The Institute of Paper Chemistry

Appleton, Wisconsin

Doctor's Dissertation

The Effect of Strain Applied During Drying on the Mechanical Behavior of Paper

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June, 1961

THE EFFECT OF STRAIN APPLIED DURING DRYING ON THE MECHANICAL BEHAVIOR OF PAPER

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for the degree of Doctor of Philosophy
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June, 1961

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INTRODUCTION

As paper is dried during its manufacture, it is subjected to stresses and strains imposed by the paper machine. In the drier section, for example, the sheet is often stretched while it is still wet, by differential drier speeds. In addition, the sheet may be stressed at the couch roll and in the press section. It has been recognized for sometime that the application of stress to paper before it is fully dried may strongly affect the response to stress of the dried sheet. It would not be expected, moreover, that the application of stress to a wet sheet would involve the same effects noted when a dry sheet is stressed. Since different paper machines apply different schedules of stress to the sheet, this effect is important for the control of commercial sheet properties. Intelligent manipulation of the mechanical history of the sheet during manufacture may provide the papermaker with increased control over the properties of his final product.

This thesis is a study of the influence of mechanical straining of incompletely dried paper on the properties of the fully dried sheet. Major consideration is given to strength properties and the manner in which the sheet responds to stress.

HISTORICAL REVIEW OF THE EFFECTS OF STRESS APPLIED DURING DRYING

The effect of stress applied to a sheet during the course of its manufacture on the mechanical properties of the dried paper has been recognized for some time. Early workers (1-4) were largely concerned with the development of tensile strength anisotropy in paper, and they recognized the influence of dry end variables in that regard. Arlov and Ivarsson (5) conducted a rather complete investigation into the effects of draws and felt tension upon the mechanical properties of paper, utilizing load-elongation relationships for analytical purposes. They found that if shrinkage is prevented by employing tight draws and felts, decreased extensibility of the finished paper results. They found that a "mechanical conditioning" effect occurs, but only in the direction of tension. Similar investigations have been carried out by Carter (6) and Cottral and Gartshore (7).

An interesting series of laboratory experiments was carried out by Edge (8, 9). Edge found that if a sheet was stretched almost to the breaking point while still wet and then dried with no shrinkage, the ratio of the machine-direction tensile strength to the cross-machine-direction tensile strength would approach a value of four. In this discussion, the term "machine direction" refers to the direction of stress application. Edge observed that the average value of the tensile strength in the two directions remained about the same, since as the machine-direction strength doubled, the cross-machine-direction value was halved.

Fujiwara (10) concluded that the effect of tension during drying upon the mechanical properties of paper depends upon the degree of pressing, the degree of beating, and the method of beating. This would suggest that the effect is related to the amount of fiber surface in contact. Fujiwara found that the amount of tension in the cross-machine direction influences the effect of tension applied simultaneously in the machine direction during drying, but that the influence is not strong and that the essential nature of the longitudinal effects was not altered.

Higgins, Goldsmith, and Harrington (11) and Brecht and Pothmann (12) obtained load-elongation curves for paper dried under various constant loads. It was found that as the stress during drying was increased, the ultimate strength increased, but that there is an optimum drying stress beyond which the sheet is weakened by additional loading during drying. Sapp and Gillespie (13) reported that tension during drying first increases tensile strength to values 5 to 10% greater than that of the unstretched sheet, then tends to weaken the sheet as greater loads are applied. Ivarsson (14) found no improvement at all in ultimate strength through application of strain during drying. All of the authors, however, agree that tensions during drying markedly reduce the extensibility of the finished sheet.

In an early investigation, Briner and Guild (15) took samples from different parts of a paper machine and allowed them to dry without further restraint. They observed a critical moisture content at 60% solids below which stretching doesn't weaken the final sheet but above which it does. They concluded that the effect of tension during drying is to weaken paper, although in practice tension may be necessary to produce a flat sheet.

Several authors have presented explanations of the observed effects. It should be noted, though, that very little direct experimental data have been obtained to support these theories. The earliest workers associated sheet anisotropy entirely with fiber alignment, and this concept was unchallenged for many years. Robertson and Bailey (16) used tensile strength anisotropy as a measure of fiber orientation and concluded that most of the fibers were oriented in the drier section, probably through stretching of the sheet. This theory has been generally discarded since Edge (8) and Steenberg (17) found that a completely random sheet could develop strong directionality if merely prevented from shrinking in one direction.

Danielson and Steenberg (18) investigated fiber orientation by observation of tagged fibers. They found that the combing action of the wire was the chief cause of alignment. To evaluate the effect of stretching on orientation, samples were taken from different sections of a paper machine from which the finished sheet was received at a rate 20% greater than the wire speed. Changes in fiber alignment were found to be small.

In a discussion of the physical nature of paper strength, Corte and Schaschek (19) suggest that while during drying there may not be any significant fiber alignment, stretching may bring the fibers closer together in the transverse direction, favoring the formation of hydrogen bridges in the transverse direction as compared with the longitudinal direction. Thus, an orientation of the hydrogen bonds may be responsible for the observed anisotropy. In a later paper, Corte, Schaschek, and Broens (20) present evidence that breaking extension is not a function of the maximum or average drying stress developed, but rather is a function of the time integral of the drying stress. These authors suggest that during drying the wet fibers shrink and internal movements occur, and during the process fiber-fiber bonds are broken. They postulate that the rupture energy is lowered by an amount equal to the energy of the fiber-fiber bonds broken. The measure of energy to rupture used by these authors is highly suspect.

Van den Akker (21) has suggested that an important part of the increase in tensile strength caused by drying under tension is the equalization of distribution of stress among the fibers. He points out that when the moisture content is high, the fibers and fiber-to-fiber bonds are in a relatively plastic state and, thus, during drying tension causes fibrous elements between points of bond to become straighter. In that way, all the fibrous elements would partake more equally of the load than if there were no tension. Further, when the paper dries, this condition becomes frozen-in.

While proposing that fiber orientation probably has but little effect on this problem, Steenberg (17) suggested that the fine fibrils between the fibers may become aligned when the sheet is stretched. He pointed out that this "nap" or fibrillar material is fine enough so that only a very small displacement would be sufficient to cause them to align.

This action would change the internal structure of the bond, increasing its strength in the direction of tension. Breitveit (22) proposed that a similar orientation of the fibrils may be brought about by the backward flow of water in the nip of the presses.

Berkley and Barker (23) and Landt and Rulon (24) suggested that tension during drying will tend to align the fibrils in the machine direction and the alignment will tend to pack the fibrils more closely. Also, it is seen that the crystallites in the sheet will be aligned, and the situation will be similar to that which occurs when viscose is stretched during spinning. These authors maintain that this effect will increase the tensile strength and the elastic modulus in the machine direction, and increase the density of the sheet. A reduction of elastic modulus and tensile strength was predicted in the cross-machine direction.

PRESENTATION OF THE PROBLEM

A substantial body of evidence has been presented which indicates that the mechanical history of paper before it is completely dried markedly alters the mechanical properties of the fully dried sheet. Generally, the tensile strength has been found to increase and the ultimate elongation to decrease as the stress applied during drying is increased. Some workers have noted a reverse in the direction of change in tensile strength when very high loads were applied to the wet sheet. It is noted that most of the previous laboratory investigators applied known constant loads to the sheets during drying to vary their mechanical history.

The purpose of the present work is to study the effect that straining a wet handsheet has on the properties of the final, dry sheet. In this study strain was used as the independent variable. Handsheets were strained immediately after wet pressing and held at constant elongation for the remainder of the drying operation. The operation of applying the elongation after wet pressing is termed "wet straining". Wet straining was employed because drying under constant load suffers from the inability to distinguish effects occurring during different phases of drying. During the early stages of drying, a constant load probably causes the fibers to slip past one another, and during the latter stages, the mechanism is more similar to that which occurs during a tensile creep test. Stretching of the sheet occurs as long as the load is supported by the specimen. Correspondingly, wet straining involves an uncontrolled, although definite stress history. Wet straining seems to correspond more closely to the mechanical treatment given paper by the paper machine. The technique is able to separate the effects of strain applied at different stages of drying.

The study was limited to a single pulp, although the degree of beating was treated as a variable. All of the sheets were wet strained at 36% solids.

Two objectives may be delineated. The first is to make a systematic examination of the effect of wet straining on the mechanical properties of paper. These mechanical properties include tensile strength, ultimate elongation, the load-elongation relationship, elastic modulus, and certain viscoelastic behavior. Such a study has never been reported previously in the literature, although several extensive studies concerning drying under constant load have appeared.

The second major objective is to develop a logical, coherent theory to explain the changes in mechanical properties induced by wet straining. Such a theory would provide a sound interpretation of the changes in strength and response to stress, and would be based upon changes in bonding characteristics, intrinsic fiber strength, and the internal structure of the sheet. The theory necessarily would be cognizant of all nonchemical factors affecting the mechanical properties of paper.

A major part of the effort in this work is devoted to a study of the effect of wet straining on the viscoelastic behavior of paper.

It is known that many of the most desirable properties of paper are not properly evaluated by strength tests alone, and great strength is not necessarily the most desirable characteristic for paper. During that large portion of a paper product's life which occurs prior to failure, we are necessarily interested in prerupture response to stress. For example, the work required for rupture may be as important as the tensile strength in the case of bag paper. In addition, it is becoming increasingly apparent that tests of viscoelasticity may be valuable tools for examining the mechanical history and changes in the structure of paper. Such use was predicted by Steenberg (25) in an early paper, and has been explored by Brezinski (26).

The experimental program was focused on five major areas.

(1) The preparation of handsheets with different degrees of wet straining.

(2) The determination of the mechanical properties of these handsheets, using the Instron load-elongation tester.

(3) The examination of the intrinsic fiber strength of these handsheets.

(4) The examination of the bonding characteristics of these handsheets.

(5) The examination of the viscoelastic properties of the handsheets, using the tensile creep test.

These areas are discussed and evaluated in some detail in the body of this report.

PRELIMINARY CONSIDERATIONS

THE STRUCTURE AND THE STRENGTH OF PAPER

The mechanical properties of paper are those which are generally considered to be important in assessing the response of paper to stress. Classically, these include the tensile strength, ultimate elongation, elastic modulus, and the amount of work necessary to cause rupture. It is recognized, however, that other properties, such as creep under stress and the ability to relax stress under constant elongation, are also important to the mechanics of paper. The proper understanding of these factors requires a knowledge of the chemistry and physics of paper. The present discussion will emphasize the physical, rather than the chemical aspects of paper strength, although the two cannot be conveniently separated.

Cellulose is a polymer of anhydroglucose units linked by beta-1,4 glycosidic bonds. According to the crystalline micelle theory, the polymer chains are arranged in roughly parallel order and are bound to one another by secondary bonding forces. Areas within which the molecular chains are truly parallel become crystalline through superior organization of the secondary bonds. The fundamental strength of cellulose is derived from both the primary bonds which bind the atoms and the atomic groups into chains, and the secondary bonds which bind the molecular chains into crystallites.

When natural cellulosic fibers are disintegrated by mechanical means, the smallest structural units observed are called microfibrils. These are found to be 150-250 A. wide, and of great, but indeterminate length (27). Frey-Wyssling (28) has suggested that the microfibril is a bundle of finer structural units called micelle strings. The micelle strings, on further degradation of the microfibril, as by hydrolysis or oxidation, yield the crystallite particles. These crystallite particles are believed to be regions of comparatively highly crystalline cellulose that are surrounded in the microfibril by regions of less crystalline cellulose that are more subject to chemical attack.

When fibers are examined with a light microscope, the structural entities known as fibrils may be observed. Fibrils result from the fraying of the fiber by mechanical treatment, such as beating. These stringlike fragments, attached to the fiber, have no particular size, but vary in width down to the dimensions of the microfibril. Emerton (27) has presented a more complete description of fibrils and their relation to fiber structure. In conventional paper, it is commonly observed that the fibers lie generally in planes parallel to the surfaces of the sheet. This effect may be notes in photomicrographs of the cross section of paper, such as those published recently by Marton (29).

The strength of paper is dependent upon many factors, some of which are only vaguely understood. Generally, these factors may be divided into three groups. These are: (1) the strength of the fibers and other components of which the sheet is made, (2) the extent and strength of the bonds which hold the elements of the sheet together, and (3) the manner in which stress is distributed among the elements of the sheet when the sheet is in tension.

In addition to effects of fiber geometry, fiber strength is related to the chemical composition and the degree of polymerization of the cellulose, the degree of crystallization, the size and general nature of the crystallites, and the distribution of these factors. Sisson (30) and Sisson and Clark (31) have found the orientation of the crystallites in the fiber to be related to fiber strength. Higher strength is observed in fibers with crystallites well oriented with the long axis. It is not known, however, if crystallite orientation is the fundamental variable in this regard, because of the co-variance of other factors.

Van den Akker, Lathrop, Voelker, and Dearth (32) investigated the relative importance of fiber failure and bond breaking in sheet failure. This was done by observing the relative number of tagged fibers broken and pulled intact across the line of rupture. It was found in both tearing and tensile failure, that a substantial portion of the tagged fibers were broken. The percentage broken increased with beating time. It was not possible to tell if tensile rupture was initiated by bond failure or by fiber failure.

The current theory of sheet strength considers the effects of fiber entanglement to be small and the major source of fiber cohesion to be interfiber bonding forces. Campbell (33) has proposed that during the final stages of drying, small quantities of water held between the fibers and fibrils pull the solid material together through very large pressures derived from surface tension forces, and that as the last traces of water are evaporated, molecular bonds of the secondary type are formed between neighboring cellulose units. Lyne and Gallay (34-36) analyzed this mechanism further and concluded that when the sheet reaches about 8% solids, it is held together by surface tension forces, arising from menisci formed as the water layer recedes into the fibrous structure, which are proportional to the length of fiber-water contact. They increase steadily up to a solids content of about 25%, after which they become less important and the compacting force depends more upon the effective internal pressure of the water, as suggested by Campbell.

The manner in which the components of paper are bonded to each other determines to a large extent the strength of the sheet. While secondary attractive forces of all types exist between molecules of cellulose, the many hydroxyl groups present attract one another mainly by hydrogen bonding (37). Corte and Schaschek (19) have recently thrown new light on the nature of hydrogen bonding in paper. By examining the equilibrium between deuterium oxide-water vapor mixtures and cellulose, it was learned that the amount of hydroxyl groups forming the interfiber hydrogen bonds lies in the range of 0,5 to 2% of all hydroxyl groups present. Their data also suggest that there is a multiplicity of bond energies between the hydroxyl groups, indicating a spectrum of bond strengths.

It is most likely that fibers within a sheet are extensively bonded along their entire length, although some workers have visualized comparatively few bonds per fiber length. The work of Brezinski (26) has indicated that fibers in a sheet are not free to twist and change shape when the sheet is stressed, and this suggests a compact structure. Carson (38) and Bublitz, Dappen, and Van den Akker (39) found that the effective pore size in paper is typically in the range of 10^{-4} to 10^{-5} cm. These figures suggest very small pores. If a very compact fibrous structure did not exist, a larger effective pore size would be anticipated.

For hydrogen bonds to form, it is necessary that the molecules approach each other very closely, since the attractive forces fall off very rapidly as the distance between the molecules increases. This distance is of the order of a few Ångstrom units. Since rigid solid surfaces are very rough and the real area of contact for rigid surfaces is small (40), it is necessary that the fiber surfaces be prepared so that intimate contact between fibers may be realized.

When cellulosic fibers are beaten in a polar medium, they swell. As the fiber swells, it becomes more flexible because bonds are broken between the cellulose molecules in the amorphous regions. Plasticization does not occur in the crystalline portions because water cannot enter the crystalline structure. Several investigators (41-43) concluded that swelling is necessary for satisfactory fiber bonding. If the fibers are beaten in a medium which does not permit the swelling to occur, very little or no strength exists in the final sheet (41), even though it is subsequently formed from a water suspension (44).

Emerton (27) has suggested that the repeated flexing of the fiber during beating also acts to plasticize the fiber. This breaking of bonds within the fiber, or internal fibrillation, makes the fiber more flexible or conformable. Conformability is the property which allows a fiber to form an intimate association with its neighboring fibers or fiber particles. It is a property which is not completely understood and has not been measured directly. The ability of fibers to conform is important in wet pressing. Under pressure, the fibers tend to form around one another and produce a coherent sheet. Conformable fibers retain much of this coherence after the pressure is removed. It is seen that after wet pressing, conformable fibers are in a good position to take advantage of the surface tension forces mentioned above (33), which begin to operate after about 30% solids (34). Further, Thode and Ingmanson (45) have suggested that increased flexibility leads to less fiber damage, promoting more efficient wet beating. Swanson (46) has provided an excellent review of many factors related to fiber bonding.

Total bonding strength depends upon the bonded area, the strength of the bonds, and the distribution of these factors. Measurement of bonded area is difficult since its evaluation is sensitive to the method used. Measurement of bonded area has been made by the light-scattering technique (47-50) and the gas adsorption technique (51,52). Recent advances in these methods have been discussed by Ingmanson and Thode (53) and by Swanson and Steber (54).

The contribution of bonded area to sheet strength may depend upon the internal structure of the bond. This suggestion has been made by Van den Akker (55), who considered bonds formed between two types of surfaces. The first type is characterized by an intact fibrillar system and the second type is characterized by a substantial portion of the microfibrils and macrofibrils having been partially torn away so that the surface of the never-dried fiber, surrounded by water, is in a fuzzy condition. Consideration is given to the difference in mechanical properties between bonds formed between the two different types of surfaces, and the possibility of anisotropy in bond strength is discussed. It is hypothesized that in a typical well-bonded sheet the individual fiber-fiber bonds are subjected to simple shear forces when the sheet is stressed in a direction parallel to the plane of the sheet.

Campbell (56) has suggested that not all of the bonds contribute to the strength of paper. He proposes that a great deal of the bonded surface is broken in the earlier stages of loading while distortions take place in the course of setting up the continuous chains of bonded units which carry the final load. It is pointed out that the energy necessary to separate two surfaces has little to do with the force required to separate them, the latter quantity depending primarily on the number of bonds which must be broken simultaneously.

The third factor of importance mentioned above, affecting the strength of paper, is the manner in which stress is distributed within a sheet when supporting a load. Paper is classed as a macroscopically nonhomogeneous material. There is a great variety in the size and shape of the elements which compose the sheet. The least strain resulting from a load will be realized when the stress in all of these diverse elements is uniformly distributed. The variation in local stress within a sheet has never been measured. However, it does not seem likely that a very efficient distribution is ever achieved.

The problem of stress concentration in structural members has been discussed by Timoshenko (57), among others. It is pointed out by Timoshenko that abrupt changes in cross section give rise to great irregularities in stress distribution, and the presence of such irregularities means that at certain points the stress is far above the average. To use a familiar example, changes in the distribution of stress caused by the introduction of a hole in a flat plate in tension were analyzed mathematically and it was found that great changes in stress level are created in the vicinity of the hole, although the stress level drops fairly rapidly to the normal level at points somewhat remote from the hole.

Alfrey (58) has discussed the nature of stress distribution in high polymeric materials and suggests it is not correct to assume that a homogeneous macroscopic stress is evenly divided over a given cross-sectional area down to molecular dimensions, even in completely amorphous polymers. In the case of polycrystalline materials, such as cellulose, there is an enormous inhomogeneity of the local stress, even where the macroscopic stress is completely uniform. In paper, stress must be transmitted through the fibers and particles of the sheet, and many opportunities exist for stress inhomogeneity on a macroscopic scale. In addition, the distribution of stress in paper may be complicated by variable local basis weights related to poor formation, and by the different mechanical properties of different components of the sheet. The degree of bonding between the load-supporting elements of the sheet would also seem to be a particularly important factor.

If a material distributes stress in a nonuniform manner among its load-supporting elements, it will be weaker than if the elements all share the stress uniformly. This is because the elements under high stress will fail first and, hence, the load they carried will be distributed among the remaining elements. This effect has been discussed by Timoshenko (57) for structural elements generally, and seems pertinent to the fibrous structure of paper.

Very little is known of the nature of stress distribution in paper or of how it affects a sheet's properties. Brezinski (26) has obtained evidence that the increase in tensile strength brought about by wet pressing is related to an improved ability to distribute stress evenly among the elements in the sheet. Arlov (59) investigated the effect of fiber-length distribution on the load-elongation properties of paper and suggested that the nature of the stress distribution differed among the sheets with differing fiber lengths. Beyond these, little experimental work has been presented relative to the distribution of stress in paper.

VISCOELASTICITY AND THE MEASUREMENT OF VISCOELASTIC PROPERTIES

A viscoelastic material has been defined as one which follows the superposition principle (60). Thus, such a material could be represented by a model constructed from elements which obey Hooke's elastic law and elements which obey Newton's viscosity law. However, it is perhaps better to define a viscoelastic body as one which exhibits both instantaneous elastic effects and delayed deformation when subjected to an externally applied stress. Such a definition would include in the realm of viscoelasticity nonrecoverable time-dependent effects.

The superposition principle was originally proposed by Boltzmann (61) to describe the response to stress of various polymeric materials. It has been subsequently extended and discussed by Leaderman (62). The principle applies only to recoverable time-dependent effects. Essentially, it states that a substance will respond to a complicated sequence of loading and unloading as if each load were applied independently for an infinite period of time and that the deformation at any time during the test will be the simple algebraic summation of the deformations due to all of the loads in the sequence at that instant. In this respect, the removal of load is considered to be the application of a negative load. The response to stress of a material which follows this principle is called "linear viscoelastic response." If a material responds linearly, its stress-strain ratio, although a function of time, is independent of stress.

Theoretically, for a linear viscoelastic body, the same information can be derived from any time-dependent loading pattern (60). However, for materials which exhibit large nonrecoverable deformations, such as paper, this is not true, and special care must be taken in the selection and interpretation of viscoelastic tests for these materials. The mathematical relationship between the different types of tests have been reviewed by Gross (63).

Ferry (64) recently has discussed methods for the measurement of viscoelastic properties. These techniques may be divided into three types. These are: (1) dynamic techniques, (2) transient techniques, and (3) other time-dependent techniques. These will be discussed very briefly here, primarily in relation to their applicability to paper. The discussion is taken largely from Ferry.

Using dynamic techniques, a stress which varies sinusoidally with time is imposed, and the resulting strain, which also varies sinusoidally but generally out of phase with the stress, is measured as a function of frequency. Such measurements have been discussed by Alfrey (58) and Leaderman (65). They have been applied primarily to amorphous-type polymers. Dynamic techniques have not been applied to paper, although Kurath (66) has used such methods to study wet pads of cellulosic fibers.

With transient or step-function methods, the stress (or strain) is zero up to a given instant, and then changes discontinually to a finite value. For some purposes, the stress (or strain) may change discontinuously from one finite value to another finite value, or to zero. Methods wherein the stress is determined as a function of time after a sudden application of strain are termed "stress relaxation" methods. In a creep experiment, the strain is determined as a function of time after sudden application of stress. Step-function experiments may be carried out with the sample in tension, shear, torsion, or compression.

Other time-dependent techniques include monotonic changes of stress or strain with time. These tests are often applied to paper, and are referred to as load-elongation measurements. In such experiments, stress or strain is increased at a constant rate. Such tests commonly are carried out with the sample in tension, and the test is continued until rupture. Alternately, the sample may be elongated at a constant rate of increase of stress.

Measurement of the viscoelastic behavior of materials such as paper which exhibit complex time behavior is facilitated by simple time sequences in the mechanical test. The mechanical tests most easily interpreted are those in which either stress or strain is held constant. A suitable method of this sort, applicable to paper, is the tensile creep test. If the rate of change of straining or stressing is held constant, the interpretation becomes more difficult because of the relatively complicated time sequence imposed by the test. The difficulty is most severe if the material is capable of a relatively large amount of time-dependent deformation. A method of analysis of load-elongation curves for paper has been presented by Steenberg and coworkers (67), although it is not capable of dealing with nonrecoverable deformation, which is characteristic of paper.

Load-elongation measurements and tensile creep measurements have been used to examine the viscoelastic behavior of paper. Tensile creep tests are the more desirable from a theoretical viewpoint because of their ability to separate the effects of time and stress. In addition, they are not experimentally complex. Both types of measurements are used in this work.

Several terms and concepts frequently encountered in the literature concerning viscoelasticity should be defined and explained. When a viscoelastic material is subjected to a tensile stress, it exhibits an immediate elastic deformation and a time-dependent deformation. The immediate elastic deformation occurs immediately upon application of the load. The extent of the immediate elastic deformation is believed to be directly proportional to the applied stress. This deformation is considered to be the result of the deformation of primary valence bonds, the changes in primary valence bond angles, and the extension of secondary bonds, all of which are completely reversible mechanisms.

The time-dependent deformation may either be recoverable or nonrecoverable. Recoverable delayed deformation, or delayed elastic deformation, is believed to be principally related to configurational response in polymeric materials. This effect is related to the tendency of polymer molecules reversibly to assume statistically preferred configurations when subjected to external stress. Reversible changes of phase, however, may also account for recoverable delayed deformations. Delayed elastic deformation is often evaluated by examining the extent and nature of the recovery from creep deformation. It should be noted, though, that the total recovery exhibited by many materials, including paper, is strongly dependent upon factors such as temperature and relative humidity. Therefore, a quantity designated as recoverable deformation is meaningful only if the conditions of recovery are described.

It follows that the nonrecoverable deformation is meaningful only at stated conditions of recovery. In many polymeric materials, nonrecoverable deformation is believed to be largely related to viscous flow or the actual transfer of entire molecules past one another, although this does not seem possible in the case of cellulose since the crystallites would inhibit molecular flow. Leaderman (62) has discussed the possibility of irreversible crystallization in the case of nylon as contributing to nonrecoverable deformation, and this may also be applicable to cellulose.

Another cause of nonrecoverable deformation may be the establishment of metastable or "frozen-in" molecular configurations, which appear stable at test conditions. The apparently stable state may be created by strong intermolecular binding forces which inhibit recovery. Such intermolecular forces are particularly strong in cellulose and cellulose derivatives, and are largely related to the hydroxyl groups spaced along the cellulose polymer. Actually, any apparent state of equilibrium in the dimensions of these polymers is likely to be metastable. Plasticizing the molecules by raising the relative humidity, for example, may reduce the intermolecular forces and thereby affect the extent of nonrecoverable deformation.

The above discussion of immediate elastic deformation and time-dependent deformation is taken largely from Alfrey (58) and Brezinski (26). The reader is referred to these authors for a more complete treatment.

THE RESPONSE OF PAPER TO STRESS

When paper is subjected to a tensile stress, it may break immediately, or it may support the stress for some period of time. Rance (68) and Jacobsen (69) found a relationship between the load and the logarithm of the time period that the load is supported by paper before rupture. This implies a stress-dependent mechanism within the structure of the sheet affecting the strength of the sheet. This mechanism may be related to the observation of Maynard (70) and McKee (71) who found that the thickness of paper may increase while supporting a load. This increase has been attributed to the breaking of fiber-fiber bonds. Sanborn (72) noted a decrease in sheet caliper produced by tensile loading, and suggested that the different effect may be related to different fiber properties, such as flexibility.

Other evidence of stress and time-dependent changes in internal sheet structure has been obtained by Nordman, Gustafsson, and Olofsson (73) and Sanborn (72). These workers noted an increase in the light-scattering coefficient of paper after it was subjected to stress, and found a relationship between the change in scattering coefficient and the work done by the load on the paper. It is generally believed that the light-scattering coefficient varies directly with the unbonded area in the sheet, so a change in the internal sheet structure is indicated. It is anticipated that a change in the internal structure of the sheet would affect the manner in which stress is distributed in the sheet when the sheet is in tension. Since the internal structure apparently changes continuously, the stress distribution would also undergo continuous change.

A considerable body of literature has been published describing and explaining the viscoelastic behavior of paper. Work in this area began in 1944 with the investigations of Gibbon (74) and Farebrother (75), who were concerned with the nonlinear response of paper to stress. The development of some of the current ideas concerning the viscoelastic nature of paper will be briefly reviewed here. The reader is referred to Rance (76) for a complete review of work done before 1952.

In 1947, Steenberg (25) published the first of a series of articles by Swedish workers describing the load-deformation properties of paper. These workers emphasized that the viscoelastic behavior of paper was dependent upon the previous mechanical treatment of the specimen, the orientation of the specimen with respect to the paper machine, the relative humidity and temperature and the rate of straining. It was recognized that paper exhibits both recoverable and nonrecoverable time-dependent deformation.

Steenberg (77) advanced the concept of microcreping to account for the nonrecoverable deformation. Microcreping is a superficially invisible creping effect whereby it is hypothesized that the fibrous elements between points of bonding are bent. When the sheet is loaded, the fibers are pulled into straighter configurations. Rance (76) has criticized this proposal, pointing out that since all papers except the thinnest tissues are several fiber layers thick, a randomly bonded three-dimensional fiber assemblage could not be expected to unkink.

Rance (76, 78) proposes that, rather than through microcreping, nonrecoverable deformation is a consequence of the rupture of fiber-to-fiber bonds at an ever-increasing rate until final termination of the test by rupture. In this view, the shape of the stress-strain curve depends very largely on the spectrum of degrees of slackness in the network structure, for the extensibility is due to the taking up of successive increments of slackness as successive bonds are broken. Rance accounts for the time dependency of reversible extension by referring to a combination of elastic deformation of fibrous elements, plus a frictional sliding of fibers past one another. Maynard (70, 79) suggested that bond breaking plus friction accounts for irreversible extensibility, and found that paper subjected to strain in the post-yield range of tests exhibits an increase in bulk, which he attributed to the rupture of fiber-fiber bonds.

Nissan (80,81) has presented a mathematical analysis of the response of paper to stress, based on the assumption that in straining paper, only the hydrogen bonds of the amorphous regions of the cellulose matrix are strained. The macroscopic strain is equated to the cumulative bond strain, and it is pointed out that since the differential coefficient of energy potential of the bond is not linear, the stress-strain relationships are not linear. The bonds are weak and break readily, producing creep and stress relaxation. Finally, it is postulated by Nissan that a broken bond will reform when it next meets the appropriate portion of another broken bond. Therefore, internal rupture is, in part, self-healing. The mathematical expressions used by Nissan describe response in terms of parameters derived from either viscoelastic or spectroscopic data.

Ivarsson (82) studied the mechanical conditioning of paper in repeated load-elongation tests. Although the bulk of the nonrecoverable deformation was removed in the first load-unload cycle, many cycles were necessary before the response approached reversibility. It was suggested that the effect, rather than being related to a phase change to a more highly crystalline state as in rubber, was related to the organization of already crystalline elements, as through the orientation of the fibers. It was pointed out that such a mechanism would make an observed increase in elastic modulus understandable.

Brezinski (26) investigated the tensile creep properties of paper and observed a degree of ideality in creep response which, he postulated, would not be expected if macroscopic uncurling or straightening of the fibers in the sheet made significant contributions to the total delayed deformation. He suggested that the rate-controlling mechanisms of deformation operate entirely on a molecular level. Early delayed creep deformation could be described by a power equation of the form,

$$y = Bt^{A} + C, \qquad (1)$$

where A, B, and C are constants, t is the time the specimen is under a tensile load, and y is the percentage of deformation created in the specimen by the tensile load, calculated on the basis of the original length of the sheet. This "exponential creep" was attributed to configurational rearrangement and increased alignment of the molecular chains in the amorphous areas of the polymer. It should be noted that although early creep is best described by a power equation, it is usually termed "exponential" creep.

Later delayed deformation could be described by a logarithmic equation of the form,

$$\underline{y} = \underline{K} \log \underline{t} + \underline{C}', \qquad (2)$$

where K and C' are constant at a given apparent initial stress. It was suggested that this logarithmic creep could be related to the rotation of the molecular chains in the fringe areas. Creep deformation was divided into recoverable and nonrecoverable creep. It was found that a large portion of the nonrecoverable creep exhibited by paper could, in fact, be recovered if the sample was subjected to humidity during the recovery period higher than that used during the creep phase. Such a recovery after humidification, indicative of a metastable state in mechanically conditioned paper, was found by Mark and Press (83) to occur in viscose.

EXPERIMENTAL PROCEDURES AND TECHNIQUES

PREPARATION OF HANDSHEETS

DESCRIPTION OF PULP

The pulp used in this study was a Rayonier softwood alpha pulp, primarily Western Hemlock, commercially available as Rayocord G. A fiber analysis showed that no hardwood fibers were present. The pulp was received as dry lap and was stored at room conditions. The pulp was refined in a Valley laboratory beater according to Institute Method 403. Before beating, the pulp was soaked in water for four hours and was defibered in a Williams Standard pulp disintegrator. The pulp was beaten with a load of 5500 g, on the bedplate.

At each degree of beating used, several beater loads of pulp were prepared. After beating, a small amount of formaldehyde was added to the pulp, and the pulp was dewatered to a consistency of about 20% solids. The pulp was crumbled automatically, and the crumbled pulp from different beater loads was blended to insure uniformity.

Four pulps were prepared for this study. Each pulp is designated by the Schopper-Riegler freeness to which it was refined. Pulps 290, 460, 650, and 760 were beaten to Schopper-Riegler freenesses of 290, 460, 650, and 760 cc., respectively. Pulp 760 was further treated to increase its average fiber length. This pulp was screened in a Clark classifier, and the material which passed through the 100-mesh screen was discarded. The arithmetic average fiber lengths of Pulps 290, 460, 650, and 760 are 0.433, 0.600, 0.797, and 1.080 mm., respectively. These data were obtained using the semiautomatic Fiber Length Recorder developed at The Finnish Pulp and Paper Research Institute.

SHEET FORMING AND PRESSING

All sheets were formed on a 20-inch square sheet mold fitted with a 75-mesh "Monoplane" wire. This wire was provided by Appleton Wire Works Corp., and was selected to minimize wiremarking. The wire was fitted to a copper frame to facilitate handling.

Water for the sheetmaking operation was filtered by three Ful-Flo filters set in parallel, and the water in the system was recirculated. The usual practice was to form eight preliminary handsheets to bring the fines content in the white water to a nearly constant value. The next sheets prepared were kept and dried in the manner described below. No more than four of these handsheets were prepared at one time. Before each sheetmaking session, the water in the system was changed and the apparatus was cleaned. A small amount of formaldehyde was added to the water to protect the handsheets from bacterial growth during the drying operation.

A head of water above the wire of about 54 inches was used. This produced a consistency of about 0.005% and effectively eliminated flocculation, promoting good formation. After the water drained and the wet web was formed, the sheet was covered with a wet blotter, and then the wire, new sheet, and wet blotter were lifted together onto a vacuum box. A pressure difference of about 28 inches of mercury was applied to the sheet for 20 seconds, and then the new sheet and wet blotter were removed from the wire.

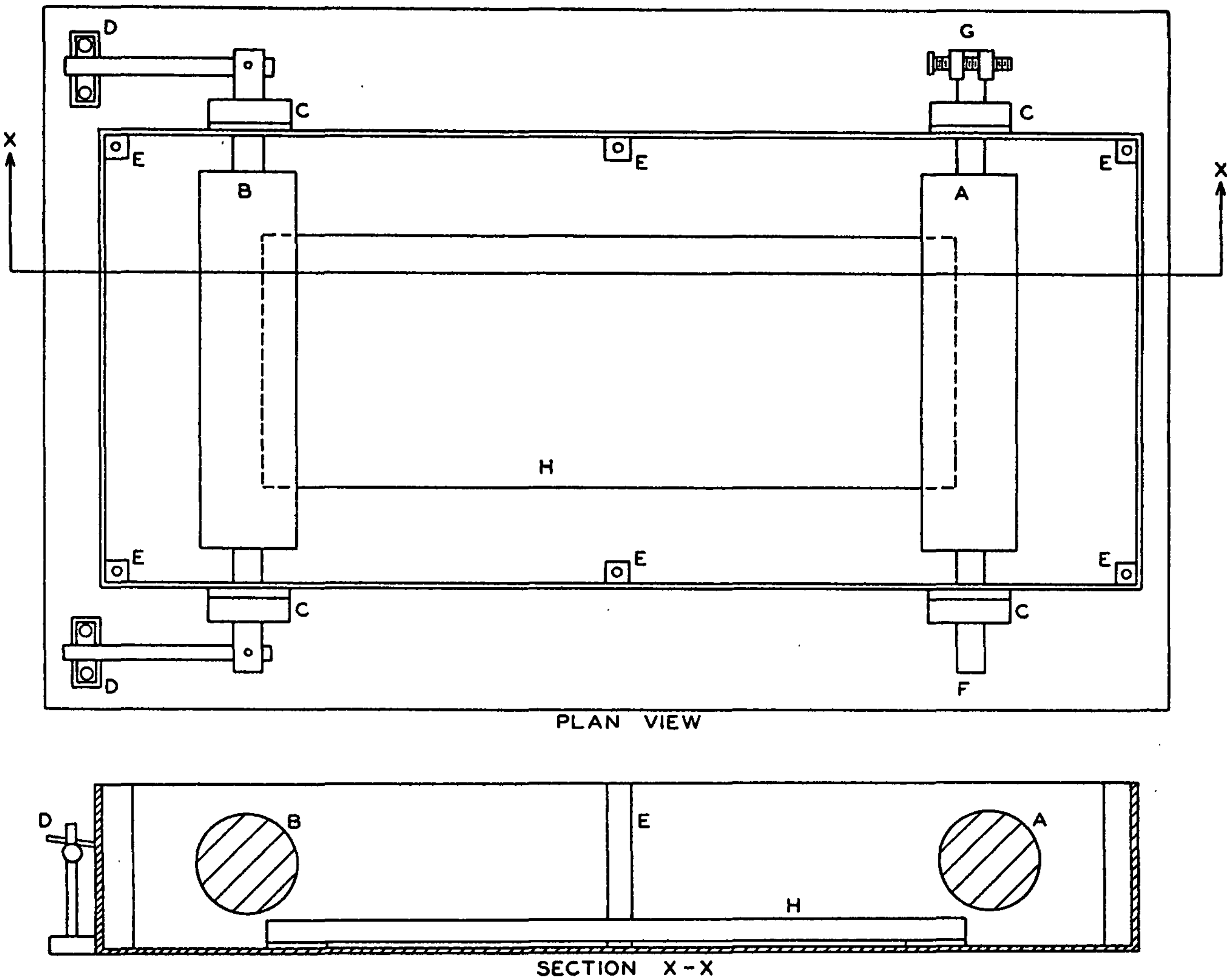
A wet blotter, 14 by 20 inches in size, was placed over the sheet, and the wet web was trimmed to this size with a razor blade. Two additional wet blotters were placed on either side of the sheet, and 10 dry blotters were put on each side of this assembly. At this point, the sheet was ready for pressing. Sheets were always carried through the pressing operation singly, as described.

Pressing was carried out with a 90-ton Elmes press. The sheets were loaded in five even steps to 50 p.s.i. during a one-minute period and then held at this pressure for about 5 minutes, depending upon the freeness of the pulp. Pressing was scheduled to produce a solids content in the pressed sheet of 32%. Deviations in solids contents from this were found to be small. The variation of solids content within the sheet also was investigated. Samples taken from different parts of the sheet were found to have an average deviation of 0.3% solids, and this was considered to be acceptable. A similarly small value was found to represent the variation in basis weight within the sheet. Since only a fraction of the sheet was to be dried and used for testing, variations in basis weight and moisture content in the area ultimately dried for use may be considered to be small.

SHEET-DRYING TECHNIQUES

The purpose of the sheet-drying equipment was to prepare handsheets subjected to controlled unidirectional strain during drying. The wet-straining operation always occurred at 36% solids. The equipment is shown in Fig. 1. It consisted essentially of a tray of mercury, H, set between two cylinders, A and B. The axes of the cylinders were parallel to one another and to the plane of the mercury surface. The lowest point of each cylinder was located near and at the same height as the mercury surface. The sheet to be dried was placed on the mercury, and each end was passed under a cylinder and clamped to that cylinder. One of the cylinders, B, was unable to move, while the other, A, could be rotated in position to strain the sheet. The rotating cylinder was clamped into a stationary position after the prescribed amount of strain was applied to the web and remained clamped until the sheet was fully dried.

Each of the cylinders was supported at either end by ball bearings, C, which were lubricated with a light oil. The stationary cylinder was held in place by two arms, one at each end, passing through and perpendicular to its axis. The arms rested on the "roller brakes," D, and prevented the cylinder from turning. The torque created in the cylinders by the stress developed by the sheet was transmitted to the arms as a bending moment. A system of strain gages was affixed to the arms to allow the measurement of the stress history of the sheet during drying. Each stationary cylinder was associated with four strain gages which were arranged as the four resistances of a Wheatstone bridge. When the system was stressed, the bridge was unbalanced and the extent of imbalance, measured by a Rubison galvanometer, was calibrated against torque on the cylinder.



A ROTATABLE CYLINDER
B STATIONARY CYLINDER
C BEARING HOUSING
D ROLLER BRAKE
E COVER SUPPORT
F FLEXIBLE COUPLING TO MOTOR ASSEMBLY
G CLAMP
H TRAY FOR MERCURY

Figure 1. Sheet Drying Equipment

A sample to be dried in this manner was cut from the pressed handsheet with a new razor blade and was very carefully placed on the mercury. The strip measured 4-1/2 inches in width and 18 inches in length. The long axis of the sheet was perpendicular to the axes of the cylinders. Before being placed on the mercury surface, a piece of 1-inch wide kraft gummed tape was affixed to each end of the wet web, just covering the ends of the web. Previously drawn fiducial marks on the kraft tape were aligned with corresponding marks on the cylinders to insure the proper alignment of the sheet in the unit. Scotch cellophane tape was used to hold the kraft tape in place for clamping.

With the properly aligned wet web next to the cylinder, covered by the kraft tape, several strips of blotter stock were placed over the kraft tape and were clamped to the cylinder. This clamp consisted of a metal bar which when in place was bolted firmly to the cylinder. A layer of foam rubber was set between the metal bar and the blotter stock to promote uniform clamping pressure. Clamping was aided by the diffusion of glue from the kraft tape through the wet web, which caused the web to adhere to the cylinder.

After the web was clamped in place, the Lucite cover for the drying unit was clamped in place, completely sealing the area enclosing the paper to be dried. The cover was provided with 14 small (no. 56 drill) holes through which moisture vapor could escape at a slow rate, allowing the sheet to dry. Since the drying equipment was placed in a room maintained at 50% R.H. and 73°F., the sheets dried at a uniform, slow rate. Immediately after the sheet and the cover were in place, the sheet was wet strained. A Bodine 1800 r.p.m. synchronous motor was coupled in series with a Zero-Max variable-speed torque converter and a Winsmith worm-gear speed reducer (1 to 900 ratio) to provide a straining mechanism, and this assembly was attached to the rotating cylinder at the point indicated in Fig. 1. The assembly was adjusted to strain the wet web at the rate of 1% per minute.

To strain the sheet, the motor was turned on and the galvanometer associated with the strain gages attached to the stationary cylinder mentioned above was observed. When the galvanometer needle began to move, indicating tension in the sheet, it was known that the sheet was being strained. By carefully timing the straining operation, it was possible to apply approximately the desired amount. However, this was never used as the final measurement of the degree of wet straining. After the proper amount of wet straining was applied, the motor was turned off and the cylinder was clamped in a stationary position. Both cylinders remained stationary for the remainder of the drying period.

The operation of introducing the sheet into the drying unit took somewhat less than 10 minutes. During this period, evaporation could take place from the surface of the sheet into the air. To promote uniformity, the operations which had to be carried out with the sheet exposed to the atmosphere were scheduled and timed with a stopwatch. For example, the cover was always placed on the drying unit 9 minutes and 20 seconds after the sheet was first exposed. As a result of the exposure, the sheet gained 4% solids, and, therefore, since wet pressing was scheduled to produce 32% solids in the sheet, wet straining always occurred at 36% solids.

It was found empirically that after 192 hours (8 days) in the drying unit, the sheet was at about 88% solids, and that after 8 days drying proceeded at a very slow rate. Therefore, at that point, the cover was removed and after allowing 3 hours for the sheets to attain moisture equilibrium with the room conditions, the sheets were unclamped and removed. The equilibrium solids content of the sheets was 92.5% at standard conditions. After removal from the drying units, the dried sheets were enclosed in aluminum foil and stored at standard conditions. At no time were the fully-dried sheets exposed to any but the prescribed conditions. It is believed that wrapping the sheets in foil and storing them in a box inside a cabinet minimized the effect of small variations in temperature and humidity which are produced even by the best air-conditioning systems.

It was important that a reliable method be developed to measure the degree of wet straining (DWS). The DWS may be defined as the amount the sheet is strained during drying divided by the original length of the sheet after wet pressing, expressed as a percentage. In order to measure this quantity, two dyed fibers were laid upon the wet sheet just prior to wet pressing, and these were made part of the sheet by the pressing action. After pressing, the distance between the closest reaches of the fibers was measured, and this same line was measured after the sheet was dry. From these two measurements, the degree of wet straining was calculated. The DWS is reported to the nearest 0.1% and is believed to be accurate to 0.1%.

Several aspects of the design of the sheet-drying equipment should be discussed. It was felt to be important that the web be placed in a horizontal position. If the web were hung in a vertical fashion, the upper portions would be subjected to greater stresses than the lower portions because of the cumulative weight of the web itself. With the sheet in a horizontal position, though, support had to be provided for the middle portion of the web to prevent its sagging. Supporting the middle with a rigid surface would have been unsatisfactory since free lateral shrinkage of the sheet would have been prohibited and the restraint to shrinkage or stretching created by the contacting surfaces probably would not have been reproducible.

Floating the sheet on a mercury surface avoided these difficulties since the fluid surface could move with the sheet when the web was either stretched or allowed to shrink. However, the use of the mercury introduced the problem of keeping the mercury clean. Before each sheet was introduced to the drying unit, the mercury surface was cleaned by touching to it a strip of Scotch cellophane tape or by using an improvised vacuum cleaner. In addition, the mercury was periodically removed and washed in a very dilute solution of nitric acid.

The dimensions of the wet web used in the drying unit were 4-1/2 by 18 inches, and this long and narrow strip was clamped at the ends and was 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 unable to shrink. It was found that the middle 8 inches of the strip exhibited very little concavity, and in that portion the sides of the web were very nearly parallel. Furthermore, it was found that there was no significant difference in the mechanical properties of test strips taken from this middle section. Therefore, it was concluded that the mechanical history of the paper in the middle area was uniform, and testing was confined to that area.

In a series of preliminary experiments, it was found that if allowed to air dry without restraint in all directions, paper would curl and cockle severely. It was reasoned that this effect was related to differential rates of shrinkage in different parts of the sheet due to moisture gradients in the sheet. In other words, if two contingent areas of the sheet were at different levels of dryness, they would also be at different stages of shrinkage, and these would interact, creating cockle. Although this analysis has been known for sometime, it seems to have been published first by Smith (84).

Because of the critical nature of the measurements to be made upon the sheets, every effort was made to inhibit curl and cockle. Good sheet formation was promoted by forming the web from a very dilute suspension. In order to reduce the effect of moisture gradients mentioned above, the sheets were dried very slowly to allow the diffusion of water through the fibrous system. By using the slow-drying technique, acceptable sheets were prepared even though lateral shrinkage was allowed.

HANDSHEET STRESS HISTORY

Some knowledge of the stress history of the handsheets is useful in understanding the nature of the mechanical treatment to which they were subjected. It was possible to follow the development of stress in the sheet with the strain-gage system discussed above. The first phase of the stress history occurred when the sheet was at 36% solids and was strained to the desired degree. The stress level attained in this phase was low, but depended upon the extent of straining. The analysis provided by Lyne and Gallay (34) serves to describe this operation. At this stage, the coherence of the sheet depends largely upon surface tension and resulting frictional forces between the fibers. Because of the slow rate of drying, the wet-straining operation is considered to have occurred at a constant solids content, even though the operation might have extended as long as six or seven minutes. Also, because of the slow drying, there is little danger that drying would occur unevenly through the sheet, causing the parts of the sheet closer to the surface to be drier than the parts more remote from the surface.

After wet straining, when the sheet was clamped at constant extension, the stress level decayed with time to a very low value. This decay continued until the shrinkage forces became predominant. Thereafter, the tension built up until the sheet was fully dried. When the cover was removed, there was a sudden jump in the tension as the last excess water evaporated quickly.

A systematic study of the changes in total stress history created by wet straining was not undertaken. It is not believed that large differences exist. The tension in the sheets three hours after the cover was removed may be regarded as the final tension developed, and these tensions were recorded for handsheets prepared from Pulps 760, 650, and 460. These data are presented in Table I. The data are given in terms of kilograms per square millimeter, and refer to the kilograms of tension developed per calculated cross-sectional area of airdry cellulose in a plane perpendicular to the direction of tension, expressed in square millimeters. For purposes of comparison, one square millimeter of cross-sectional area corresponds to a one-inch wide strip of 62 grams per square meter basis weight.

TABLE I
FINAL TENSIONS DEVELOPED DURING DRYING

Pulp 760		Pulp 650		Pulp 460	
DWS, %	Tension, kg./mm.^{2}	DWS, %	Tension, kg./mm.^{2}	DWS, %	Tension, kg./mm.^{2}
1.6	0.86	0.0	1.32	0.7	1.35
2.2	0.84	0.9	1.40	1.8	1.33
2.3	0.90	1.6	1.57	2.1	1.38
4.5	0.91	2.2	1.50	3.4	1.33
5.0	0.94	3.5	1.50	4.7	1.30
6.3	0.89	5.1	1.32	6.3	1.21

These data are of the same order of magnitude as similar data presented by Ivarsson (14), but are somewhat larger. The differences may be related to differences in the pulps and in the specific techniques used. Although these drying stresses are not large when compared with the ultimate strength of the dry sheets and with the stresses used in most tensile creep tests, they are not small, and they emphasize the importance of reproducible methods in the preparation of handsheets. The absolute differences in the drying tensions produced by wet straining do not seem to be large and suggest that all of the handsheets prepared from a single pulp had similar stress histories. A more comprehensive investigation of the effect of wet straining on drying stress might reveal details of regular changes produced by the straining action.

INSTRON LOAD-ELONGATION MEASUREMENTS

The mechanical properties of the handsheets prepared in the manner described above were examined with an Instron Universal Testing Instrument. The ability of the instrument to determine paper properties has been examined by Van den Akker and Hardacker (85). These mechanical properties include tensile strength, ultimate elongation, elastic modulus, and the amount of work necessary to cause rupture. 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 behavior of the test specimen.

In these tests, the Instron was fitted with line-contact clamps. Van den Akker and Hardacker (85) and Sanborn and Diaz (86) have found that such clamps are necessary for accurate work of this nature. The clamps were set for a gage length of 8 inches, and test strips were one inch wide.

Because of the time necessary to prepare each handsheet and because each dried handsheet was only about four inches wide (after shrinkage from 4-1/2 inches), it was not practical to use more than a single test strip from each handsheet for this part of the program. However, as a check on the uniformity of sheet properties, several of the handsheets were subjected to more than one Instron test. A series of duplicate tests run on several of the handsheets prepared from Pulp 650 indicated that the average deviation from the means tensile strength within a handsheet was less than 2% of the recorded strength.

All Instron tests were carried out at 73°F. and 50% relative humidity. The samples were dried to these standard conditions and were stored at these conditions in a sealed container to minimize the effect of small fluctuations in humidity and temperature. In all cases, the rate of straining was 6.2% per minute.

The values of work-to-rupture reported in this investigation are a measure of the work necessary to rupture the paper specimen and are calculated by measuring the area under the load-elongation curve. This measurement is carried out automatically by an integrator which is part of the Instron. This automatic integrator has been calibrated by The Paper Evaluation Group of The Institute of Paper Chemistry and has been found to be very reliable.

THE MEASUREMENT OF BONDING STRENGTH

The measurement of the force necessary to cause tensile failure along a plane within and parallel to the surface of a sheet of paper is commonly referred to as a "bonding strength" test. This is because the single most important contributor to strength in this "*z*-direction" is the strength of the bonds between the fibers. It is believed that little fiber damage is brought about when the sheet is disrupted in such a manner. This is largely due to the general orientation of the fibers in a direction parallel to the surfaces of the sheet. This is not so in the traditional tensile strength test, in which case it is known that a considerable number of fibers are broken (32).

Since so little is known concerning the structure of bonds, it is presumptive to call the transverse tensile strength an absolute measure of bonding strength. The internal structure of bonds may make bond strength anisotropic, and the nature of the stresses imposed upon the bonds may be quite different in the transverse direction as compared to one of the other sheet directions. Therefore, it is best to consider the z-direction tensile strength test as a measure of bonding strength, and not to apply any absolute significance to the values obtained. If the structure of the bonds were understood and if the nature of the stresses imposed during the test could be completely analyzed, it might be possible to assign a more rigorous meaning.

The development of a suitable z-direction tensile strength test has had a long history. In 1923, an anonymous author (87) bonded a paper sample between two wooden blocks with sealing wax and then pulled them apart in a Schopper tensile tester. This procedure was modified by Abrams (88), who used silicate and cellulosic adhesives, and by Kessler (89), who experimented with metal adaptors to replace the wooden blocks. Other preliminary work was done by Sutermeister and Porter (90), Brecht and Blikstad (91), and Sutermeister and Osgood (92). The

Institute of Paper Chemistry (93) published a series of papers in which the problem of determining the transverse tensile strength of paper was analyzed.

Eames (94) has recently developed equipment for measuring the transverse tensile strength of clay coatings. The problem may be divided into two parts. These are: (1) the choice of a suitable adhesive and (2) the mounting and testing of the samples. The choice of a suitable adhesive may be the most critical problem. Eames listed several factors concerning this choice, which may be generalized and summarized as follows:

(1) The adhesive must have a tensile strength substantially higher than that of the specimen being tested.

(2) Adhesive penetration into the specimen must be small but intimate contact must be made with the surface.

(3) The adhesive must cure without requiring elevated temperature or pressure.

(4) No solvent may be released after bonding is initiated.

(5) No stresses may be set up in the specimen during the curing of the adhesive.

Eames also developed a suitable mounting jig and aligning device for testing the samples.

Van den Akker (95) has discussed several aspects of the technique of measurement of transverse tensile strength. He pointed out that nonuniform thickness of the test specimen will create a nonuniform stress in the test area. Such an effect would be especially critical in the case of paper, which is known to have severe local variations in thickness. This analysis emphasizes the importance of good formation for paper subjected to this test.

The technique developed by Eames (94) was modified by Jappe and Kaustinen (96) working at The Institute of Paper Chemistry, and was applied by these workers to determine the transverse tensile strength of paper. The technique of Jappe and Kaustinen, using the modified Eames equipment, was used in this work.

Stated briefly, the technique involves mounting in proper alignment two steel, cylindrical lugs on either side of the paper sample. A measured, uniform layer of adhesive is used to attach the lugs to the sample. When the adhesive has cured, the samples are tested by applying a uniform tensile stress accurately parallel to the axis of the test lugs. The lugs and the aligning device used for testing the samples have been described by Eames (94). The adhesive used was an epoxy resin manufactured by The Armstrong Products Company under the trade name of Armstrong Adhesive A-1, catalyzed by an amine-type activator, Activator A. This adhesive met all of the requirements listed above for proper adhesive characteristics.

The adhesive was measured and applied to the lugs by the method described by Eames (94). After the adhesive was applied, the lugs were transferred to the mounting device shown in Fig. 2 and 3. Figure

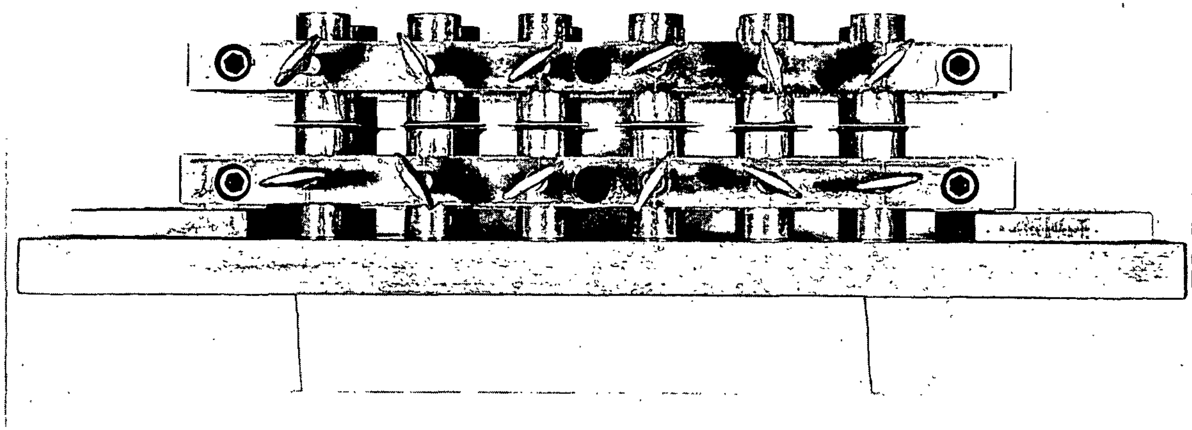


Figure 2. Fully Assembled Apparatus for Mounting Transverse Tensile Strength Samples

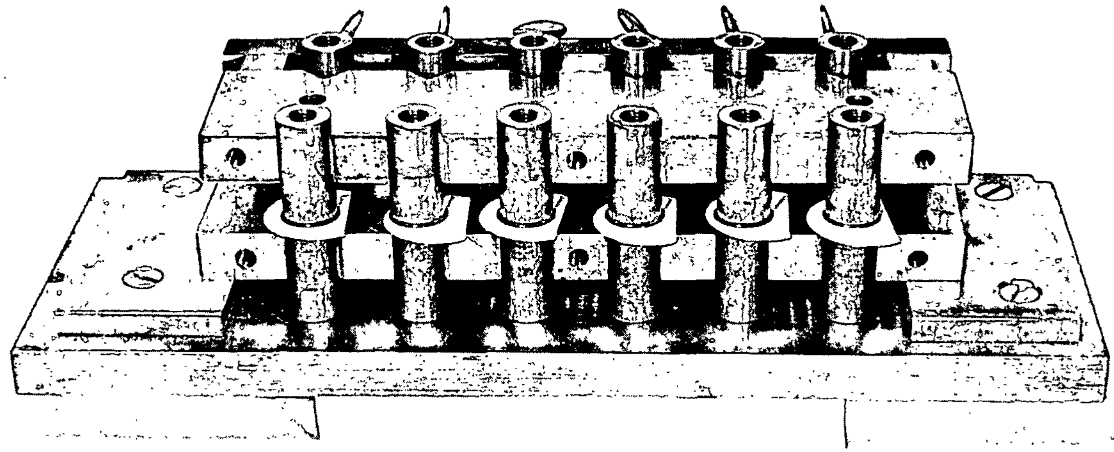


Figure 3. Transverse Tensile Strength Apparatus, Disassembled and Ready for Removal of Lugs

2 shows the samples in place with the mounting unit fully assembled. In order to assemble this unit, the lower set of lugs is first assembled, the paper samples are put in place, and then the entire upper set of lugs, previously mounted, is fitted in place, guided by two pins. The paper samples were always placed on the adhesive 20 minutes after the catalyst was mixed with the epoxy resin. Figure 3 shows the apparatus partially disassembled, ready for the removal of the lugs. The usual practice was to wait at least 20 hours before removing the lugs to allow complete curing of the resin. It is seen that a maximum of 12 samples could be prepared at one time.

The excess adhesive and paper sample were trimmed from the sides of the lugs before testing. This operation had to be carried out very carefully so the bonded structure would not be prematurely damaged. The sample area tested measured 0.196 sq. in.

After the sample had been tested, it was possible to examine the test area for adhesive penetration. This was carried out with the aid of a binocular microscope. It was found that the adhesive would penetrate if low-basis-weight, lightly beaten samples were tested. The penetration also produced a characteristically higher variation in within-sample test results. However, penetration was unimportant for most handsheets when care was taken in sample preparation.

TENSILE CREEP MEASUREMENTS

DESCRIPTION OF APPARATUS

The tensile-creep-testing apparatus designed by Brezinski (26) at The Institute of Paper Chemistry was used in this study. The apparatus measures the deformation of a specimen subjected to a constant tensile load. The upper clamp remains stationary, and the movement of the bottom clamp is measured directly with a micrometer using an electrical contact device. The equipment is shown in Fig. 4. A more complete description has been given by Brezinski (26).

To determine the position of the lower clamp, the micrometer shaft, F, is lowered by rotating the micrometer until the needle on the lever arm, A, contacts the lower clamp. Lowering the micrometer bar farther would break an electrical circuit which runs between the block, B, the lever arm, and the frame. The lever arm is unbalanced, and the needle, D, is normally in contact with the block, B, so that the electrical circuit is normally complete. Proper alignment of the micrometer shaft is maintained by a pin, G, which rests upon a guide bar. The lever arm is unbalanced by only 1 or 2 grams, which has a negligible effect on the lower clamp position.

Two types of clamps were used in this study. Initially, the flat-face clamps designed by Brezinski (26) were employed. Comparison of these clamps with a set of line-contact clamps, similar to those recommended by Van den Akker and Hardacker (85), showed that specimens held by the flat-face clamps exhibited up to 7% more deformation during the tensile creep tests than did the line-contact clamps. This indicated that partial pull-out was occurring between the faces of the flat-face clamps. The majority of the tensile creep data reported in this work and all of the data dependent upon the absolute magnitude of the creep deformation were obtained with the line-contact clamps. Some data, the

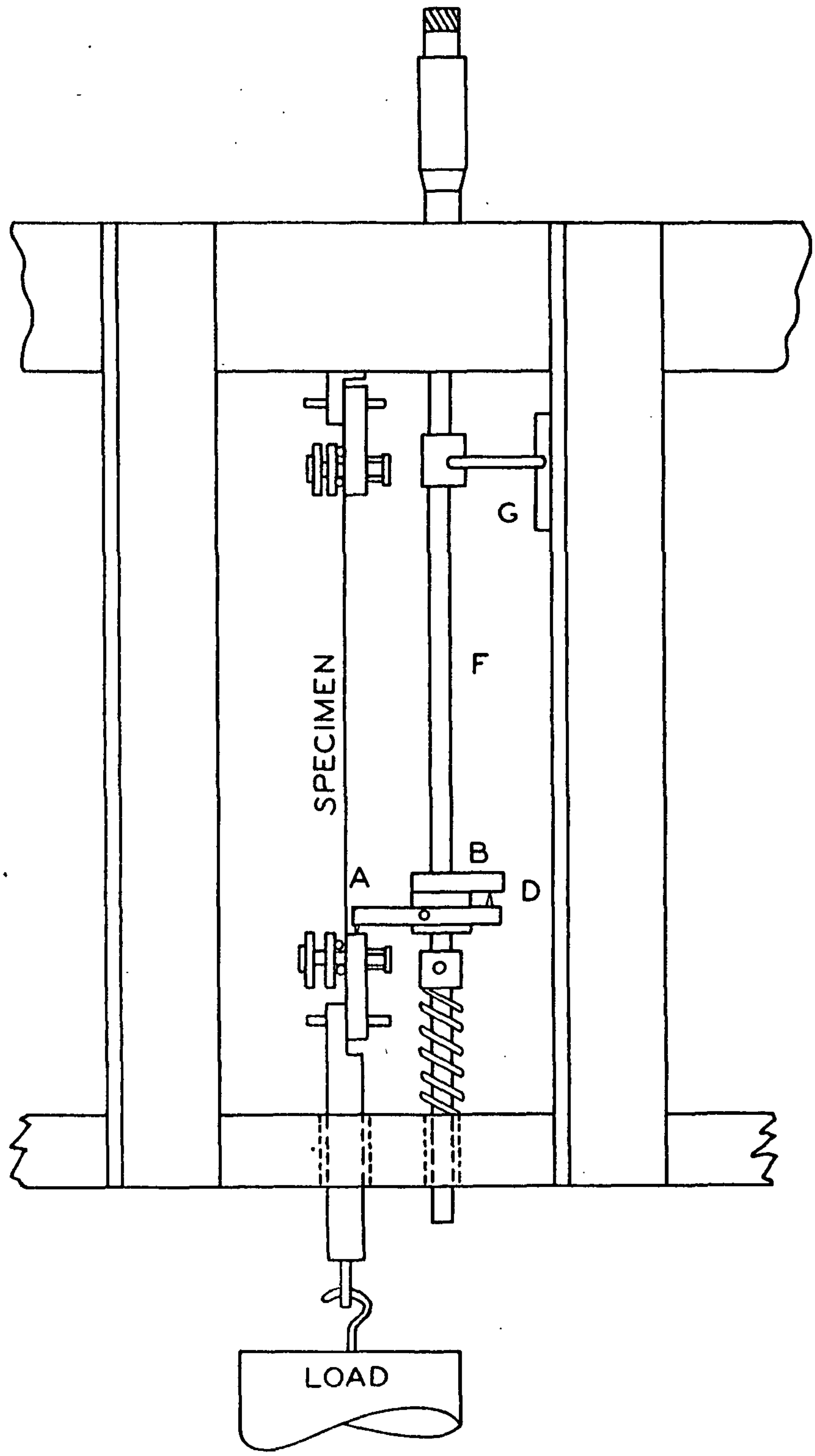


Figure 4. Creep Testing Apparatus

value of which rests upon the relative magnitude of creep deformation, were obtained with the flat-face clamps. The occurrence of the latter is clearly distinguished in this report.

The line-contact clamps consisted of a 1/8-in. diameter rod pressed against a flat surface with the sample between the rod and the flat surface. The clamps were spring-loaded, and a pressure of 135 lb. per linear inch was maintained on the specimen. Each clamp was pinned to a short section of rod, milled flat at one end, as shown in Fig. 4. The upper rod fitted freely into a hole in the bottom of the upper support bar and was pinned in position. The two top support pins are perpendicular to one another, forming a universal joint, insuring proper alignment and loading of the specimen. The lower clamp rod passes through a hole in the bottom support bar, and an eyelet attached to its lower end receives a hook attached to the load. The clamps were removable from the assembly to facilitate insertion of the specimens in the clamps.

DESCRIPTION OF CREEP-TESTING TECHNIQUES

All of the tensile creep tests were carried out at 50% R.H. and 73°F. The initial gage length of the specimens between the line-contact clamps was 8.25 inches, and between the flat-face clamps the gage length was 8.00 inches. For both clamp types, the initial specimen width was 0.87 inches. Specimens were normally handled at their ends, in areas not subjected to testing. The samples were properly aligned in the clamps with a jig constructed for that purpose. This jig also maintained the correct distance between the clamps during insertion of the specimens.

Specimens were cut for creep testing and for other purposes from the central nine inches of the dried handsheets, in which area the properties of the sheet were considered to be uniform. Cutting of specimens was carried out with a razor blade. Each specimen was weighed individually, and from this weight and the known specimen length, the cross-sectional area of the solid cellulosic material in a plane perpendicular to the direction of the test was calculated. This calculation was made using an assumed density for airdry cellulose of 1.55 g. per cc. This calculated cross-sectional area was used to determine the apparent initial stress, which was defined as the weight of the total applied load, expressed in kilograms, divided by the calculated cross-sectional area of airdry cellulose, expressed in square millimeters. The total applied load includes the weight of the clamp.

After a specimen was fixed in the clamps, it and the clamps were mounted in the frame. In this position, the specimen supported the weight of the lower clamp. The weight of an individual flat-face clamp was 300 grams, and the weight of an individual line-contact clamp was 315 grams. With the specimen in place, an initial reading was taken to determine the relative position of the lower clamp. Calculations of the increase in sample length were made relative to this initial reading.

The determination of the initial position of the lower clamp was done as soon as possible after the specimen was in place. The application of the load was made soon after that to avoid any extensive creep under the weight of the clamp. The load was applied gently to avoid any sharp impulse through the specimen, and this application took an estimated

0.5 second. The first measurement of deformation was taken as soon as possible; for an average specimen under an average load, the first reading could be taken at about 10 seconds. Time was measured starting with the application of the load.

Because the initial measurement of the position of the lower clamp was made with the specimen sustaining the weight of the clamp, a correction should be made for the elastic deformation produced in the specimen by the clamp. Such a correction is difficult to make because the elastic deformation produced by the clamp load is difficult to measure. The correction is in the vicinity of 3.0 mils, however, and the measured deformations relative to the initial position of the lower clamp were increased by that amount to afford a reasonable approximation to the correct absolute deformation.

Two types of measurements of recovery characteristics were used in this work. The first type utilized no load on the specimen during the recovery period. During the recovery phase, the clamp was supported by a yoke, and the clamp weight did not bear upon the specimen. When a measurement of specimen length was to be made, the yoke was removed and the clamp load held the specimen taut. As soon as the measurement was taken, the yoke was again used. In calculating recovery deformations obtained with this method, a correction was made for the elastic deformation produced by the clamp load. As above, the correction was estimated to be 3.0 mils.

The second type of recovery test used the weight of the clamp on the specimen during the entire recovery phase. This type of test required less handling of the specimen, and did not require manipulation of the lower clamp, avoiding any chance that it may not be correctly aligned upon removal of the yoke. However, interpretation of data obtained in this manner is complicated by the creep which occurs, superimposed on the recovery, due to the weight of the clamp. In tests of relatively long duration, this effect is small. According to Boltzmann's superposition principle, the creep during the recovery phase is equivalent to the creep which would occur during that time interval if the total load on the specimen during both the creep and the recovery phases was the clamp load.

Calculations of extent of deformation are expressed as "per cent deformation." This value was obtained by dividing the deformation produced by the applied load by the gage length of the specimen. The result was expressed as a percentage. In creep tests, the deformation produced by the applied load was determined relative to the initial position of the sample under the clamp load, corrected for the elastic deformation produced by the clamp load. In recovery, the deformation was determined relative to the final position of the specimen during the preceding creep test. In all cases for creep and recovery, percentages were calculated using the initial gage length of the specimen, and no correction was made for the change in length during the test.

EXPERIMENTAL RESULTS AND DISCUSSION

LOAD-ELONGATION MEASUREMENTS

The load-elongation characteristics of the handsheets, obtained with the Instron Universal Testing Instrument by the techniques described in another section of this report, are shown in Fig. 5-8. In each of these figures, load-elongation curves of several handsheets dried in the manner previously described are shown. Each of the figures is for a single pulp, distinguished by its refining history. In each figure, load-elongation curves for handsheets with different degrees of wet straining are presented. Each curve is labeled with the degree of wet straining to which it was subjected.

The Instron curves were used to examine changes in tensile strength, ultimate elongation, and the amount of work necessary for rupture, brought about by wet straining. This information is assembled in Table II for the separate pulps. The data are treated in detail below.

The values for apparent stress in Fig. 5-8 and the values for tensile strength given in Table II are presented as kilograms per square millimeter. The "square millimeter" term refers to the cross-sectional area of airdry cellulose in a plane perpendicular to the test direction, and was calculated in the same way that the "apparent initial stress" term was calculated for the tensile creep tests. The work-to-rupture values given in Table II are in terms of centimeter-kilograms per cubic centimeter, and refer to the centimeter-kilograms of work necessary to rupture a sheet one centimeter long with a calculated cross-sectional area of one square centimeter.

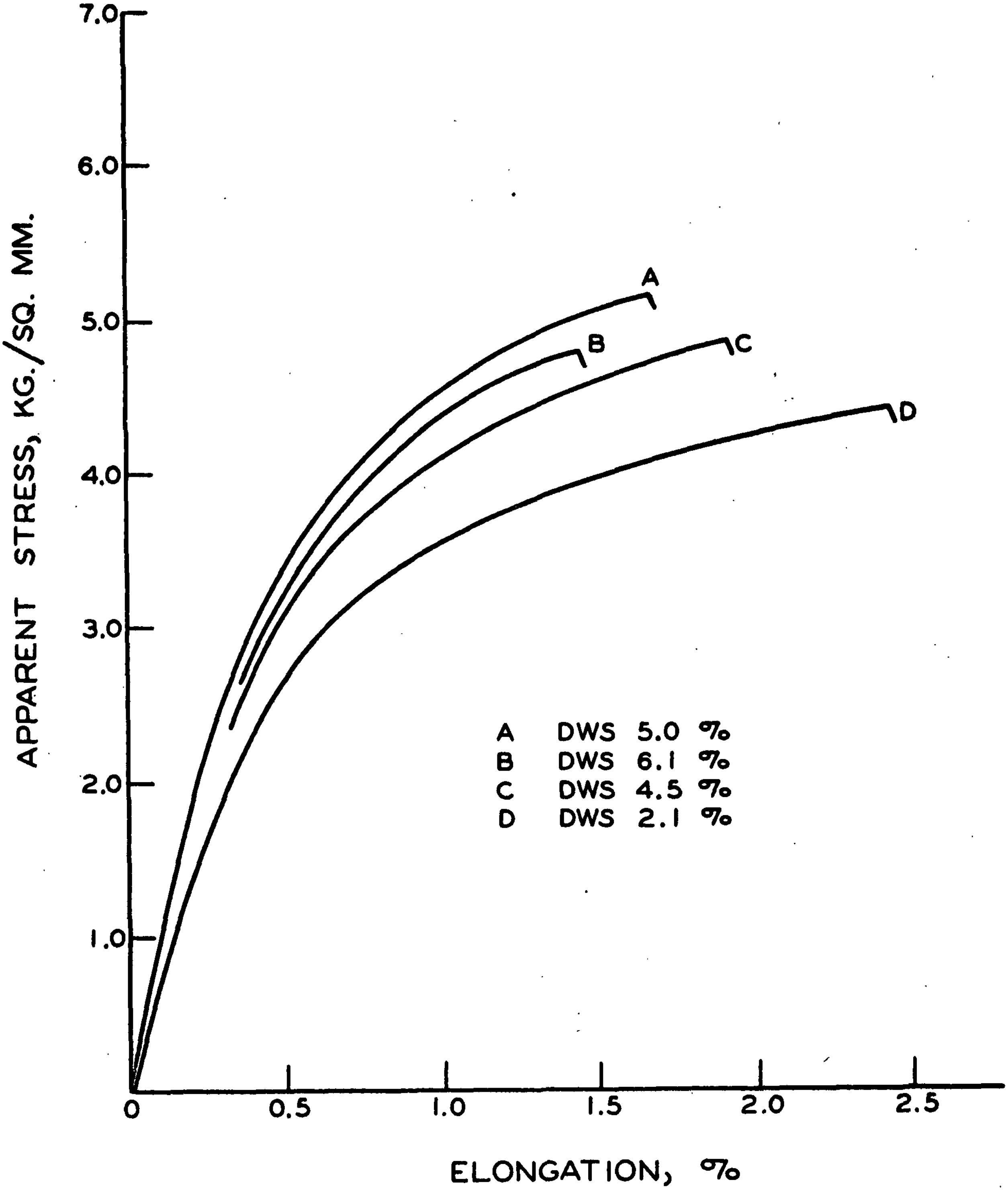


Figure 5. Load-Elongation Curves for Pulp 760

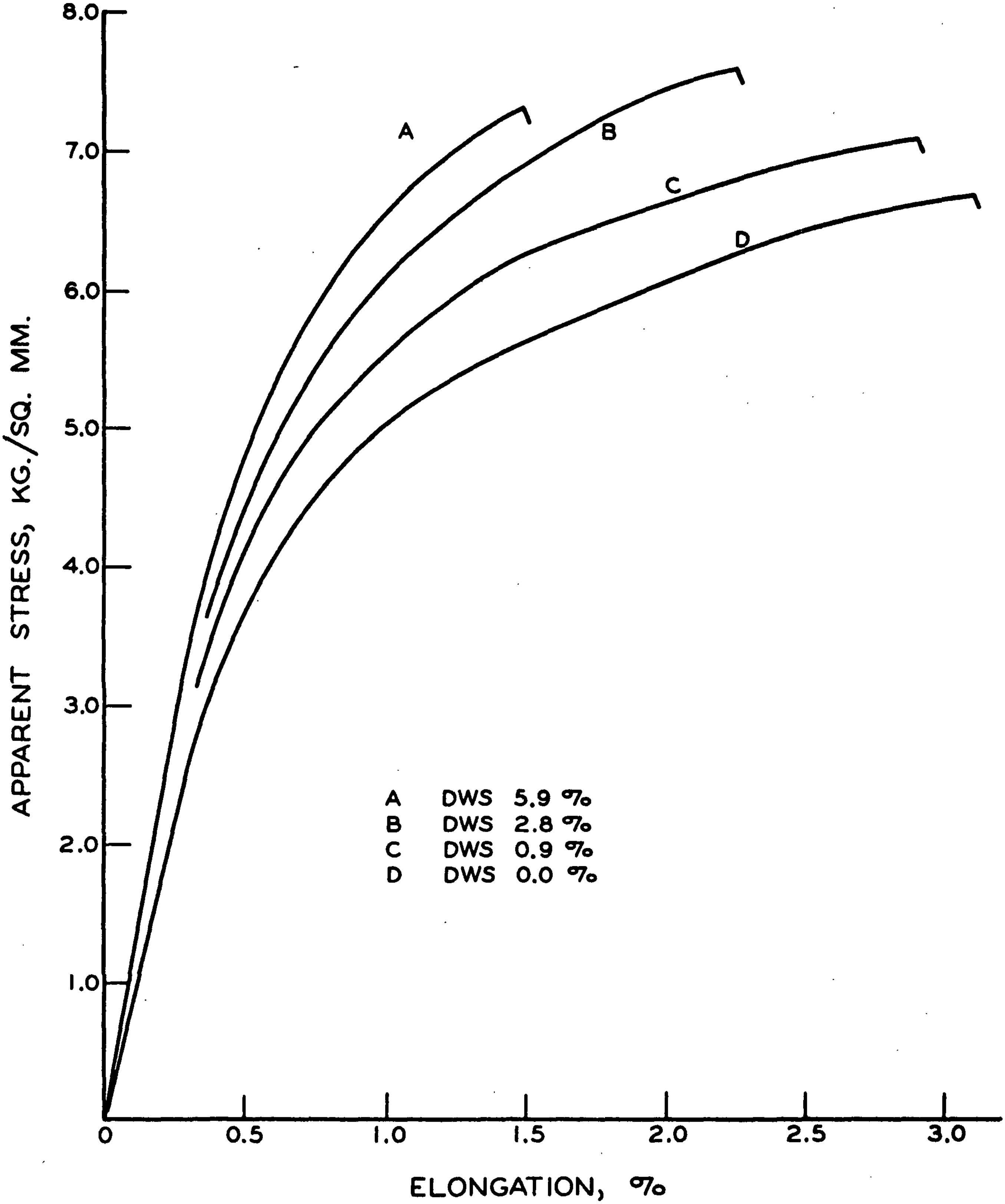


Figure 6. Load-Elongation Curves for Pulp 650

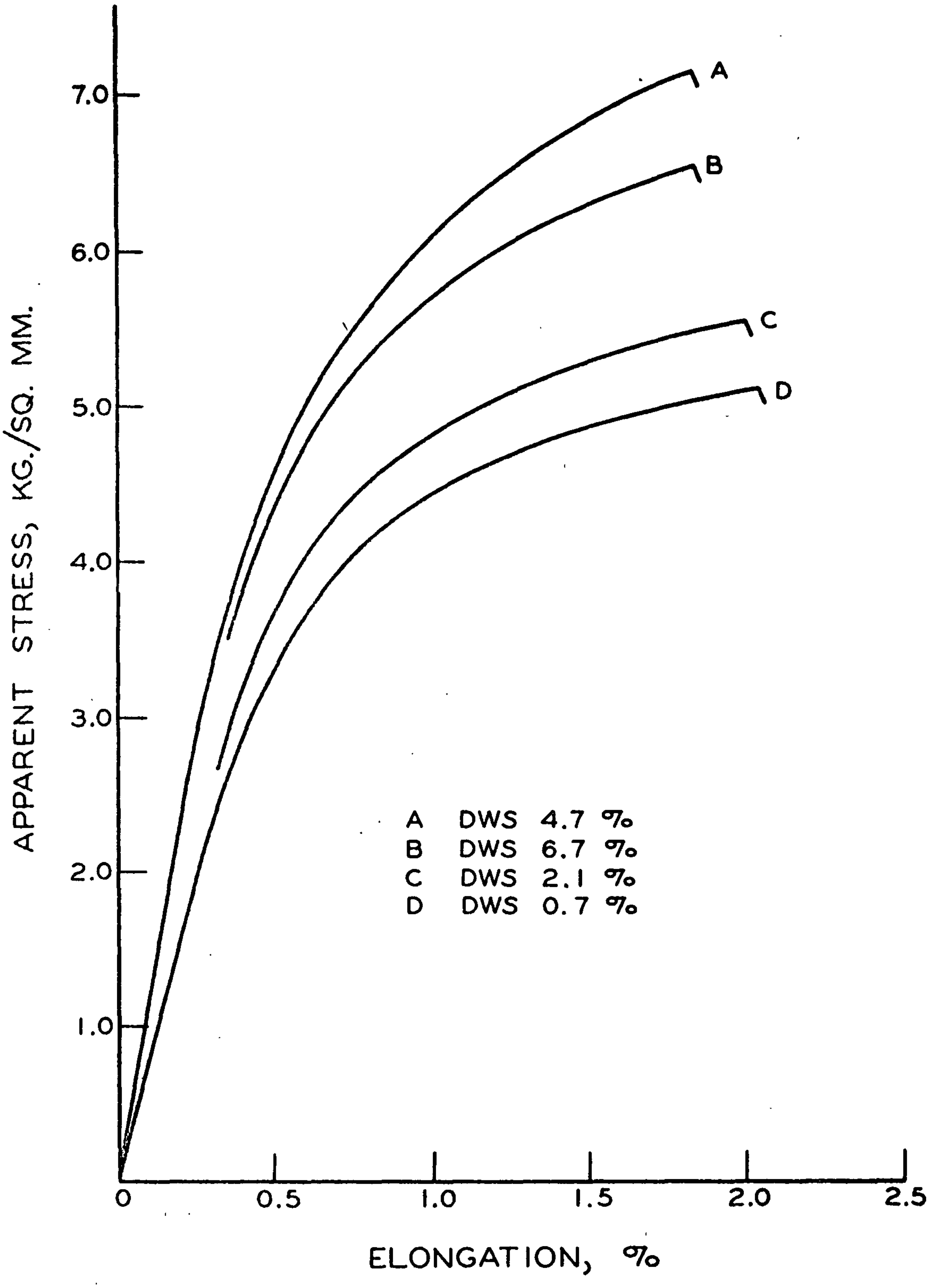


Figure 7. Load-Elongation Curves for Pulp 460

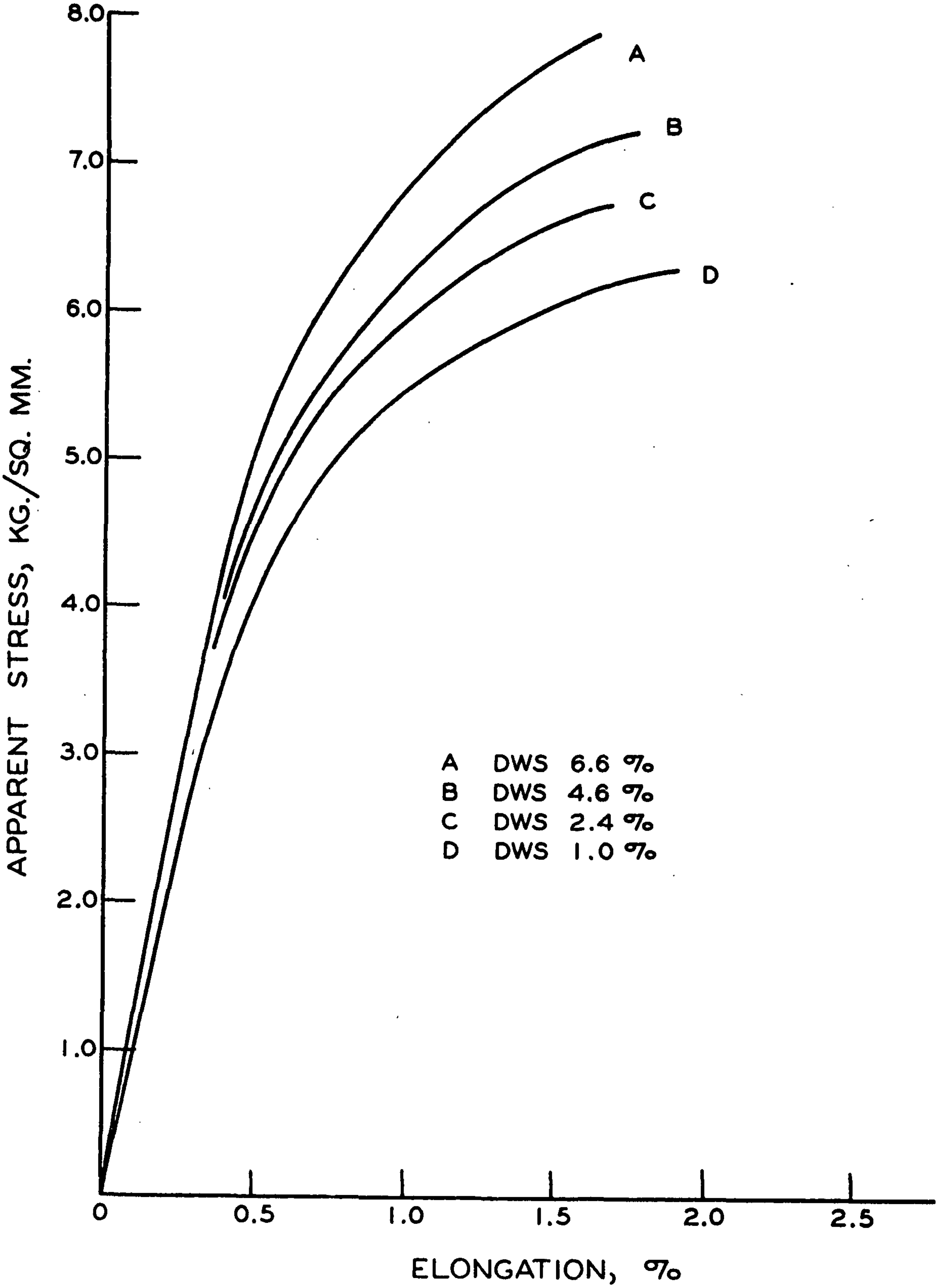


Figure 8. Load-Elongation Curves for Pulp 290

TABLE II
THE MECHANICAL PROPERTIES OF HANDSHEETS SUBJECTED TO DIFFERENT DEGREES OF WET STRAINING

Degree of Wet Straining, %	Tensile Strength, kg./sq. mm.	Ultimate Elongation, %	Work-to-Rupture, kg.-cm/cc.	Basis Weight, g./sq.m.
		Pulp 760		
1.2	4.51	2.44	8.75	66.6
2.1	4.51	2.44	9.02	63.3
2.2	4.34	2.28	7.72	60.0
2.3	4.46	2.62	9.18	64.7
3.1	4.64	2.38	8.40	62.4
4.5	4.89	1.93	7.03	63.4
5.0	5.10	1.63	6.07	66.6
6.1	4.74	1.45	4.94	64.3
6.3	4.68	1.54	5.39	62.1
		Pulp 650		
0.0	6.72	3.12	15.68	65.0
0.9	7.13	2.75	14.70	65.6
1.6	7.42	2.75	15.60	65.5
2.2	7.52	2.50	14.35	64.2
2.3	7.57	2.32	12.16	85.0
2.8	7.64	2.25	12.38	64.1
3.5	7.80	2.18	9.76	84.8
4.5	7.80	2.06	10.80	84.7
5.1	7.63	2.00	10.82	84.7
5.9	7.30	1.46	7.84	64.0
6.0	7.28	1.63	8.18	83.2
		Pulp 460		
0.7	5.13	2.04	7.94	72.3
1.8	5.64	2.01	8.56	69.1
2.1	5.59	2.01	8.46	67.4
3.4	6.21	1.93	8.85	67.4
4.2	6.75	2.12	9.60	67.0
4.7	7.17	1.83	9.60	69.1
6.3	7.15	1.81	9.30	66.0
6.7	6.58	1.83	8.80	66.0
		Pulp 290		
1.0	6.31	1.89	8.97	87.6
1.9	6.53	2.12	10.43	85.0
2.4	6.74	1.68	8.35	79.6
4.0	7.21	1.94	10.29	70.9
4.6	7.22	1.76	9.14	81.5
4.9	6.98	--	---	82.1
5.1	7.42	1.38	7.10	77.0
6.6	7.90	1.64	9.25	80.7

TENSILE STRENGTH

The effect of wet straining on tensile strength for the four pulps used in this study is shown in Fig. 9-12. It is seen that wet straining first tends to increase the tensile strength of paper prepared from these pulps but, as the straining is continued, a maximum strength is attained, after which further wet straining brings about a reduction. Such a maximum, however, was not observed in the case of Pulp 290. The tensile strength of this pulp increased continuously over the range studied as the degree of wet straining (DWS) was increased. If wet straining were continued on to higher values, a maximum might have been observed.

Although the effect of basis weight was not subjected to thorough examination, it might be noted in Table II that the basis weights of sheets made with Pulp 650 were varied through rather wide limits. Regardless of basis weight, the points established a unique relationship.

It is evident that the degree of beating is an important variable affecting the effect of wet straining on tensile strength. If the initial part of the tensile-strength curves are extrapolated to zero degree of wet straining, an estimate may be made of the per cent increase in tensile strength up to the maximum strength observed. For Pulps 760, 650, and 460, the maximum observed increases in strength were 25, 18, and 54%, respectively. With Pulp 290, the sheet with the highest DWS exhibited tensile strength 33% greater than the extrapolated value for zero DWS.

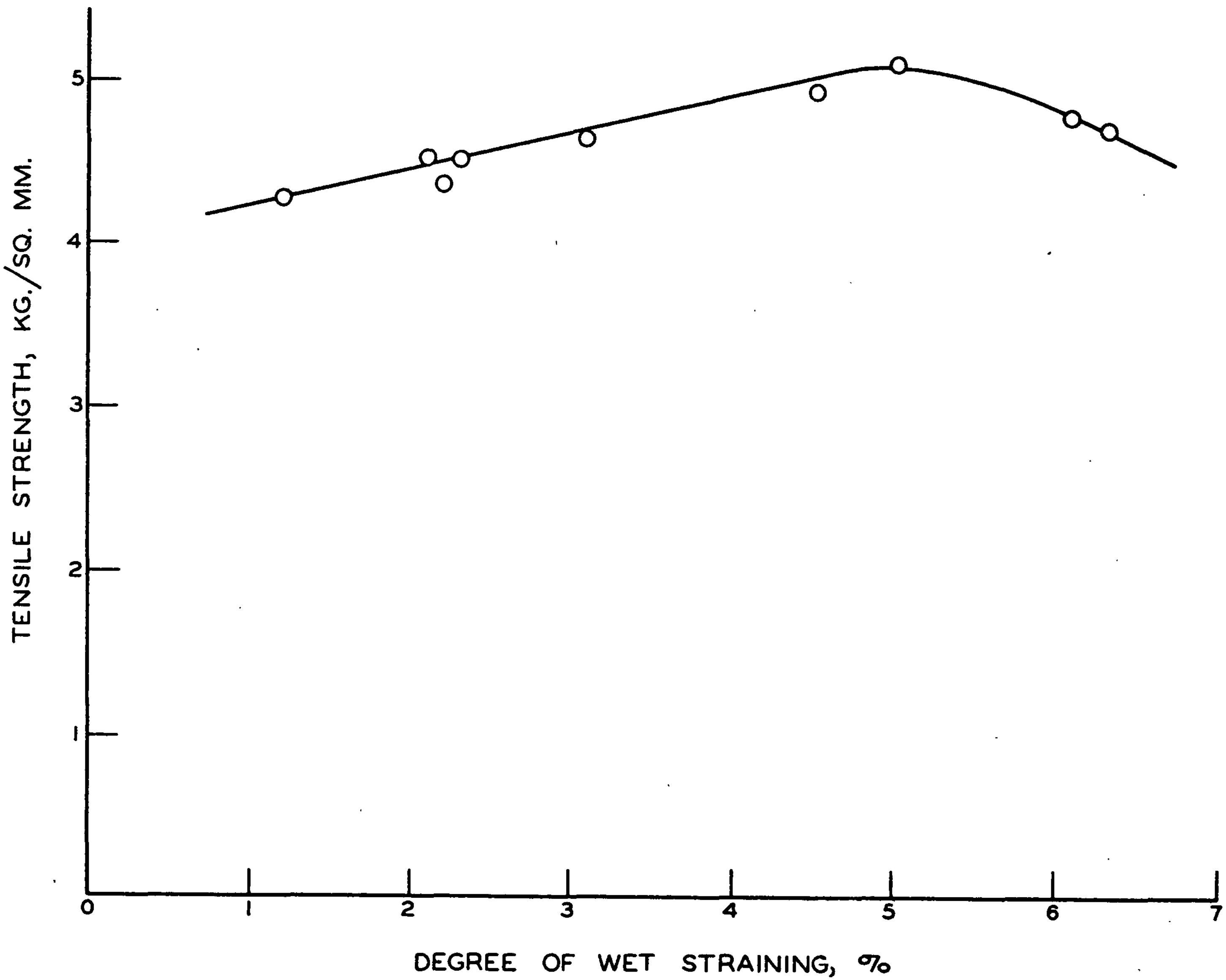


Figure 9. The Effect of Wet Straining on Tensile Strength for Pulp 760

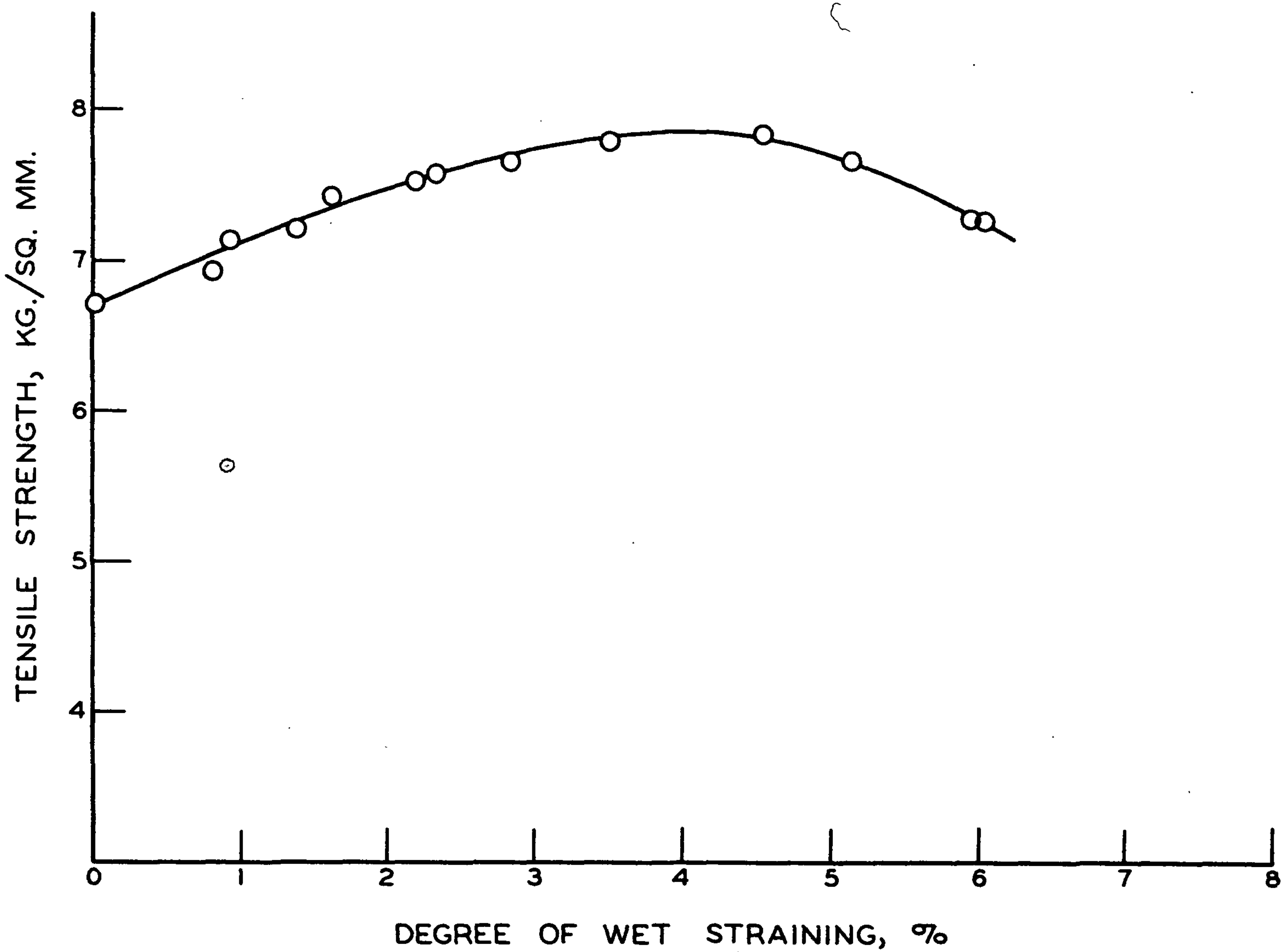


Figure 10. The Effect of Wet Straining on Tensile Strength for Pulp 650

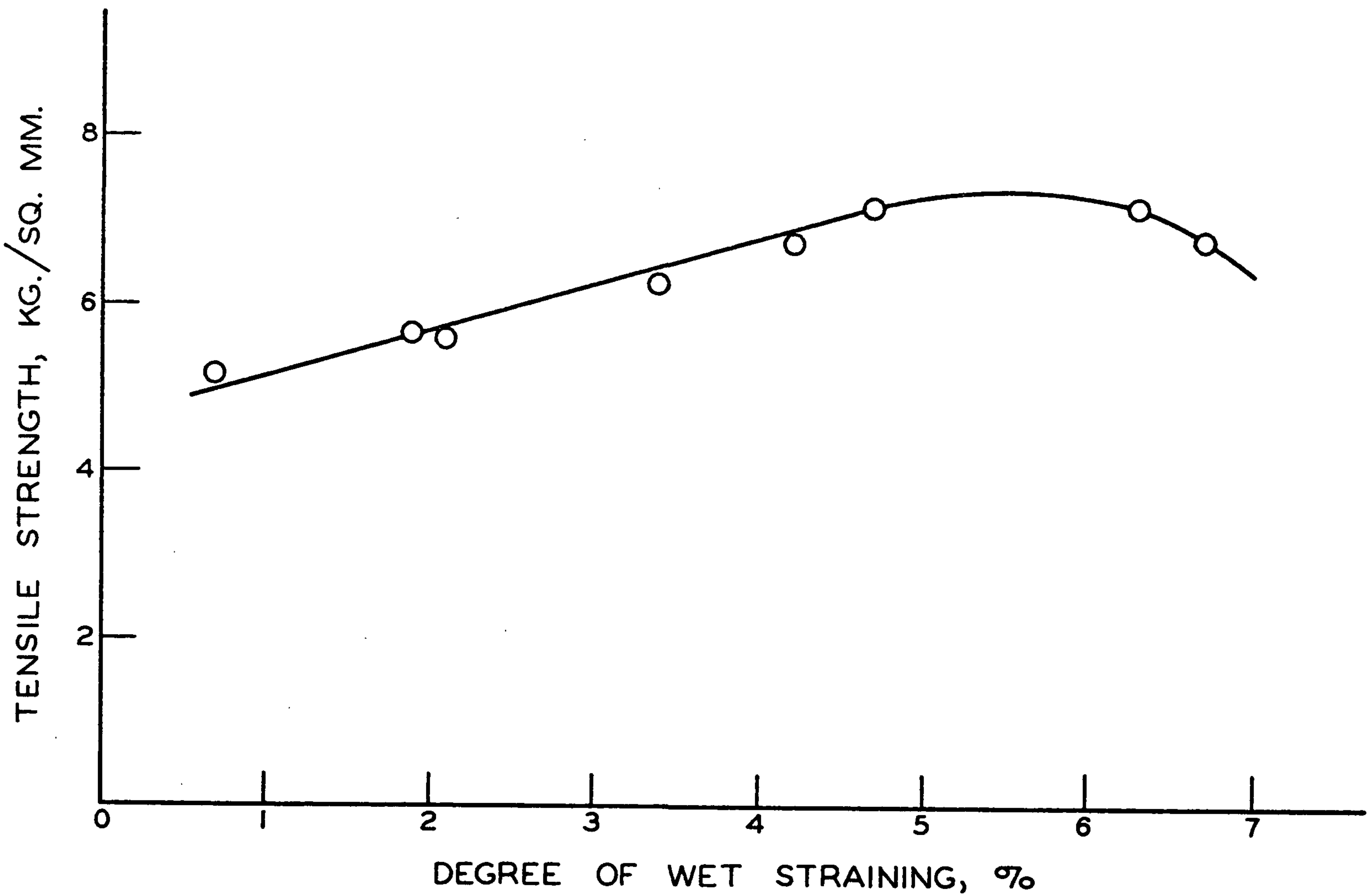


Figure 11. The Effect of Wet Straining on Tensile Strength of Pulp 460

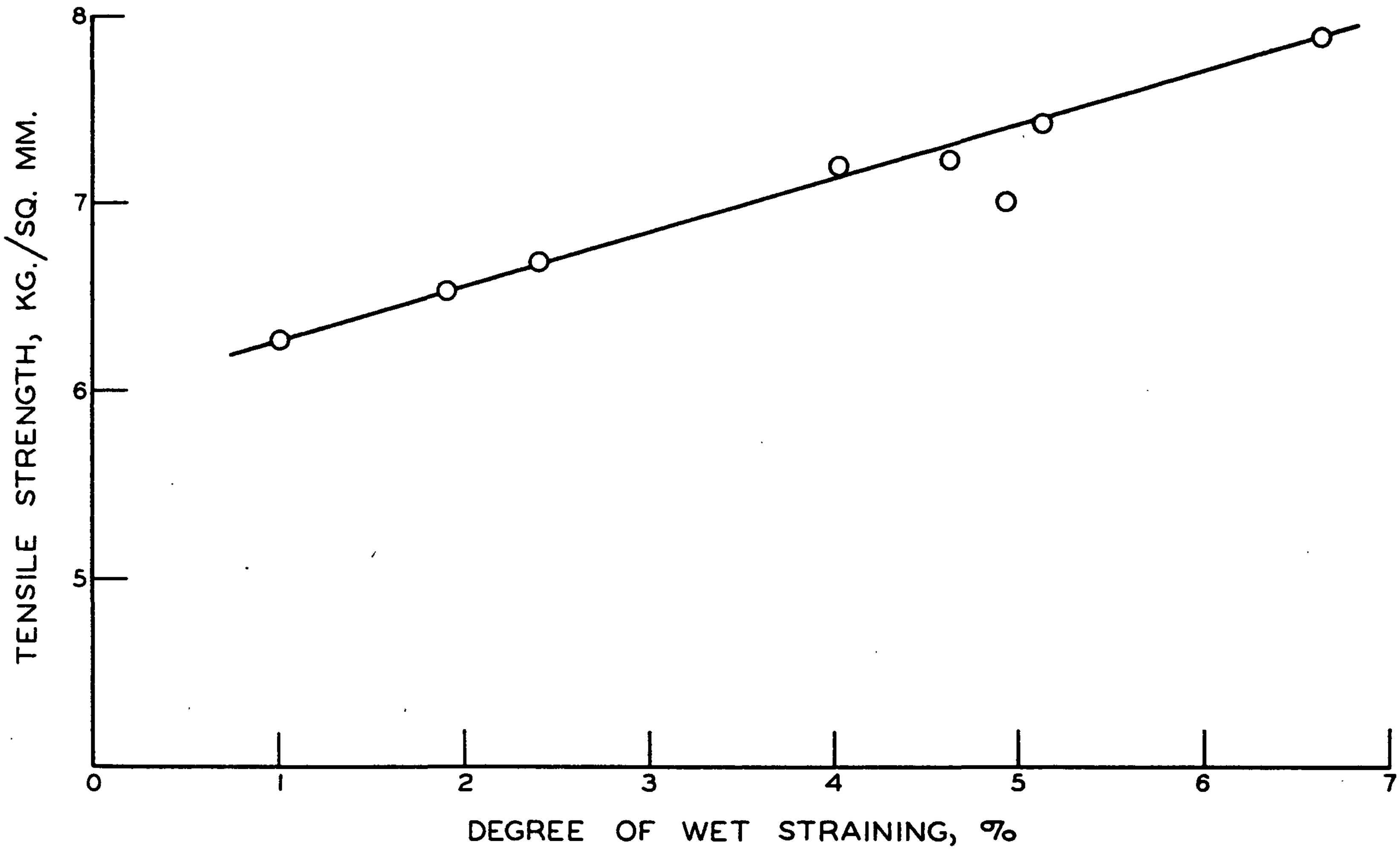


Figure 12. The Effect of Wet Straining on Tensile Strength of Pulp 290

These increases in tensile strength are quite substantial. It seems apparent that, regarding tensile strength, Pulp 460 was best able to profit from wet straining. This fact may be related to a fortuitous combination of several basic pulp characteristics affected by refining, or by the handling of the sheet prior to wet straining. It is possible that a different wet-pressing schedule, for example, may substantially improve the potential of one or more of the pulps for deriving particular benefits from wet straining. The basic pulp characteristics which are important in this regard are unknown, although it seems likely that they include the basic geometry of the fiber and physical properties of the fiber such as conformability. These comments are applicable to all of the sheet properties affected by wet straining.

ULTIMATE ELONGATION

The effect of wet straining on sheet elongation at the point of rupture in the load-elongation tests is shown in Fig. 13 and 14 for the different pulps. In these figures, the ultimate elongation of the dried sheets, in the ordinate, is plotted against the degree of wet straining, in the abscissa. Both are expressed as percentages. Ultimate elongation depends upon the nature of the response of the sheet to stress and upon the tensile strength of the sheet. It is often useful in determining the applicability of paper for a particular use.

An examination of the figures reveals that the effect of wet straining is to reduce the ultimate elongation. This is in accordance with other work which has appeared in the literature. It is evident,

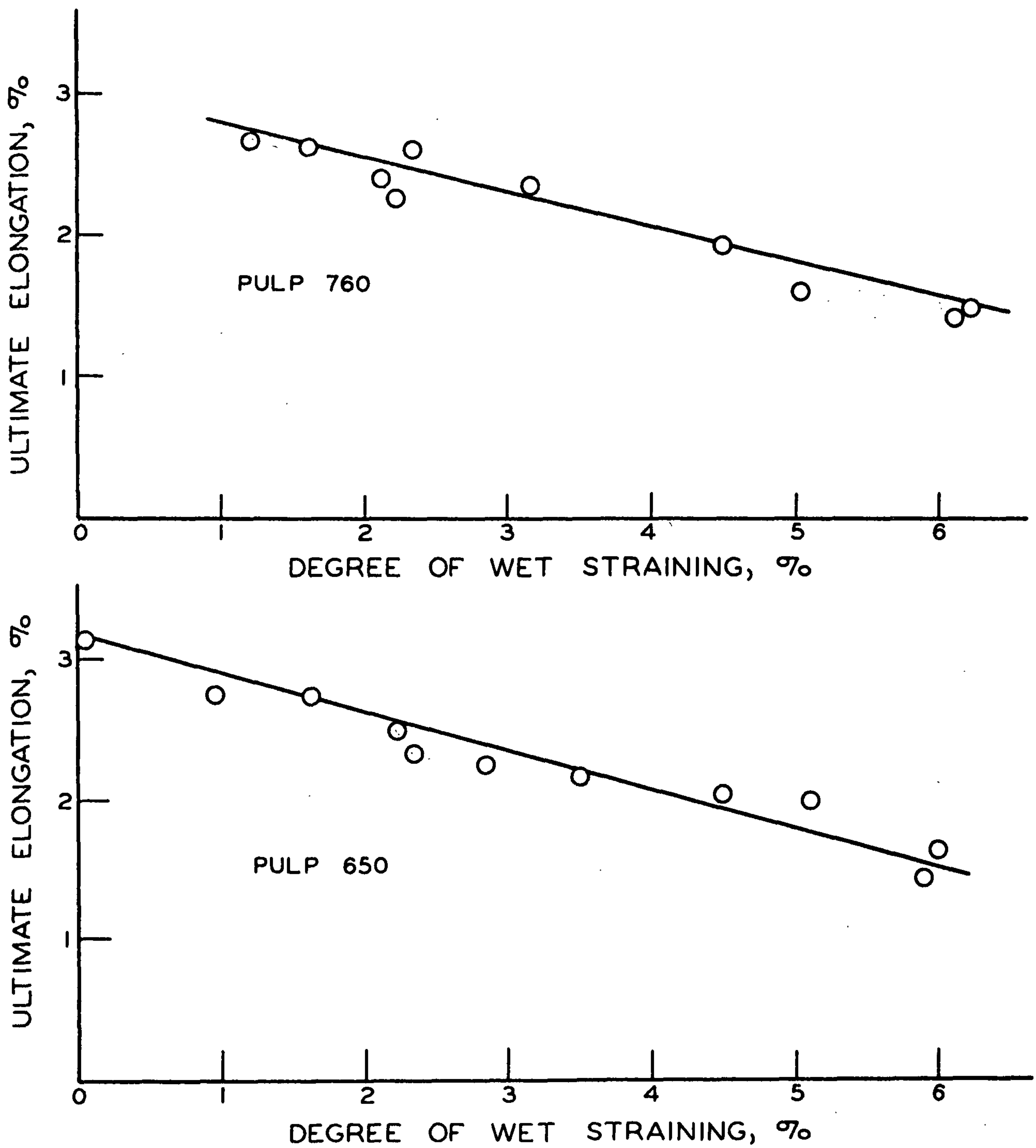


Figure 13. The Effect of Wet Straining on the Ultimate Elongation of Pulps 760 and 650

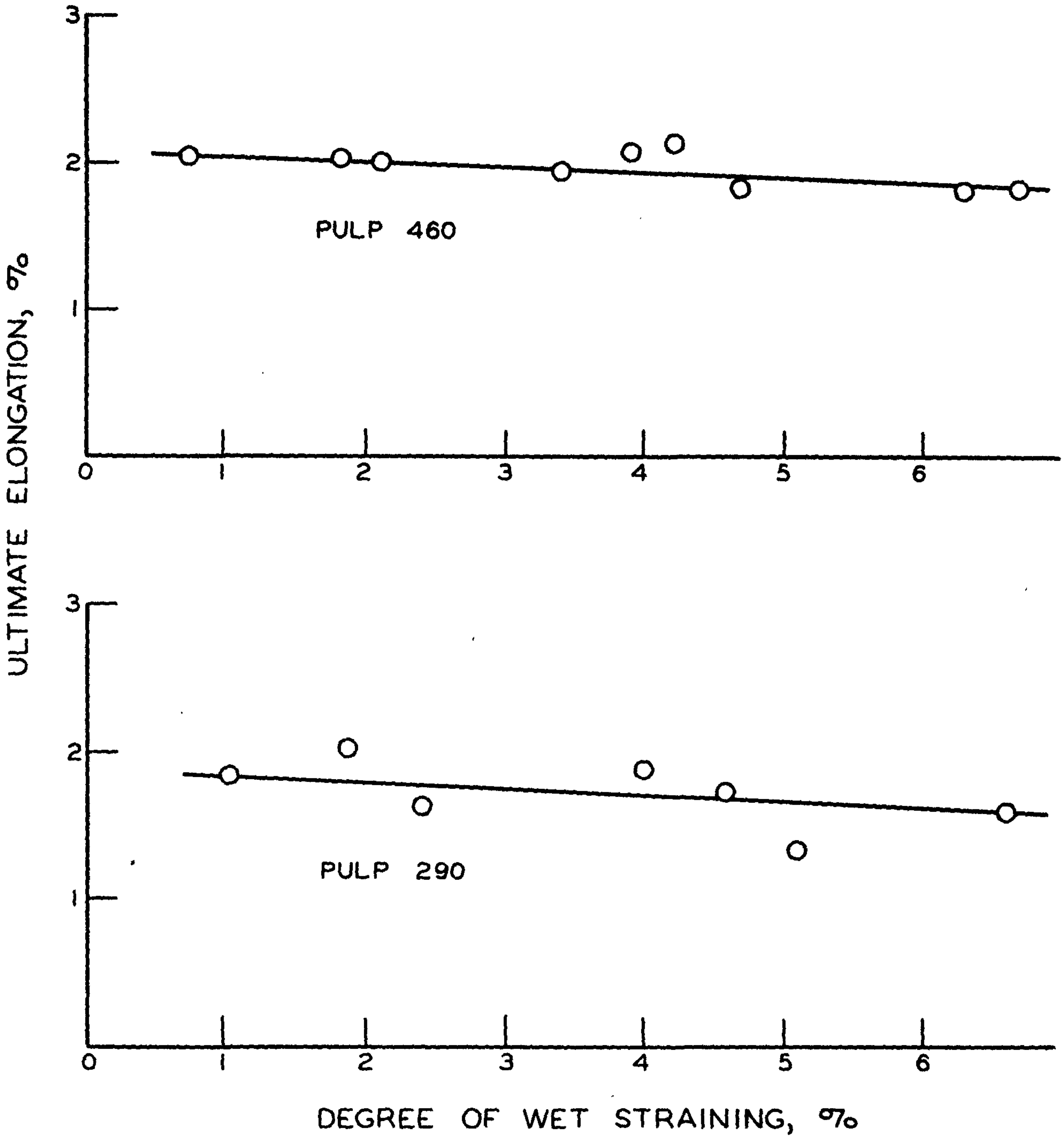


Figure 14. The Effect of Wet Straining on the Ultimate Elongation of Pulps 460 and 290

however, that the degree of beating exerts an important influence over the effect. For Pulps 760 and 650, the ultimate elongation at a DWS of 6% is about half the ultimate elongation for sheets with no wet straining. Pulps 460 and 290, however, which were more extensively refined, exhibit far less drop.

The data obtained using sheets prepared from Pulp 290 are of markedly poorer quality. This may be related to poorer sheet formation due to the slowness of the pulp. However, it was not reflected in the tensile strength data.

WORK TO RUPTURE

"Work-to-rupture" refers to the total energy absorbed by a specimen in a load-elongation test up to the point of rupture. Work-to-rupture was obtained using the integrator attached to the Instron. In all of these tests, the specimen was strained at the rate of 6.2% per minute. A different straining schedule might have changed the absolute value of the work-to-rupture, although it is not likely that the nature of the effect would have been significantly modified.

The changes in work-to-rupture created by wet straining are shown in Fig. 15 and 16. It is seen that the effect is very significant. Again, the strong influence of refining on the effect is evident. Pulps 760 and 650 both exhibit a marked reduction in work-to-rupture as the DWS is increased. The values for Pulp 460 appear to rise through a maximum at about the same DWS at which the tensile strength reaches a maximum. There

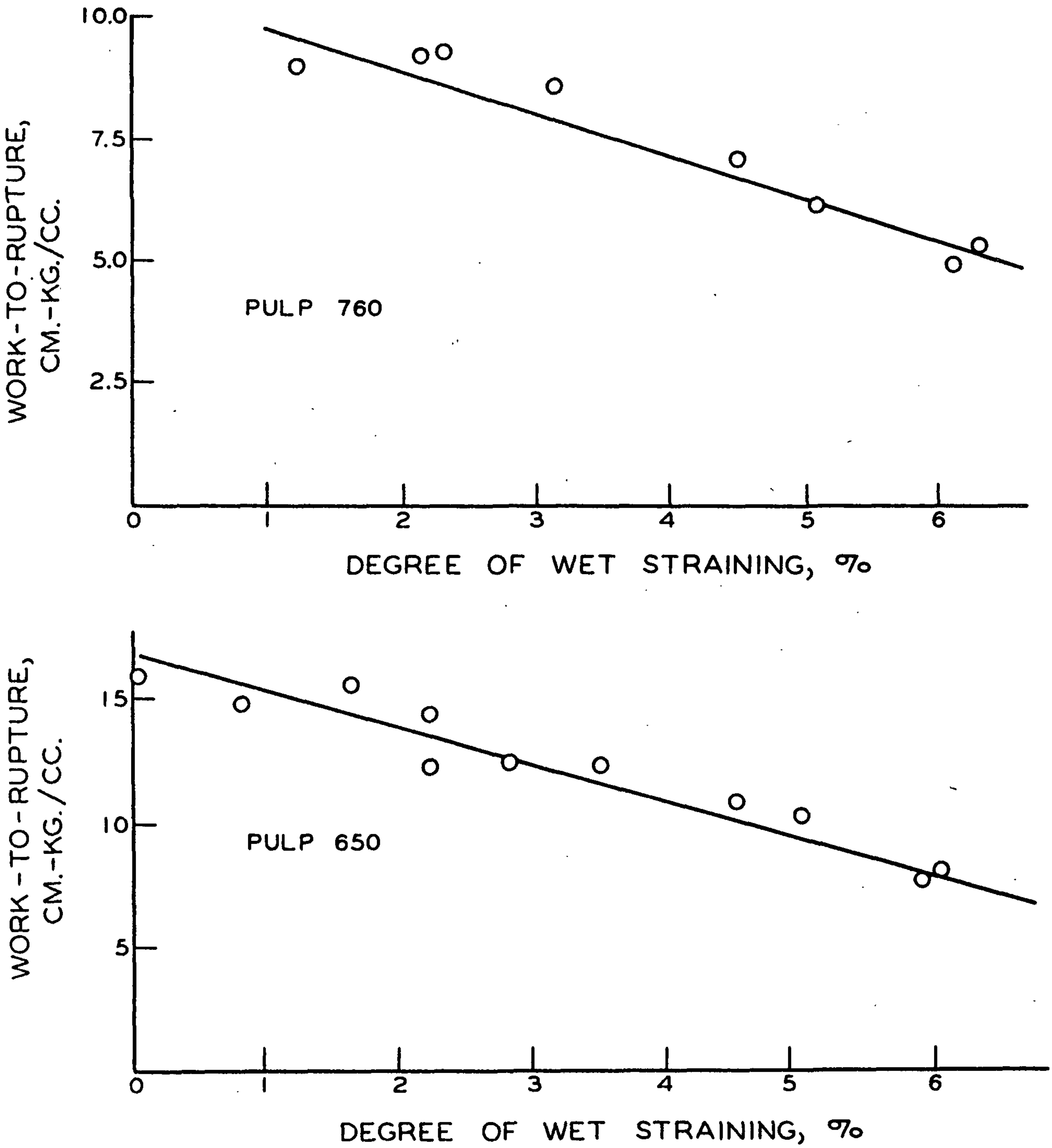


Figure 15. The Effect of Wet Straining on Work-to-Rupture for Pulps 760 and 650

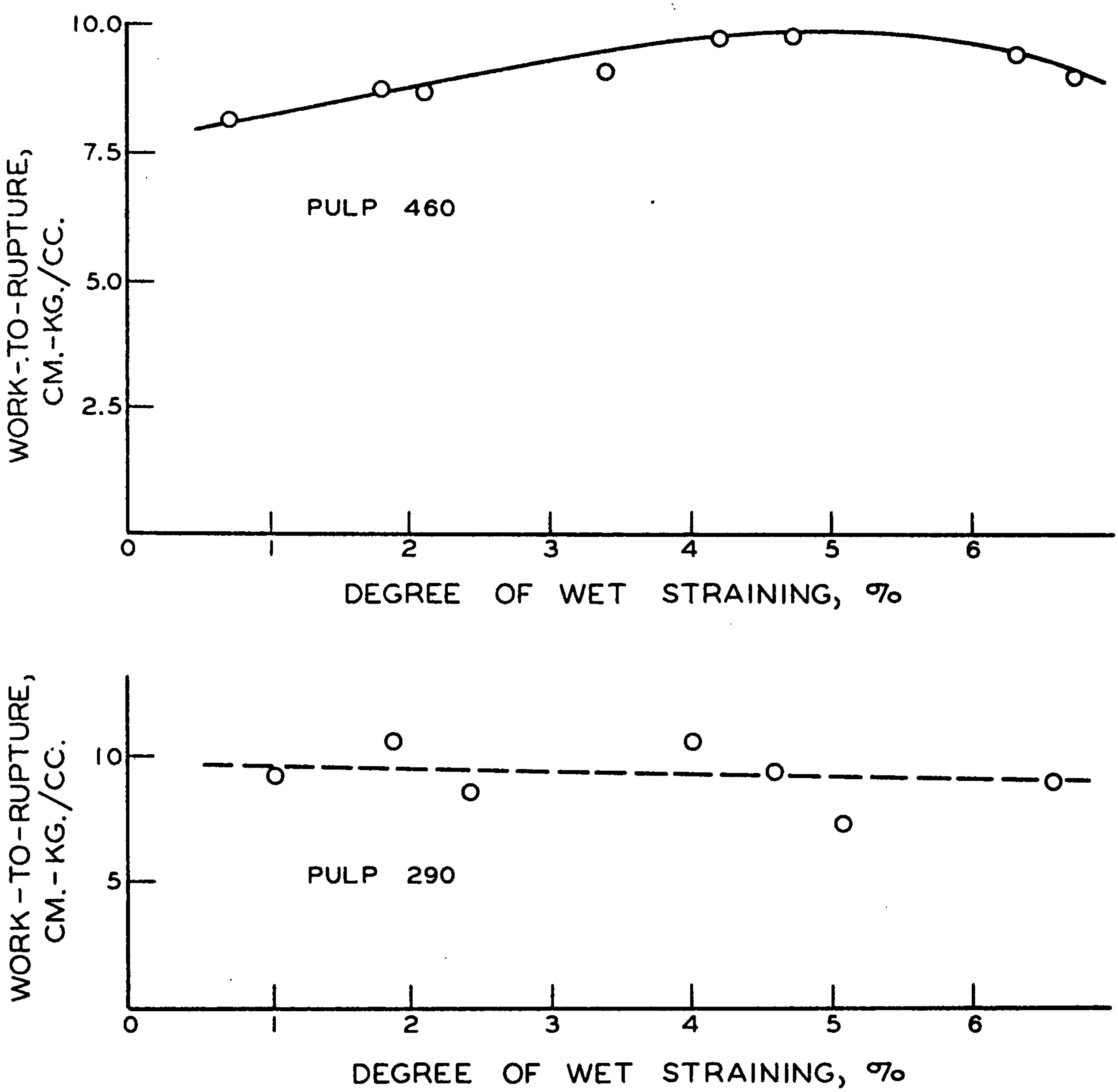


Figure 16. The Effect of Wet Straining on the Work-to-Rupture of Pulps 460 and 290

seems to be little change in work-to-rupture in Pulp 290. As with its ultimate elongation, the work-to-rupture data for Pulp 290 show a considerable amount of scatter.

It is believed that work-to-rupture and ultimate elongation depend upon both the strength of the sheet and the prerupture response to stress of the sheet. Strength and prerupture response to stress are not independent, since both are affected by many of the same factors, such as stress distribution, the chemical-physical structure of the cellulose, and, presumably, bonded area. A function such as work-to-rupture depends upon the interrelationship of these factors, and this interrelationship may be very complicated. Therefore, it is presumptuous to explain changes in work-to-rupture without making a very careful study of all of these factors. Further, explaining changes in work-to-rupture by pointing to concomitant changes in ultimate elongation is not worthwhile, since ultimate elongation is equally complicated.

When paper and many textile fibers are subjected to repeated cycles of loading and unloading, the amount of nonrecoverable deformation is found to decrease with subsequent cycles. When the deformation produced by the applied load is largely recoverable, the specimen is said to be "mechanically conditioned" to stress. The specimen is only mechanically conditioned, however, for creep loads and test durations which are less than or equal to those of the previous loading-unloading cycles, and further nonrecoverable creep may occur if these limits are exceeded.

It follows that mechanical conditioning reduces the amount of work necessary to rupture a specimen. Since wet straining has been found, by previous workers, to reduce the work-to-rupture of paper, the effect often has been considered one of mechanical conditioning (5). It is now seen that increased wet straining does not necessarily reduce work-to-rupture, and it may in fact increase work-to-rupture. Therefore, the effect of wet straining should not be considered solely as one of mechanical conditioning. However, the effect may involve the removal of potential for nonrecoverable creep along with other mechanisms affecting the response of the sheet to stress. This possibility will be considered in more detail in another part of this report.

The observation by previous workers that wet straining invariably reduces the ultimate elongation or the work-to-rupture may be related to the technique of wet straining which they used. These workers usually applied a constant stress to the sheet during the entire drying operation, and this stress was still holding the sheet in tension when the sheet was dry. It is known (26) that such a tensile stress will remove nonrecoverable deformation from a dry sheet, and this may be the cause of the observed reduction in work-to-rupture.

THE EFFECT OF WET STRAINING ON INTRINSIC FIBER STRENGTH

Wet straining has long been associated with preferred fiber orientations in the sheet. The theory proposes that when the sheet is wet strained, the fibers tend to become aligned in the direction of the applied stress. The effects of wet straining are attributed to this supposed alignment. Proponents point out that as sheet strength increases in the machine direction, cross-machine-direction strength is often observed to decrease.

Some work has been done to examine the validity of this theory. Robertson and Bailey (16) found that on a fourdrinier machine, tensile strength anisotropy is developed mainly in the drier section. Danielson and Steenberg (18), after a very careful examination, concluded that on a paper machine, fiber orientation is produced mainly on the fourdrinier wire. Therefore, there seems to be no relationship between fiber orientation and tensile strength anisotropy. From the results of the present study, it would appear that the changes in tensile strength observed by Robertson and Bailey were primarily related to stresses applied to the sheet in the drier section.

Other workers have proposed that if paper is stretched during drying, there is a general alignment of the fibrils in the sheet in the direction of the applied strain. In this view, although the fibers would retain their original orientation, fibrils extending from the fibers would not. The fibrillar orientation would tend to make the sheet denser, and therefore stronger. Other changes in sheet properties are held to be related to anisotropy in the mechanical properties of the fibrils in their long and transverse directions.

Because of the unlikelihood that wet straining affects gross fiber alignment, no program to study fiber orientation directly was planned. However, a program was undertaken to examine the intrinsic strength of the fibers in the direction of wet straining. This was carried out using the zero-span tensile-strength technique, which has been shown (32) to provide a realistic measure of the intrinsic strength of the cellulosic material which comprises paper. If wet straining aligns either the fibers or a significant number of fibrils in the machine direction, an increase in zero-span tensile strength would be observed.

This reasoning is supported by an analysis of the zero-span technique developed by Van den Akker, Lathrop, Voelker, and Dearth (32), who considered the forces on an idealized fibrous system in the vicinity of the zero-span clamping jaws. The response of the fibers to the force applied during the test is assumed to be Hookean. It is found that the tension in a fiber produced by a zero-span tensile load is equal to $F \sin^2\theta$, where θ is the angle the fiber makes with the clamping line, and F is the tension in a fiber oriented in the direction of the applied load. The component of fiber tension which opposes the applied force is $F \sin^3\theta$. It follows that the zero-span tensile strength will be dependent upon the distribution of fiber orientations in the sheet.

Zero-span clamping jaws, originally proposed by Jacobsen (97), have been developed by Gunther (98) and Clark (99), among others. In the present work, jaws designed by Wink at The Institute of Paper Chemistry were used. Wink (100) has studied the effect of bonding on the zero-span tensile strength values obtained with these jaws, and has concluded that the effect, while significant, is small. It is believed that the zero-span tensile strength provides a valid measure of fiber strength. In the present investigation, primary interest is directed at changes produced by wet straining at each degree of beating. If such an effect exists, it might be expected to create an increase in the zero-span tensile strength values.

The zero-span tensile strengths of handsheets prepared with different degrees of wet straining are presented in Table III. It is seen that wet straining has no effect on the intrinsic strength of the fibers in the direction of straining. The hypothesis of equal zero-span tensile strengths for all degrees of wet straining for these pulps falls well within 95% confidence limits.

It is concluded that wet straining does not increase the intrinsic strength of the fibers in the direction of straining, and therefore it is not likely that gross fiber realignment or fibril orientation are related to the wet-straining effect. This does not mean that fibril orientation does not take place. Rather, it is an indication that, even if such orientation occurs, its effect is probably of minor importance.

THE EFFECT OF WET STRAINING ON BONDING CHARACTERISTICS

It has been found that small amounts of wet straining causes the tensile strength of paper to increase. This increase in strength could be due to an effect on the strength of the bonds between the fibers. Stronger interfiber bonding may be the result of an increase in the relative bonded area or of an increase in the actual intrinsic strength of the bonds. In either case, the total strength of the bonds between the fibers could be increased.

A technique for the measurement of the transverse tensile strength of paper has been described in an earlier section of this report. The transverse tensile strength is commonly used as a measure of bonding

TABLE III
THE ZERO-SPAN TENSILE STRENGTH OF SHEETS SUBJECTED TO DIFFERENT DEGREES OF WET STRAINING

Pulp 760		Pulp 290	
Degree of Wet Straining, %	Zero-Span Tensile Strength, kg./sq. mm.	Degree of Wet Straining, %	Zero-Span Tensile Strength, kg./sq. mm.
1.4	34.4	1.0	31.7
2.2	34.0	2.4	33.2
3.1	34.5	4.9	31.6
5.0	34.2	6.6	33.2
6.3	34.9		

Pulp 650	
Degree of Wet Straining, %	Zero-Span Tensile Strength, kg./sq. mm.
1.4	40.0
2.6	42.7
2.9	40.7
5.4	40.9
6.3	42.1

strength, since it involves mainly the breaking of bonds between the fibers, and should involve little fiber rupture.

A limitation of the approach taken in this study should be pointed out. Considering the effects of wet straining, Steenberg (17) suggested that the observed increase in strength was related to a reorientation of the fibrils in the area of the bond which, perhaps, would be caused by only a very small relative movement of the fibers. This would increase the strength of the bonds in the direction of a standard tensile strength test by altering the structure of the bond. However, this improved structure may not be effective in another direction; e.g., the transverse direction. Therefore, a test of the bonding strength by measuring the transverse tensile strength may not be appropriate. However, at the present time it is the best approach available.

The transverse tensile strengths of handsheets prepared with different degrees of wet straining from Pulps 650, 460, and 290 are shown in Fig. 17. The data are presented in Table IV. A similar investigation of handsheets prepared from Pulp 760 was not carried out because of penetration of this more porous pulp by the adhesive. This difficulty might have been overcome by increasing the basis weight of the sheets prepared from this pulp. No attempt was made to do this, however, because it was felt that the three suitable pulps available reasonably represent the nature of the effect.

The results are reported in terms of pounds per square inch. The "pounds" term refers to the force necessary to separate the two lugs attached to either side of the paper sample. The area term refers to the measured planar area of the faces of the lugs, or alternatively, to the measured planar area of the tested sample. It bears no relation to the actual area created by the rupturing of the bonds in the sheet. If this area were known, then it would be possible to have a true measure of the intrinsic bonding strength. The value obtained should be regarded as a measure of the force necessary to cleave the sheet in a plane parallel

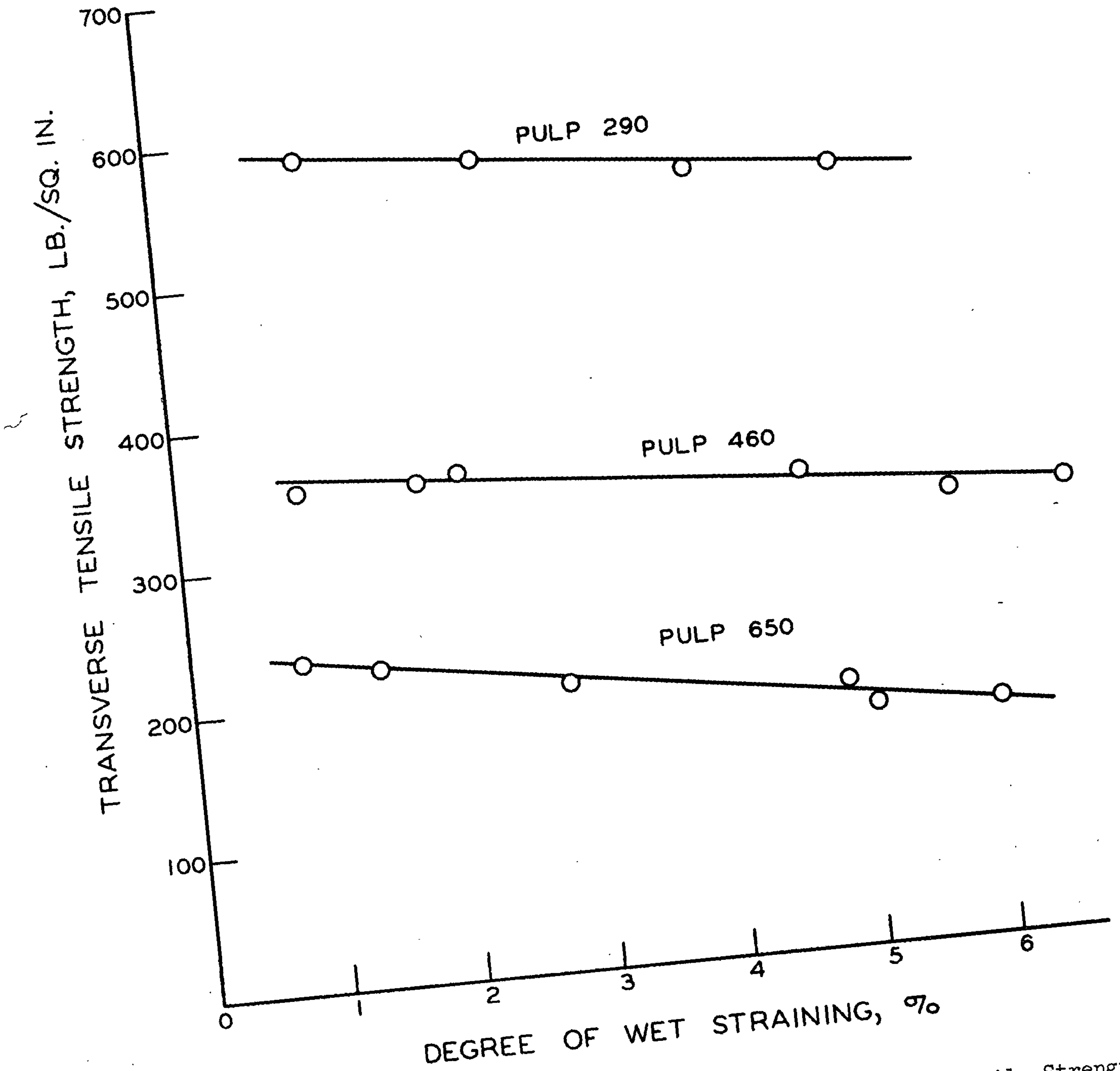


Figure 17. The Effect of Wet Straining on the Transverse Tensile Strength

TABLE IV
THE EFFECT OF WET STRAINING ON THE TRANSVERSE TENSILE STRENGTH

	Degree of Wet Straining, %	Transverse Tensile Strength, lb./sq. in.
Pulp 650	0.8	231
	1.4	224
	2.8	202
	4.9	189
	5.1	170
	6.0	168
Pulp 460	0.9	352
	1.2	354
	2.1	355
	4.7	337
	5.8	318
	6.7	318
Pulp 290	1.1	586
	2.4	576
	4.0	556
	5.1	551

to the surface of the sheet, and is thus an indication of the relative total strength of the bonds between the fibers.

As the degree of beating is increased, the total bonding strength is increased. This is obvious from Fig. 17, where it is seen that the bonding strength of Pulp 290 is approximately twice that of Pulp 650. This difference is largely related to the increased surface area of the more highly beaten pulp and the more compact structure of the sheet. However, the test is not sufficiently understood to attribute quantitatively the differences to particular factors.

As the degree of wet straining is increased, the transverse tensile strength of the sheets decreases, indicating that wet straining reduces the bonding strength of paper. This is concluded from the results of tests using handsheets prepared from all three pulps examined in this manner. It is noted that as the degree of beating is increased, the percentage drop in transverse tensile strength decreases. This effect may be related to the increased conformability and decreased fiber length of the more refined pulp.

In order to obtain some information concerning the effect of wet straining on the bonding of handsheets prepared with Pulp 760, the optical properties of these handsheets were investigated. The methods used have recently been reviewed by Ingmanson and Thode (53). By measuring the two diffuse reflectances, $\underline{R}_o$, the reflectance of a single sheet backed by a black cavity, and $\underline{R}_\infty$, the reflectance of a sheet backed by a thick pad of the same material, the scattering power, $\underline{sW}$, may be obtained from charts. Determination of the basis weight, $\underline{W}$, of the sheet permits calculation of $\underline{s}$, the specific scattering coefficient. In the present work, the reflectances, $\underline{R}_o$ and $\underline{R}_\infty$, were determined using the General Electric recording spectrophotometer, using a wavelength of 650 mμ. The basis weights of the sheets were carefully determined at 50% RH, 73°F. Six specimens were tested from each handsheet.

The specific scattering coefficient depends upon the interfacial area between the fibers and air, and it is this dependency that is utilized in the optical technique for estimating bonded area. The assumption is made that $\underline{s}$ is directly proportional to the fiber specific surface, $\underline{A}$. Thus,

$$\underline{s} = \underline{kA}$$

where k is a dimensionless constant and A is the area expressed on an area-per-unit-mass basis. When s is measured on a handsheet, it is reasoned that the area involved in fiber bonding does not scatter light. Therefore, s is a measure of the unbonded fiber specific surface.

The effect of wet straining on the scattering coefficient of handsheets prepared from Pulp 760 is shown in Fig. 18. The scattering coefficients of the dried handsheets are seen to rise as the degree of wet straining is increased. This would indicate that the extent of unbonded surface capable of scattering light is increased or, alternately, the extent of bonded area is decreased by wet straining. This latter follows if the reasonable assumption is made that the newly exposed fiber surface appears only at the expense of the bonded area. It is possible that wet straining affects the scattering coefficient by altering the optical characteristics of the fiber surface. This could be brought about by a change in the index of refraction of the cellulose or by altering the structure of the fibrils on the fiber surface. It is not believed, however, that the forces produced on the fiber surfaces during wet straining were sufficient to create such effects.

The effect of wet straining on the scattering coefficient of handsheets prepared from Pulp 650 is shown in Fig. 19. Again, the same rise in scattering coefficient is noted, and it is concluded that wet straining decreases the optical contact between the fibers of the dried sheet. It is noted that for Pulp 650, the scattering coefficient does

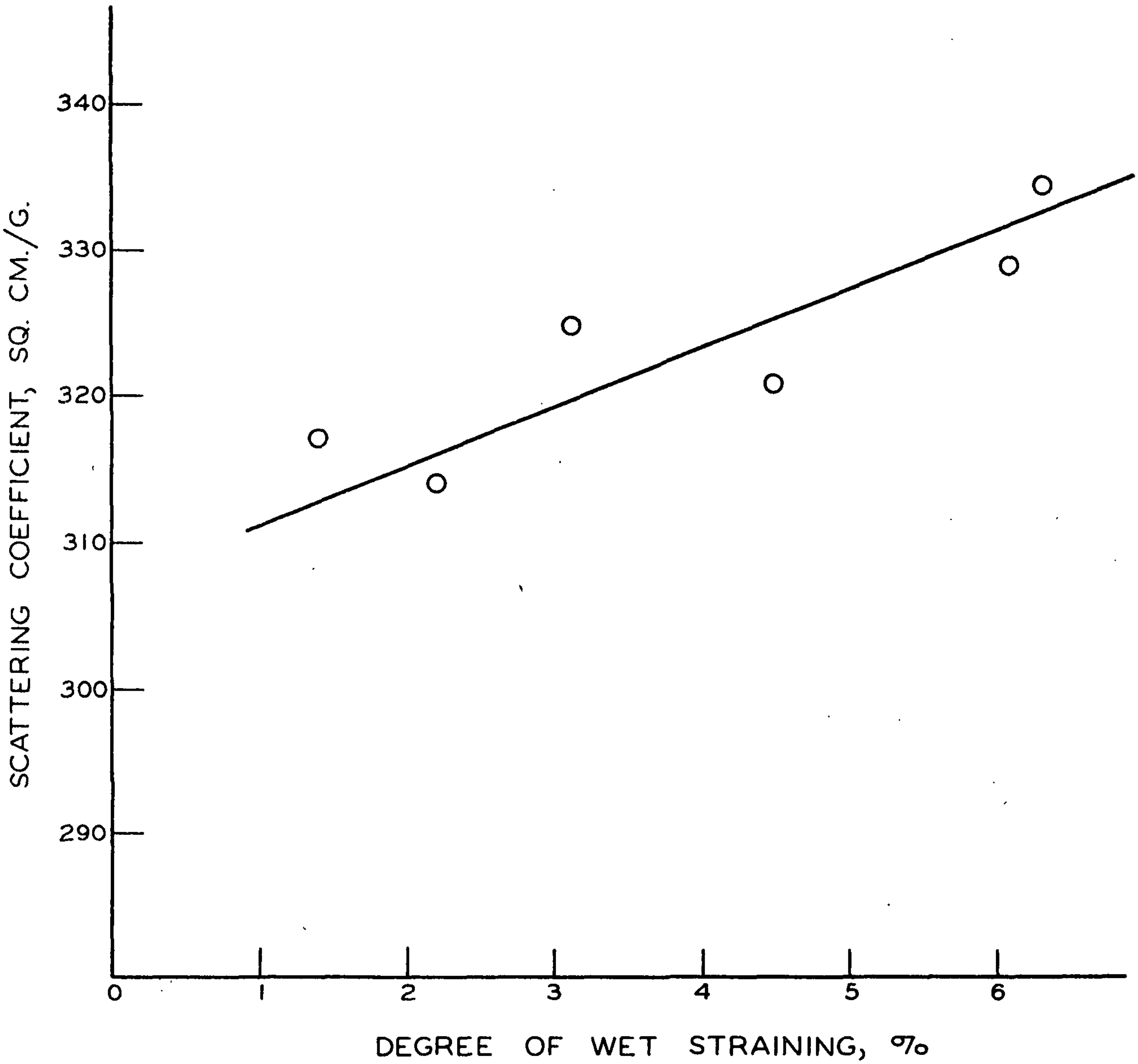


Figure 18. The Effect of Wet Straining on the Light-Scattering Coefficient of Pulp 760

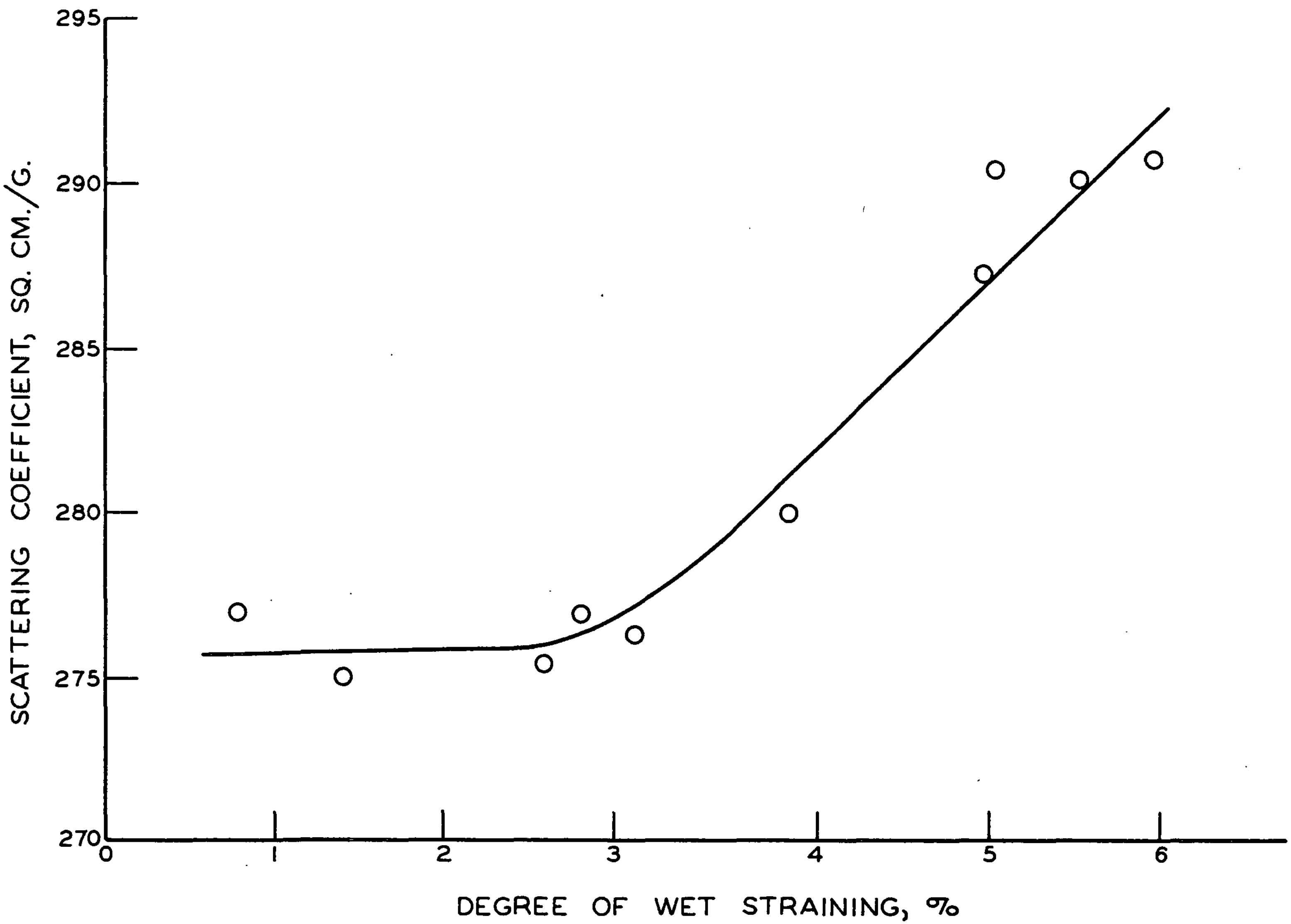


Figure 19. The Effect of Wet Straining on the Light-Scattering Coefficient of Pulp 650

not begin to rise until a degree of wet straining of about 3% is reached. The reason for this is not clear. No such flat portion is found in Fig. 17 for this pulp, and the bonding strength is seen to fall continuously. This suggests that although the optical contact of the fibers was not impaired, there was a drop in the bonding strength. The author hesitates to put any emphasis on the shape of the curves involving the scattering coefficients because of the possibility that the specimen surfaces were contaminated by contact with the mercury. Such contamination would certainly introduce variability in these data, and this could be misleading since only a limited number of handsheets were available for testing.

It is emphasized that all wet straining took place at 36% solids. The work of Lyne and Gallay (34) would indicate that at this solids content, there is only meager bonding between the fibers and that this bonding accounts for only a small part of the total bonding in the dried sheet. It does not seem likely that the breaking of a part, or even all, of the bonds present at 36% solids accounts entirely for the decrease in bonded area observed in these sheets. Even if many of these early-formed bonds are broken, they may be able to reform during a later stage of the drying period.

Rather, it seems more likely that during wet straining, part of the potential for bonding during the remainder of the drying period is destroyed. It is suggested that this may occur if wet straining changes the proximity of the fibers to one another so they are not in an advantageous position for bonding. The theory of the conforming action of the fibers during wet pressing has already been discussed. This theory suggests that, during wet pressing, the fibers are made to conform around one another so they are in a good position for bonding through the Campbell effect. The increased scattering coefficients would be expected if wet straining undid some of this conforming action. Perhaps some of the coherence of the sheet produced by wet pressing is removed by wet straining and the dried sheet is then less well bonded. Such a theory would also account for the decreased bonding strength previously observed.

The observed decrease in bonding effectiveness is of interest in consideration of the increased tensile strength of these sheets observed over the same range of wet straining. The tensile strength which is measured may be determined by several factors, one of which is bonding. It is probable that the curve which is obtained by plotting the degree of wet straining _versus_ tensile strength is the result of several competing factors which are affected by wet straining. Since the curve generally passes through a maximum and then decreases, it may be suspected that the decreased bonding effectiveness is the major contributor to changes in tensile strength after the maximum has been reached. Another hypothetical mechanism may act to raise the tensile strength to the maximum, and then may become less effective in changing the strength when further increases in wet straining are introduced.

FIRST CREEP

CHARACTERIZATION OF FIRST-CREEP RESPONSE

A creep test is used to determine the elongation-time relationship for a specimen supporting a load. The first time a specimen is loaded in a tensile-creep test is called the first creep test. If after some time the load is removed and a period of recovery is allowed, followed by the reapplication of the load, the second period during which the specimen is under load is called the second creep test, and so on. Similarly, the period of recovery immediately following the first creep test is called the first recovery test. This system of nomenclature is used throughout this report. A creep curve describes the relationship between deformation and time produced by a tensile load during the period of the test. It must be accompanied by a description of the apparent initial stress imposed upon the specimen. In the present work, the apparent initial stress was calculated by dividing the weight of the lower clamp plus the weight of the applied load by the cross-sectional area of the airdry cellulose supporting the load.

Several typical first-creep curves are shown in Fig. 20. Because of the rapid decline in the rate of delayed deformation after the early part of the test, the logarithm of time is commonly chosen for the abscissa. The ordinate is deformation, expressed as a percentage of the original gage length of the specimen. Each creep curve is accompanied by the value of the apparent initial stress applied to that particular specimen. In Fig. 20, three different apparent initial stresses are represented, which amount to 35, 55, and 68% of the tensile strength in a load-elongation test. The tests were arbitrarily ended after 24 hours. This was not possible for the specimen subjected to the apparent initial stress of 3.21 kg./sq. mm. since it broke during the test. The measurements were made at 50% R.H. and 73°F. These curves were all obtained on specimens cut from the same handsheet, prepared from Pulp 760 and wet strained 3.5%.

As the apparent initial stress is increased, the total deformation of the specimen is increased. A valuable insight into this behavior may be had by considering the master creep curve concept, applied to paper by Brezinski (26). Brezinski found that master creep curves for paper could be constructed from creep curves such as those presented in Fig. 20 by reducing the deformations by a factor of the apparent initial stress and shifting the reduced curves along the log-time axis until they coincide in the regions of overlap. A master creep curve, constructed in this manner, is shown in Fig. 21. This master creep curve was constructed from the creep curves previously presented in Fig. 20. The curve has the time axis of the creep test at 1.68 kg./sq. mm., since that test was selected arbitrarily as the base. The curves at the higher initial stresses were shifted toward greater times to form the master creep curve. A similar master creep curve may be constructed from the data obtained with a handsheet prepared from Pulp 650, which are presented in the Appendix as Creep Tests 49, 50, and 51. This latter handsheet was prepared with a degree of wet straining of 1.4%.

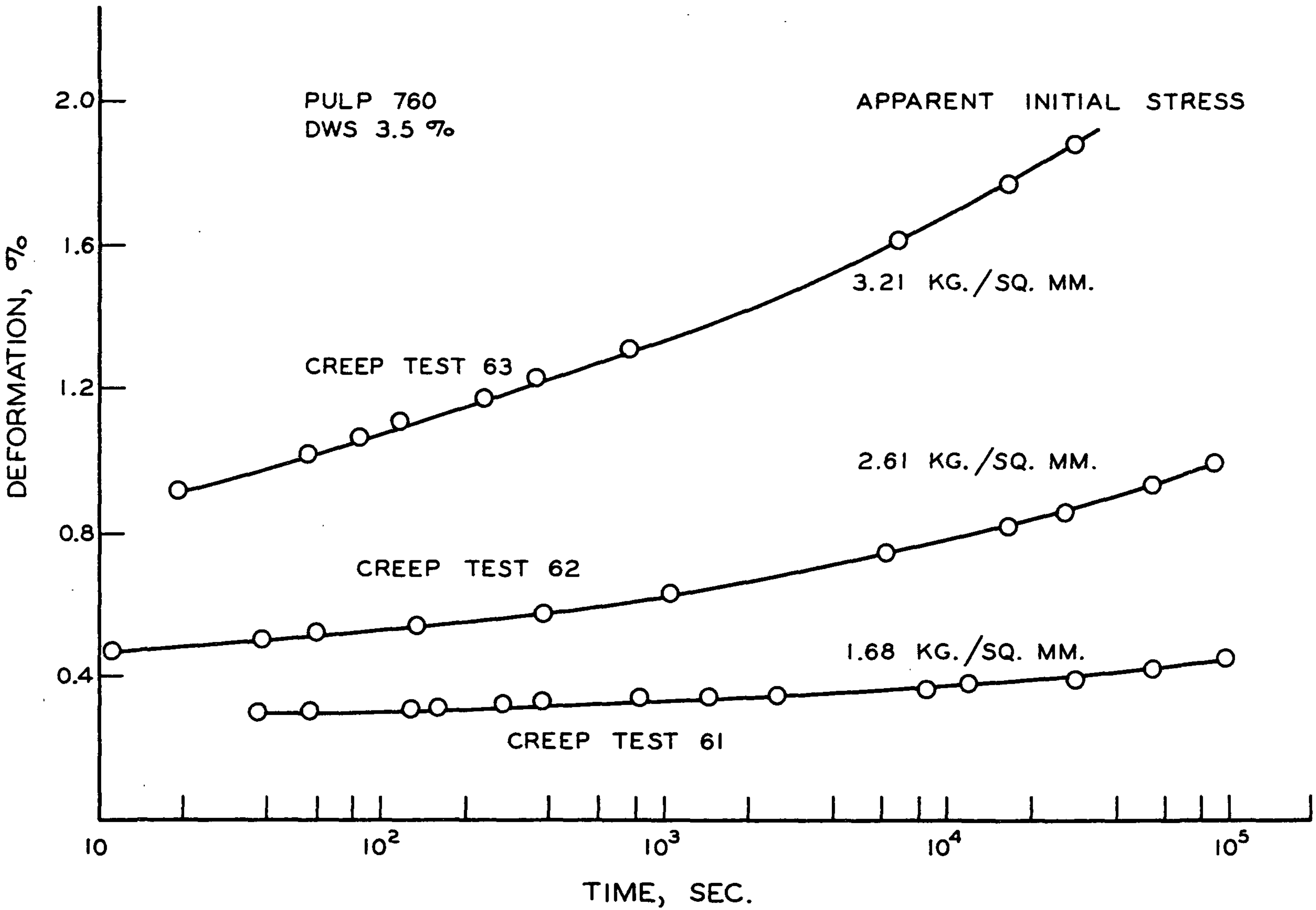


Figure 20. The Effect of Stress on First Creep

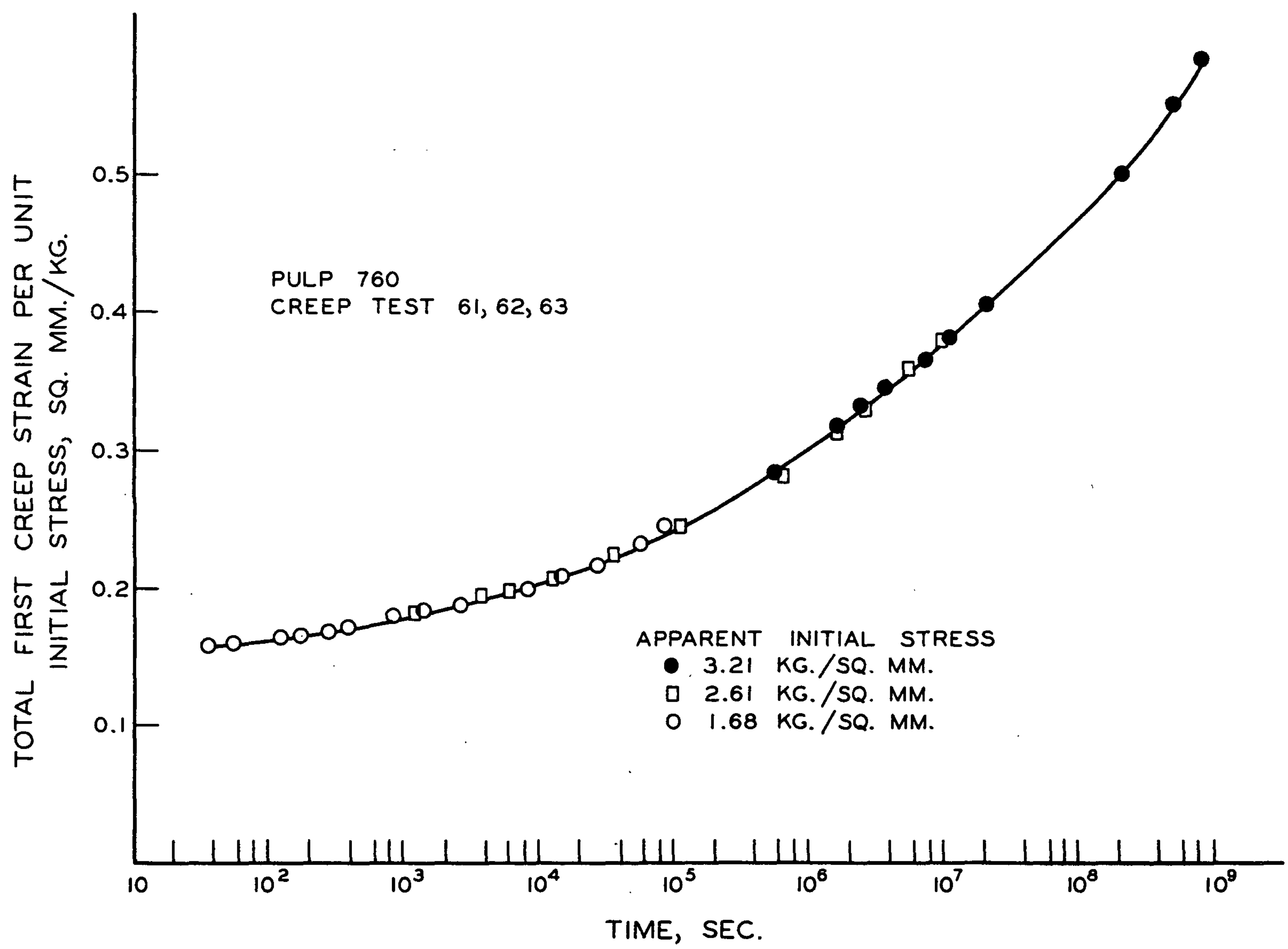


Figure 21. Master Creep Curve for Handsheet Wet Strained 3.5%

It would appear that wet straining has not impaired the applicability of the master creep concept. The master creep curve presented was obtained on a comparatively free pulp, subjected to a relatively high degree of wet straining. If wet straining were to invalidate use of the master creep concept, as perhaps through the effects of reduced bonding, it should be apparent with handsheets prepared from this pulp.

THE EFFECT OF WET STRAINING ON FIRST CREEP

In order to examine the first creep of handsheets prepared with different degrees of wet straining, it is necessary to put the first creep curves on a suitably comparable basis. For this reason, a series of handsheets prepared with different degrees of wet straining from the same pulp were subjected to first creep tests using the same apparent initial stress. The choice of stress was influenced by the strength of the sheets made from each pulp and by the desirability of a sizable delayed deformation to accentuate any effects. It is not likely, though, that the size of the apparent initial stress employed would influence the nature of the observed effects.

Several first-creep curves of this sort, obtained with sheets prepared from Pulp 650 are shown in Fig. 22. For all of the curves, the apparent initial stress was 4.00 kg./sq. mm. Similar curves for handsheets prepared from Pulp 760, obtained using a constant apparent initial stress of 2.60 kg./sq. mm., are shown in Fig. 23. All of the tests shown here were completed after 24 hours. It is evident that wet straining markedly alters the nature of the first creep of these

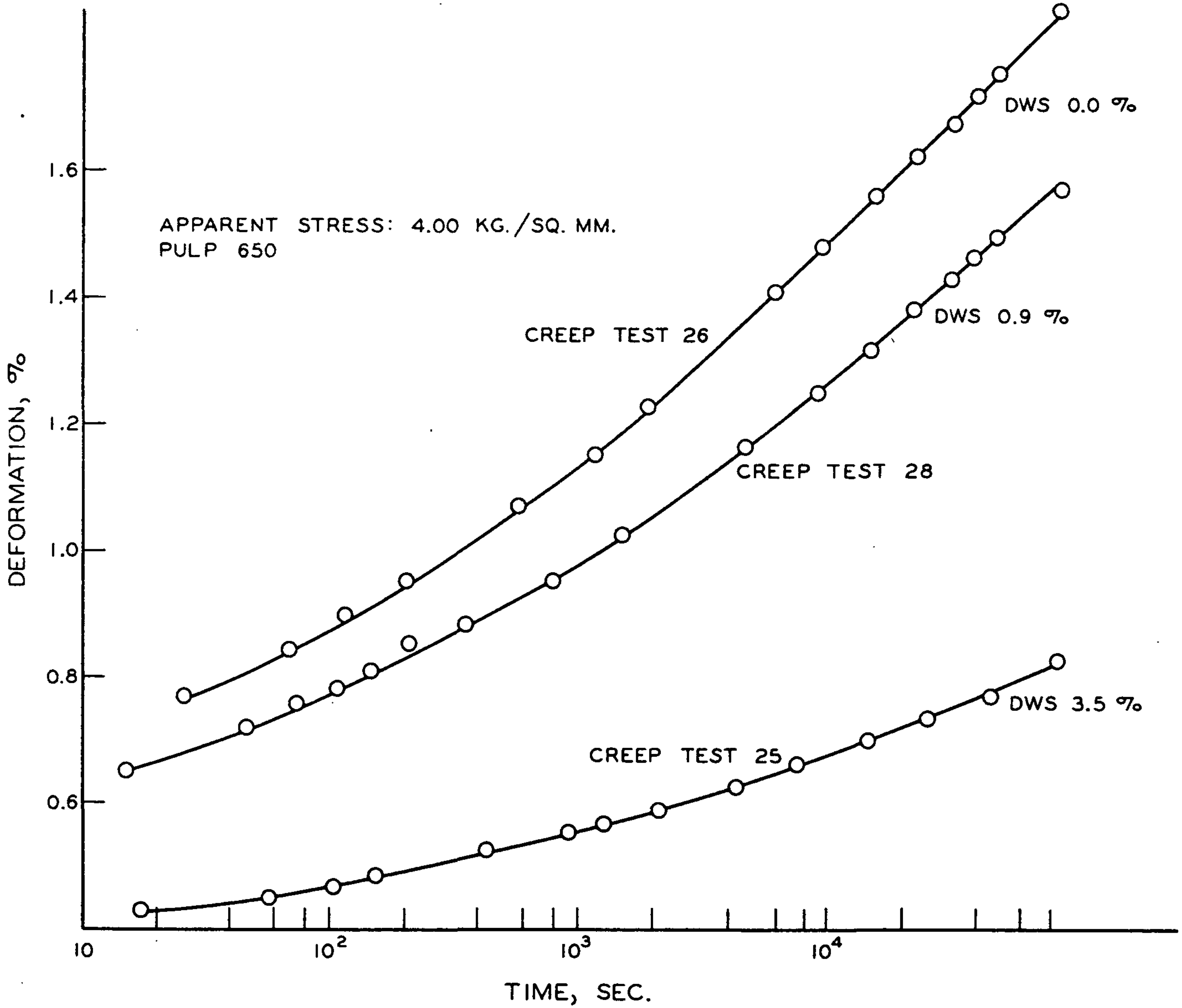


Figure 22. First Creep Curves for Handsheets of Different Degrees of Wet Straining

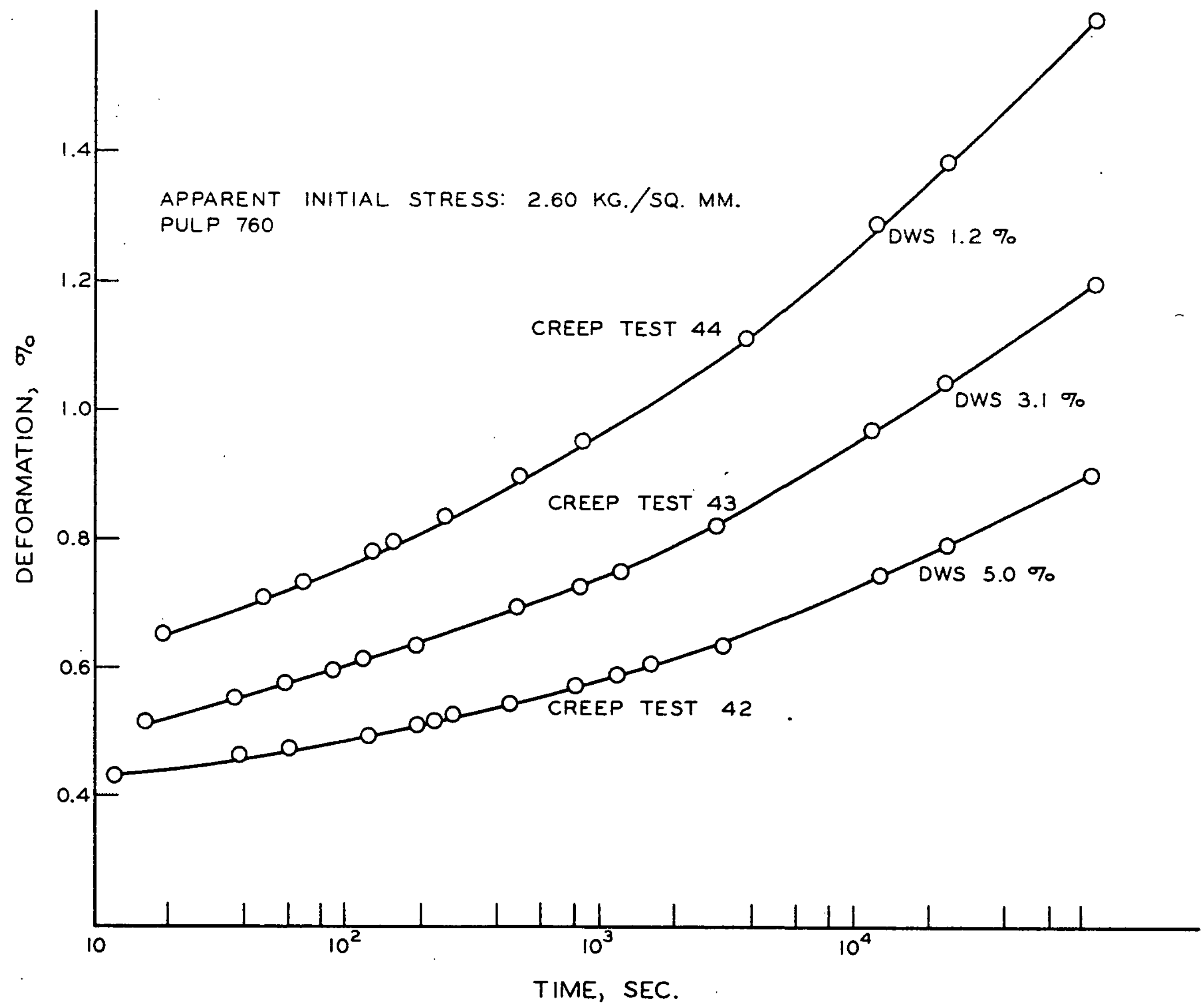


Figure 23. First Creep Curves for Handsheets of Different Degrees of Wet Straining

sheets. The curves are quite distinct, and differences in total deformation are apparent. Further, it appears that wet straining has created changes in the shape of the first creep curves.

It is of value to consider the change in the extent of deformation brought about by wet straining. For this purpose, a measure of extent of deformation is needed and must be selected arbitrarily. The total first-creep deformation after 24 hours will be used. The total first-creep deformation at any time consists of the sum of the immediate elastic deformation and the delayed deformation up to that time.

The effect of wet straining on the total first-creep deformation of specimens subjected to 4.00 kg./sq. mm. for 24 hours is shown in Fig. 24. The response of handsheets made from Pulps 650 and 460 is shown. These curves have a characteristic shape which would not be changed if a different measure of extent of creep deformation were used. It is seen that as the degree of wet straining is increased, the total creep deformation drops, passes through a minimum, and then increases. A large change in total first-creep deformation created by wet straining is apparent.

Handsheets prepared from Pulp 760 exhibited slightly different behavior. Total first-creep deformation in 24 hours produced by an apparent initial stress of 2.60 kg./sq. mm. at different degrees of wet straining is shown in Fig. 25. Although the drop in total creep deformation created by low degrees of wet straining is noted, no later rise in deformation is apparent. The data presented in Fig. 24 and 25 are given in Table V.

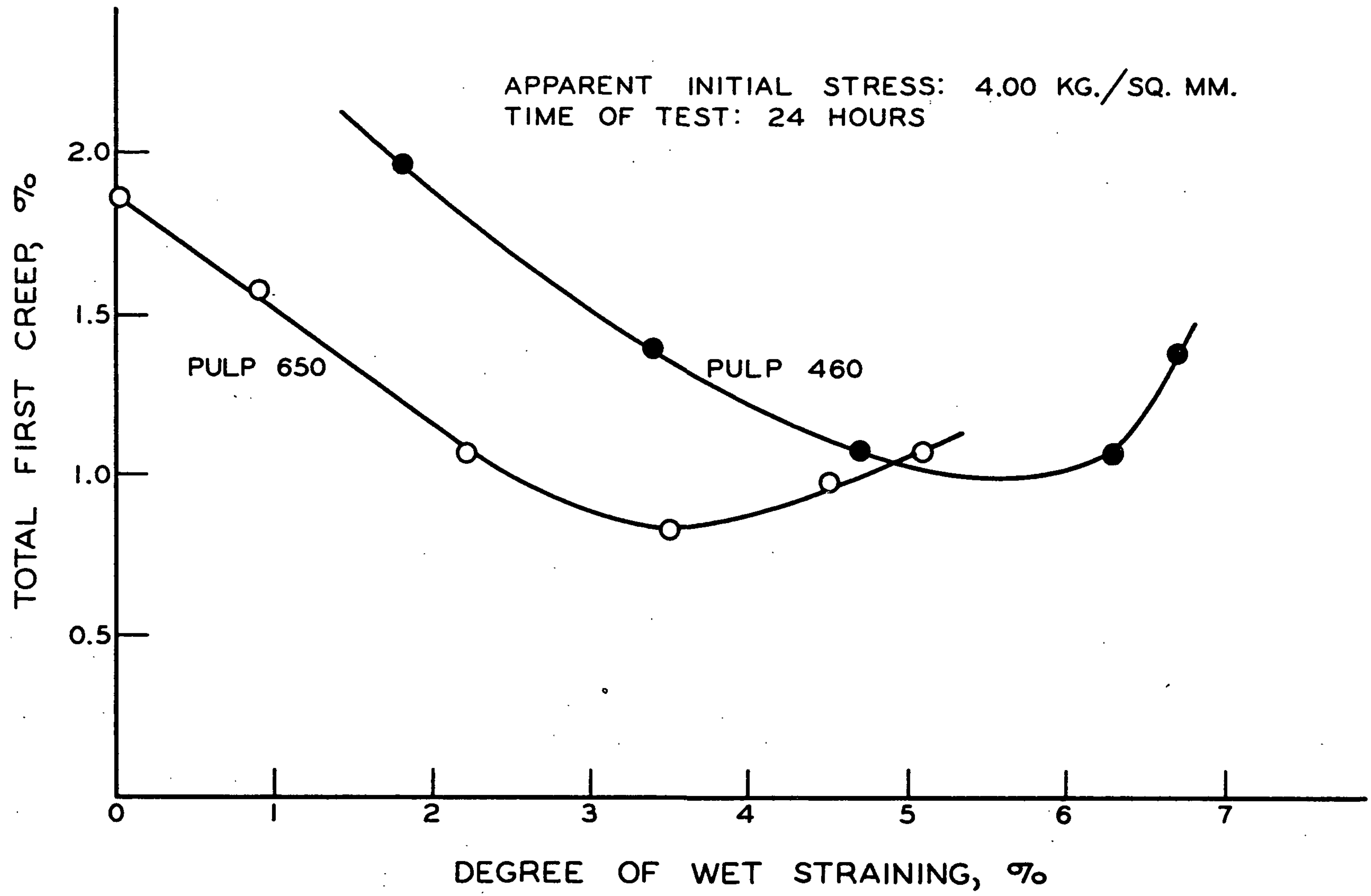


Figure 24. The Effect of Wet Straining on Total First Creep

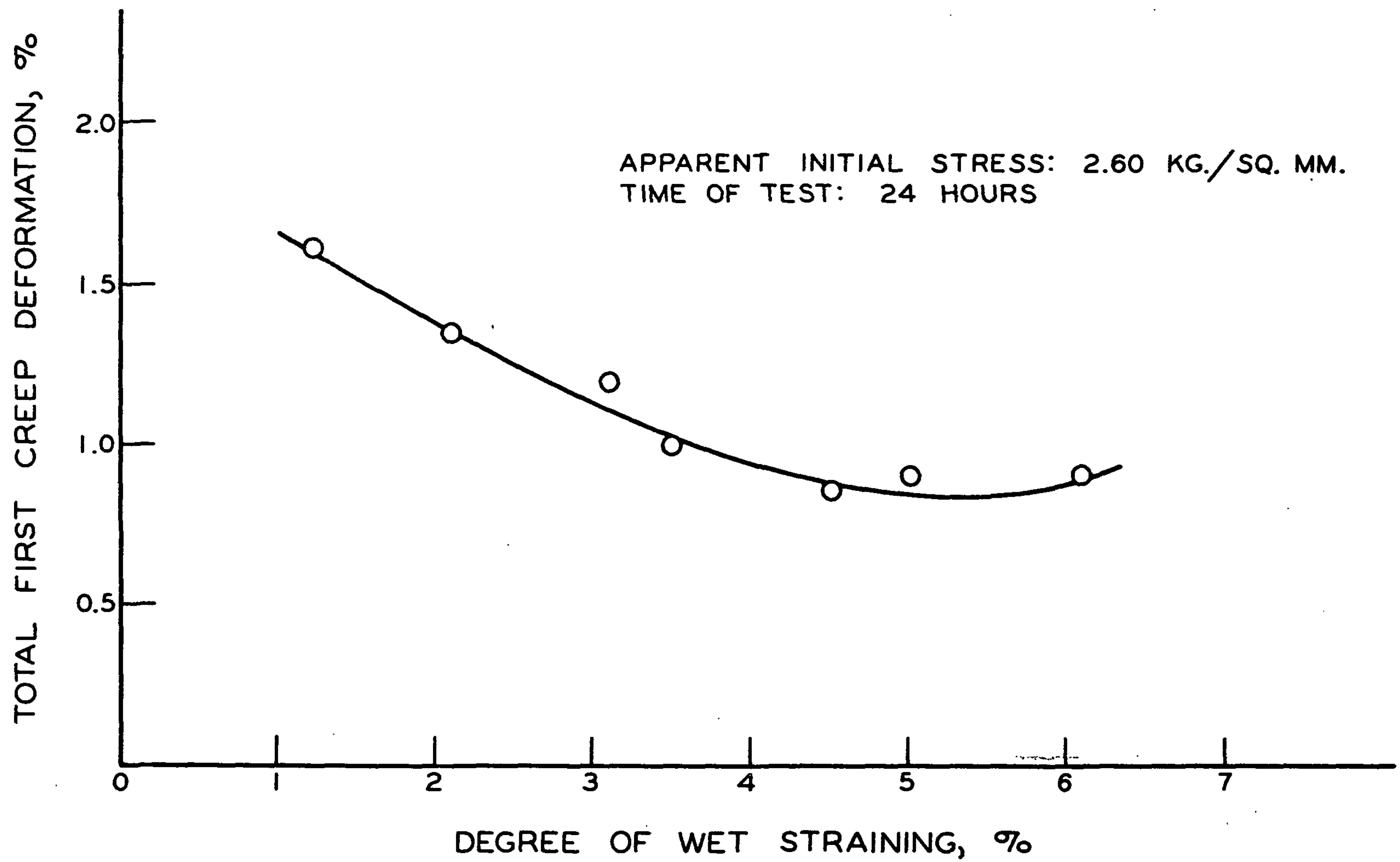


Figure 25. The Effect of Wet Straining on the Total First Creep of Handsheets Prepared from Pulp 760

TABLE V
TOTAL FIRST-CREEP DEFORMATION FOR HANDSHEETS
AT DIFFERENT DEGREES OF WET STRAINING

Duration of Test 24 hours

Pulp	Apparent Initial Stress, kg./sq. mm.	DWS, %	Total First Creep Deformation, %
760	2.60	1.2	1.608
		2.1	1.350
		3.1	1.202
		3.5	1.000
		4.5	0.852
		5.0	0.904
		6.1	0.892
650	4.00	0.0	1.855
		0.9	1.575
		2.2	1.063
		3.5	0.853
		4.5	0.955
		5.1	1.063
460	4.00	1.8	1.970
		3.4	1.388
		4.7	1.069
		6.3	1.073
		6.7	1.388

Inspection of the curves shown in Fig. 22 and 23 suggests that wet straining has affected the extent of delayed deformation produced by these handsheets. This effect may be examined more closely in Table VI, where the delayed deformation between 100 seconds and 24 hours has been presented as a function of wet straining for handsheets prepared from Pulps 650 and 460. Delayed deformation is one component of the total deformation and is a measure of the extent of time-dependent deformation. It is not practical to measure its absolute value because of the difficulty in accurately determining the instantaneous deformation, and, as was done in this case, an arbitrary time interval during which the deformation is measured is usually selected. It is seen in Table VI that the delayed deformation passes through a minimum in much the same manner as does the total creep deformation.

TABLE VI
DEFORMATION BETWEEN 100 SECONDS AND 24 HOURS FOR HANDSHEETS WITH DIFFERENT DEGREES OF WET STRAINING

DWS, %	Delayed Deformation, %	DWS, %	Delayed Deformation, %
Pulp 460		Pulp 650	
1.8	1.071	0.0	1.225
3.4	0.688	0.9	0.795
4.7	0.504	3.5	0.363
6.3	0.503	4.5	0.445
6.7	0.666	5.1	0.497

Note: Apparent initial stress = 4.00 kg./sq. mm.

A comparison of Fig. 22 and 23 with Fig. 20 suggests that the effect of wet straining is similar to that of altering the effective stress responsible for the deformation of the sheet during creep. This is supported by the effect on delayed deformation which, according to the master creep concept, is stress-proportional in its extent. It is suggested that although the apparent initial stress is held constant in these tests, the effective stress which determines the reaction of the specimen to loading has been affected by the wet-straining action.

If the changes brought about in first creep by wet straining are compared with the changes in bonding characteristics noted earlier, an interesting phenomenon is revealed. Figure 17, 18, and 19 indicate that as wet straining is increased, the bonding between the components of the sheet becomes progressively diminished. However, it is found concurrently that the response of the paper to stress is generally diminished with increased wet straining. In other words, sheets with less well-developed bonds between their fibers are able to exhibit less creep than some sheets with greater bonding. This is particularly well documented for Pulp 650.

It is meant to point out by this that bonding characteristics constitute only one factor among several which govern the response of paper to stress. Since the extent of bonding between the fibers apparently is diminished by wet straining, it is most likely that the change in creep characteristics is related to changes in the internal structure of the sheet which, in turn, change the stress distribution when the sheet supports a load. Apparently, it is not necessary that bonds between the fibers become more numerous for the stress distribution to become more uniform, although increasing the number of points of bond or increasing the bonded area may produce a more uniform stress distribution. Brezinski (26) suggested that such an effect occurs during wet pressing, which causes a drop in response to stress and a rise in bonded area.

The observation that response to stress may drop as bonded area is reduced casts strong doubt on theories of response to stress which depend primarily upon bond breaking for the rate-controlling mechanism. An increased response would be predicted by such theories if the degree of bonding is reduced, since each bond would be required to support an increased share of the load. In this situation, the bonds would break sooner, and the postulated taking-up of slackness between points of bond would occur at an increased rate, quickening the observed rate of response to stress.

MULTIPLE-CYCLE CREEP MEASUREMENTS

A substantial portion of first creep is known to be nonrecoverable at test conditions during a recovery period equal in length to that of the creep period, provided very low stresses or very short test times are not used. It follows that the mechanism of first-creep deformation is not completely reversible during the recovery period, and that paper will not follow Boltzmann's superposition principle. If the capacity for nonrecoverable deformation is removed by subjecting the specimen to one or more cycles of creep and recovery, the specimen is said to be mechanically conditioned for the stress used and for the test conditions employed.

When paper is subjected to a series of alternate creep and recovery periods, using the same load for all of the periods of creep, the response of the specimen during successive creep tests is progressively diminished. This is evident from Fig. 26, which shows the response of the same sheet to the apparent initial stress of 2.60 kg./sq. mm. during several creep phases of a multiple-cycle creep test. These creep curves were obtained using a handsheet prepared from Pulp 760, wet strained 1.2%. Each period of creep and each period of recovery lasted 24 hours, and during recovery phases a residual load of 315 grams remained on the specimen. The ninth creep (9C) test refers to the ninth time the specimen was subjected to the tensile creep load. In determining the extent of response in multiple-cycle creep tests, the original gage length of the specimen is always used when calculating percentages, and the increase in length of the specimen during the course of the cycles of the test is neglected. However, the extent of response in any creep test is always measured relative to the length of the sample following the preceding recovery phase.

Although the response to stress continues to diminish even after several cycles of creep and recovery, it is seen that the difference in response between the fourth and ninth creep tests is comparatively small. This illustrates the generally observed phenomenon that after about the fourth cycle in a multiple-cycle test of this sort, the additional drop in response is small. The drop in creep response in successive cycles is commonly attributed to mechanisms of response which are not reversible at test conditions during the time of the recovery period. It follows that creep response in creep tests after the first are primarily related to reversible mechanisms. Since the response continues to drop even after the third and fourth creep test, a diminishing capacity for creep by reversible mechanisms is indicated. Because of this effect, the definition of recoverable creep capacity is difficult, and it is preferable to describe the mechanical treatment, the conditions of temperature and humidity, and the nature of the measurements taken rather than to assign to any one particular calculation the responsibility of being "the recoverable creep."

Whatever mechanisms of recoverable or nonrecoverable deformations are involved, it is evident from Fig. 26 that mechanical treatment of paper is capable of markedly reducing the response of paper to stress. Since wet straining is, by its nature, a form of mechanical treatment, serious consideration must be given to the proposition that wet straining alters the response to stress of paper by a mechanism similar to that which occurs when paper is mechanically conditioned to stress. The drop in creep may be related to a diminished capacity for nonrecoverable creep and nothing else. Therefore, it is important to determine whether or not wet straining affects the recoverable creep of paper in addition to affecting the total creep.

The effect under consideration is illustrated by the curves shown in Fig. 27. Two specimens were cut from the same handsheet, which was prepared from Pulp 760 and which was wet strained 3.5%. One specimen was subjected to a stress of 2.61 kg./sq. mm. for 24 hours; the other to a stress of 1.68 kg./sq. mm. for 24 hours. After a 24-hour recovery period, second creep tests at 2.61 kg./sq. mm. were run on each specimen for 24 hours. These correspond to the conditions of the more severe mechanical treatment initially imposed on one of the specimens. The first creep of the specimens occurred during the mechanical treatment phase.

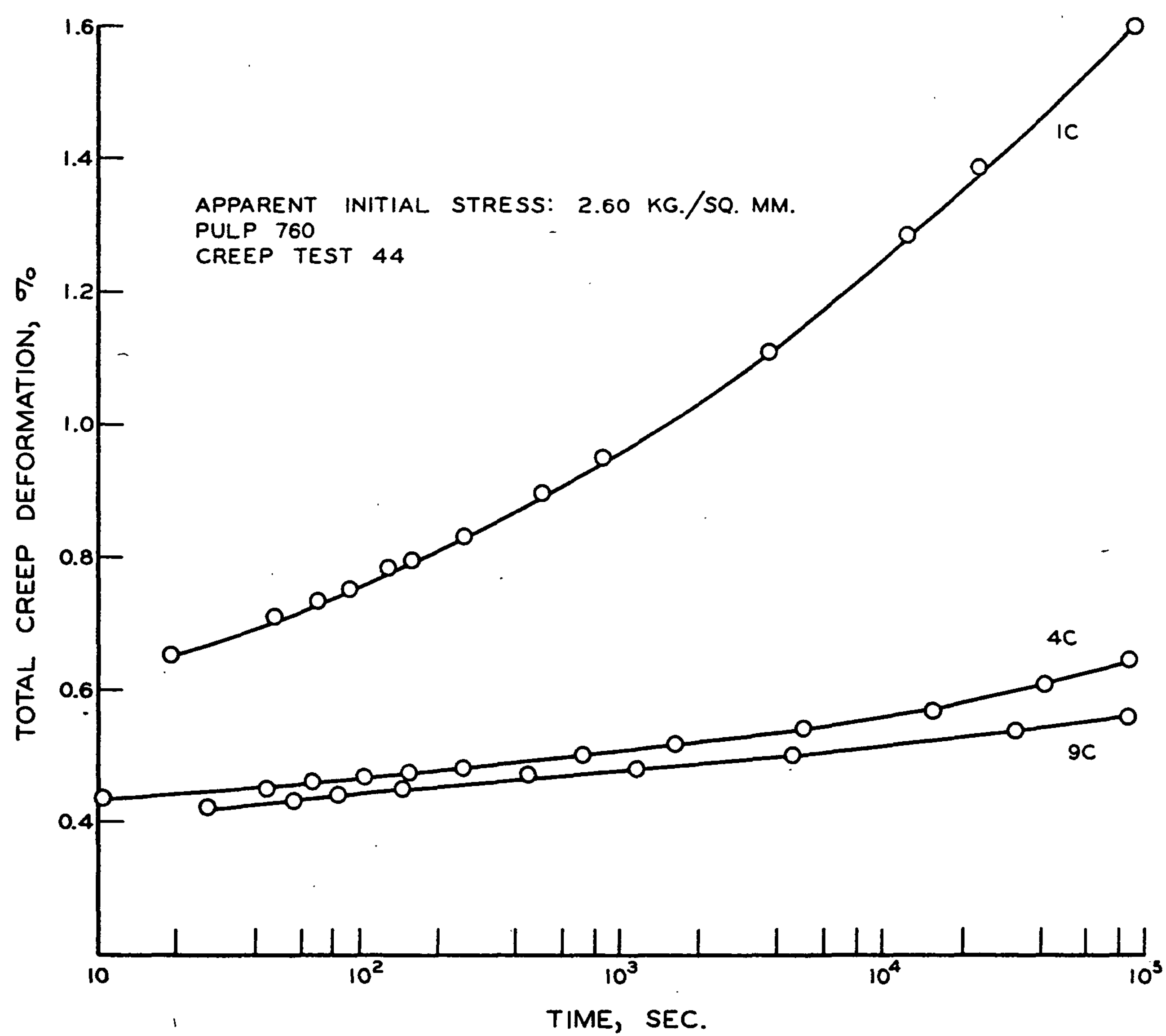


Figure 26. First, Fourth, and Ninth Creep in a Multiple-Cycle Test

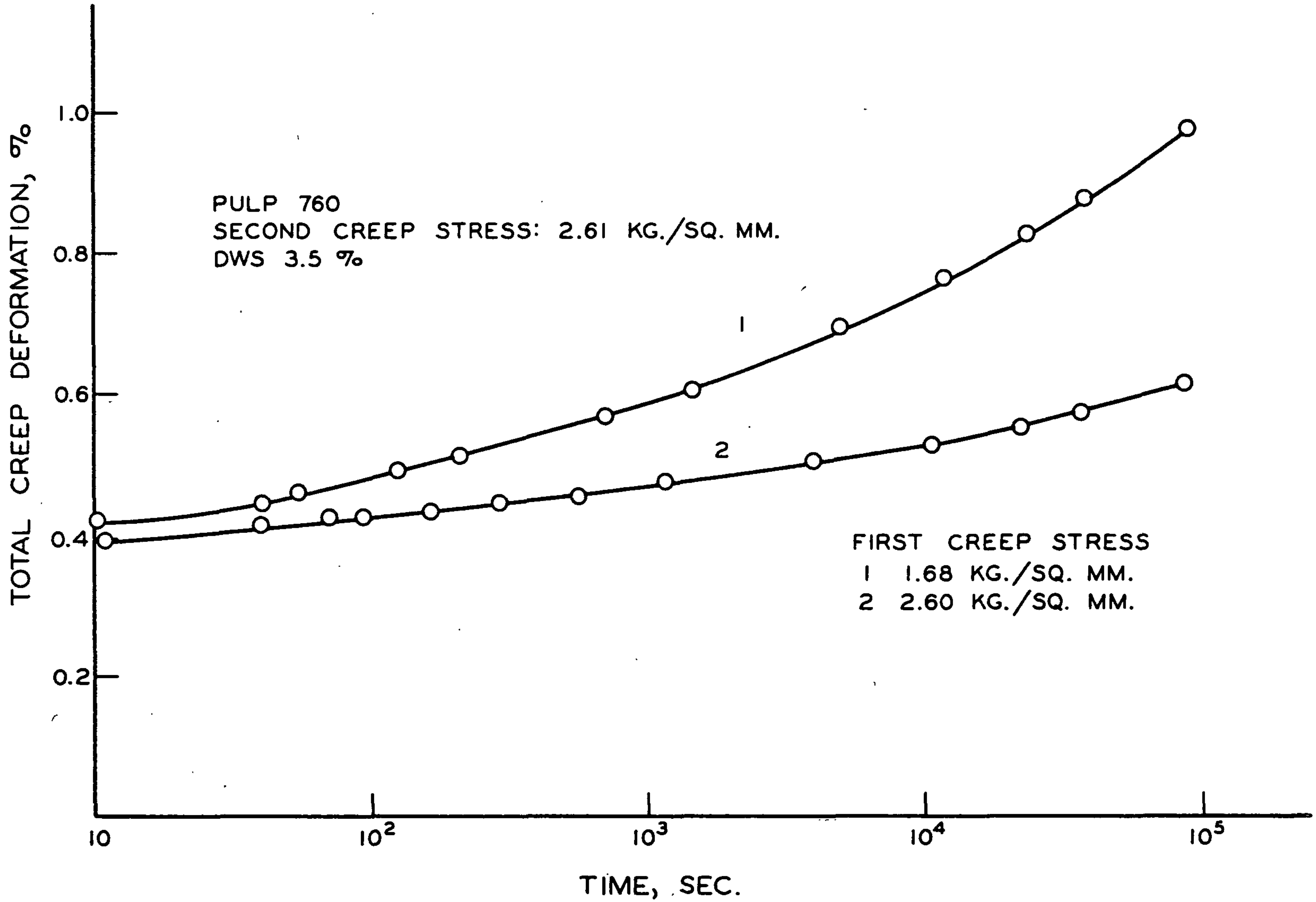


Figure 27. Second Creep Response Following First Creep Tests at Different Apparent Initial Stresses

The second creep of the specimen subjected to the more severe mechanical treatment is substantially lower than the response of the other sample. Since both of these specimens were taken from the same handsheet and both were subjected to the same second-creep stress, it seems apparent that the difference in response is due to additional nonrecoverable deformation occurring in the sample subjected to the less severe initial mechanical treatment. The fact that the disparity between the curves is most marked at later times suggests that mechanism of response associated mainly with the more advanced stages of first creep are responsible for the nonrecoverable deformation. Whatever the mechanism, it is evident that previous mechanical treatment exerts a strong influence on the extent of creep response. Further, it is not known how to assess the extent or nature of previous mechanical treatment from consideration of any one creep curve, although a proper analysis of this problem may be fruitful.

Since it has been demonstrated that additional nonrecoverable creep occurs even after the first few creep phases in multiple-cycle tests, care must be taken in discovering and identifying differences in recoverable creep. It is found, however, that after several cycles, the amount of additional nonrecoverable creep produced in each cycle becomes comparatively small, and the creep response in these later cycles may be used cautiously as a measure of recoverable creep. When such a technique is used, it is assumed that creep resulting from nonreversible mechanisms occurs primarily in the first few cycles, and deformation after the first few cycles is produced primarily by reversible mechanisms. To determine if definite differences in creep by recoverable mechanisms exist between sheets prepared with different degrees of wet straining, a series of these sheets was subjected to multiple-cycle tests. It was reasoned that if no differences in recoverable creep capacity exist between these sheets, their response to stress after several cycles of creep and recovery, or their response to stress after being "mechanically conditioned," would be approximately equal.

To examine the applicability of this technique, two specimens were cut from a handsheet prepared from Pulp 760 which had been wet strained 3.5%. These specimens were subjected to multiple-cycle creep test, using 24 hours for each creep and each recovery phase. During the first creep phase, apparent initial stress of 2.61 kg./sq. mm. and 1.68 kg./sq. mm. were used, respectively. During the second creep phase, apparent stresses of 2.61 kg./sq. mm. were applied to each specimen. The second creep curves for these specimens have been presented in Fig. 27, and the disparity between their responses have been discussed. The tests were continued with the same schedule after this second creep test; in every case an apparent stress of 2.61 kg./sq. mm. was used in the creep phases. The response of the specimens in each creep test after the first is shown in Table VII.

During the successive cycles of creep and recovery, the creep response of the sheets becomes closer. After the fifth creep test, the response of the specimen subjected to the lower first-creep load is only 2.5% greater than the response of the other specimen at the

TABLE VII
TOTAL CREEP DEFORMATIONS DURING MULTIPLE-CREEP TESTS

DWS 3.5%

Specimen 1

Creep cycle	1	2	3	4	5
Apparent stress, kg./sq. mm.	1.68	2.61	2.61	2.61	2.61
Creep deformation, %	0.413	0.981	0.623	0.578	0.538

Specimen 2

Creep cycle	1	2	3	4	5
Apparent stress, kg./sq. mm.	2.61	2.61	2.61	2.61	2.61
Creep deformation, %	1.000	0.679	0.569	0.543	0.525

same stage. Presumably, the responses would become even closer in later cycles. It is concluded that the difference in creep response created by the difference in apparent stress during first creep is essentially removed after the repeated application of the second-creep apparent stress, as was done in this control.

The response to multiple-cycle creep tests of handsheets prepared with different degrees of wet straining from Pulp 650 was examined in the manner described. The tests employed 24-hour periods of creep and recovery and an apparent initial stress of 4.00 kg./sq. mm. The handsheets used had degrees of wet straining of 0.0, 0.9, and 3.5%. During recovery phases, a load of 300 grams remained on the specimens. The tests were carried out using the flat-face clamps. The data are shown in Fig. 28. In this figure, the total creep deformation is shown for each cycle of the multiple-cycle test.

For each specimen examined in this series, the greatest drop in response to stress occurs during the first cycle. After the fourth cycle, the drop in extent of response in each succeeding creep phase is comparatively small. Therefore, it is reasonable to assume that the response to stress after the fourth cycle is largely through mechanisms which are reversible.

However, it is apparent that even after five or six cycles, there are distinct differences in the response to stress of sheets prepared with different degrees of wet straining. In the eighth creep cycle, the sheet wet strained 0.0% exhibits a deformation 40% greater than the sheet wet strained 3.5%, and the sheet wet strained 0.9% is deformed 30% more than the sheet wet strained 3.5%. These differences are very significant. Further, no tendency for the lines to converge is apparent.

Similar conclusions are obtained from consideration of the results of multiple-cycle tests obtained using sheets prepared from Pulp 760, which are shown in Fig. 29. These data were obtained using the line-contact clamps. During the 24-hour creep phases, the specimens were subjected to an apparent initial stress of 2.60 kg./sq. mm., and during the 24-hour recovery phases, a load of 315 grams remained on the specimens. On the basis of these tests, it must be concluded that the

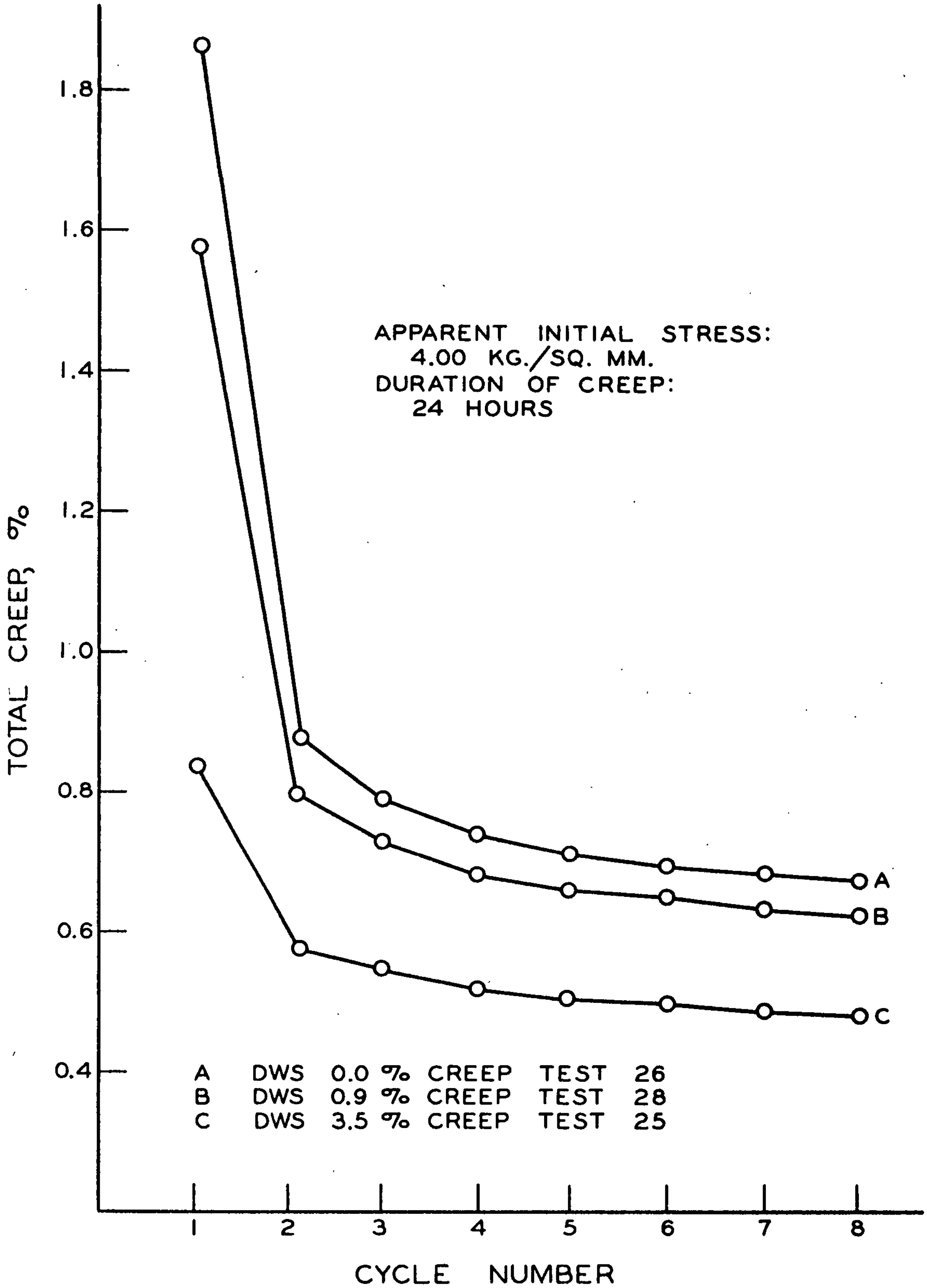


Figure 28. The Total Creep Response in Successive Cycles of a Multiple-Cycle Test

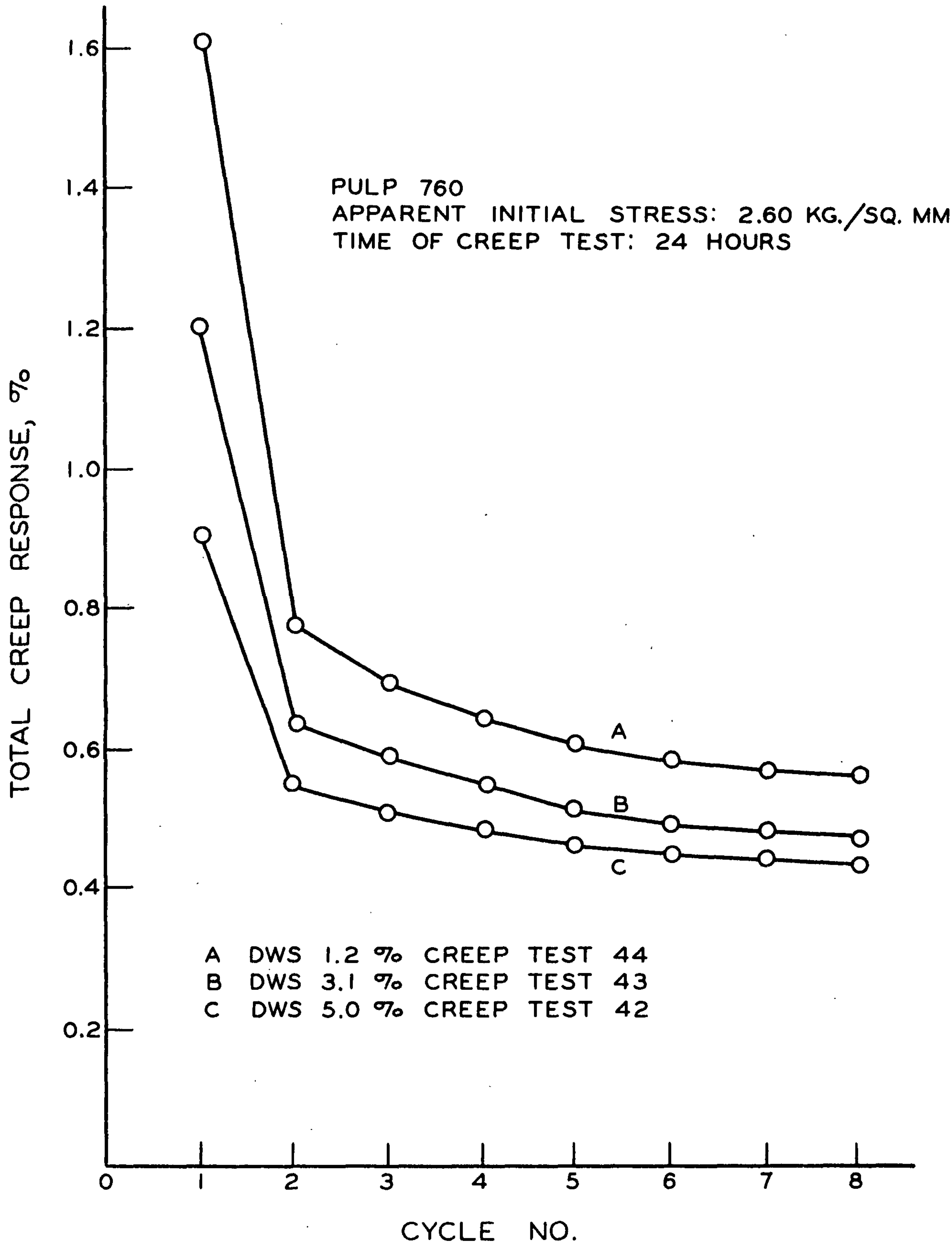


Figure 29. Total Creep Response in Successive Cycles of a Multiple-Cycle Test

effect of wet straining is not solely one of reducing the capacity of paper for nonrecoverable deformation. Evidently, deformation by recoverable mechanisms is also affected.

A more detailed view of this effect may be had from Table VIII. In this table, changes in total fourth creep brought about by wet straining are shown. The data were obtained from handsheets prepared from Pulp 650 which were subjected to multiple-cycle creep tests using an apparent initial stress of 4.00 kg./sq. mm. The flat-face clamps were used, and the specimens were subjected to the clamp load during the recovery periods. The total fourth creep is seen to pass through a minimum as the degree of wet straining is increased. If the assumption is made that fourth creep is a reasonable measure of recoverable creep, it may be concluded that wet straining brings about marked changes in the extent of creep by reversible mechanisms and that the changes are similar to those created in total first creep, shown in Fig. 24, and in delayed deformation, shown in Table VI. These concomitant effects suggest a general change in the magnitude of the response to stress of the sheets, created by wet straining.

CREEP RECOVERY CHARACTERISTICS

The removal of the load from the specimen may be considered, for many purposes, to be similar in effect to the addition of a negative load. When the load is removed, the first response is an immediate elastic deformation, opposite in direction to the elastic deformation which occurred when the original load was applied. Following the

TABLE VIII
TOTAL FOURTH CREEP DEFORMATION AT DIFFERENT DEGREES OF WET STRAINING FOR PULP 650

DWS, %	Total Creep Deformation, %
0.0	0.740
0.9	0.680
3.5	0.524
4.5	0.537
5.1	0.564

Note: Apparent initial stress = 4.00 kg./sq. mm.
Time: 24 hours

immediate elastic recovery, there is a time-dependent recovery, again opposite in direction to the time-dependent creep. The time-dependent recovery is generally attributed to retarded elastic mechanisms or to the reversible change of phase of crystalline cellulose to amorphous cellulose.

THE EFFECT OF WET STRAINING ON RECOVERY

It would seem that the best measure of creep by recoverable mechanisms would be the recovery following creep. However, several factors concerning the recovery characteristics of paper suggest that this apparent equality may not be taken for granted. Brezinski (26) found that the extent of recovery in multiple-cycle tests diminishes in a manner similar to that of the creep, as the number of cycles is increased. This would suggest that at least part of the creep which occurs by mechanisms which are reversible cannot be recovered. Further, it is found that recovery is consistently significantly less than creep in creep tests after the first. In fact, second recovery curves are often found to lie lower than third creep curves. This behavior has been investigated to some extent by Brezinski (26). However, until some of the obscurity surrounding the area is removed, questions concerning recoverable creep should be approached very cautiously, and care must be taken in drawing firm conclusions.

Several first recovery curves obtained with handsheets prepared from Pulp 760 with different degrees of wet straining are shown in Fig. 30. These first recovery curves followed first creep tests extending 24 hours, with the specimens sustaining a first-creep apparent initial stress of 2.60 kg./sq. mm. During the recovery phase, a residual load of 315 grams remained on the specimens. The convention of plotting recovery deformations as positive in relation to the position of the specimen at the end of the creep test was adopted. When calculating recovery deformations, the gage length of the sheet prior to the first application of the creep load was employed. In other words, the increase in sheet length due to creep was neglected. The recovery was determined relative to the length of the specimen at the end of the preceding creep phase.

It is evident from Fig. 30 that wet straining creates signficant changes in the recovery characteristics of the handsheets. The effect of increased wet straining on the total first recovery of sheets made from Pulps 460 and 650 is shown in Fig. 31. These data represent total

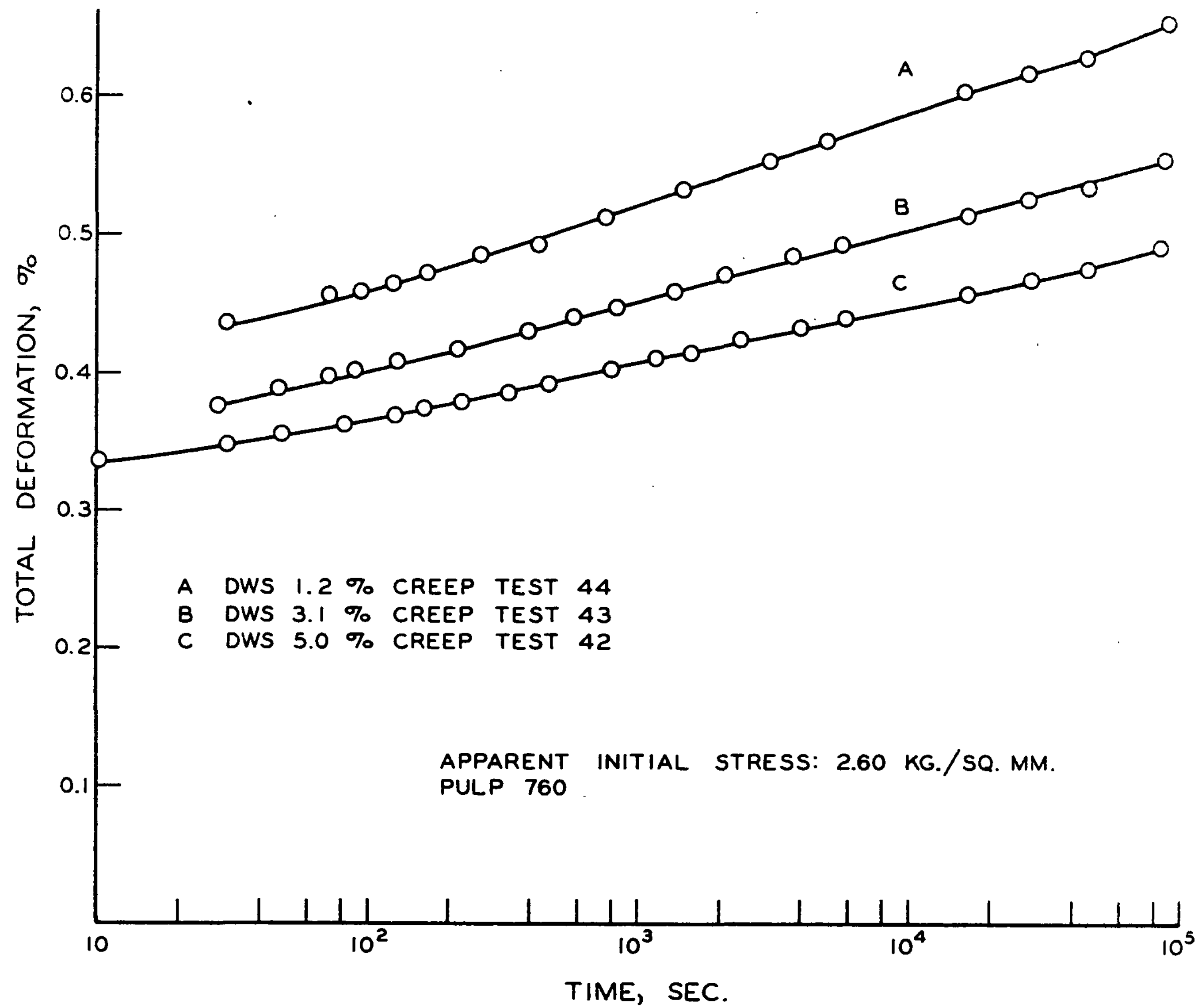


Figure 30. First Recovery Curves for Handsheets with Different Degrees of Wet Straining

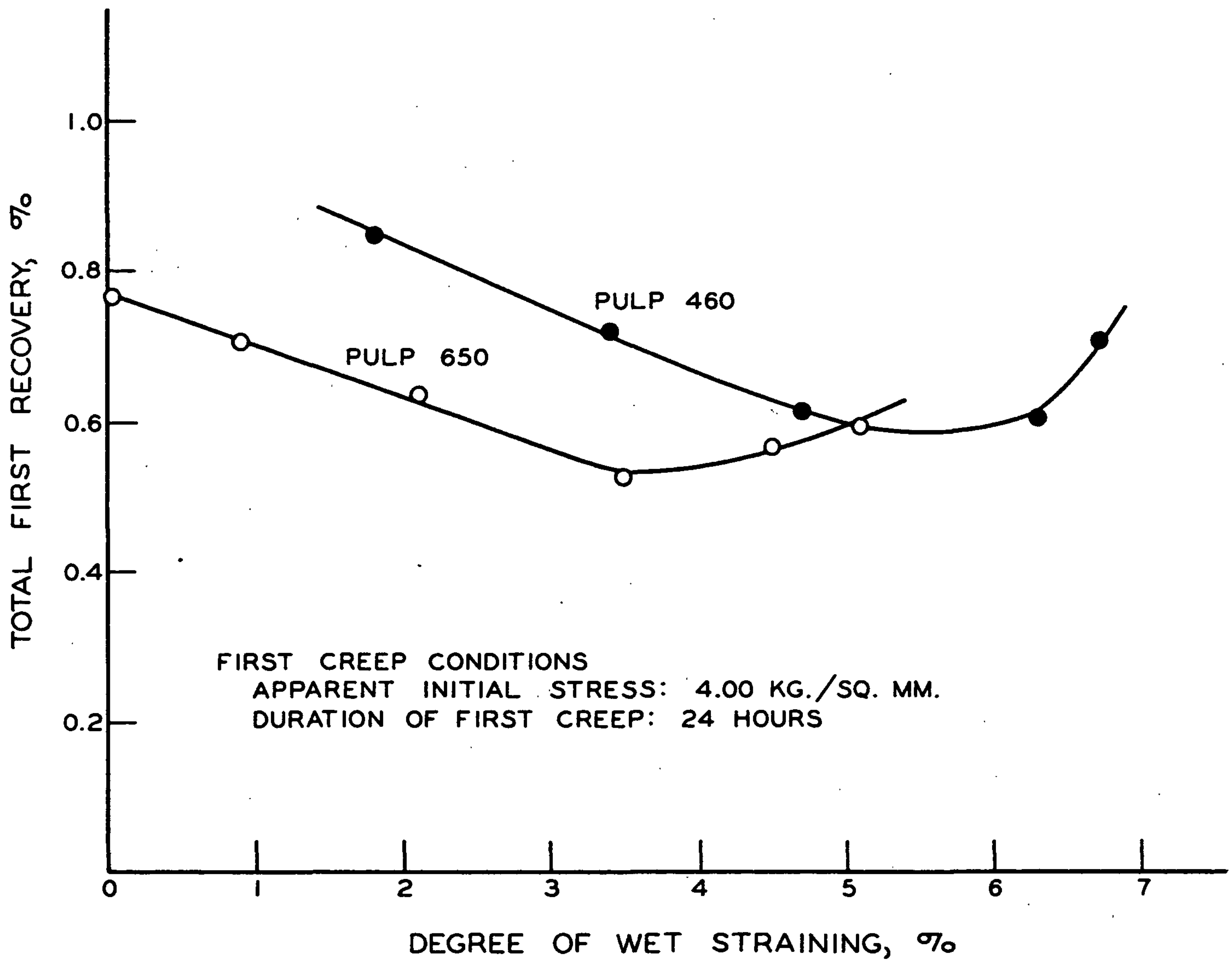


Figure 31. The Effect of Wet Straining on Total First Recovery

recovery following first creep tests extending 24 hours, during which the specimens supported 4.00 kg./sq. mm. During recovery, the specimens supported the weight of the clamps. The curves pass through minima at about the same degree of wet straining at which the total first creep deformation passes through a minimum. The phenomenon supports the previously proposed suggestion that wet straining affects the capacity of paper for creep by reversible mechanisms.

THE RELATIONSHIP BETWEEN CREEP AND RECOVERY

The ability of the first-creep response of paper to form master creep curves has been demonstrated by Brezinski (26), and has been shown to be apparently unaffected by wet straining in the present work. It follows from this characteristic ability that all types of response--exponential, transitional, and logarithmic--will occur in first creep starting with any apparent initial stress, although they will occur at different times and will be linearly related in amount to the apparent initial stress. Implicit is recognition of the orderly manner in which paper deforms under stress at loads less than the breaking load.

It would be expected then that this orderly response would be reflected in the recovery characteristics of paper. Brezinski (26) found that there is a unique relationship between total first creep in a definite period of time and total first recovery in the same period of time, when the recovery period and the creep period are equal in length. This relationship is found by plotting total first recovery against total first creep. The data are obtained using different apparent initial stresses. It was learned that this relationship is not strongly affected by refining history, although the amount of recovery for a given amount of creep was somewhat lower for a lightly beaten pulp.

The existence of this relationship may be used to examine the effect of wet straining on nonrecoverable deformation. It is evident that if wet straining removes nonrecoverable deformation from the first-creep response, the amount of recovery corresponding to a particular first-creep response will be greater than if a larger part of the first-creep response were due to nonrecoverable mechanisms. If all of the nonrecoverable deformation were removed, the recovery would approach the creep in extent. Therefore, if the first creep-first recovery relationship for equal periods of creep and recovery were determined for handsheets with different degrees of wet straining, a family of curves should be obtained, the highest curve corresponding to the sheet with the least capacity for nonrecoverable deformation.

A series of experiments was designed in which the total recovery in 24 hours was to be compared with the total creep in 24 hours, for handsheets with different degrees of wet straining. When this was done, it was apparent that, regardless of the degree of wet straining, there is a unique relationship between first creep and first recovery. A single curve, rather than a family of curves was obtained. Further, it was found experimentally that the unique relationship between creep and recovery is independent of the length of the period of creep and recovery, as long as the creep period is as long as the recovery period. As was anticipated, the relationship is independent of the apparent initial stress.

The data obtained in these tests are given in Table IX for Pulps 650, 460, and 290. No handsheets prepared from Pulp 760 were used in this part of the program. The data are plotted in Fig. 32. A smooth curve may be drawn through the data obtained for the pulp at any degree of beating. However, the shape of the curve is not strongly affected by beating, and in Fig. 32, a single curve is drawn through all of the data. These tests were carried out using the line-contact clamps.

The discovery of the unique relationship between creep and recovery for sheets of different degrees of wet straining is most significant. It indicates that the amount of recoverable deformation is related only to the first-creep deformation, and is not affected by wet straining. The effect of changing the degree of wet straining on determining this relationship is similar to changing the apparent initial stress, for although both affect the position of individual datum points on the curve, neither is able to change the shape of the curve. This observation argues strongly for considering the effect of wet straining to be largely one of shifting the response to stress to different times, in a manner similar to that of changing the apparent initial stress. This follows since, using a constant stress, the only factor which is known to determine the relative amounts of recoverable and nonrecoverable deformation is the time of the test. Turning again to Fig. 24 and 25, it would seem that as the total response to stress

TABLE IX
COMPILATION OF TOTAL FIRST CREEP AND TOTAL FIRST RECOVERY DATA AT DIFFERENT DEGREES OF WET STRAINING

DWS, %	Time of Creep or Recovery Test, sec.	Apparent Initial Stress, kg./sq. mm.	Total First Creep, %	Total First Recovery, %
		Pulp 650		
0.9	86,400	4.48	1.656	0.850
1.4	2,820	3.10	0.473	0.410
1.4	3,720	3.58	0.714	0.554
1.4	86,400	3.38	0.849	0.604
1.6	86,400	4.70	1.556	0.813
2.2	84,700	4.82	1.776	0.864
2.8	2,820	2.45	0.249	0.214
3.0	7,200	2.62	0.357	0.301
3.0	7,200	4.43	1.151	0.736
3.0	3,720	4.70	1.200	0.748
3.3	86,400	1.38	0.178	0.162
3.5	86,400	4.83	1.276	0.748
3.5	86,400	2.16	0.394	0.331
4.1	2,520	4.18	0.778	0.582
4.1	84,700	4.72	1.446	0.806
5.8	2,520	4.83	0.556	0.467
		Pulp 460		
0.7	86,400	2.29	0.545	0.428
2.1	86,400	3.97	1.706	0.920
2.1	86,400	2.49	0.632	0.477
3.9	9,020	2.58	0.518	0.432
3.9	9,020	3.70	1.248	0.789
4.2	8,300	4.33	1.224	0.760
4.2	8,300	3.97	0.892	0.642
4.2	86,400	3.97	1.089	0.693
4.7	86,400	2.42	0.338	0.298
		Pulp 290		
1.9	86,400	3.64	1.026	0.760
1.9	4,920	3.64	0.786	0.556
1.9	4,920	1.83	0.242	0.231
4.9	1,860	3.76	0.648	0.525
4.9	1,860	3.53	0.569	0.483
6.6	86,400	3.83	0.628	0.510
6.6	86,400	3.59	0.566	0.502

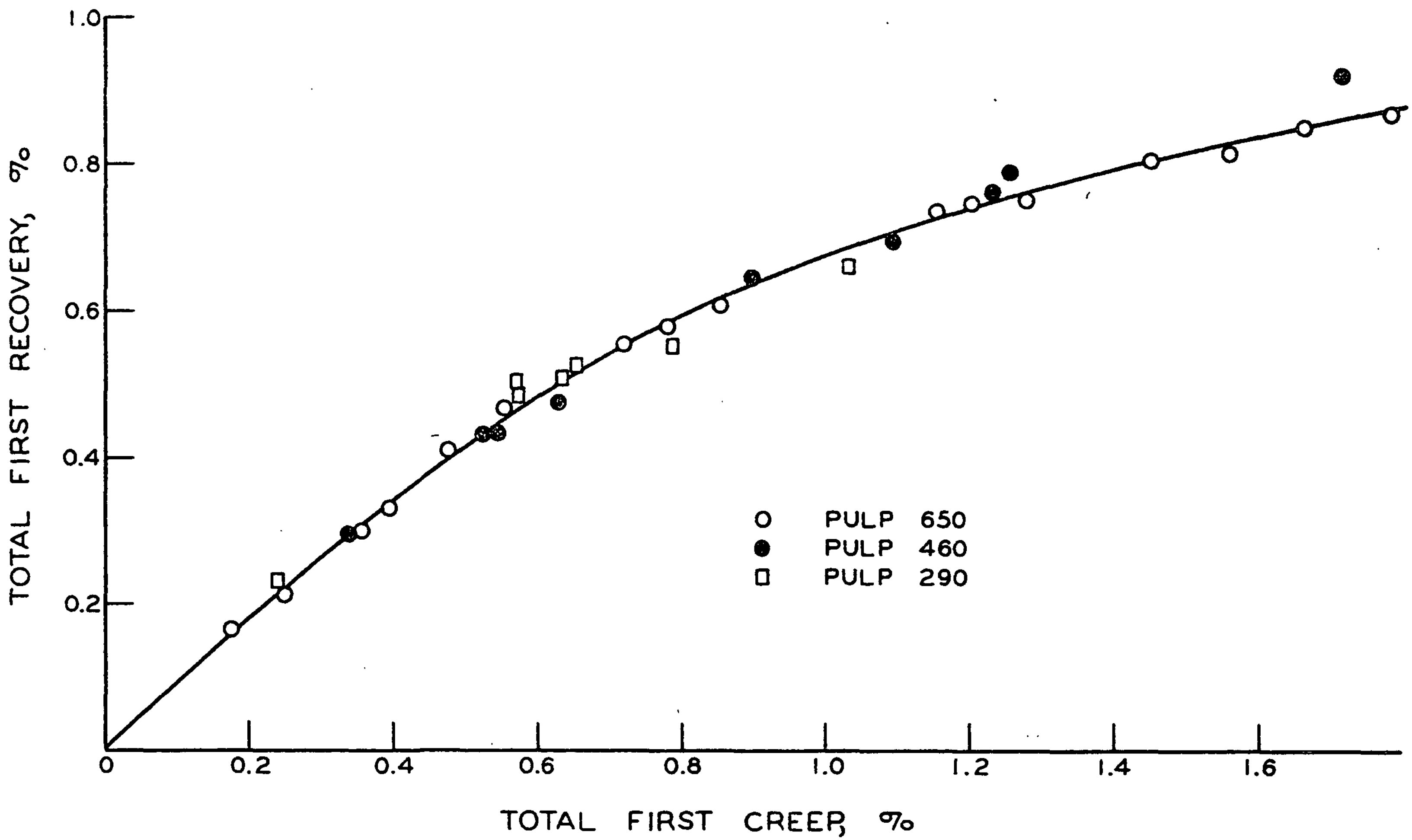


Figure 32. The Relationship Between Total First Creep and Total First Recovery

is reduced, the response at 24 hours, or at any other particular time, is characteristic of creep by mechanisms which would have occurred earlier if the stress distribution had not been made more uniform. After the minimum in these figures is reached, the stress distribution presumedly becomes less efficient, the total response at any constant apparent initial stress increases with increased wet straining, and the creep at any particular time is characteristic of creep by mechanisms which would have occurred later in the sheets with the more uniform stress distribution.

It is proposed that this effect is produced by the creation of a new fibrous structure in the sheet by the action of wet straining. When the new fibrous structure is made to support a load, the response of the sheet to the load may be different because the new structure involves a new distribution of stress among the fibrous elements of the sheet, and the load may be effectively supported by more structural units. This in turn alters the stress imposed on any one structural element, and so the response of any one element may be changed. If more structural elements are made to support the load, the total response of the sheet will be reduced. In this manner, the effective stress among the load-supporting elements of the sheet may be changed, although the apparent stress may be unaffected. Further, this effect would act to increase the tensile strength of the sheet.

It was found, in constructing Fig. 32, that the relationship is unaffected by the length of the creep or the recovery periods, as long as these periods are equal. The relationship, as depicted, would be unaffected if all of the points corresponding to tests run with creep periods other than 86,400 seconds (24 hours) were removed. This may be seen by comparing the data in Table IX with the figure.

These data suggest that the amount of recovery depends only upon the absolute magnitude of the creep deformation. Apparently, the manner in which the creep deformation is achieved does not influence the result. The creep deformation may be produced by any combination of apparent stress and time. It is not clear why this result is achieved, and its significance in terms of the master creep curve is not understood. However, the significance of these data regarding the mechanism and nature of the wet-straining effect are unaffected by this additional observation.

It should be noted that if the data presented by Brezinski (26) are treated in the same manner, no such relationship is obtained. Similarly, no regular relationship was observed in the present study when the flat-face clamps, which were used by Brezinski, were employed. It is suggested that this discrepancy is related to the use of the line-contact clamps in the present study and the use of the flat-face clamps in the previous study.

CREEP AND RECOVERY AT CONSTANT STRESS

It has been suggested that the effect of wet straining on the viscoelastic behavior of paper is largely one of shifting the time of response to stress by producing a change in the internal structure of the sheet. Specifically, it is proposed that reduced response to stress is the result of a more efficient distribution of stress when the sheet sustains a load. The ability of this theory to explain changes in the viscoelastic behavior of paper must be tested by the most direct means available. One approach would be to examine changes in the shape of the creep curves obtained with constant apparent initial stress on handsheets prepared with different degrees of wet straining, and to compare them with changes created in the shape of creep curves obtained in tests using different apparent initial stresses on specimens cut from a single sheet.

For example, it might be pointed out that in Fig. 22, which shows the first creep of handsheets prepared from Pulp 650 when subjected to the same apparent initial stress, the curve from the sheet with the lowest degree of wet straining exhibits a straight-line portion, indicative of logarithmic response, while a substantial portion of the lowest curve in the series can be fit to an exponential equation. If the master creep concept is applicable, this would indicate that for the higher curve, the deformations are by mechanisms characteristic of relatively late response, while, for the lower curve, the mechanisms are those characteristic of relatively early response. Therefore, it would follow that the effective stress in each handsheet is different, and the difference is caused by wet straining.

However, such changes are often subtle, and difficult to analyze. For example, in the case of Pulp 760, the response at any apparent initial stress rarely advanced beyond the earliest stages of logarithmic creep before the test was ended by the failure of the specimen.

Analysis of these curves would involve the identification of relatively late and relatively early phases of exponential and transitional creep. Not enough is known concerning creep to confidently carry out such an analysis. The observation that handsheets prepared from Pulp 760 failed before a well-defined logarithmic portion of the creep curves could be obtained is consistent with the general pattern of response of paper to stress, and indicates that logarithmic creep is not necessarily the characteristic mode of response of the sheets to stress prior to tensile failure. Failure may occur at any stage of deformation.

Another approach would be to demonstrate behavior which is characteristic of relatively late or relatively early response to stress. One such characteristic, which has been pointed out by Brezinski (26), is the ability of successive creep and recovery curves to fall very closely together if the extent of creep is not allowed to extend beyond comparatively early mechanisms of response. It is immaterial how the extent of creep is limited to early mechanisms of response, and either a short period of creep or a low apparent initial stress is effective. It is observed that successive creep and recovery curves fall further apart if the extent of creep is allowed to continue until comparatively later types of rate-controlling mechanisms are effective.

This behavior is illustrated by the curves shown in Fig. 33. These are fourth creep and fourth recovery curves obtained in multiple-cycle tests run on a single handsheet prepared from Pulp 760, wet strained 2.1%. The line-contact clamps were used, and the specimens

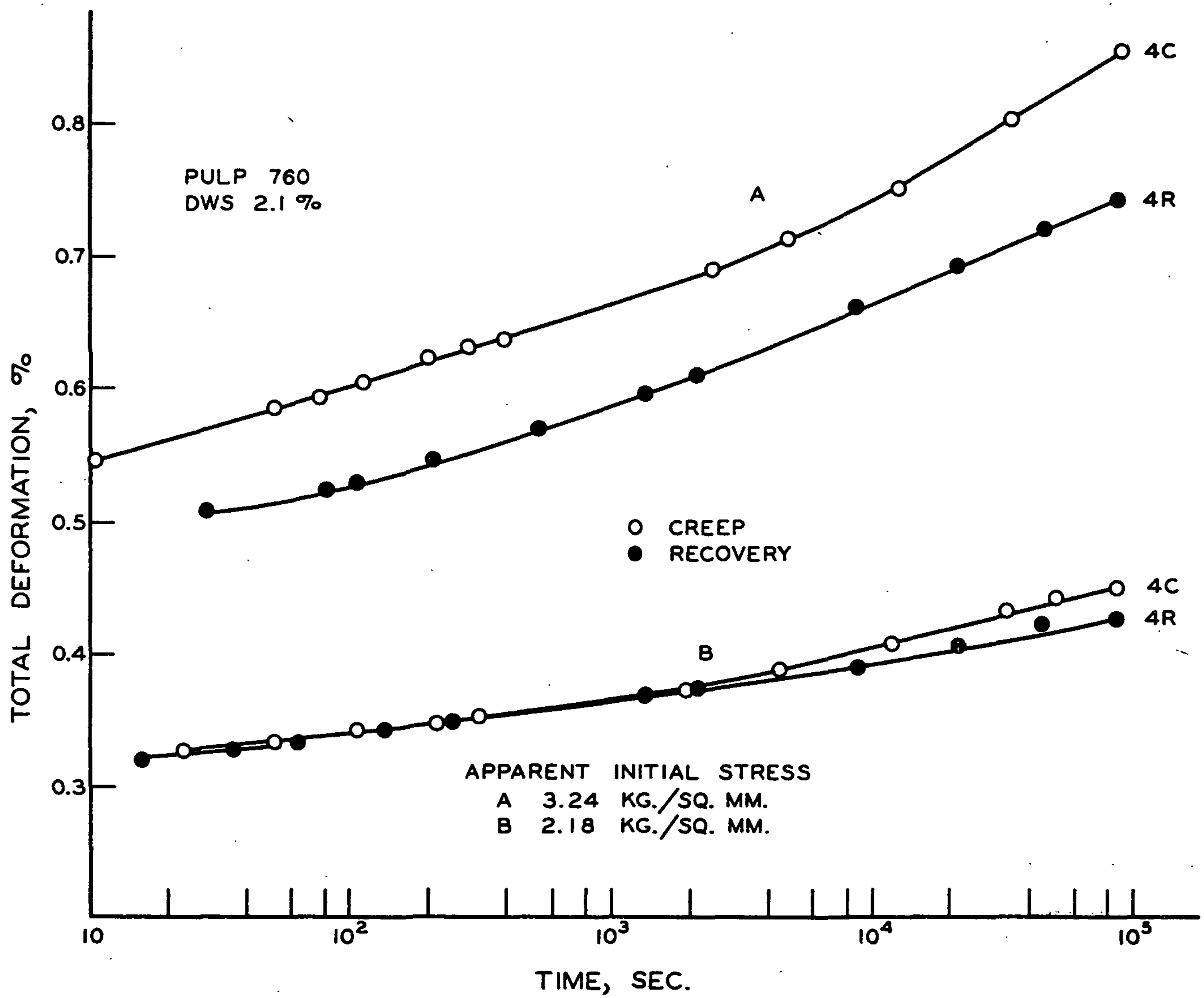


Figure 33. Fourth Creep and Fourth Recovery at Different Apparent Initial Stresses

supported the weight of the clamps during recovery. The fourth creep and fourth recovery curves of the specimen with the lower apparent initial stress are almost coincident. The curves for the other specimens are distinctly separate. The disparity would have been greater were it possible to apply a larger stress to the latter specimen without the specimen breaking.

Examination of the data obtained in the present study indicates that as the extent of total creep deformation at a constant apparent initial stress is reduced by the action of wet straining, successive creep and recovery curves lie closer together. This effect is illustrated by the fourth creep and fourth recovery curves shown in Fig. 34. These creep and recovery curves were obtained using an apparent initial stress of 2.60 kg./sq. mm. on handsheets prepared from Pulp 760. Degrees of wet straining of 1.2 and 5.0% are represented. The total first-creep deformation at 24 hours at these stresses are 1.6 and 0.9%, respectively, as shown in Fig. 25. It is seen that the fourth creep and recovery curves of the handsheet exhibiting less total first-creep deformation in 24 hours lie distinctly closer together. In these tests, the weight of the line-contact clamps remained on the specimens during the 24-hour recovery periods of the multiple-cycle tests.

Further evidence is given in Table X where the difference in extent of response between fourth creep and fourth recovery tests are tabulated against degree of wet straining. The total first creep in 24 hours is shown also. An apparent initial stress of 4.00 kg./sq. mm. was used in the creep phases. The specimens were cut from handsheets

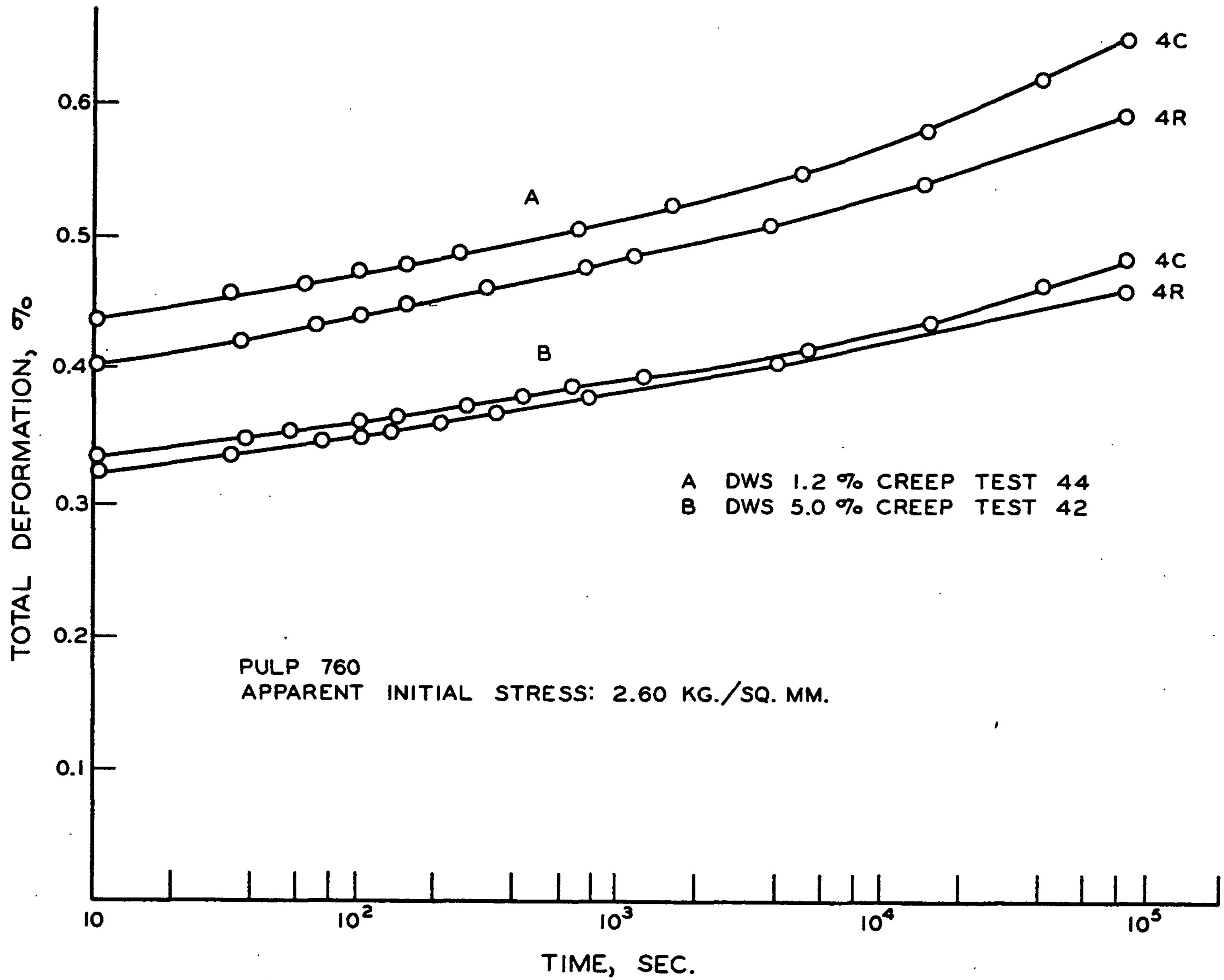


Figure 34. Fourth Creep and Fourth Recovery of Handsheets with Different Degrees of Wet Straining

prepared with Pulp 650. These multiple-cycle tests were run using the flat-face clamps during the 24-hour recovery periods. As the extent of total first-creep response is decreased, the difference in extent of response of the creep and the recovery tests becomes closer. Both functions pass through a minimum at the same degree of wet straining, and the generality of this behavior is apparent.

TABLE X
THE DIFFERENCE IN EXTENT OF FOURTH CREEP AND FOURTH RECOVERY AT DIFFERENT DEGREES OF WET STRAINING[a]

DWS, %	Total First Creep, %	Difference Between Fourth Creep and Fourth Recovery, %
0.0	1.855	0.517
0.9	1.575	0.477
3.5	0.830	0.365
4.5	0.985	0.376
5.1	1.075	0.398

[a]Pulp 650 used; apparent initial stress = 4.00 kg./sq. mm.

APPARENT ELASTIC MODULUS

In assessing the extent of structural change brought about in the sheet by wet straining, it is desirable to use a gage which is independent of time. In this way, complications associated with time-dependent effects may be avoided. Among the time-independent mechanical properties of paper is the <u>elastic modulus</u>. It is readily seen that the immediate elastic deformation of a material is a strong function of the number of elements within the structure which contribute in supporting the load. The greater the number of load-supporting elements present, the less will be the immediate elastic deformation, since each load-supporting element will be strained less. If the immediate elastic deformation of two sheets is different when both are sustaining equivalent loads, the sheet exhibiting the smaller immediate elastic deformation will have the greater apparent elastic modulus.

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 shape. Hooke's law states that the stress set up within an elastic body is proportional to the strain to which the body is subjected 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.

Paper is not an elastic material. Brezinski (26) has shown that even under very low loads, the deformation of paper is time dependent. However, it was demonstrated that the extent of time-dependent deformation is stress proportional, and at low loads the rate of time-dependent deformation is low. Because of this, it is often possible to obtain a valid estimate of the elastic modulus of paper by measuring the initial slope of the load-elongation curve. 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. This method is used in the present work.

The change in apparent elastic modulus brought about by wet straining is shown in Fig. 35 for handsheets made from Pulps 760, 460, and 290. These data were obtained by measuring the slope of the initial part of the load-elongation curves. The quality of these data is very good. It is preferred to refer to these values as apparent elastic moduli because of the difficulty, previously noted, in rigorously defining stress. The units of the moduli are given as kg./sq. mm., and are presented as the apparent stress per unit strain. The strain is calculated as the elongation of the specimen divided by the specimen length.

It is evident that wet straining creates significant changes in the elastic modulus. Considering sheets prepared from Pulps 760 and 460, the elastic modulus rises and passes through a maximum as the degree of wet straining is increased. A pronounced drop after the maximum elastic modulus in Pulp 760 was not observed, and this probably reflects the lack of rise in first creep after the minimum in Fig. 23. The elastic moduli of sheets prepared from Pulp 290 rise continuously as wet straining is increased. The parallel of this behavior with changes observed in tensile strength, total creep deformation, and recoverable creep is apparent. These data are presented as further evidence that wet straining is able to alter the internal structure of paper and to alter the manner in which paper supports a load. It is suggested that the degree of wet straining corresponding to the highest elastic modulus has created the most efficient distribution of stress attained among the sheets prepared from that particular pulp.

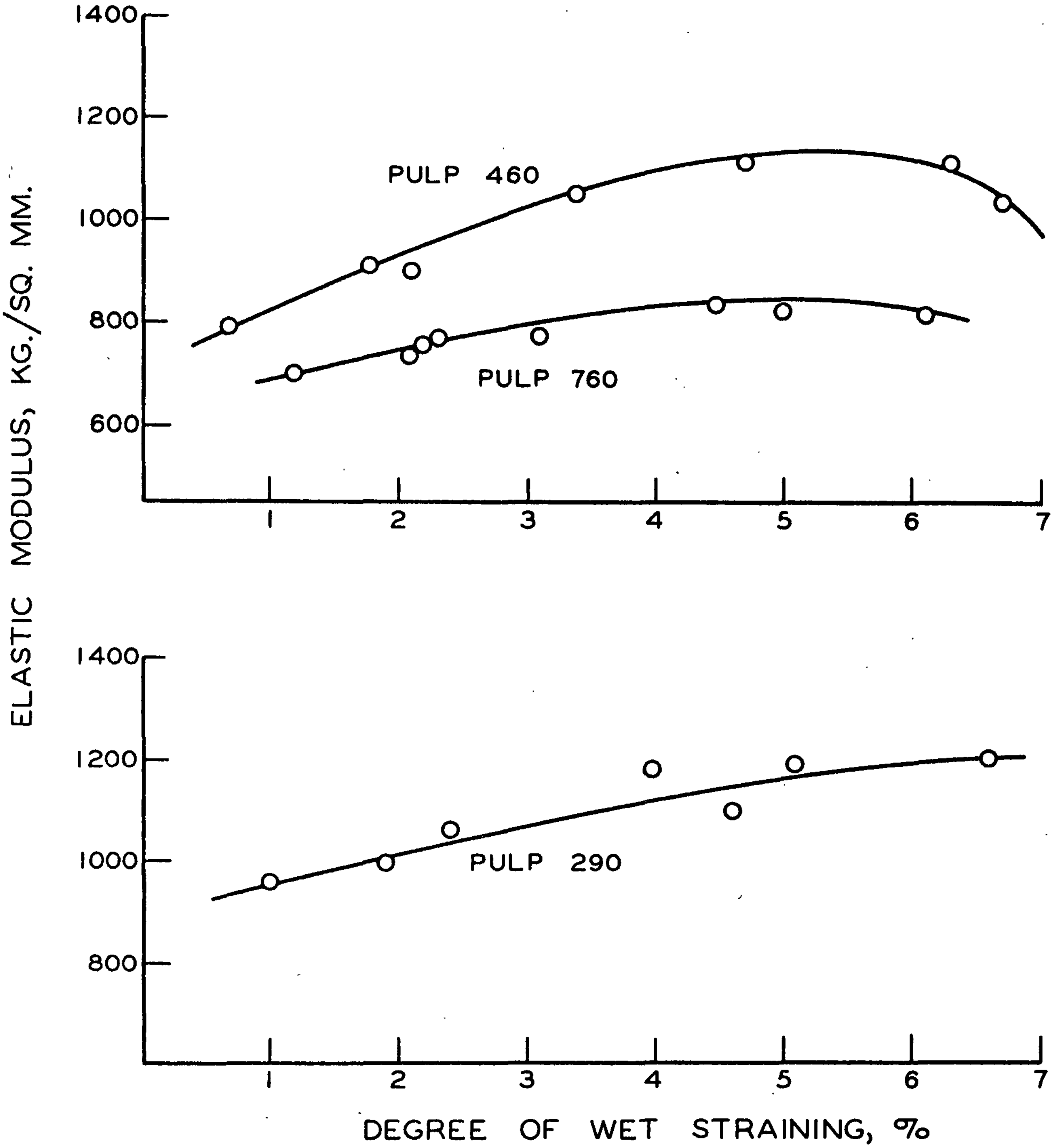


Figure 35. The Effect of Wet Straining on Elastic Modulus

The effect of wet straining on the elastic modulus of handsheets prepared from Pulp 650 is shown in Fig. 36. These data demonstrate the same effect noted above for the other pulps. Two sets of data are presented, however. The first set was obtained by measuring the initial slope of the load-elongation curves. These data were used to construct the curve in the figure.

The other set of data was obtained using tensile creep curves. Six specimens from different handsheets were subjected to relatively low tensile creep loads. These data appear in the Appendix as Creep Tests 30-35. Since low tensile stresses were used, the data could be fitted to power equations of the type shown as Equation (1). The position of the lower clamp, when the specimen supported only the weight of the clamp, was used as the initial position, and no correction was made for the strain created by the clamp load. Correspondingly, only the applied load was used in calculating the stress.

If it is assumed that the power equation is applicable at zero time, it follows that the immediate elastic deformation is equal to the value of the constant, $\underline{C}$, in Equation (1). Using the calculated apparent initial stress applied to the specimen, the elastic modulus can be calculated. These data are shown in Table XI, along with other values previously presented in Fig. 35 and 36.

Figure 36 indicates that the moduli obtained from the tensile creep data lie above, but close to, the data obtained from the Instron load-elongation curves. It might be expected that the moduli from the

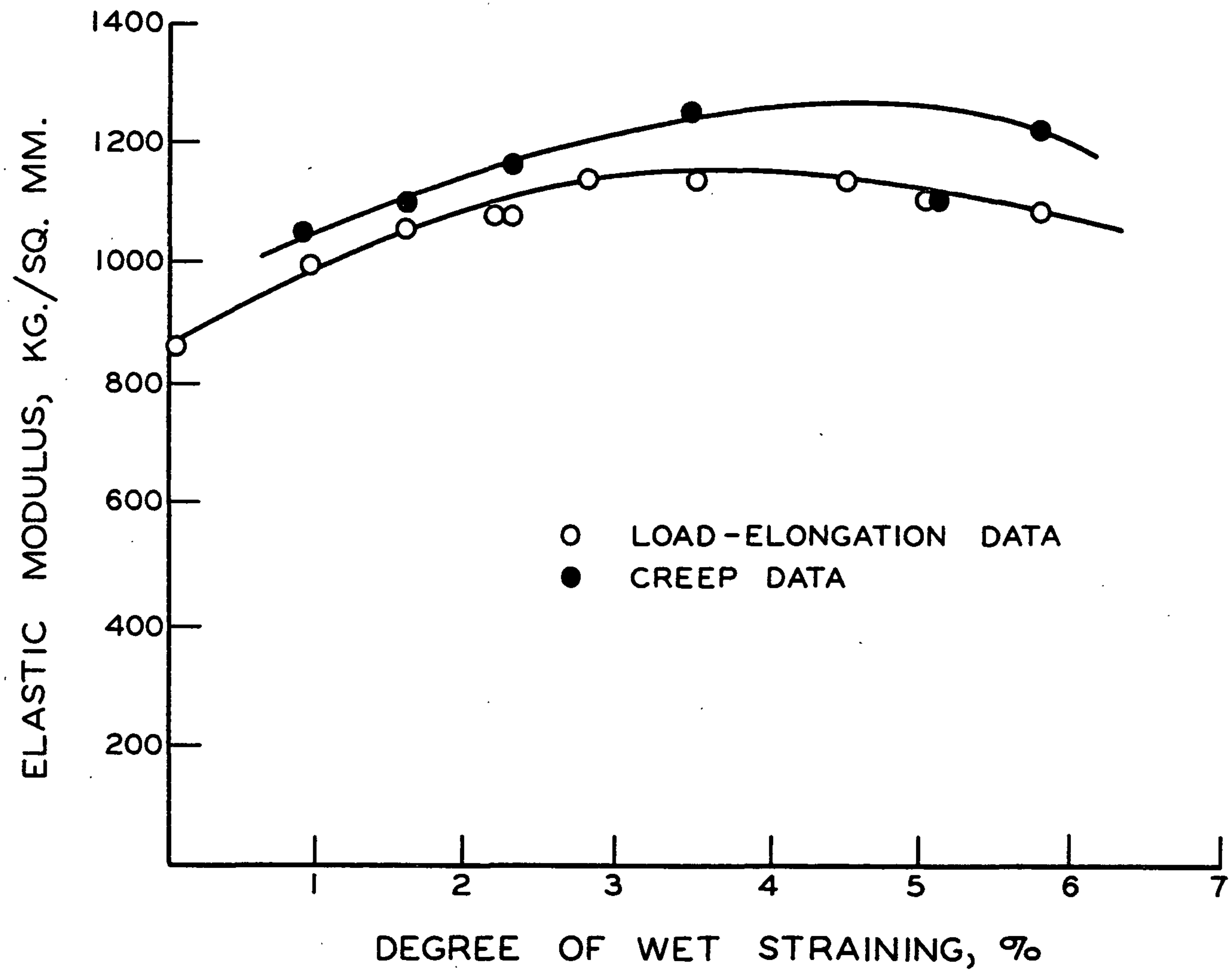


Figure 36. The Effect of Wet Straining on the Elastic Modulus of Handsheets Prepared from Pulp 650

load-elongation curves would tend to be erroneously low, because of creep occurring during the tests. The observation that the values obtained from both tests lie quite close together suggests that the data obtained represent reasonably well the elastic moduli of the handsheets.

The task of fitting the creep data to power equations was carried out with the aid of an IBM 610 Digital Computer. All of the data fit very closely, and the standard deviations obtained were in the range of 0.001%. This would suggest that the creep-testing equipment measures changes in delayed deformation very precisely.

An attempt was made to fit creep curves obtained using handsheets prepared with different degrees of wet straining into a single master creep curve using a simple function of the elastic modulus to "correct" the stress-reduction factor of the deformation. This effort was encouraged by the finding that the exponential creep of all of the handsheets of Pulp 650 which were tested could be fitted to an exponential equation using the value 0.21 for the exponent. However, the curves would not fall into a single master creep curve. It is suggested that this failure is related to changes in the basic shape of the creep curves produced by the changes in stress distribution created by wet straining.

TABLE XI
ELASTIC MODULI OF HANDSHEETS AT DIFFERENT DEGREES OF WET STRAINING

Pulp	DWS, %	Elastic Modulus, L-E, kg./sq. mm.[a]	Elastic Modulus, TC, kg./sq. mm.[a]
650	0.0	867	
	0.9	1000	1050
	1.6	1054	1100
	2.2	1073	
	2.3	1074	1120
	2.8	1145	
	3.5	1137	1250
	4.5	1140	
	5.1	1122	1100
	6.0	1096	1230
760	1.2	702	
	2.1	730	
	2.2	754	
	2.3	770	
	3.1	774	
	4.5	842	
	6.1	821	
	6.3	856	
460	0.7	795	
	1.8	909	
	2.1	893	
	3.1	1062	
	4.7	1121	
	6.3	1122	
	6.7	1042	
290	1.0	958	
	1.9	995	
	3.4	1062	
	4.0	1179	
	4.6	1093	
	5.1	1190	
	6.6	1198	

[a] L-E: derived from load-elongation data; TC: derived from tensile creep data.

SUMMARY AND CONCLUSIONS

Equipment was designed and constructed to elongate wet handsheets and to maintain the elongation until the sheet was fully dried. The process of applying the elongation is termed "wet straining." The degree of wet straining (DWS) is defined as the amount of elongation divided by the original sheet length, expressed as a percentage. In this study, wet straining always occurred at 36% solids, and the rate of wet straining was fast, compared with the rate of drying. The purpose of the investigation was to examine the effect of wet straining on the mechanical properties of fully dried paper. The range of degrees of wet straining studied extended from 0 to 7%.

A softwood alpha pulp was used in all the work. The pulp was beaten to four different freenesses in a Valley beater. The four pulps were designated by the Schopper-Riegler freeness, expressed in cubic centimeters, to which they were beaten; i.e., Pulps 760, 650, 460, and 290.

Examination of the load-elongation properties of these pulps indicates that as the degree of wet straining was increased, the tensile strength of the handsheets increased, passed through a maximum, and then decreased. The tensile strength of the most beaten pulp, Pulp 290, increased continuously, but it is suggested that further wet straining of this pulp might have produced a maximum in the strength. The tensile strength increase was greatest in the case of Pulp 460.

Although the ultimate elongations of Pulps 290 and 460 were not markedly affected, the ultimate elongations of Pulps 650 and 760 were approximately halved by wet straining. Work-to-rupture values for Pulps 760 and 650 were also greatly reduced. The work-to-rupture values of Pulp 460 were seen to pass through a maximum, while those for Pulp 290 did not appear to be affected. In all of the mechanical properties discussed, the degree of beating was seen to exert a very strong influence on the effect of wet straining.

The zero-span tensile strength of the sheets was found not to be affected by wet straining. As the DWS was increased, the transverse tensile strength of three of the pulps was found to decrease. It was not practicable to measure the transverse tensile strength of the least beaten pulp, Pulp 760, because of penetration through the sheet by the adhesive necessary to grasp the sheet in the transverse direction. The light-scattering coefficients of Pulps 760 and 650 were measured, and indicated that optical contact between the fibers decreased as the DWS was increased. The scattering-coefficient data were viewed cautiously, however, because a very large quantity of data was not available, and because of the possibility of surface contamination of the specimens by mercury used in their preparation.

The tensile creep test was used to examine the viscoelastic properties of the handsheets. The total response of specimens with different degrees of wet straining to the same apparent initial stress after an arbitrary time interval was found to decrease and pass through a minimum as the DWS was increased. The rise in response after the minimum had been reached was not as marked in the case of Pulp 760 as with Pulps

650 and 460. No difficulty was encountered in constructing master creep curves from first creep curves from wet-strained specimens, using the technique of Brezinski (26).

A series of multiple-cycle creep tests was performed in which the same apparent initial stress was applied and removed from the same specimen many times. In these tests, the periods of creep and recovery were equal in duration. After many cycles in such tests, it was found that distinct differences still remained in the creep response of specimens with different degrees of wet straining. The total fourth creep was found to change in the same manner as did the total first creep, as the degree of wet straining was increased. This was interpreted as an indication that the extent of creep by recoverable mechanisms was affected by wet straining. This interpretation was supported by the observation that the total first recovery of handsheets with different degrees of wet straining, after first creep tests under the same apparent initial stress for equivalent times, was affected in the same manner as the total first creep and total fourth creep.

It was found that a unique relationship exists between total first creep and total first recovery at equal periods of creep and recovery, which is independent of degree of wet straining, time, and stress. The relationship was not strongly affected by beating. It was hypothesized that if differences in capacity for nonrecoverable deformation existed between the handsheets, such a unique relationship would not have been obtained. Large differences in nonrecoverable creep would have been expected if wet straining caused large differences in the final tensions produced by shrinkage during drying.

Differences between total creep and total recovery during fourth creep and fourth recovery tests were examined. It was found that wet straining created regular changes in this function. As the total first creep was reduced by wet straining, the difference in extent of fourth creep and fourth recovery became less.

The elastic modulus of handsheets wet strained different amounts was determined using the initial slope of the Instron load-elongation curves. Moduli of handsheets prepared from Pulps 650 and 760 were found to rise, pass through a maximum, and then fall, and the degree of wet straining was increased. The drop after the maximum was reached was not as sharp in the case of Pulp 760. The elastic modulus of handsheets prepared from Pulp 290 appeared to rise continuously as wet straining was increased. Moduli for handsheets prepared from Pulp 650 were also estimated by fitting early tensile creep response to an exponential equation and solving the equation to find the deformation at zero time. These values were found to be close to the values obtained from the load-elongation curves, and appeared to be affected by wet straining in a similar manner. It was noted that early tensile creep from handsheets prepared from Pulp 650 could all be fitted to an exponential equation, using a common value (0.21) for the exponent.

The preceding statements serve to summarize the experimental work completed in this study. The observed changes in total first creep, recoverable deformation, and elastic modulus suggest that wet straining affects the manner in which stress is distributed in the sheet when the sheet is in tension. It is hypothesized that when a load is applied to paper, the stress developed is distributed in a nonuniform manner within the sheet. Such nonuniformity is characteristic of most materials, but probably is particularly severe in the case of paper because of the irregular geometry of the fibers and the dependency of the coherence of the sheet upon bonding between the fibers.

If this stress distribution is changed, the measured response of the sheet to stress will be affected. If the distribution becomes more uniform, the response to stress will be reduced because more of the components of the sheet will share in supporting the load. A more uniform stress distribution will produce a higher stress in components which previously supported less than their share of the load, and less stress in components which previously supported more than their share of the load. It is emphasized that the response of paper to stress is dependent not simply upon an average or median stress, but upon the distribution of stress within the sheet. This distribution affects the entire mechanical behavior of paper.

Regarding the viscoelastic behavior of these sheets, the data suggest that the effect of wet straining is to change the time dependency of response to stress. If, in fact, the structure of the sheet has been changed, this effect would be anticipated from the master creep concept. Thus, if the stress distribution is made more uniform, the rate of deformation in a tensile creep test, at any particular time under a particular apparent initial stress, would be characteristic of mechanisms of response which would have occurred earlier if the structure had not been changed. In other words, if the structure is changed to provide a more efficient distribution of stress, the response in a creep test will be retarded in a manner similar to that which would occur if the apparent initial stress were reduced.

The basic mechanism whereby the stress distribution in the sheet is changed is not known and cannot be described with certainty at the present time. It is hypothesized that when the sheet is wet strained, the fibers mainly slide past one another, although some hydrogen-bond breaking may occur. This sliding or slipping action would seem to cause some of the fibrous elements to assume slightly different relative positions which, when the sheet is dry, would be more effective in contributing to the support of a load. This action may involve the straightening out of bends and kinks between points of bonding. Because the zero-span tensile strength apparently was unaffected by wet straining, gross fiber realignment probably is not involved. After the sheet has dried, it would be expected to be stronger and to deform less under a load applied in the direction of wet straining.

The hypothesized mechanical actions are consistent with the finding that the bonding effectiveness of the fibers is decreased by wet straining. Apparently, the sliding and straightening of the fiber elements destroys some of the coherence of the sheet, and the ability of the sheet to form interfiber bonds during the remainder of the drying period is impaired. The weakening of the sheet by this behavior is apparently overcome by the improvement in stress distribution created by small amounts of wet straining, since it is found that small amounts of wet straining cause the tensile strength of the sheet to increase.

The observed changes in creep response and elastic modulus suggest that small amounts of wet straining tend to improve the stress distribution, but that this improvement is halted and the effect is reversed as the action is continued. This reversal is probably related to the disruption of the sheet noted above. The hypothesized disruption could produce both the decrease in bonded area and the tendency for the stress distribution to become less uniform, and would account for the drop in tensile strength at higher degrees of wet straining which was observed.

Because of the effect of beating on the observed results, it is unwise to draw firm, general conclusions concerning the effect of wet straining on strength properties. Changing the method of refining or using a different pulp may produce entirely different results. For example, it was found in the present study that wet straining generally decreased work-to-rupture for Pulps 760 and 650 but somewhat increased work-to-rupture for Pulp 460. In every case, the observed change was probably the combined result of the effect on response to stress and the effect on tensile strength. If the fibers involved had different length distributions or different flexibilities or if any of a number of the physical properties of the fibers were different, different results might have been obtained. It seems likely, though, that changes in stress distribution and transverse tensile strength will be intimately involved in the effect.

It must be emphasized that in the present study wet straining occurred only at 36% solids. If sheets were to be wet strained at a higher solids content, different results will certainly be observed.

When the fibers are drier, they are less flexible and will react differently to strain. Also, many more interfiber bonds will be present at higher solids contents, which will affect the nature of the results. It is unlikely, for example, that wet straining at a higher solids content will not affect capacity for nonrecoverable deformation, as was observed in the present work. It probably is best to consider the sheet at 36% solids as being near an extreme where the fibers are highly plasticized and where there is little interfiber bonding. The opposite extreme would be the fully dried sheet.

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APPENDIX

All of the data used in the construction of the creep curves shown in this report are presented in this appendix. The time is given in seconds, measured from the instant of application or removal of the load. The deformations are reported in mils. The type of clamp used is also indicated. The initial specimen length in the case of the flat-face clamps is 8.00 inches, and in the case of the line-contact clamps, 8.25 inches. Unless it is otherwise indicated, the specimen sustained the weight of the clamp during the recovery periods. The following abbreviations were used.

- **AIS** apparent initial stress, in kg./sq.mm.; this includes the clamp weight and the applied load.
- **AAIS** apparent applied initial stress, in kg./sq. mm.; this does not include the weight of the clamp.
- **DWS** degree of wet straining, %.

All of the tests were carried out at 50% R.H. and 73°F. The details of the test procedures are presented in the body of the report.

Creep Test 25

DWS 3.5%
AIS 4.00
Pulp 650
Flat-face Clamps

First-Creep

Seconds	Mils
17	31.2
57	33.2
101	34.5
153	35.8
212	36.6
427	39.1
918	41.5
1266	42.8
2150	44.4
3178	46.1
4270	47.4
5320	48.7
7643	50.3
9185	51.4
14810	53.3
18870	54.3
25640	56.2
33165	57.3
45500	59.1
86400	63.5

First-Recovery

Seconds	Mils
12	32.8
44	34.2
77	35.5
118	36.2
475	38.8
1065	40.3
1806	41.0
3730	42.6
5340	43.7
13170	45.2
26360	46.4
40150	47.4
86400	48.7

Second-Creep

Seconds	Mils
22	27.9
58	29.0
90	29.5
127	29.8
150	30.0
223	30.5
507	31.6
973	32.6
1500	33.4
3306	34.4
8180	35.9
11240	37.6
36290	39.6
86400	42.3

Second-Recovery

Seconds	Mils
86400	37.4

Third-Creep

Seconds	Mils
86400	40.3

Third-Recovery

Seconds	Mils
86400	37.0

Fourth-Creep

Seconds	Mils
86400	38.8

Fourth-Recovery

Seconds	Mils
86400	36.5

Fifth-Creep

Seconds	Mils
86400	37.4

Fifth-Recovery

Seconds	Mils
86400	35.5

Sixth-Creep

Seconds	Mils
86400	36.7

Sixth-Recovery

Seconds	Mils
86400	35.0

Seventh-Creep

Seconds	Mils
86400	35.8

Seventh-Recovery

Seconds	Mils
86400	34.2

Eighth-Creep

Seconds	Mils
86400	35.3

Eighth-Recovery

Seconds	Mils
86400	34.5

Creep Test 25
(continued)

Ninth-Creep

Seconds	Mils
86400	34.7

Ninth-Recovery

Seconds	Mils
86400	33.6

Creep Test 26

DWS 0.0%
AIS 4.00
Pulp 650
Flat-face Clamps

First-Creep

Seconds	Mils
26	58.6
68	64.7
115	68.8
156	71.3
201	73.4
240	74.9
279	76.5
308	77.3
567	82.9
681	84.9
1160	89.7
1345	91.8
1870	95.7
2227	97.6
6305	110.5
15010	122.2
22880	127.7
31170	131.9
37570	134.8
46800	140.2
86400	148.5

First-Recovery

Seconds	Mils
13	34.7
37	36.6
57	37.5
87	38.2
115	39.0
143	39.7
186	40.2
256	41.0
290	41.3
397	42.1
688	43.6
887	44.0
1125	44.9
1487	45.8
2210	47.0
3475	48.5
6365	50.2
8590	51.1
14240	53.0
23090	54.4
37190	55.6
45700	56.1
86400	57.8

Second-Creep

Seconds	Mils
24	
24	39.7
53	41.1
75	41.8
117	42.8
155	43.5
183	43.9
215	44.4
265	45.0
423	46.1
589	47.0
870	48.1
1145	48.9
1630	49.8
2472	50.9
5750	53.3
8450	54.6
13550	56.4
18940	57.9
25600	59.2
38700	61.9
86400	66.6

Second-Recovery

Seconds	Mils
86400	54.8

Third-Creep

Seconds	Mils
86400	60.1

Third-Recovery

Seconds	Mils
86400	53.5

Fourth-Creep

Seconds	Mils
86400	56.1

Fourth-Recovery

Seconds	Mils
86400	51.7

Fifth-Creep

Seconds	Mils
86400	53.8

Creep Test 26
(Continued)

Fifth-Recovery

Seconds	Mils
86400	50.6

Sixth-Creep

Seconds	Mils
86400	53.0

Sixth-Recovery

Seconds	Mils
86400	49.9

Seventh-Creep

Seconds	Mils
86400	51.2

Seventh-Recovery

Seconds	Mils
86400	49.0

Eighth-Creep

Seconds	Mils
86400	51.0

Creep Test 28

DWS 0.9%
AIS 4.00
Pulp 650
Flat-face Clamps

First-Creep

Seconds	Mils
15	49.1
46	54.6
74	57.6
103	59.7
144	61.8
256	65.7
355	68.0
801	72.6
1075	76.3
1465	79.1
1753	80.9
4425	90.4
6105	93.6
9060	97.8
14920	102.9
22750	108.1
30970	111.9
37360	114.1
46905	117.0
86400	123.0

First-Recovery

Seconds	Mils
8	31.9
37	34.0
66	35.1
143	36.5
170	37.1
272	38.1
305	38.3
604	40.2
895	41.3
1680	43.3
3050	45.1
5845	47.0
8160	47.9
13810	49.4
22710	50.4
36760	51.5
39260	51.9
86400	53.4

Second-Creep

Seconds	Mils
14	35.3
45	37.5
75	38.8
96	39.4
166	40.4
209	41.0
318	42.0
592	43.1
886	44.3
1403	45.4
2100	46.8
5375	49.1
8090	50.2
13090	51.6
18560	52.5
25220	53.9
38330	56.1
86400	60.4

Second-Recovery

Seconds	Mils
86400	51.0

Third-Creep

Seconds	Mils
86400	55.6

Third-Recovery

Seconds	Mils
86400	49.5

Creep Test 28
(continued)

Fourth-Creep

Seconds	Mils
86400	51.4

Fourth-Recovery

Seconds	Mils
86400	47.7

Fifth-Creep

Seconds	Mils
86400	49.8

Fifth-Recovery

Seconds	Mils
86400	47.0

Sixth-Creep

Seconds	Mils
86400	48.9

Sixth-Recovery

Seconds	Mils
86400	46.5

Seventh-Creep

Seconds	Mils
86400	47.7

Seventh-Recovery

Seconds	Mils
86400	45.9

Eighth-Creep

Seconds	Mils
86400	47.2

Creep Test 30

DWS 2.3%
AAIS 1.50
Pulp 650
Line-contact Clamps

First-Creep

Seconds	Mils
17	12.1
54	12.5
140	12.7
214	12.8
475	13.1
730	13.5
1080	13.8
1745	14.0
2118	14.1
3262	14.4
5970	15.0
10700	15.5
22085	16.4
29100	16.5
72000	17.7
84500	18.1

Creep Test 31

DWS 5.1%
AAIS 2.38
Pulp 650
Line-contact Clamps

First-Creep

Seconds	Mils
12	18.6
42	19.3
83	19.6
337	20.7
763	21.2
1315	21.9
1701	22.1
2827	22.7
5560	23.5
10440	24.6
21780	26.2
28605	26.7
72000	29.3
84500	29.8

Creep Test 32

DWS 6.0%
AAIS 2.35
Pulp 650
Line-contact Clamps

First-Creep

Seconds	Mils
31	18.4
75	18.7
108	18.9
386	19.7
795	20.6
1940	21.8
4670	22.7
9640	23.9
21040	25.5
27690	26.0
72000	28.1
84500	28.6

Creep Test 33

DWS 3.5%
AAIS 2.07
Pulp 650
Line-contact Clamps

First-Creep

Seconds	Mils
19	15.3
51	15.9
79	16.0
151	16.4
351	16.9
431	17.0
723	17.4
1286	18.0
1890	18.1
3720	18.9
10360	20.1
18240	21.0

Creep Test 34

DWS 1.6%
AAIS 3.68
Pulp 650
Line-contact Clamps

First-Creep

Seconds	Mils
18	32.0
54	33.8
85	34.7
117	35.6
143	36.0
206	37.1
291	38.1
503	40.0
613	41.2
1058	42.9
1765	45.2
3430	48.7
10070	54.7
17200	58.0

Creep Test 35

DWS 0.9%
AAIS 3.00
Pulp 650
Line-contact Clamps

First-Creep

Seconds	Mils
11	31.6
41	33.7
68	34.9
98	35.8
240	38.3
391	39.8
650	41.3
1490	44.5
3080	47.6
9720	53.9
17555	57.7

First-Recovery

Seconds	Mils
10	24.9
30	25.8
48	26.4
82	27.0
126	27.5
161	28.0
223	28.3
330	28.9
471	29.4
794	30.2
1155	30.9
1638	31.3
2370	32.0
3907	32.8
5798	33.4
16440	34.9
27390	35.6
44965	36.2
86400	37.6

Creep Test 42

DWS 5.0%
AIS 2.60
Pulp 760
Line-contact Clamps

First-Creep

Seconds	Mils
12	32.5
38	35.1
60	36.1
84	37.0
122	38.0
150	38.5
197	39.3
226	39.7
269	40.3
453	42.1
808	44.2
1156	45.5
1536	46.9
3100	50.2
12710	58.4
23155	62.5
86400	71.5

Second-Creep

Seconds	Mils
86400	42.3

Second-Recovery

Seconds	Mils
86400	36.3

Third-Creep

Seconds	Mils
86400	39.1

Third-Recovery

Seconds	Mils
86400	35.9

Creep Test 42
(continued)

Fourth-Creep

Seconds	Mils
9	25.0
38	25.9
56	26.4
106	26.9
144	27.3
265	28.0
433	28.5
666	29.1
1280	29.8
5245	31.4
15670	33.2
40640	35.4
86400	37.0

Fourth-Recovery

Seconds	Mils
10	23.8
33	24.6
75	25.6
105	25.8
135	26.1
210	26.7
345	27.2
795	28.2
4115	30.3
15140	31.8
86400	34.7

Fifth-Creep

Seconds	Mils
86400	35.2

Fifth-Recovery

Seconds	Mils
86400	33.4

Sixth-Creep

Seconds	Mils
86400	34.0

Sixth-Recovery

Seconds	Mils
86400	32.6

Seventh-Creep

Seconds	Mils
86400	33.5

Seventh-Recovery

Seconds	Mils
86400	32.6

Eighth-Creep

Seconds	Mils
86400	33.2

Eighth-Recovery

Seconds	Mils
86400	32.2

Ninth-Creep

Seconds	Mils
9	24.1
54	25.5
80	25.7
133	26.3
198	26.5
286	26.8
548	27.4
1248	28.1
5060	29.9
32390	32.0
86400	33.0

Ninth-Recovery

Seconds	Mils
12	23.4
40	24.2
73	24.6
115	25.1
483	26.4
1165	27.3
4585	29.2
14005	30.3
86400	32.0

Creep Test 43

DWS 3.1%
AIS 2.60
Pulp 760
Line-contact Clamps

First-Creep

Seconds	Mils
16	39.5
36	42.5
57	44.4
88	46.3
118	47.5
186	49.5

Creep Test 43
(continued)

Seconds	Mils
254	51.0
477	54.4
822	57.0
1202	59.1
2838	64.7
12370	77.1
22895	83.0
86400	95.8

First-Recovery

Seconds	Mils
28	28.3
47	29.1
72	29.9
89	30.1
128	30.8
215	31.5
386	32.5
563	33.3
826	34.0
1312	34.9
2040	35.9
3583	36.9
5473	37.7
16125	39.5
27080	40.4
44655	41.2
86400	42.9

Second-Creep

Seconds	Mils
86400	49.5

Second-Recovery

Seconds	Mils
86400	41.4

Third-Creep

Seconds	Mils
86400	45.7

Third-Recovery

Seconds	Mils
86400	41.2

Fourth-Creep

Seconds	Mils
18	28.3
45	29.4
65	29.9
115	30.5
160	31.0
210	31.3
515	32.5
1065	33.4
2097	34.5
5110	35.6
15495	38.1
40460	40.3
86400	43.9

Fourth-Recovery

Seconds	Mils
11	26.7
32	27.7
52	28.3
82	28.8
155	29.4
245	30.2
483	31.0
1050	32.1
3915	34.3
14900	36.1
86400	39.4

Fifth-Creep

Seconds	Mils
86400	39.5

Fifth-Recovery

Seconds	Mils
86400	37.0

Sixth-Creep

Seconds	Mils
86400	37.5

Sixth-Recovery

Seconds	Mils
86400	35.5

Seventh-Creep

Seconds	Mils
86400	37.0

Seventh-Recovery

Seconds	Mils
86400	35.5

Eighth-Creep

Seconds	Mils
86400	35.9

Creep Test 43
(continued)

Eighth-Recovery

Seconds	Mils
86400	34.9

Ninth-Creep

Seconds	Mils
11	26.9
41	28.3
60	28.5
127	29.1
257	29.9
486	30.3
1380	31.4
4730	32.8
32050	34.8
86400	36.0

Ninth-Recovery

Seconds	Mils
19	25.6
44	26.5
82	27.0
137	27.6
275	28.1
600	28.8
1530	30.1
4355	31.2
13815	31.2
86400	34.6

Creep Test 44

DWS 1.2%
AIS 2.60
Pulp 760
Line-contact Clamps

First-Creep

Seconds	Mils
19	51.0
47	55.8
68	57.9
91	59.4
128	61.7
155	62.6
247	65.7
490	71.1
852	75.8
3590	88.7
12030	103.4
22670	111.6
86400	129.7

First-Recovery

Seconds	Mils
35	33.0
71	34.7
93	34.9
123	35.3
168	36.0
258	37.1
420	37.6
744	39.3
1475	41.0
3012	42.8
4910	43.9
15565	46.9
26550	47.9
44130	48.9
86400	50.9

Second-Creep

Seconds	Mils
86400	60.8

Second-Recovery

Seconds	Mils
86400	48.3

Third-Creep

Seconds	Mils
86400	54.5

Third-Recovery

Seconds	Mils
86400	48.2

Fourth-Creep

Seconds	Mils
10	32.9
44	34.5
65	35.1
104	35.8
154	36.3
250	37.0
712	38.5
1605	40.0
4950	42.0
15310	44.6
40460	47.7
86400	50.3

Creep Test 44
(continued)

Fourth-Recovery

Seconds	Mils
10	30.4
36	32.1
70	33.0
105	33.5
155	34.2
317	35.2
745	36.5
1170	37.2
3775	39.1
14700	41.8
86400	45.8

Fifth-Creep

Seconds	Mils
86400	47.4

Fifth-Recovery

Seconds	Mils
86400	43.9

Sixth-Creep

Seconds	Mils
86400	45.3

Sixth-Recovery

Seconds	Mils
86400	43.9

Seventh-Creep

Seconds	Mils
86400	44.1

Seventh-Recovery

Seconds	Mils
86400	42.8

Eighth-Creep

Seconds	Mils
86400	43.5

Eighth-Recovery

Seconds	Mils
86400	42.5

Ninth-Creep

Seconds	Mils
26	31.7
56	32.9
83	33.4
148	34.5
443	36.1
1140	37.0
4480	38.9
31780	41.7
86400	43.6

Creep Test 49

DWS 1.4%
AIS 2.30
Pulp 650
Flat-face Clamps

First-Creep

Seconds	Mils
10	18.5
33	19.1
55	19.6
82	19.7
146	20.0
245	20.6
573	21.1
953	21.5
1600	22.0
6640	23.8
16285	24.9
24450	25.9
43180	27.7
86400	29.3

Creep Test 50

DWS 1.4%
AIS 3.90
Pulp 650
Flat-face Clamps

First-Creep

Seconds	Mils
14	45.0
49	49.9
83	52.1
115	53.8
263	57.9
600	61.8
1570	67.3
5915	75.9
15485	84.0
23720	88.0
42460	94.0
86400	101.4

Creep Test 51

DWS 1.4%
AIS 3.38
Pulp 650
Flat-face Clamps

First-Creep

Seconds	Mils
12	34.0
35	36.2
54	37.2
86	38.5
136	39.6
203	40.7
362	42.5
681	44.6
1260	46.6
5460	51.6
11820	55.3
24050	58.4
41740	62.1
86400	67.0

Creep Test 55

DWS 2.1%
AIS 3.24
Pulp 760
Line-contact Clamps

Fourth-Creep

Seconds	Mils
10	42.2
51	45.4
77	46.0
111	46.8
197	48.4
286	49.0
386	49.5
2450	53.8
4800	55.8
12440	55.8
32890	63.1
86400	67.4

Fourth-Recovery

Seconds	Mils
28	38.8
81	40.3
108	40.5
209	42.0
523	44.1
1340	46.2
2150	47.2
8600	51.5
21000	54.1
49800	56.4
86400	58.1

Creep Test 56

DWS 2.1%
AIS 2.18
Pulp 760
Line-contact Clamps

Fourth-Creep

Seconds	Mils
23	24.1
51	24.6
106	25.2
218	25.8
312	26.2
1925	27.9
4400	29.1
12010	30.8
32440	32.6
49860	33.4
86400	34.1

Fourth-Recovery

Seconds	Mils
16	23.4
36	24.1
63	24.5
133	25.2
253	25.8
1343	27.5
2040	27.8
8070	29.1
21100	30.6
43830	31.8
86400	32.2

Creep Test 61

DWS 3.5%
Pulp 760
Line-contact Clamps

First-Creep

AIS 1.68

Seconds	Mils
8	18.0
37	18.7
56	19.1
131	19.9
162	20.0
272	20.4
370	20.8
826	22.1
1465	22.7
2528	23.2
8540	24.8
12080	26.2
28440	27.3
52800	29.3
86400	31.0

Second-Creep

AIS 2.61

Seconds	Mils
11	29.7
40	31.1
71	31.9
93	32.2
166	33.0
290	33.9
563	34.9
1160	36.4
3925	38.6
10510	41.1
22080	43.0
35930	44.5
86400	47.9

Creep Test 62

DWS 3.5%
AIS 2.61
Pulp 760
Line-contact Clamps

First-Creep

Seconds	Mils
11	35.9
38	38.6
60	39.8
137	42.0
380	45.4
1032	49.2
6025	58.5
16150	64.7
25950	68.6
52000	74.7
86400	79.4

Second-Creep

Seconds	Mils
10	31.8
35	34.0
55	35.2
124	37.5
210	39.2
700	44.0
1415	47.2
4925	54.7
11460	60.1
23085	65.7
36960	69.7
86400	77.8

Creep Test 63

DWS 3.5%
AIS 3.21
Pulp 760
Line-contact Clamps

First-Creep

Seconds	Mils
19	70.0
55	78.6
82	82.0
117	85.5
230	91.2
350	95.4
745	102.5
6605	126.9
16370	140.3
37520	149.8
break	