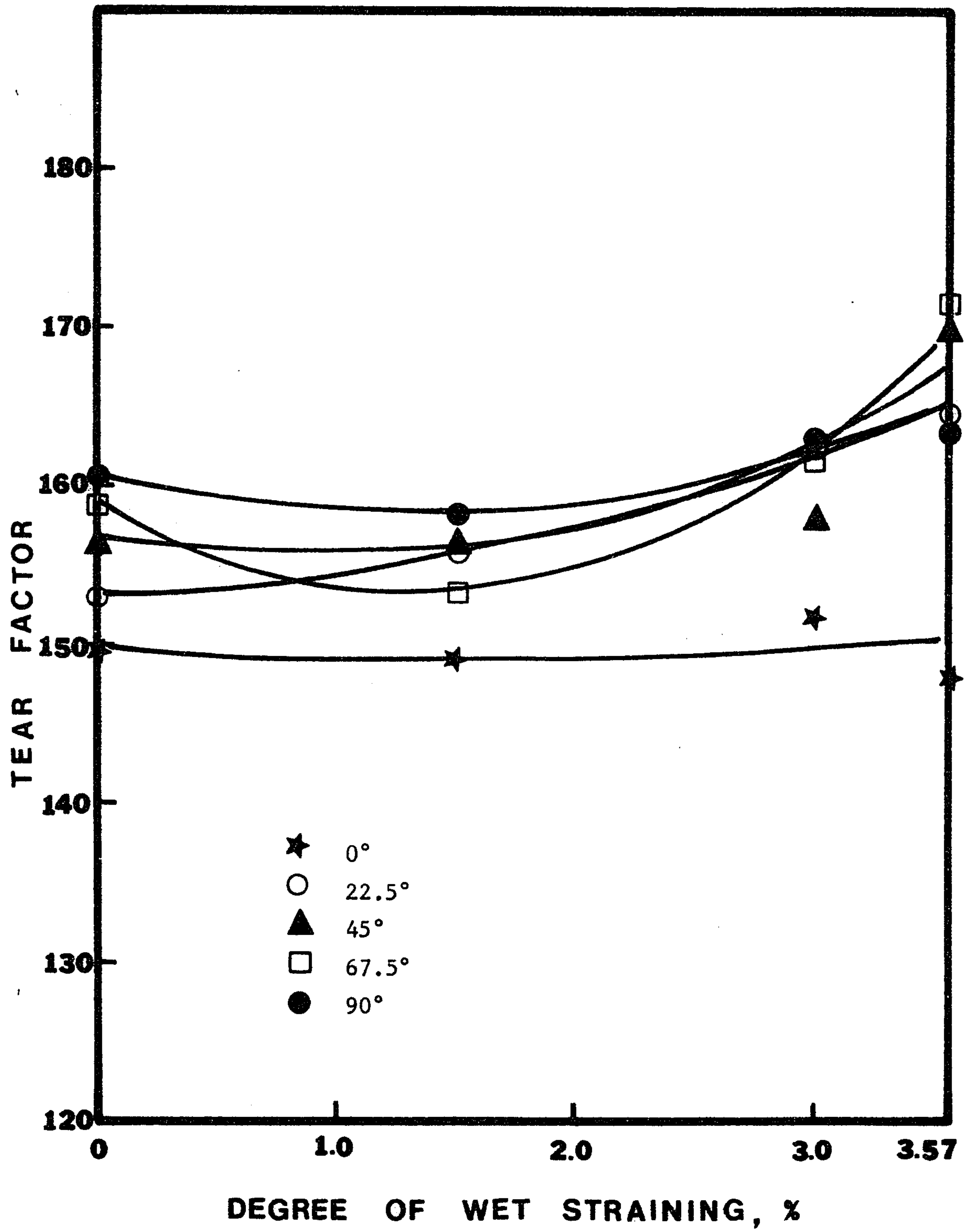


Fig. 17. The Effect of Wet Straining on the Tearing Strength of Paper at 70% RH

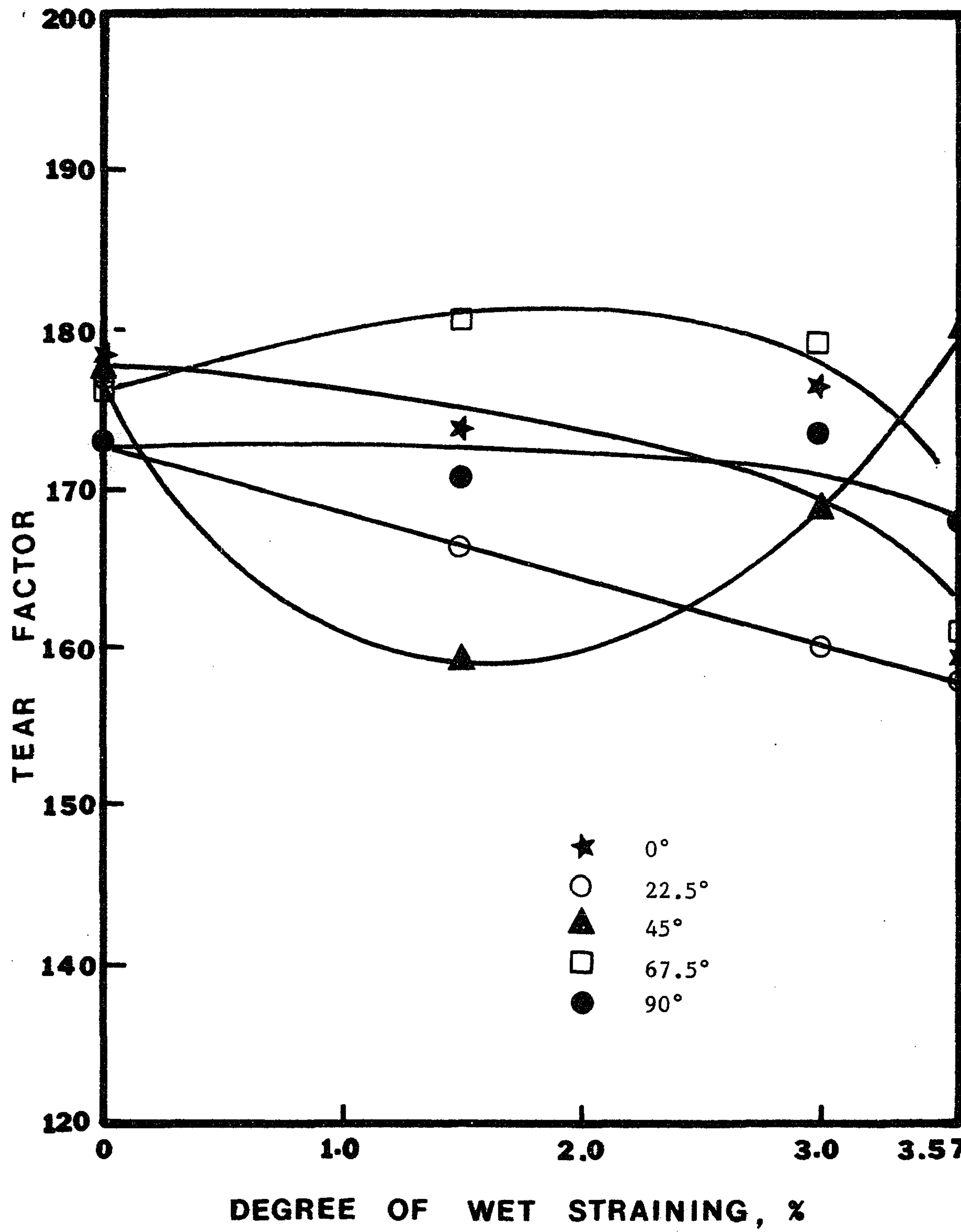


Fig. 18. The Effect of Wet Straining on the Tearing Strength of Paper at 90% RH

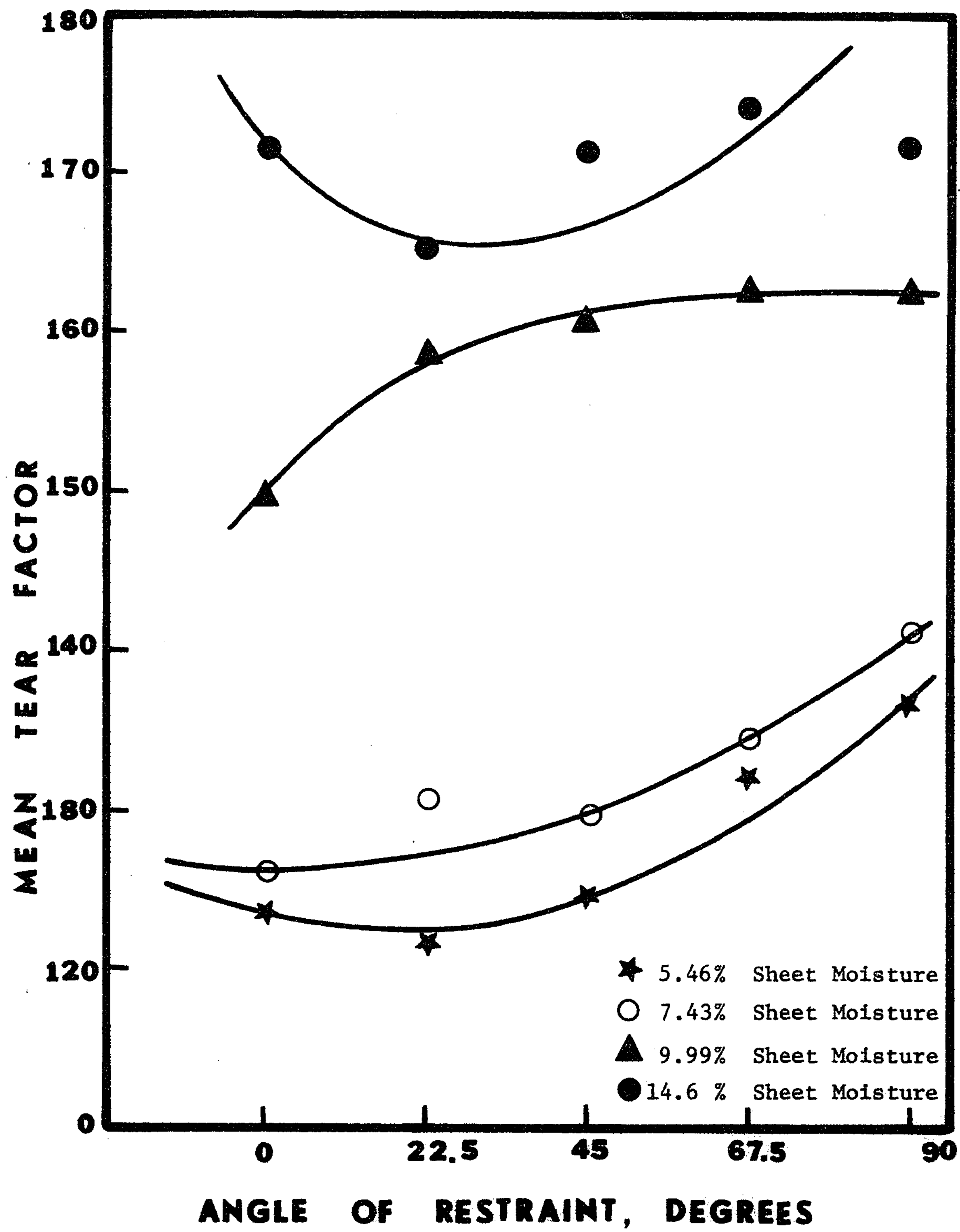


Fig. 19. The Effect of Angle of Restraint During Drying on the Mean Tearing Strength Factor

cross direction. Moisture has a pronounced influence on tearing strength. Tearing strength increases with an increase in sheet moisture content. Tearing resistance is dependent upon long fibers, loosely bonded and free to move during the tearing operation (44). Such a loose system allows distortion and dislocation of a greater number of fibers in tearing a given distance thus requiring the expenditure of more work than if the line of tear is a sharp one as experienced when the fibers are locked together firmly in a sheet of well beaten stock. Moisture reduces interfiber bonding thus allowing the fibers to undergo greater distortions and dislocations. This increases the tearing strength of paper.

The cross strain direction exhibits a higher tearing strength than the strain direction. Consequently, the SD:CD ratio is less than unity. Table VIII and Fig. 20 show the effect of wet straining and sheet moisture on tearing strength SD:CD ratio. As the sheet moisture increases the SD:CD anisotropy decreases as exemplified by the ratio approaching unity. There is no correlation between wet straining and the tearing strength anisotropy ratio.

TABLE VIII

Tearing Strength SD:CD Ratio

Sheet Moisture %	0% DWS	1.5% DWS	3.0% DWS	3.57% DWS
5.46	0.896	0.870	0.860	0.860
7.43	0.891	0.925	0.855	0.878
9.99	0.931	0.944	0.931	0.903
14.6	1.03	1.02	1.02	0.950

Table IX

Ultimate Elongation SD:CD Ratio

Sheet Moisture %	0% DWS	1.5% DWS	3.0% DWS	3.57% DWS
5.46	0.45	0.38	0.27	0.25
7.43	0.48	0.41	0.30	0.26
9.99	0.54	0.44	0.33	0.28
14.6	0.62	0.49	0.37	0.33

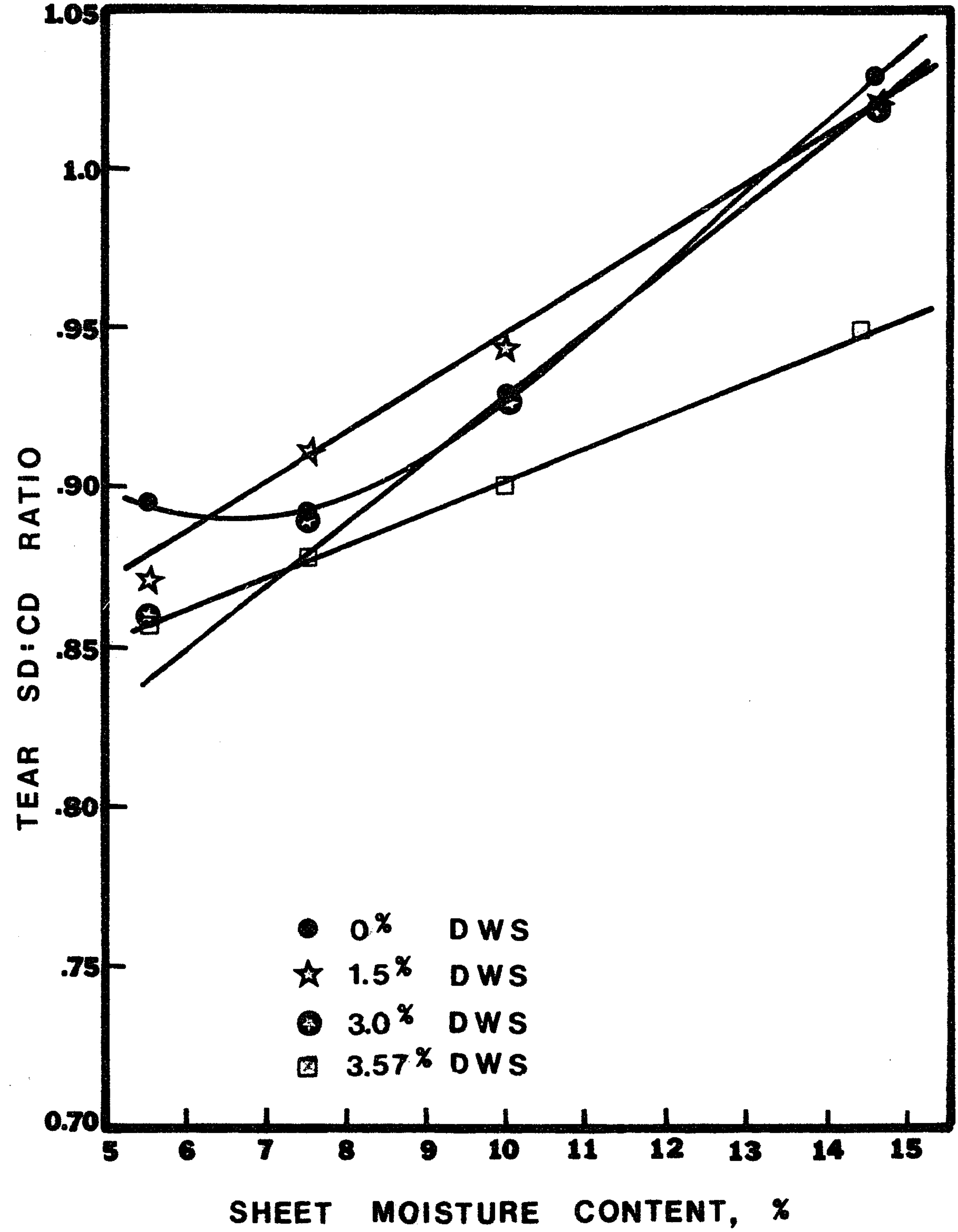


Fig. 20. The Effect of Sheet Moisture Content on Tearing Strength SD:CD Ratio

Ultimate Elongation

The effect of wet straining on sheet elongation is shown in Figures 21-24 at the different relative humidities. Ultimate elongation depends upon the nature of the response of the sheet to stress and upon the tensile strength of the sheet.

Wet straining reduces the ultimate elongation of paper. This is in accordance with other work that has appeared in the literature. According to Kallmes (18), the elongation taking place when a piece of paper is loaded depends mainly on the bending and deflection of the free fiber segments between the fiber to fiber bonds. At the same time the fibers are also elongated. Elongation of a paper thus depends on the length of the segments, the orientation of the fibers and the modulus of elasticity of the fibers.

A plausible explanation for the reduction in ultimate elongation with increase in wet straining is that during wet straining the fibers slip to some extent. This will straighten out the slightly curved and kinked segments thus reducing the overall extensibility of each fiber. Also, x-ray investigations conducted by Jentzen (23) show that the microfibrils in the secondary wall, S2 layer of the fiber become oriented, straightened and stressed by tension drying. This influences fiber elongation and modulus of elasticity.

Changes in ultimate elongation with sheet moisture and angle of restraint during drying is shown in Fig. 25. It is seen that the effect is very significant. The cross direction elongation increases

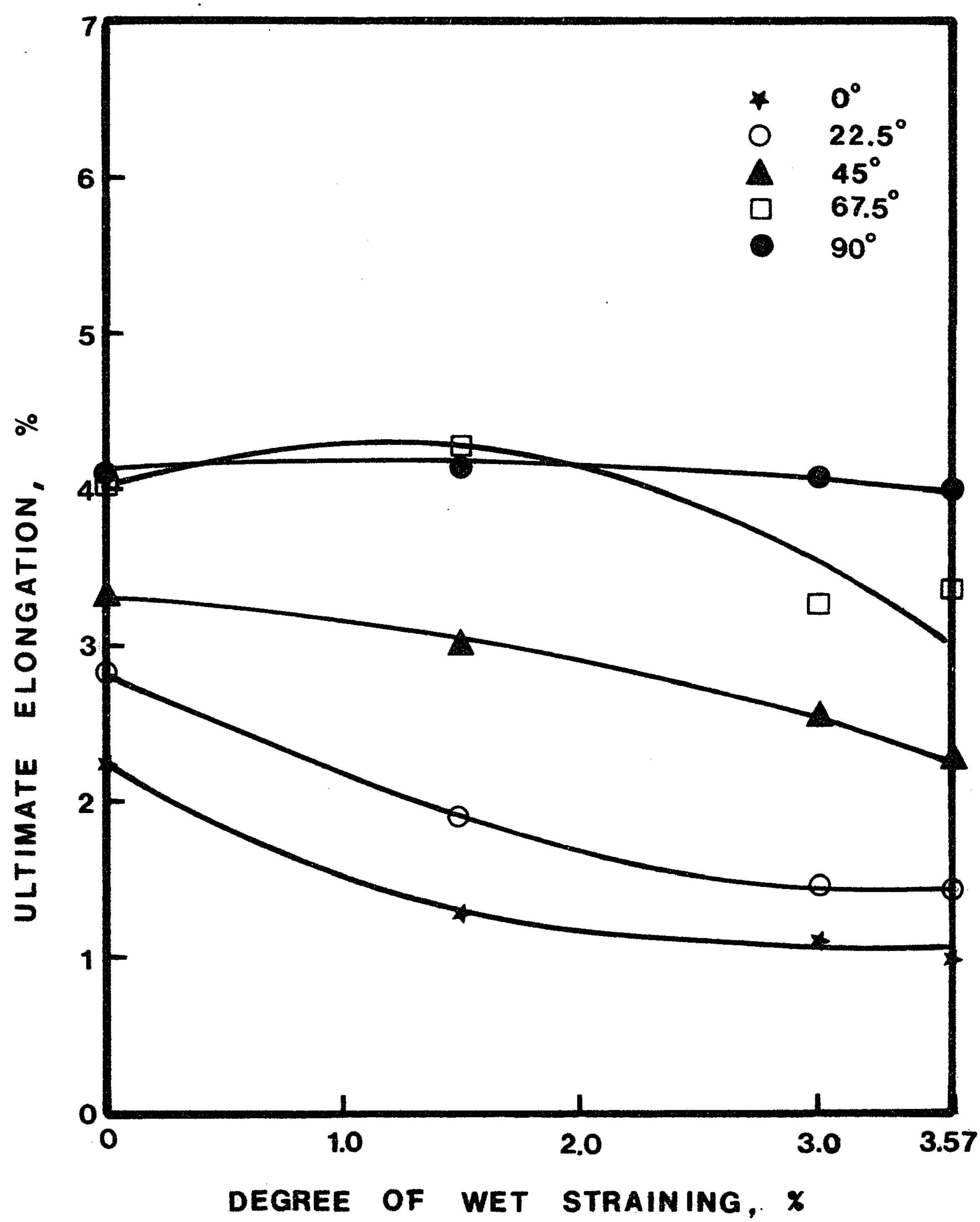


Fig. 21. The Effect of Wet Straining on the Ultimate Elongation of Paper at 30% RH

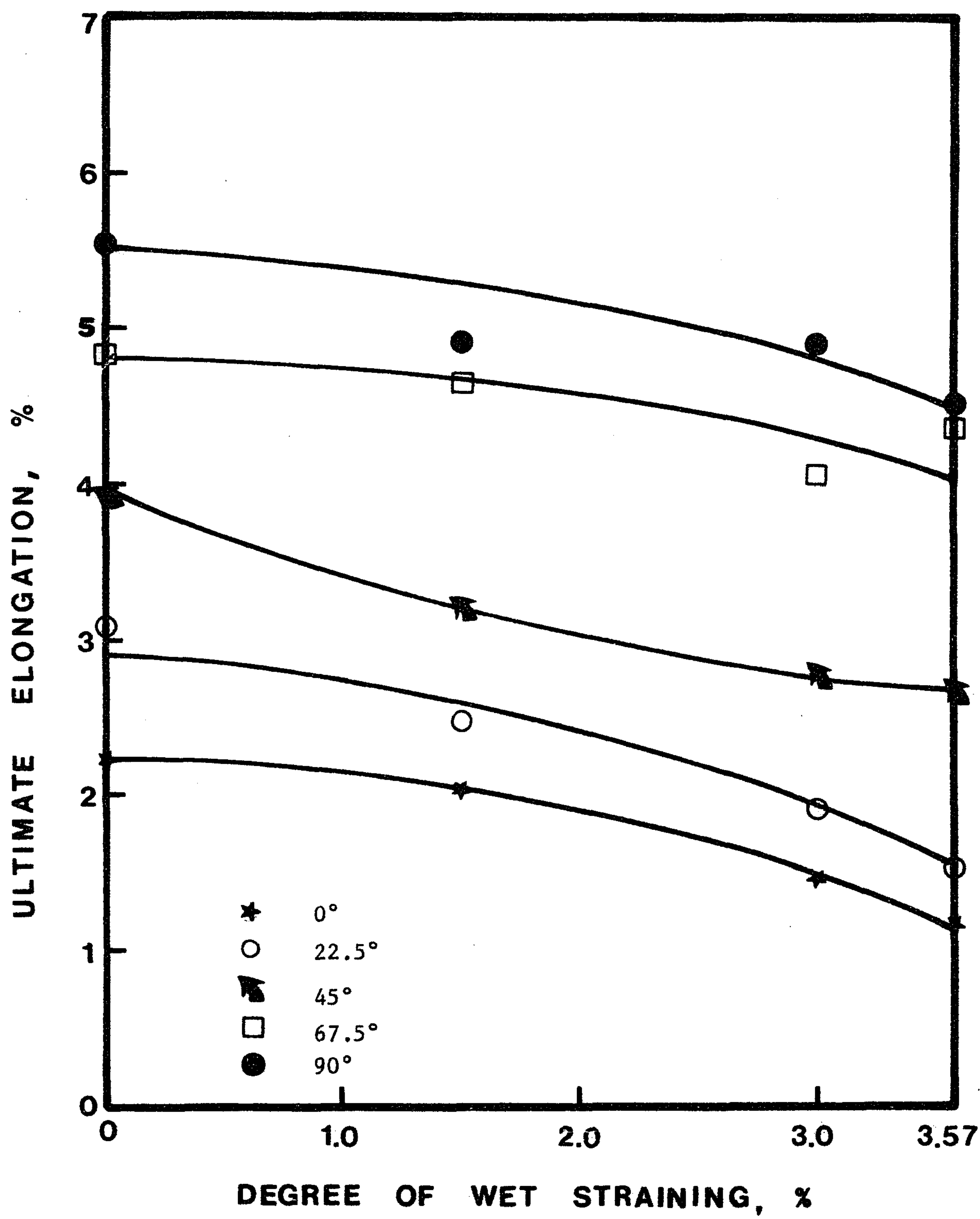


Fig. 22. The Effect of Wet Straining on the Ultimate Elongation of Paper at 50% RH

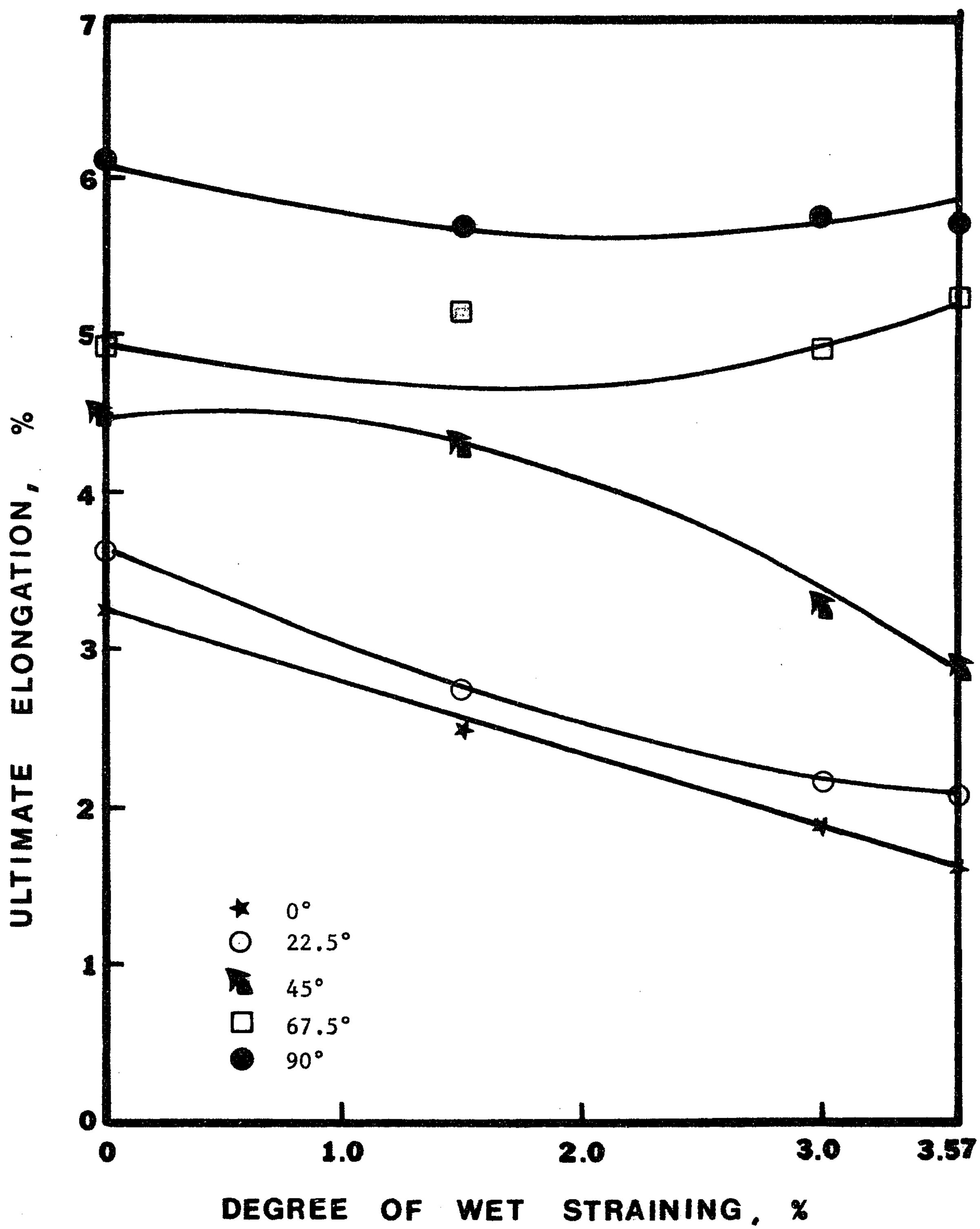


Fig. 23. The Effect of Wet Straining on the Ultimate Elongation of Paper at 70% RH

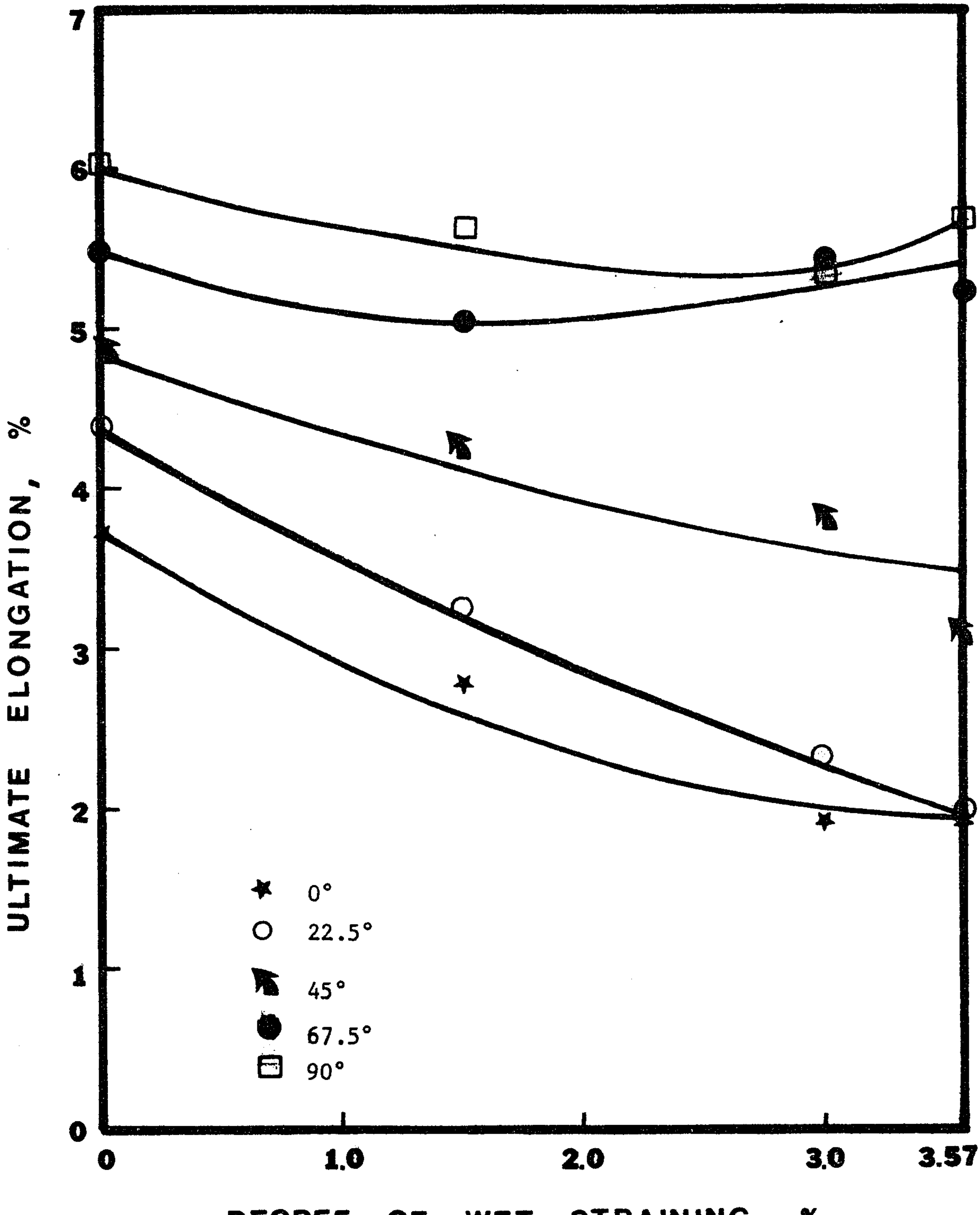


Fig. 24. The Effect of Wet Straining on the Ultimate Elongation of Paper at 90% RH

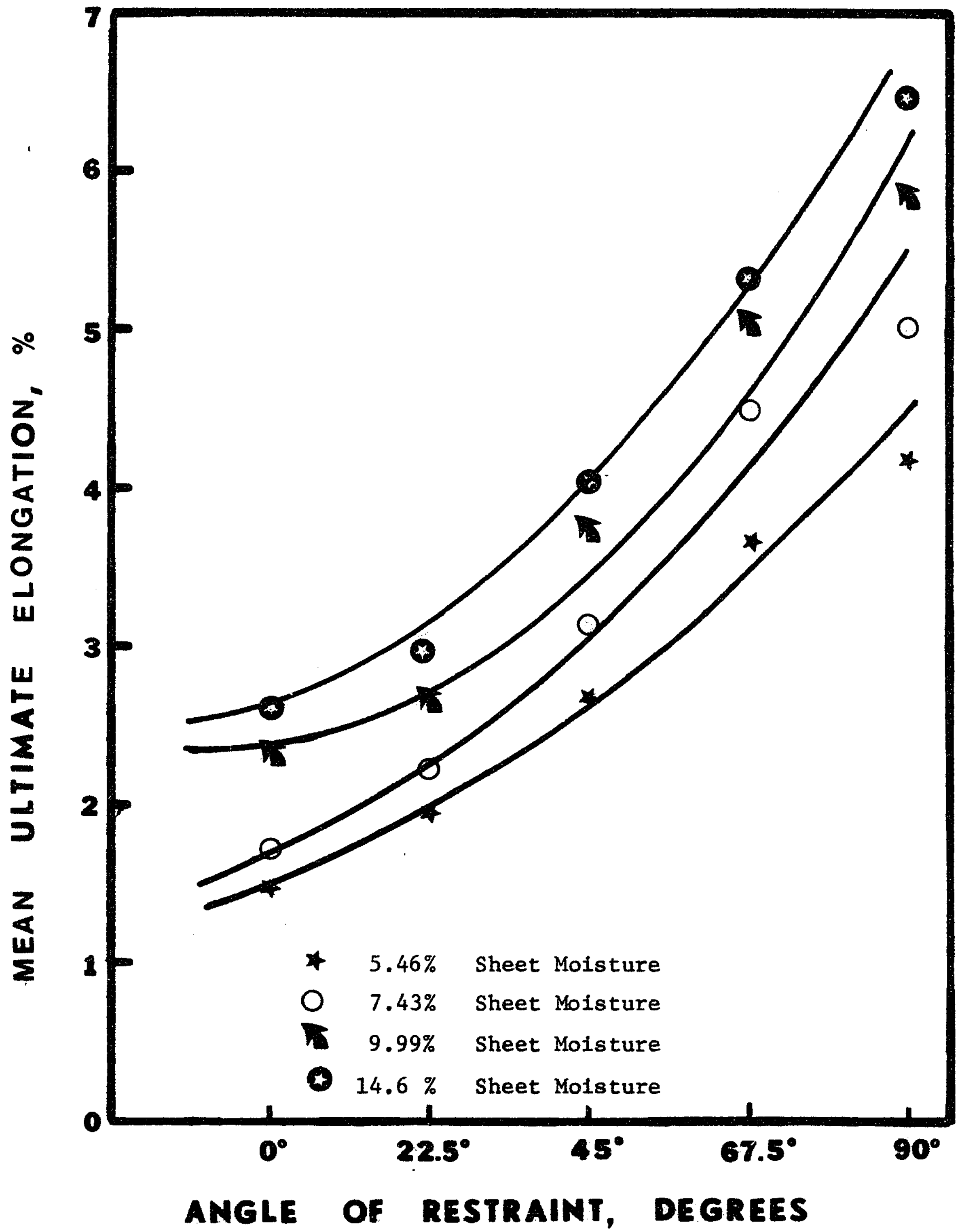


Fig. 25. The Effect of Angle of Restraint During Drying on the Mean Ultimate Elongation of Paper

at a faster rate than the machine direction with increase in moisture content. When fibers take up water and swell, the S2 layer expands laterally and in order to retain the total length of the spiral, the fiber has to become shorter (23). This, together with the improved flexibility of the fiber segments and the reduction in interfiber bonding, increases the ultimate elongation of the sheet.

Ultimate elongation SD:CD ratios are tabulated in Table IX and illustrated in Fig. 26. The reduction in ultimate elongation anisotropy with increased sheet moisture is clearly observed. The anisotropy ratio increases with increase in moisture content indicating a decrease in the directionality of the sheet. However, the sheet is a long ways from being perfectly 'symmetrical' even at the high humidities. The 3.0% and 3.57% wet strained paper looses its unidirectionality much slowly than the 0.0% strained sheet and they also demonstrate greater SD:CD anisotropy.

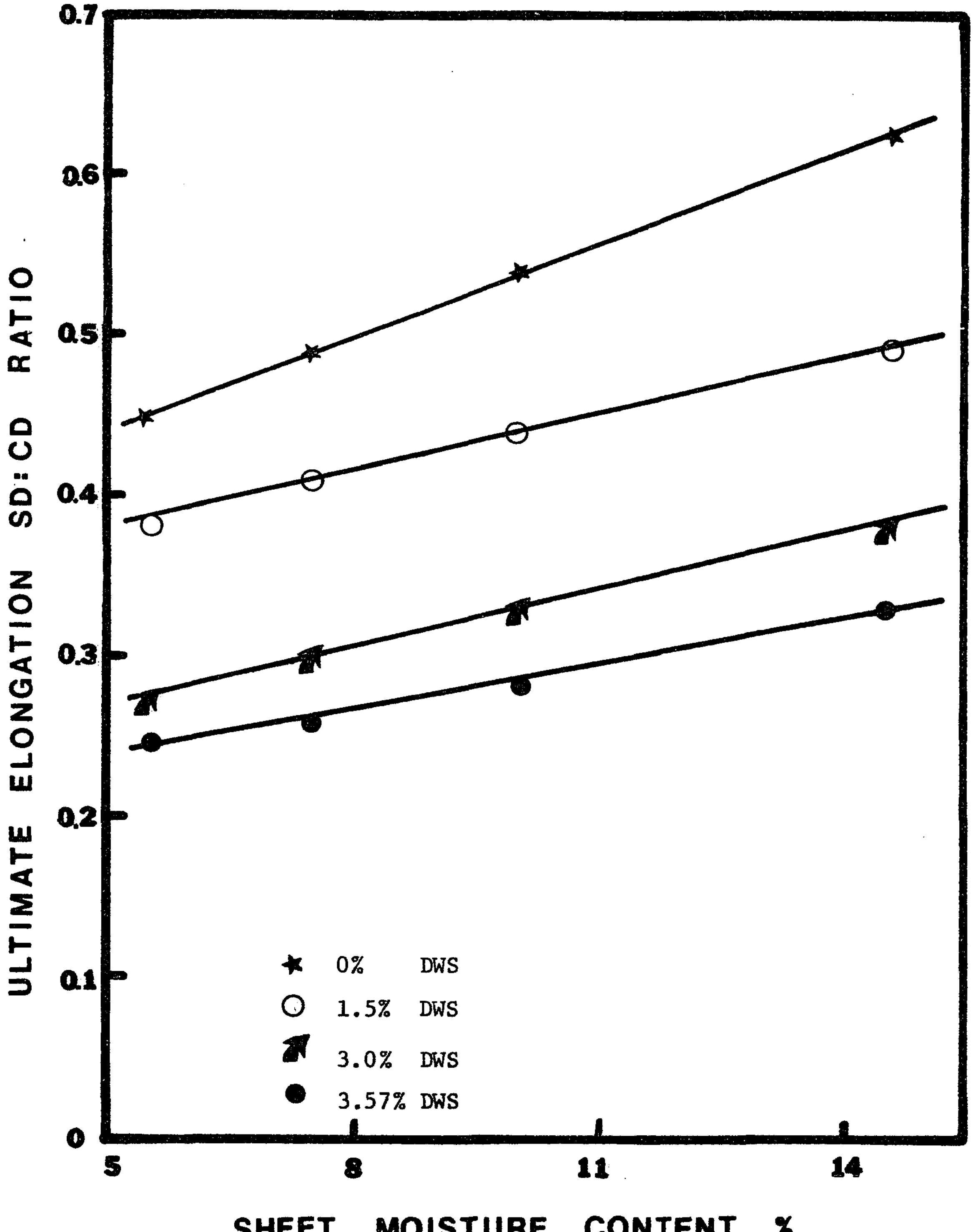


Fig. 26. The Effect of Sheet Moisture on Ultimate Elongation SD:CD Ratios

Modulus of Elasticity

A material is said to be elastic if it exhibits a reversible relationship between stress and strain, and if this relationship is not time dependent. When a load is removed from an elastic body, the body will return to its original length. Hooke's law states that the stress set up within an elastic body is proportional to the strain to which the body is subjected to by the applied load. The modulus of elasticity is defined as the ratio of the stress to the strain, and its value depends upon the units selected for stress and strain.

An estimate of the elastic modulus of paper can be obtained by measuring the initial slope of the load-elongation curve. The modulus of elasticity of handsheets subjected to various degrees of wet straining is shown in Figures 27-30. The units of the moduli are given in dynes per square centimeter. The modulus of elasticity reaches a maximum around 3.0% wet straining and then decreases. The parallel of this behavior with changes observed in tensile strength is apparent. This is further evidence that significant changes occur in a sheet when it is wet strained.

Fig. 31 demonstrates the effect of restraint during drying and moisture content on the modulus of elasticity. The machine direction exhibits a substantially higher elastic modulus than the cross direction. As moisture increases, the modulus of elasticity decreases. A 56% decrease in the machine direction and a 60% decrease in the modulus of elasticity in the cross direction resulted from increasing the sheet moisture from 5.46% to 14.6%.

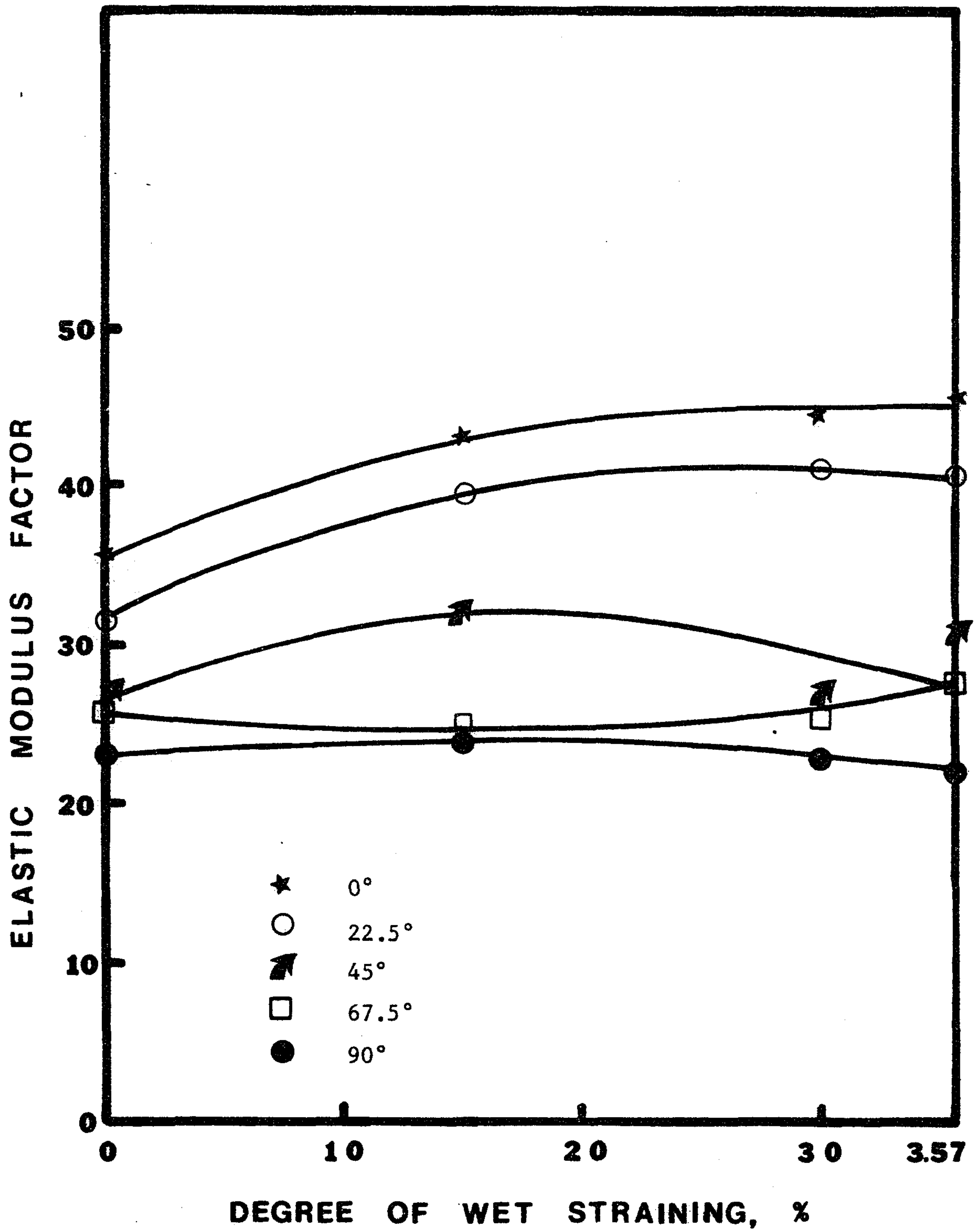


Fig. 27. The Effect of Wet Straining on the Modulus of Elasticity at 30% RH

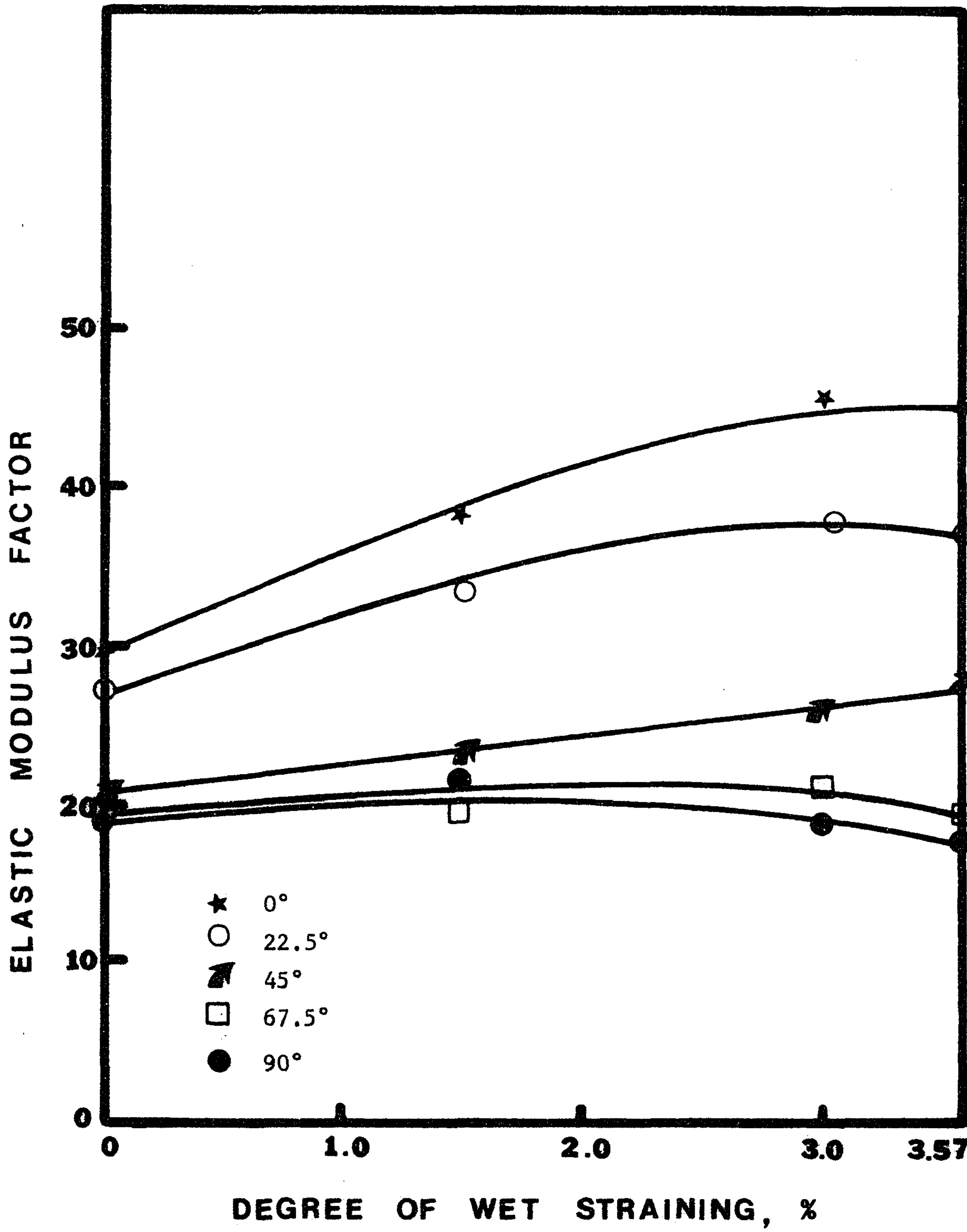


Fig. 28. The Effect of Wet Straining on the Modulus of Elasticity at 50% RH

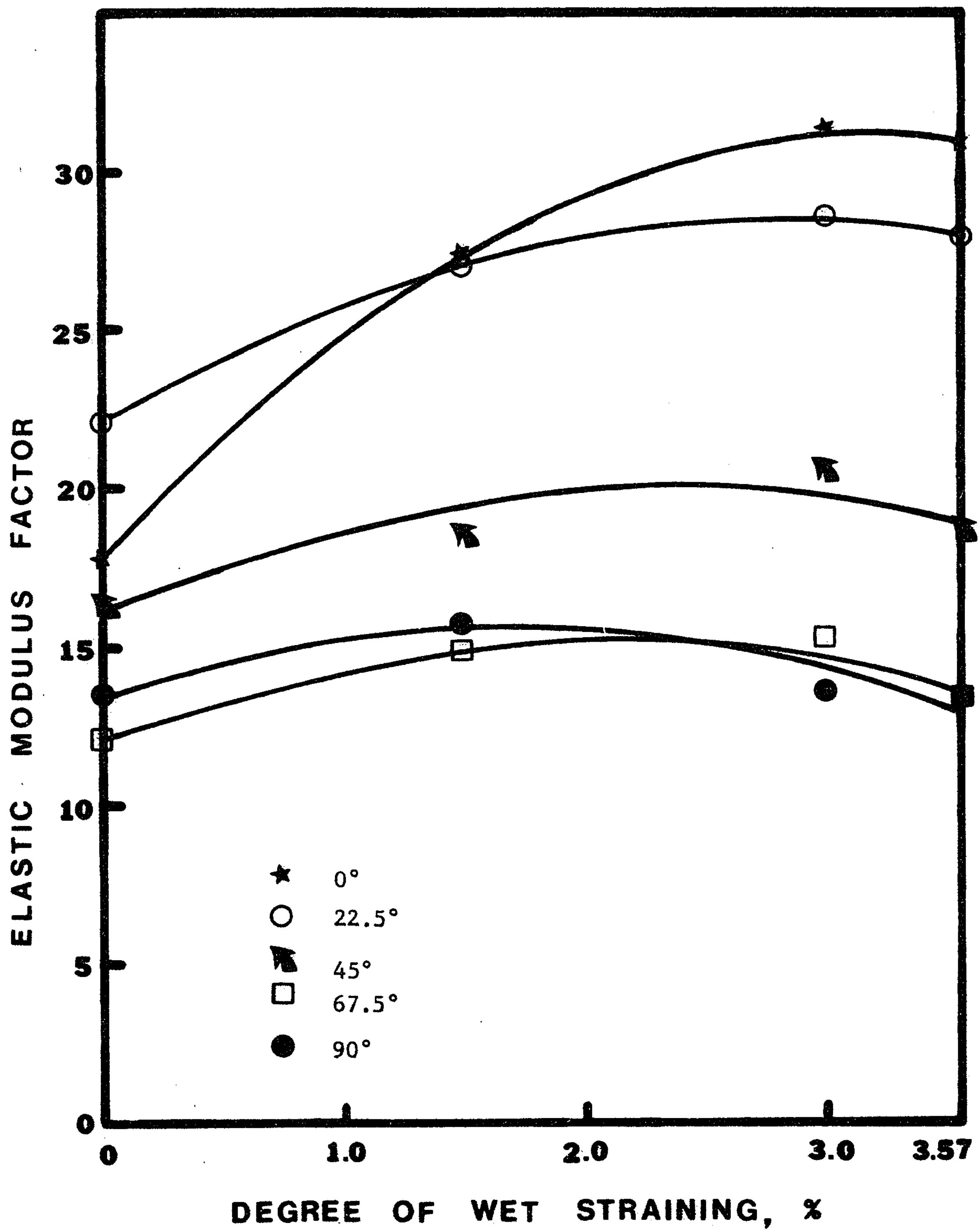


Fig. 29. The Effect of Wet Straining on the Modulus of Elasticity at 70% RH

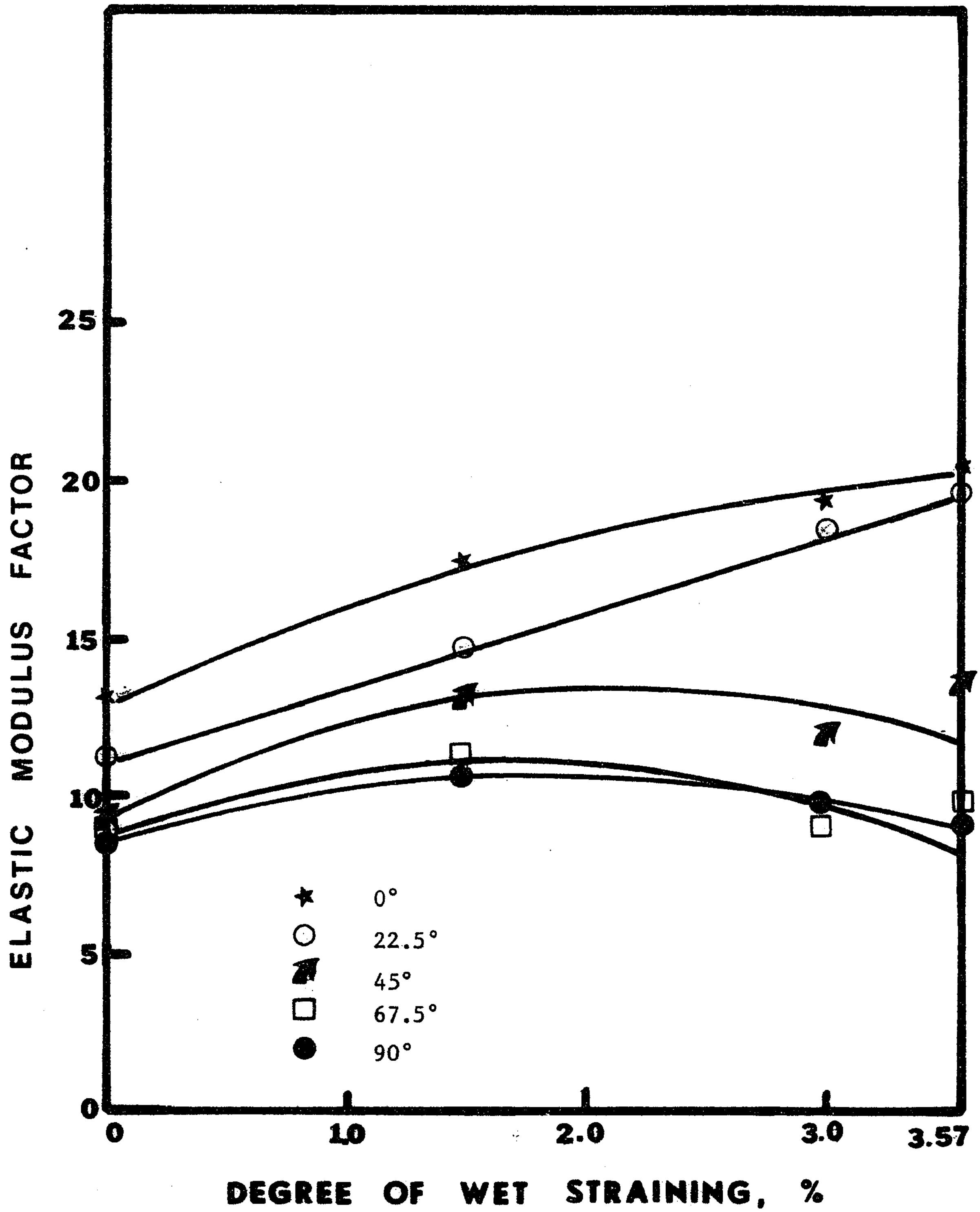


Fig. 30. The Effect of Wet Straining on the Modulus of Elasticity at 90% RH

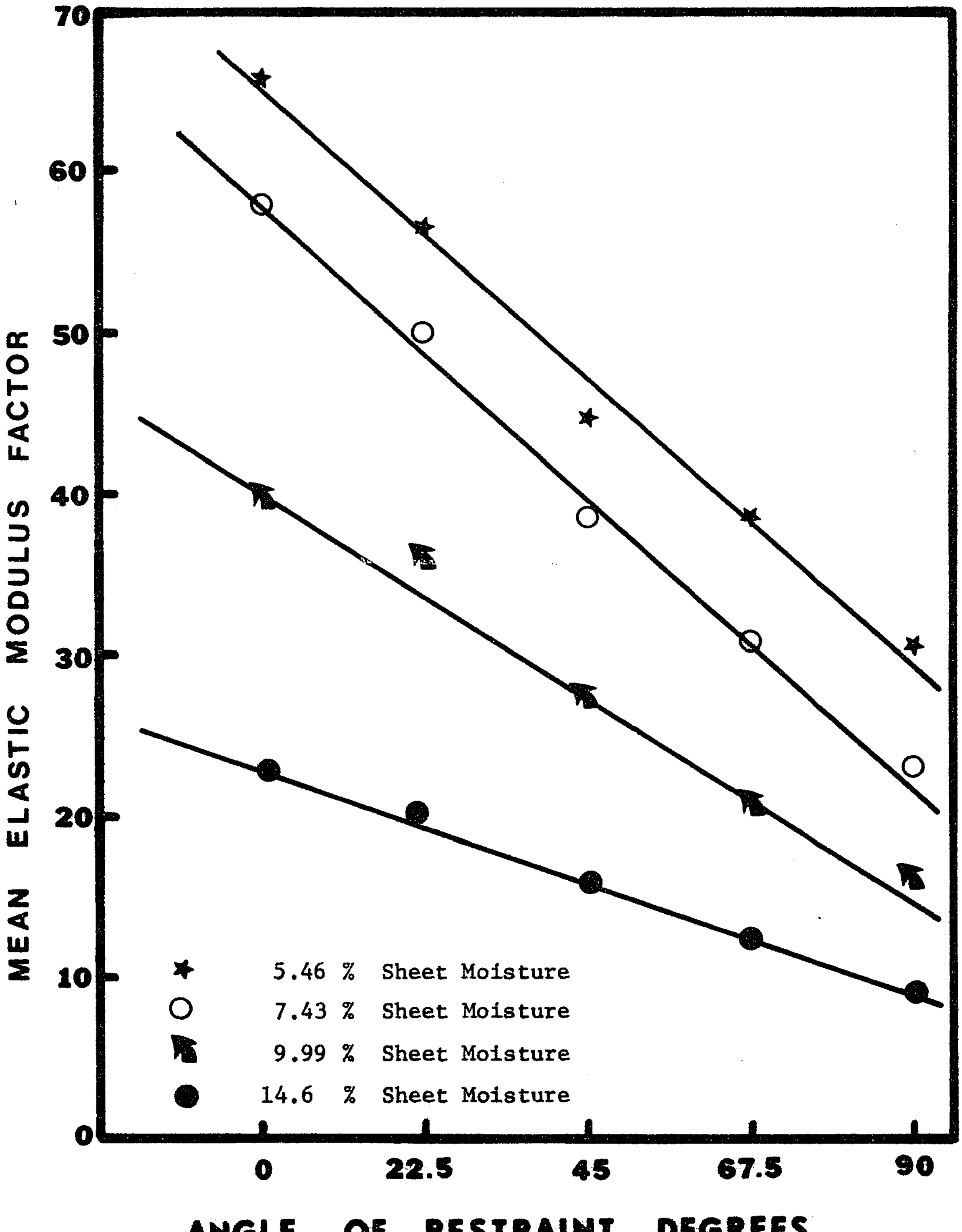


Fig. 31. The Effect of Angle of Restraint During Drying on the Mean Modulus of Elasticity Factor

Wet straining is seen to increase the modulus of elasticity SD:CD ratio of paper, Fig. 32. There is no significant effect of sheet moisture on this SD:CD anisotropy.

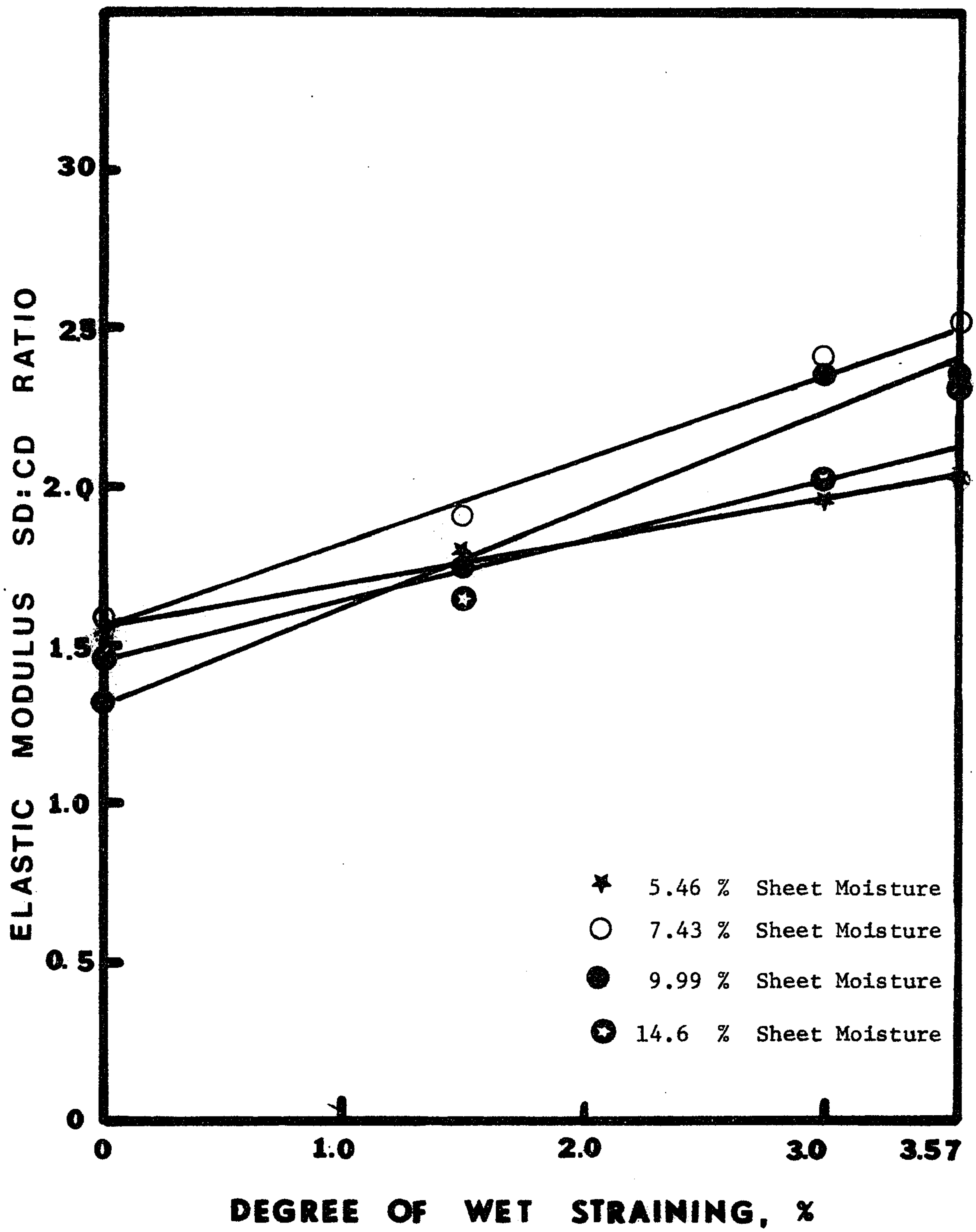


Fig. 32. The Effect of Wet Straining on the Modulus of Elasticity SD:CD Ratio

Tensile Energy Absorption, TEA

The changes in tensile energy absorption created by wet straining are shown in Figures 33-36. A marked reduction in rupture energy as the degree of wet straining is increased is observed. Wet straining is known to decrease the amount of bonding in a sheet (4). It has been shown (45) that the tensile energy absorption depends upon the number of interfiber bonds, the strength of these bonds and to a lesser extent on the strength of the individual fibers and the geometrical structure of the fiber network. Corte and Schaschek (45) have found that the application of drying stress results in the breakage of hydroxyl bonds and that the chemical energy involved in this reaction is transformed into mechanical energy. Further, the final rupture energy is lowered by this amount. This is in accordance with the observed effects of wet straining on the rupture energy.

Fig. 37 illustrates the effect of the angle of restraint during drying and sheet moisture on the rupture energy. The strain direction has a higher rupture energy than the cross strain direction. This may be due to the slight orientation of the microfibrils caused by wet straining. Sheet moisture has a negative effect on the rupture energy. The constituents of the interfiber bonds absorb moisture and swell, thus weakening the bonds.

The rupture energy anistoropy development with drying restraint and sheet moisture is shown in Fig. 38. Wet straining increases

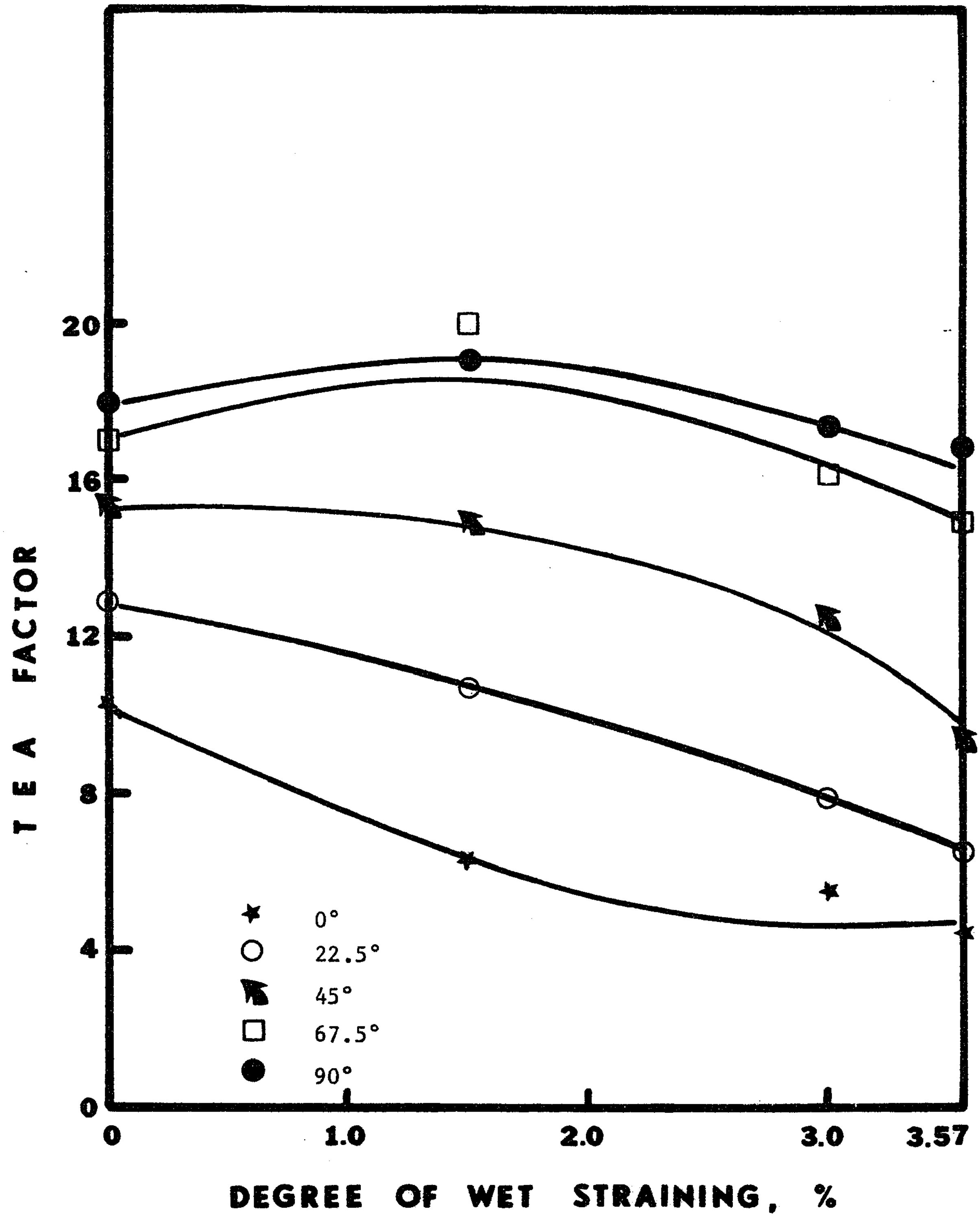


Fig. 33. The Effect of Wet Straining on the Tensile Energy Absorption of Paper at 30% RH

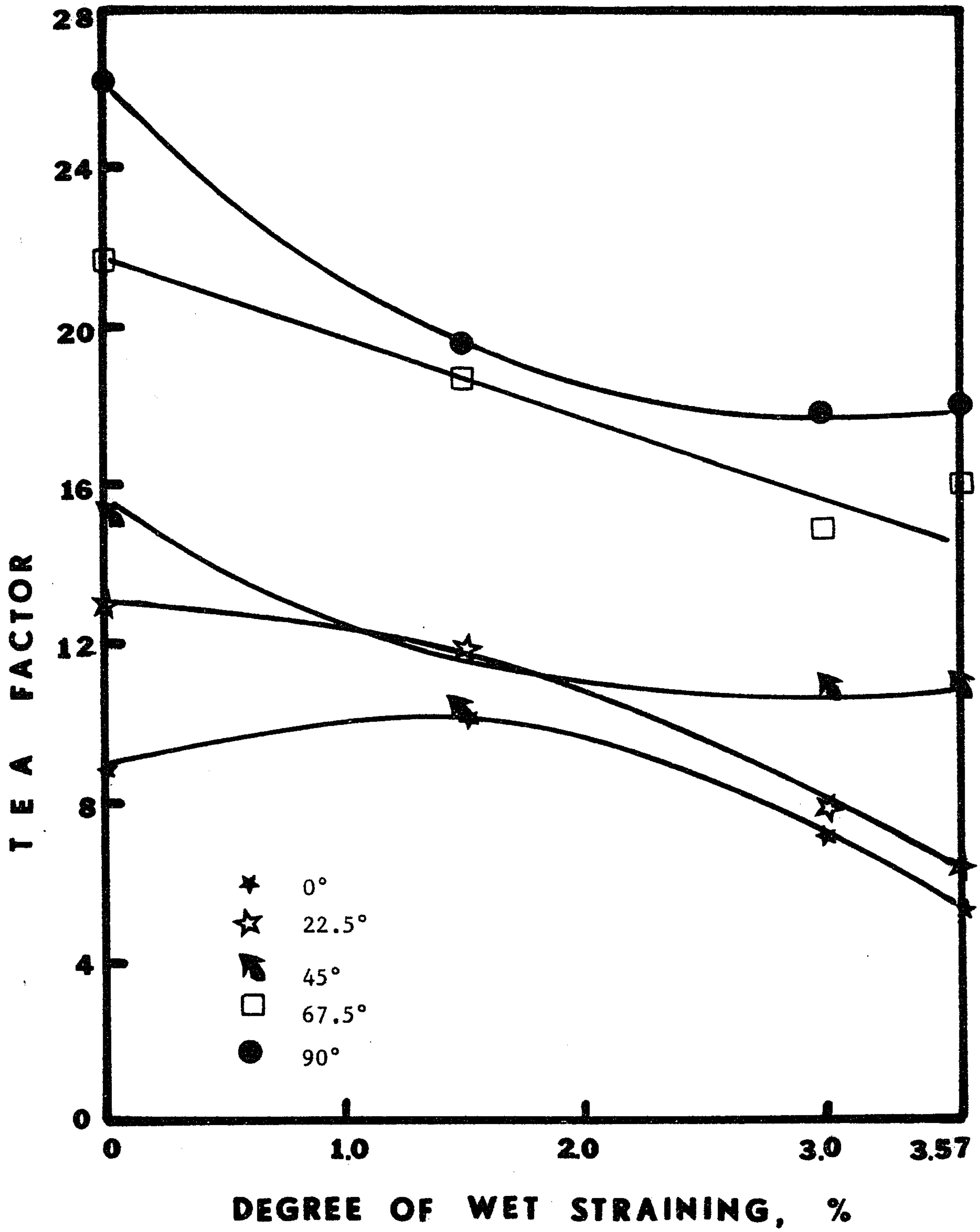


Fig. 34. The Effect of Wet Straining on the Tensile Energy Absorption of Paper at 50% RH

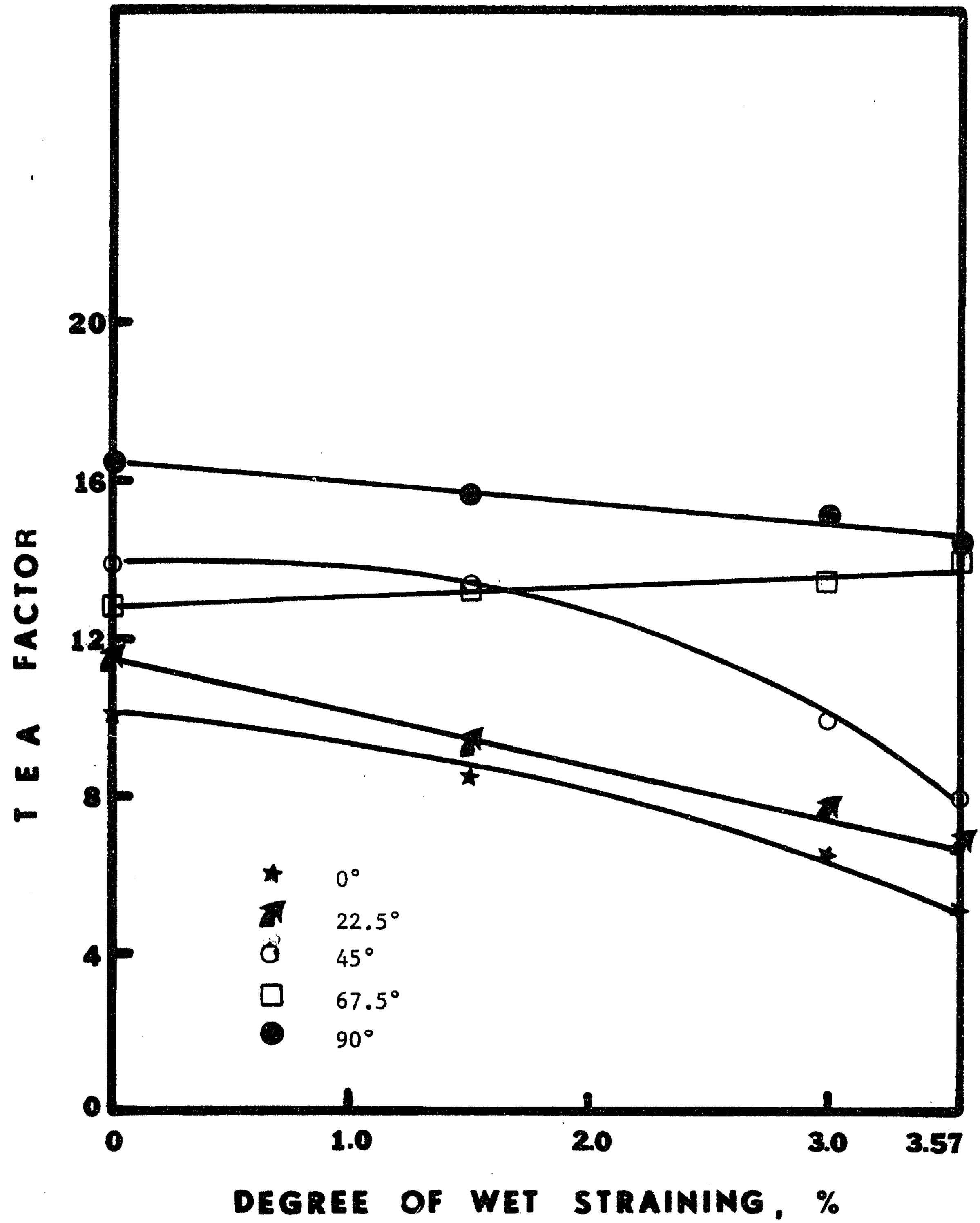


Fig. 35. The Effect of Wet Straining on the Tensile Energy Absorption of Paper at 70% RH

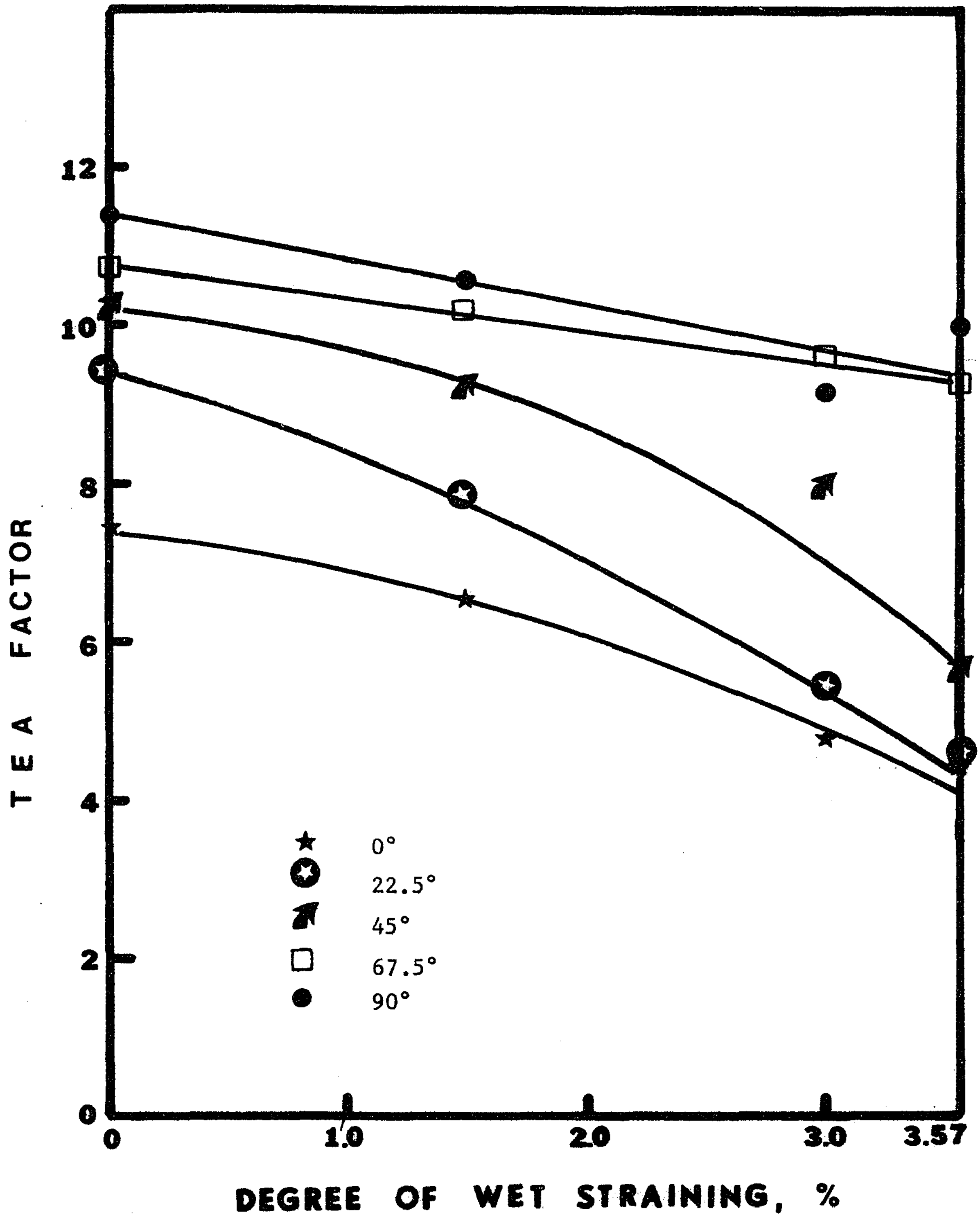


Fig. 36. The Effect of Wet Straining on the Tensile Energy Absorption of Paper at 90% RH

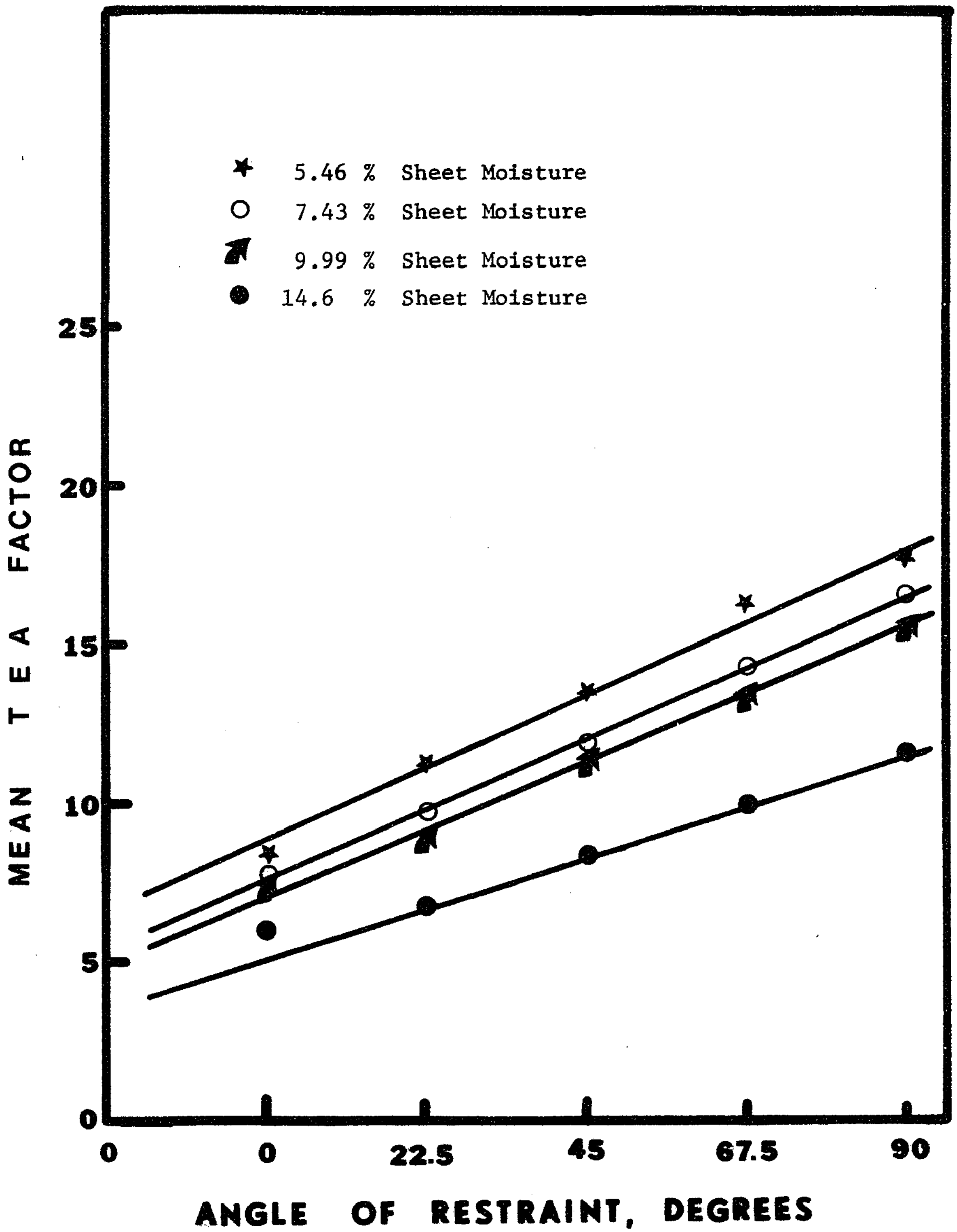


Fig. 37. The Effect of Angle of Restraint During Drying on the Mean Tensile Energy Absorption of Paper

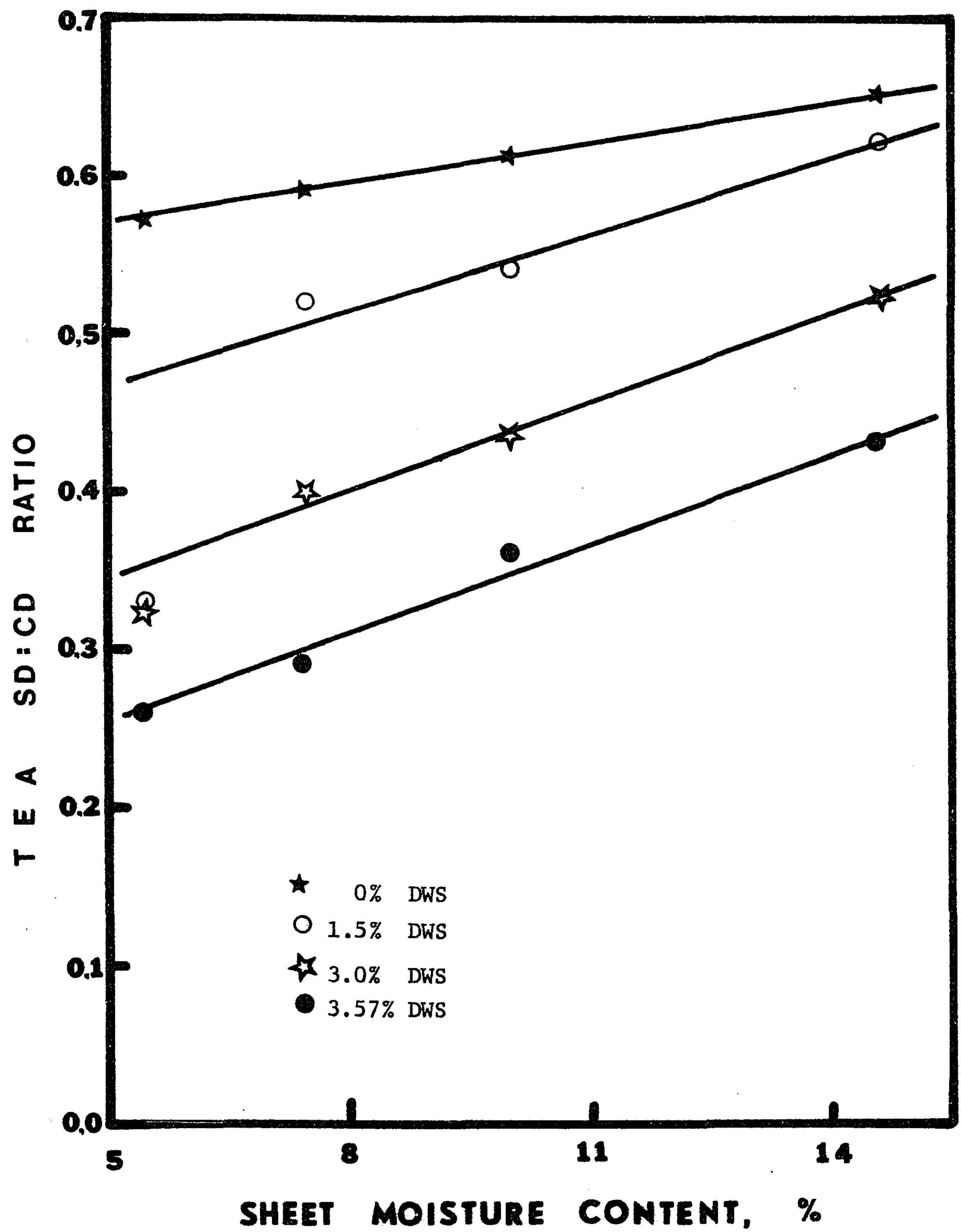


Fig. 38. The Effect of Sheet Moisture on the Tensile Energy Absorption SD:CD Ratio

SD:CD anisotropy of the paper. Sheet moisture tends to slightly decrease rupture energy anisotropy. This may be due to the improved flexibility imparted to the fibers and possible reformation of the bonds in the cross strain direction by higher sheet moistures.

Zero Span Tensile Strength

The increase in sheet strength with wet straining has long been associated with fiber orientation in the sheet. Robertson and Bailey (7) used tensile strength anisotropy as a measure of fiber orientation, noted that anisotropy developed primarily in the drier section and, hence, concluded that most of the fibers were oriented in the drier section. Steenberg and Danielson (8) using tagged fibers found that the combing action of the wire was the chief cause of alignment. Schulz (4) concluded that fiber orientation does not occur and tensile strength anisotropy developed by wet straining may be due to the straightening of the fiber segments between the interfiber bonds and redistribution of stress within the sheet. However he does not dismiss the possibility that microfibrillar orientation takes place in the direction of wet straining and the difference in the mechanical properties in the transverse and longitudinal sections of the fibrils is the cause of the anisotropy.

In order to test the validity of the above theories, various characteristics of the paper were investigated using the Pulmac Zero Span Tensile Tester. The use of this instrument to measure the fiber length, fiber strength, fiber orientation and bonding index has been discussed in another section. Since the maximum effect due to wet straining will be observed at higher levels of wet straining, tests were only conducted on handsheets subjected to 3.0% and 3.57% degree of wet straining and conditioned at 50% relative humidity.

The zero span tensile strengths of the handsheets are presented in Table X. An examination of the results reveals that the strain direction and cross strain direction zero span tensile strengths almost overlap, indicating that no gross fiber alignment took place during wet straining. The analysis does not however, verify whether fibrillar orientation occured. Figures 39-40 demonstrate the tensile strengths over a span range from 0.0 to 0.5 millimeters. The near symmetry of the strain and cross strain direction strengths is clearly visible.

The wet tensile strengths represent the paper in an unbonded condition. This is used to determine the fiber length index and the bonding index. Testing the specimens in a dry and wet condition is analogous to testing bonded and unbonded random arrays of fibers.

Table X

Zero Span Tensile Strengths of
3.0% and 3.57% Degree of Wet Strained Handsheets

DWS %	SPAN MM	ZERO SPAN TENSILE [illegible] per 25.4 MM	SAMPLE
3	[illegible]	[illegible]	SD, Dry
3	[illegible]	[illegible]	SD, Dry
3	[illegible]	[illegible]	SD, Dry
3	[illegible]	[illegible]	SD, Dry
3	[illegible]	[illegible]	SD, Dry
3	[illegible]	[illegible]	SD, Wet
3	[illegible]	[illegible]	SD, Wet
3	[illegible]	[illegible]	SD, Wet
3	[illegible]	[illegible]	SD, Wet
3	[illegible]	[illegible]	SD, Wet
3.57	0	20.6	CD, Dry
3.57	0.05	20.6	CD, Dry
3.57	0.10	20.2	CD, Dry
3.57	0.20	19.2	CD, Dry
3.57	0.40	18.3	CD, Dry
3.57	0	15.3	CD, Wet
3.57	0.05	15.0	CD, Wet
3.57	0.10	14.6	CD, Wet
3.57	0.20	15.4	CD, Wet
3.57	0.30	15.4	CD, Wet

Table X

Zero Span Tensile Strengths of
3.0% and 3.57% Degree of Wet Strained Handsheets

DWS %	SPAN MM	ZERO SPAN TENSILE KG per 25.4 MM	SAMPLE
3	0.0	21.0	SD, Dry
3	0.05	20.4	SD, Dry
3	0.10	20.4	SD, Dry
3	0.20	19.0	SD, Dry
3	0.30	18.0	SD, Dry
3	0.0	16.0	SD, Wet
3	0.05	15.6	SD, Wet
3	0.10	15.2	SD, Wet
3	0.20	14.9	SD, Wet
3	0.30	14.8	SD, Wet
3.57	0	20.6	CD, Dry
3.57	0.05	20.6	CD, Dry
3.57	0.10	20.2	CD, Dry
3.57	0.20	19.2	CD, Dry
3.57	0.40	18.3	CD, Dry
3.57	0	15.3	CD, Wet
3.57	0.05	15.0	CD, Wet
3.57	0.10	14.6	CD, Wet
3.57	0.20	15.4	CD, Wet
3.57	0.30	15.4	CD, Wet

Table X (Continued)

DWS %	SPAN MM	ZERO SPAN TENSILE KG per 25.4 MM	SAMPLE
3.57	0	21.8	SD, Dry
3.57	0.1	20.4	SD, Dry
3.57	0.2	19.6	SD, Dry
3.57	0.3	17.2	SD, Dry
3.57	0.4	16.8	SD, Dry
3.57	0	14.3	SD, Wet
3.57	0.1	13.8	SD, Wet
3.57	0.2	11.9	SD, Wet
3.57	0.3	10.3	SD, Wet
3.57	0	20.8	CD, Dry
3.57	0.1	20.1	CD, Dry
3.57	0.2	18.9	CD, Dry
3.57	0.3	18.9	CD, Dry
3.57	0.4	18.2	CD, Dry
3.57	0	15.0	CD, Wet
3.57	0.1	13.6	CD, Wet
3.57	0.2	11.6	CD, Wet
3.57	0.3	10.5	CD, Wet

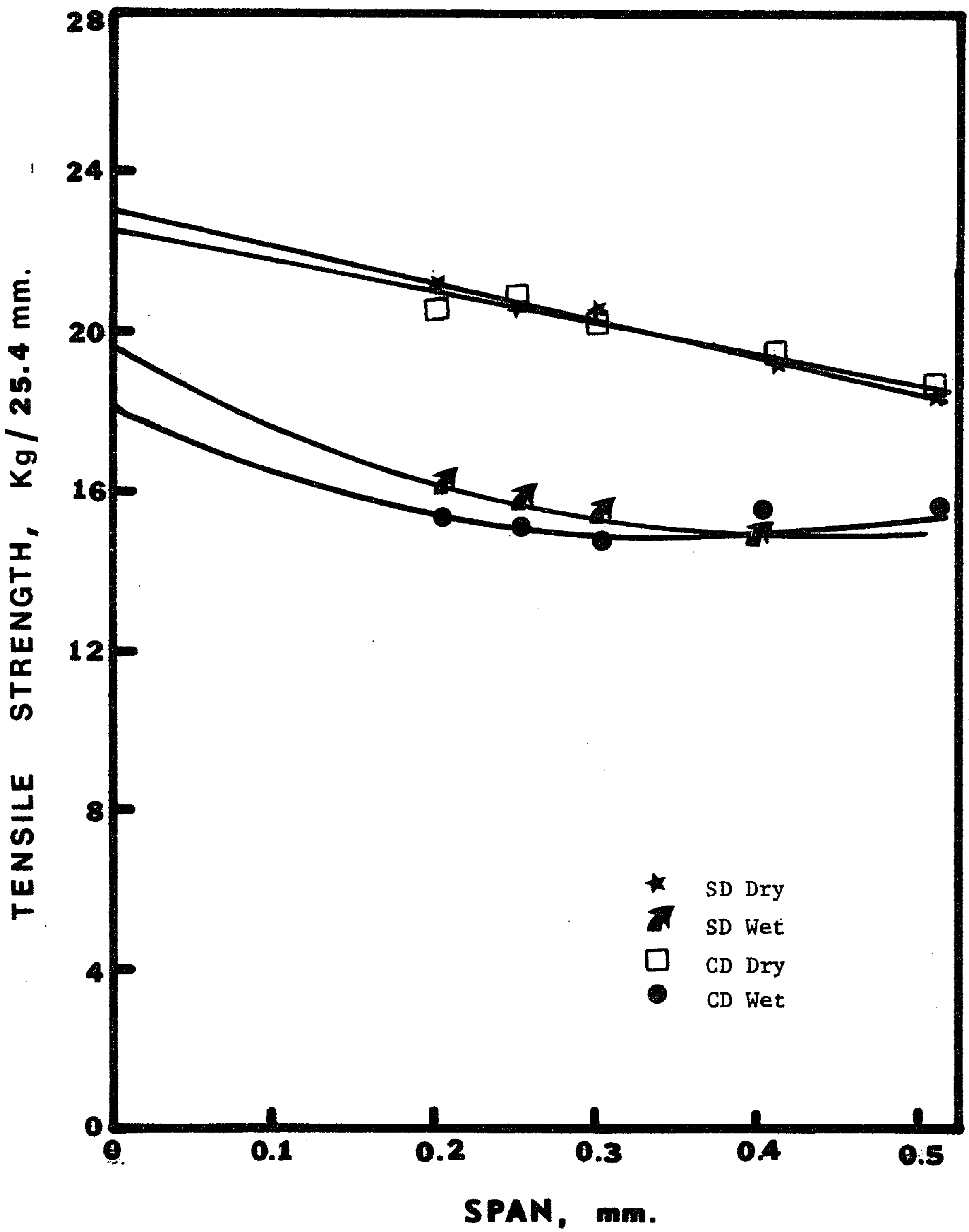


Fig. 39. Zero Span Tensile Strength of 3.0% DWS Handsheet

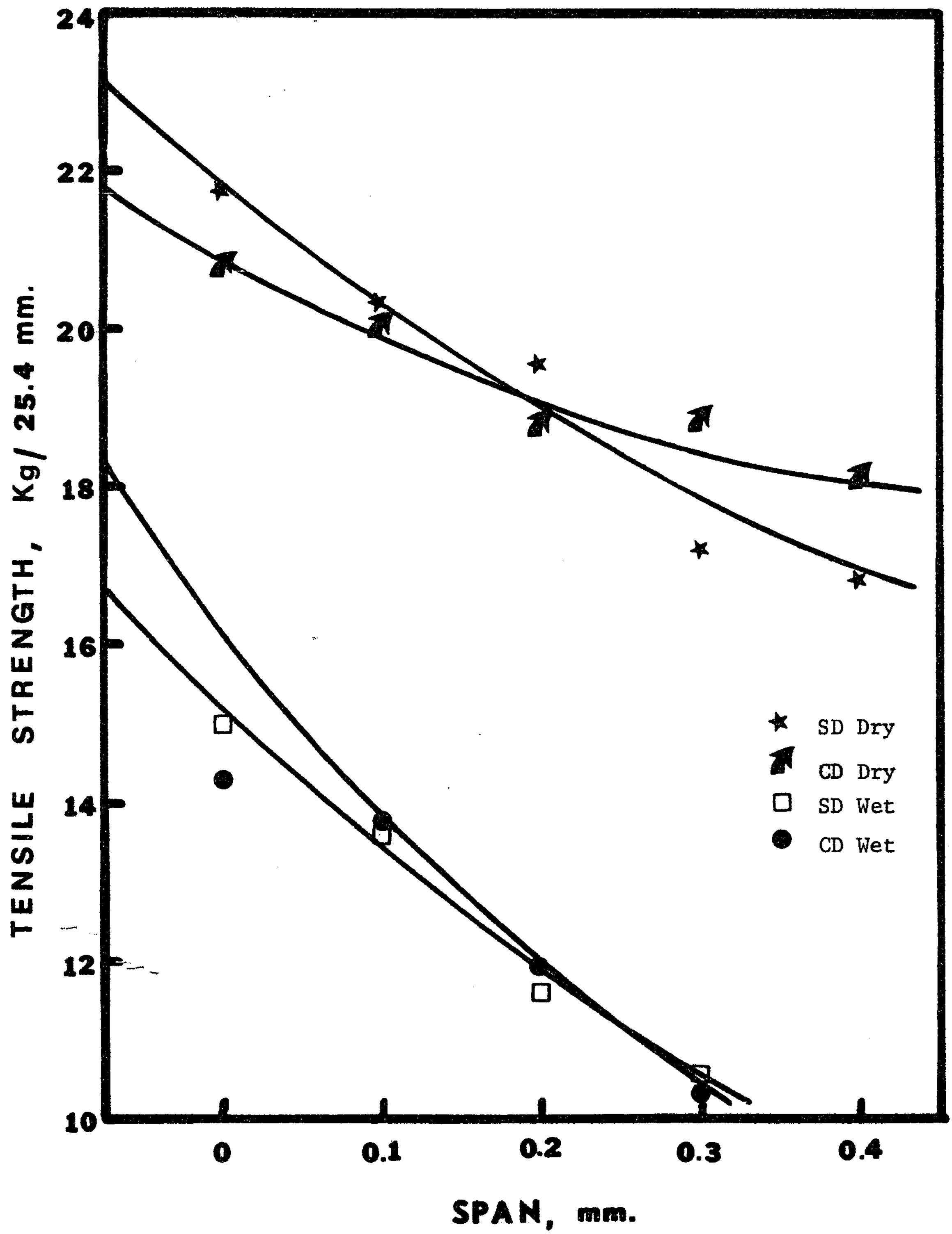


Fig. 40. Zero Span Tensile Strength of 3.57% DWS Handsheet

SUMMARY OF RESULTS

Handsheets made from Rayonier bleached, softwood kraft pulp were elongated at 38.5% solids content and maintained in this condition until the sheets were fully dried at 112°F. The mechanical properties of the paper were then evaluated at various relative humidities. The purpose of this investigation was to determine the influence of sheet moisture on the anisotropy induced in a sheet by wet straining.

Examination of the load-elongation properties of the paper indicates that as wet straining was increased, the tensile strength of the handsheets increased from 0 to 27%, and then decreased. The ultimate elongation decreased steadily with wet straining.

The effect of wet straining on the modulus of elasticity of the handsheets closely resembled the changes observed in tensile strength with wet straining. The modulus of elasticity increased approximately 2% to 75% and then decreased. The rupture energy was also significantly affected by wet straining. A steady reduction in rupture energy was observed with wet straining.

The tearing resistance of the paper initially decreased down to 24% and then increased as wet straining was increased.

The zero span tensile strength of the sheets was not found to be affected by wet straining. The strain and cross strain direction zero span tensile strengths were approximately equal indicating that no major fiber orientation occured during the wet straining operation.

Sheet moisture had a dominant effect on paper properties. Tensile strength, modulus of elasticity and the work-to-rupture of paper decreased while the tearing resistance and ultimate elongation increased with increase in moisture content.

Wet straining greatly increased SD:CD anistropy of the paper. This mechanical anisotropy was decreased approximately 50 to 70% as the sheet moisture was increased.

The preceding statements serve to summarize the experimental work completed in this study. When a load is applied to paper, the stress developed is distributed in a nonuniform manner within the sheet. Such nonuniformity is due to the irregular geometry of the fibers and the dependency of the coherence of the sheet upon the bonding between the fibers.

If this stress distribution is changed so that the components which previously supported less than their share of the load are made to support a greater fraction of the load and vice versa, the response of the paper to stress will be reduced.

Observed changes in modulus of elasticity suggest that wet straining affects the manner in which stress is distributed in the sheet when it is under tension. The zero span tensile strength data shows that no gross fiber realignment occured during wet straining. From these observations, it is hypothesised that when a sheet is wet strained, the fibers slip to some extent and this straightens the slightly kinked and curved segments, making them active from a loading point of view. Therefore, from the very beginning of loading, every fiber is ready to share a fraction of the total load and thus,

increasing the tensile strength and modulus of elasticity of the paper. At high degrees of wet straining, some bond rupture occurs which is a possible reason for the decrease in the above paper properties beyond about 3% wet straining.

Wet straining induced into a sheet a great amount of anisotropy. The inhibition of shrinkage of the fibrous network in the direction of straining resulted in a strain build-up in the sheet. Fibers are likely displaced from their original stable arrangement into a new configuration. It is hypothesised that humidification releases these dried-in strains to a certain extent. Moisture acts as a debonding agent on the fibrous network. The stiffness and resistance to bending of the fibers decrease at higher relative humidities. Also the interfiber bonds become weaker and the straightened fibers are allowed to relax and return to their original, unstrained configurations. This results in both a decrease in the tensile strength, modulus of elasticity and rupture energy of paper and a decrease in the mechanical anisotropy of the paper. It is conceivable that fibers that were made to support a fraction of the load in the strain direction, are now made more active in the cross strain direction and contribute to the strength in this direction.

Due to commercial manufacturing processes, paper is in a strained condition. Consequently, the machine and cross machine directions exhibit different mechanical properties. This anisotropy is not always objectionable, for in so far as it represents a preferential distribution of strength it can be highly desirable. For example, in papers which are subjected to a high machine direction

pull, with no pull in the cross direction. There is, however, a very wide range of papers where it is a great drawback to have a great degree of anisotropy. Such is the case with printing papers. The dried-in strains cause curl, wrinkle and misregister. It has long been a common practice among printers to store paper for some time before printing it, it being claimed that paper which had been thus 'matured' gave better results on printing. It may be just possible that this is due to the gradual release of strains in the paper and that the same result might be obtained in a much shorter time by conditioning the paper at a fairly high humidity (85% to 90% RH) and then drying it without restraint to the moisture content it is to be used at.

CONCLUSIONS

From the experimental results obtained the following can be concluded:

1. Considerable anisotropy was induced into a sheet of paper by wet straining. This anistropy reached a maximum at around 3% wet straining and then decreased.
2. Conditioning of the wet strained paper to high relative humidities gradually released some of the dried-in strains. When the paper was thus 'humidity-conditioned', the anisotropy decreased by approximately 50 to 70%.
3. Increase in sheet moisture decreased tensile strength, modulus of elasticity and work-to-rupture of paper while the tearing resistance and ultimate elongation increased.
4. The tensile strength and modulus of elasticity increased to a maximum and then decreased as wet straining was increased.
5. The ultimate elongation and rupture energy decreased steadily with wet straining.
6. The tearing resistance of the paper initially decreased and then increased as wet straining was increased.
7. Wet straining had no effect on the zero span tensile strength of the handsheets.

BIBLIOGRAPHY

1. Cottral, L. G. and Gartshore, J. L., Brit. Paper and Board Makers' Assoc., Proc. Tech. Sec. 24: 261-307 (1943).

2. Carter, W. J., Brit. Paper and Board Makers' Assoc., Proc. Tech. Sect. 25: 231-233 (1944).

3. Ivarrson, B., Svensk Papperstidn, 54, No. 21: 729-738 (Nov., 1951).

4. Schulz, J. H., "The Effect of Strain Applied during Drying on the Mechanical Behaviour of Paper". Doctor of Philosophy thesis. Lawrence College, Appleton, Wisconsin, June 1961.

5. Sapp, J. E., and Gillespie, W. F., Paper Trade J. 124, No. 9: 120, 122, 124, 126 (February 1947).

6. Fujiwara, W. J., J. Japan Tech. Assoc. Pulp Paper Ind. 11, No. 4: 30-33 (1957).

7. Robertson, J. A. and Bailey, F. W., Brit. Paper and Board Makers' Assoc., Proc. Tech. Sect. 15, No. 1: 155-159 (1934).

8. Setterholm, V. C. and Chilson, W. A., Tappi 48, No. 11: 634 (1965).

9. Carter, W. J., Proc. Papermakers Assoc. G. B. I. 25: 231 (1944).

10. Rance, H. F., In "The Rheological Behaviour of Paper", (V. G. W. Harrison, Ed.), United Press Ltd., London.

11. Corte, H. and Schaschek, H., Das Papier 9 (21/22): 519 (1955).

12. Broens, O., Das Papier 11 (5/6): 89 (1957).

13. Pritchard, E. J., Tech. Sec. B. P. and B. M. A. 35 (1): 31 (1954).

14. Lyne, L. M. and Gallay, W., Pulp and Paper Mag. Can. 51 (9): 129 (1950).

15. Robertson, J. A. and Bailey, F. W., Brit. Paper and Board Makers' Assoc., Proc. Tech. Sect. 15, No. 1: 155-159 (1934).

16. Danielson, R. and Steenberg, B., Svensk Papperstidn. 50, No. 13: 301-305 (November 1955).

17. Van den Akker, J. A. "Some Theoretical Considerations on the Mechanical Properties of Fibrous Structures". In Bolam's "The Formation and Structure of Paper", Vol. I, p. 205-41, London, Tech. Assoc. Brit. Paper and Board Makers' Assoc., Inc., 1962.

18. Kallmes, O. J. and Bernier, G. A., "Mechanical Properties of Paper", Part I, Elasticity of Handsheets. In Bolam's "The Formation and Structure of Paper", Vol. I, p. 369-88, London, Tech. Sect. Assoc. Brit. Paper and Board Makers' Assoc. Inc., 1962.

19. Campbell, J. G., Appita 16 (5): 130 (March 1963).

20. Rance, H. F., Tappi 37, No. 12: 641 (December 1954).

21. Negishi, M., J. Soc. Textile Cellulose Ind. Japan, 2: 34 (1946).

22. Negishi, M., J. Soc. Textile Cellulose Ind. Japan, 3: 21 (1947).

23. Jentzen, C. A., Tappi 47 (7): 412 (July 1964).

24. Page, D. H., Tydeman, P. A., "The Formation and Structure of Paper", Vol. I, London, Tech. Sect. Assoc. Brit. Paper and Board Makers' Assoc. Inc., 1962.

25. Gallay, W., Tappi 46, No. 11: 54-63 (November 1973).

26. Armstrong, L. D. and Christensen, G. N., Nature 191 (4791): 869 (1961).

27. Hearmon, R. F. S., and Paton, J. M., Forest Products Journal 14 (8): 357 (1964).

28. Scheiwind, A. P., Wood Sci. Technology 1 (4): 278 (1967).

29. Wilkenson, J. C., M. S. Forest Service Research Paper. Paper FPL 67, Forest Products Lab., Madison, Wisconsin (1966).

30. Stamm, A. J., Tappi 42, No. 1: 44-50 (January 1959).

31. Glynn, Jones and Gallay, W., Can. Pulp and Paper Mag., 269-277 (1958).

32. Larocque, G., Pulp Paper Mag. Can. 37, No. 4: 199-209. (March, 1936).

33. Smith, S. F., Brit. Paper and Board Makers' Assoc., Proc. Tech. Sect. 31, Part I: 107-126: discussion: 127-135 (February 1950).

34. Rance, H. F., Brit. Paper and Board Makers' Assoc. Proc. Tech. Sect. 33. Part I: 173-195: discussion: 196-199 (February 1952).

35. Brezinski, J. P., Tappi 39, No. 2: 116-128 (Feb. 1956).

36. Giertz, H. W., "The Matrix Model Structure of Paper", Presented at the Gordon Research Conference, Andover, 1969.

37. Jayme, G., Tappi 41 (11), 178A-183A, 1958.

38. Smith, S. F., Brit. Paper and Board Makers' Assoc., Proc. Tech. Sect. 31, No. 1: 107-26 (1950).

39. Van den Akker, J. A., and Hardacker, K. W., Tappi 41, No. 8: 224-231A (August 1958).

40. Boucai, E., "Zero Span Tensile Test and Fiber Strength", Pulp Paper Mag. Can. 72 (10): T313 (1971).

41. Cowan, W. F., and Cowdrey, E. J. K., Tappi 57, No. 2: 90-93 (February 1974).

42. Cook, O. M., and Bennett, W. E., "Effect of Humidity and Temerature on the Physical Properties of Paper", Brit. Paper and Board Industry Research Assoc. Report No. RA-T-90 (February, 1962).

43. Van den Akker, J. A., Tappi 48, No. 8: (Aug. 1965).

44. Richter, G. A., Tappi 41, No. 12: 777-795 (Dec. 1958).

45. Corte, H., Schaschek, H., and Broens, O., Tappi 40, No. 6: 441-47 (June 1957).

APPENDIX I

SAMPLE CALCULATION OF MODULUS OF ELASTICITY

$$\text{Modulus of Elasticity} = \frac{\text{Stress/Area}}{\text{Strain/Length}}$$

EXAMPLE

Test a strip 10 cm between jaws, 1 inch (2.54 cm) wide and 0.00483 inches caliper

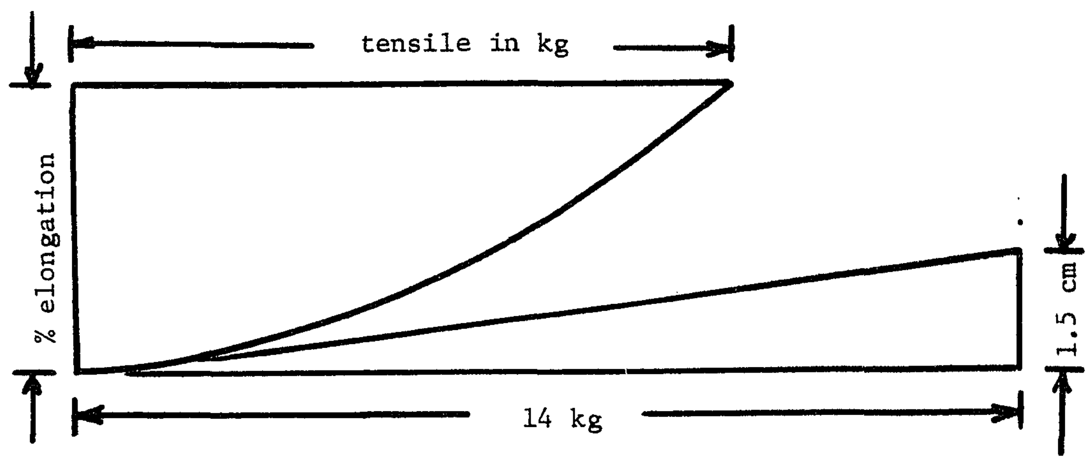


Figure 41 - Stress-strain curve.

$$\text{Modulus of Elasticity} = \frac{14}{1.5 \times (2.54)^2 \times 0.00483} \ \text{cm}^2$$

$$= \frac{14 \times 980.7 \times 1000}{1.5 \times (2.54)^2 \times 0.00483} \ \frac{\text{dynes}}{\text{cm}^2}$$

$$= 29.4 \times 10^7 \ \frac{\text{dynes}}{\text{cm}^2}$$

APPENDIX II

INTEGRATOR CALCULATIONS FOR TENSILE ENERGY ABSORPTION, TEA

TEA^1 in kg m/m^2 = 100 A^1/LW

where

A^1 = work in kg-cm
L = length of strip in cm
W = width of strip in cm

<u>EXAMPLE</u>

Test a strip 10 cm between jaws (L) and 1 inch (2.54 cm) wide (W)

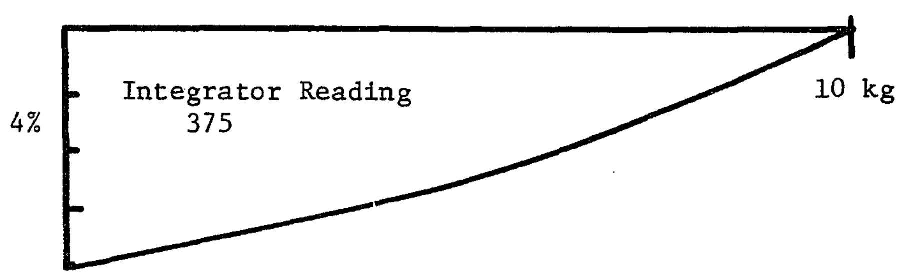


Figure 42 - Stress-strain curve.

Integrator reads 5000 if full scale for 1 minute.

$$SoA^1 \text{ (kg-cm)} = \frac{\text{Integrator Reading X Full Scale Load X Drive Speed}}{5000}$$

$$\text{In example, } A^1 = \frac{375 \times 20 \times 2.0}{5000} = 3.0 \text{ kg cm}$$

$$TEA^1 \text{ in kg -m/m}^2 = \frac{100 \times 3.0}{10 \times 2.54} = 11.95$$

<u>FOR EXAMPLE ABOVE USE:</u>

Use AX AX low on drive (2 cm/min)
Use AX AX high on recorder speed (20 cm/min)
Use 20 kg full scale