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High Speed Compression Properties of Textile Structures and Sheet-Like Materials

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Synopsis

High speed compression properties of textile structures and sheetlike materials that pass through a set of press rolls are found to be the controlling factor in determining the pressure schedule within the nip region, the loading of the rolls, and the minimum separation of the roll surfaces (nip thickness) of the press. Factors affecting the high speed compression properties of felts (napped textile structures) which are used to carry a wet sheet of paper through the press section of a paper machine are examined. The compressive stress-strain curves of a single felt design are obtained using the Plastechon High Speed Tester to simulate the strain schedule within the nip region of the press section of the paper machine. Compression curves of new, used and worn felts are obtained at deformation rates from 20 in./sec. to 100 in./sec., equivalent to paper machine speeds ranging from 1000 ft./min. to 5000 ft./min. and at various levels of water content (dry, wet and saturated). The results show that the felt offers more resistance to compression as the strain rate and/or its water content is increased. Similarly, worn felts are found to require more force to achieve a given level of compression than new, napped felts. These compression curves are used to verify a general theory for determining the load versus nip strain relationship of the press section. The results of the experiments conducted on an experimental press section tend to confirm the theory and have thus pointed to the extreme importance of the high speed compression characteristics of the material in the nip region in determining the dynamics of a press.

The passage of material through a set of press rolls is a common industrial process introduced for numerous purposes; e.g., in rolling mills, sheets of metal are squeezed through press rolls to reduce their thickness and increase their width. Similarly, in the textile mill, a woven cloth is pressed through press rolls to smooth its surface irregularities. This process is called calendering. In the papermaking process, felts are used to carry a wet sheet of paper through many sets of press rolls where, by subjecting them to a pressure gradient, some of the water is mechanically squeezed out of the wet paper and passed on through the porous structure of the felt. The basic mechanism in all these processes is the same and arises from the ability of the medium to deform and compress and thereby conform into a shape defined as the nip region. The term nip region is applied to that part of the space between the separation of the two rolls which contains the medium, while the distance between the surface of the two rolls along an axis passing through the center of the rolls is called the nip thickness.

As any compressible or deformable medium enters the nip region, it undergoes a strain according to a schedule dictated by the geometry of the nip region. For each increment of applied strain, there exists a given compressive stress within the medium whose magnitude is determined by its compressive stress-strain curve. The force necessary to sustain this stress is supplied by the loading of the rolls.

Similarly, in the exit side of the nip, the material, upon emerging from compression, begins to recover, and in so doing (and under the condition that its rate of recovery is greater than the rate of the opening of the nip region) creates a pressure which is also sustained by the roll loading. These compressive and recovery stresses comprise the pressure in the nip region, and the force of this pressure over the nip region area is equal to the loading of the rolls. When this concept is expressed mathematically, one arrives at a set of equations which relates the compression properties of the structure to: (*a*) The roll loading and the nip geometry; and (*b*) the pressure and therefore the gradient of the pressure within the nip region.

In the metal rolling process, the separation of the two rolls is fixed and the loading of the roll is allowed to vary. In the paper machine, however, the reverse condition prevails; namely, that the upper roll is hydraulically loaded and is therefore allowed to move up and down under a constant force while the felt and the wet fibers are passing through.

Although this study was initiated by the Huyck Felt Company during a program aimed at a study of the water removal capabilities of felts in the papermaking process, its basic concept as presented in this paper applies to all types of press rolls carrying deformable sheets as well as compressible textile structures.

The press roll of the paper machine is a much more complicated structure than that of other processes because it is often perforated with holes along a set pattern (called the drilled press roll), and furthermore is often covered with rubber which itself is a deformable material and which, under the pressure of the nip region, deforms and greatly alters the geometry of the nip region.

Although the presence of other secondary deformable material in the nip region does not alter the basic concept that has been outlined in this paper, it certainly does impose a great deal of difficulty in the mathematical analysis of the concept as well as any experimental procedure to verify the theoretical predictions.

The most serious effect of the introduction of a secondary deformable material, particularly rubber in the nip region is that it greatly alters the nip geometry, particularly in the outgoing portion of the nip where the recovery properties of the medium control the dynamics of the press. The absence of information regarding the recovery properties of textile structures at high speeds makes it necessary to consider the possibility that the felt does not recover as fast as the back side of the nip region of a nondeformable press roll opens up. Although this assumption at first seems highly questionable, the nature of the nip region geometry and the experimental results tend to justify it. For deformable press rolls, however, this assumption no longer holds exactly, but it was found to be quite adequate if made simultaneously with the assumption that the rubber recovers instantaneously.

The equations of the dynamics of a rubber covered roll in the press section have been derived, but since they are quite comprehensive, their presentation would be beyond the scope of this paper. The major emphasis here will be placed on a discussion of the compressive properties of the felt, which is a napped textile structure, and the effect of the factors influencing it.

Factors Influencing the Compression Curve of Textile Structures and Sheetlike Materials

The theoretical study of the dynamics of a press involves the derivation of a set of equations relating the geometry of the nip region and the pressure schedule to the compression properties of the medium, and the roll loading. The compression curve is determined experimentally by compressing a sample of the medium and recording its deformation versus the force applied during the deformation. There are, of course, certain conditions that would have to be met if the data are to be applicable to the analysis for woven textiles such as a felt that operates in a press section in conjunction with water or other liquids and whose structure varies with weave design and wears out by repeated passage through the press section. The following variables therefore must be controlled: (*a*) Moisture content; (*b*) design parameter; and (*c*) wear history.

The textile structure as a porous medium is capable of holding water. During the compression, especially at high speed, these water molecules offer a considerable amount of resistance to the motion of the crosshead of the compressing instrument and thus contribute a great deal to the load developed. This effect becomes particularly appreciable as the water content reaches the saturation level. Inasmuch as the structure entering the nip region contains water, its stress-strain curve, if it is to be applied to any investigation of the dynamics of the nip region, should include the effect of the water and its magnitude. This is done by ensuring that the sample whose compressive stress-strain curve is to be determined contains approximately the same amount of water as the structure being studied in the press.

There are two other very important factors that need be considered also. They are related solely to the dynamic conditions of the press section and are: (*a*) Strain rate; and (*b*) strain schedule.

With presses operating at ever increasing speeds, the time during which the medium remains in the nip region becomes smaller and, therefore, the rate at which it is compressed is increased. Even at press speeds of 1000 ft./min., strain rate in the nip region becomes so high that it reaches impact conditions. Furthermore, the schedule according to which the structure is compressed is fixed by the shape of the nip region, and this condition, too, must be met as closely as possible. These limit the choice in selection of an instrument that is capable of compressing and recording the stress-strain curve of relatively thin materials at various high speeds, under controlled strain schedules. The instrument used in the study of compression properties of felts was the Plastechon High Speed Tester. Although the strain schedule in the Plastechon is linear, for certain crosshead speeds it closely approximated the nip strain schedule.

In the aforementioned study, one of these variables was kept constant; namely, that of felt design. Because of the existence of literally hundreds of various possible designs of felts, it was impractical to use this as a variable, and it was therefore decided to use only one felt design characteristic, pending the outcome of the study of the relative effect of the other four variables in the compression properties of such structures.

Compression Properties of Felts and Dynamics of Press Section

Previous theoretical studies of water removal in the nip region of the press section of paper machines revealed that the loading of the roll supplies the force necessary to: *(1)* Compress the dry felt; *(2)* overcome the forces resisting the flow of water within the felt; and *(3)* accelerate water particles and move them out of the felt.

If the compression curve of a dry felt is used with these theories, the resultant load calculations constitute only that part of the roll loading which is used to compress the dry felt. If, however, the compression properties of a wet felt are employed, calculations yield the loading that is necessary to overcome all three forces, and therefore give a true image of the mechanism of water removal in the nip region (provided the strain rate requirements are met).

Furthermore, the amount of load required to sustain a given amount of deformation depends not only on the structure of the felt, but also on the way the deformation has been brought about. This includes the rate of strain as well as the strain schedule. Therefore strain rate as well as moisture content of the felt must be simulated for an accurate analysis.

Effect of Strain Rate on the Compression Curve of Felts

The strain rate which, among other variables, is directly related to the speed of the paper machine is the factor which affects the compression curve most severely. The felt is a porous structure which is comprised of an innumerable number of voids and capillaries of varying sizes and shapes formed by the interstices between the individual fibers and yarns. These voids are filled with air and/or water as the case may be, and as the felt is deformed, their volume is decreased and the pressure inside of them increases, thus forcing the fluid out of the voids. If the rate of decrease of the volume is sufficiently high, these voids are transformed into tiny orifices where the rate of discharge of the fluid reaches a maximum level and choking occurs. In other words, the fluid will not have sufficient time to get out of the voids, and so resists the change of the void volumes and,

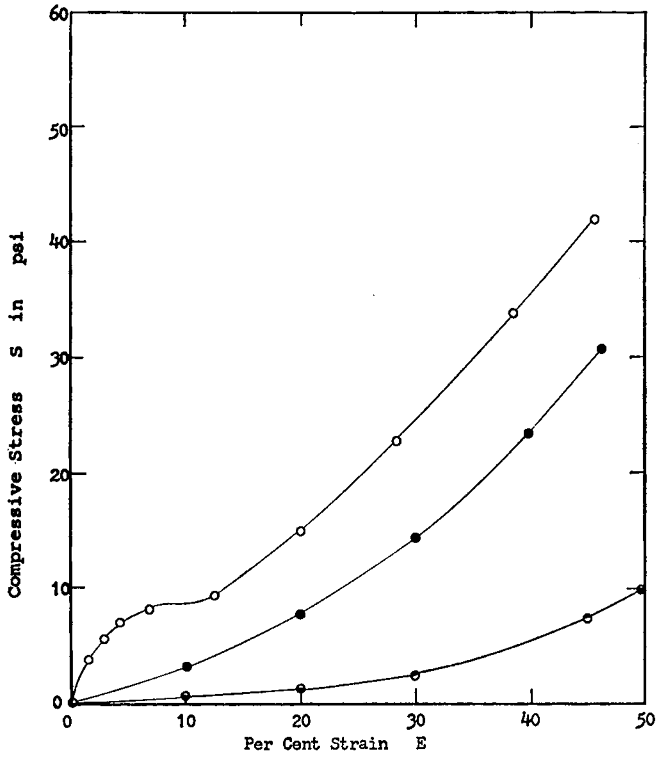

Fig. 1. Effect of strain rate on the compression curve of a felt (new and saturated): (O), strain rate equivalent to 4000 ft./min. machine speed; (●), strain rate equivalent to 1000 ft./min. machine speed; (◒), deformation rate of 2 in./mm. (Instron).

therefore, the deformation of the felt. This resistance to compression is registered as a pressure build-up between the two straining mechanisms (crosshead of the tester or the rolls of the press) and thus gives rise to the loading, or prevents deformation, as the case may be. Of course, the higher the strain rate the higher the resistance, and therefore the compressive stress, would be.

In addition to the fluid resistance, the fibers and the yarns themselves resist bending (this resistance too is strain rate dependent), thus further increasing the load necessary to deform the felt. Once the trapped fluid has been accelerated and pushed out of the voids (which would be the case when the capillaries have collapsed), the only resistance to compression would then be due to the bending of the fibers and yarns.

Effect of strain rate on the compression curve for a saturated felt is shown in Figure 1. At very low strain rates obtained in the Instron, the compression curve has a very low initial slope and is located considerably below those of higher strain rates. This is to be expected because the fluid within the voids has plenty of time to leave the voids and thus offers no resistance to compression. The resistance of the fibers and yarns to bending is the only contributor to the load developed and, initially, it is very small, accounting for the low initial slope of the curve. At strain rates comparable to machine speeds of about 1000 ft./min. (felt deformation rate of about 20 in./sec.), the fluid begins to make its presence known to the compressive load. Furthermore, at high strain rates, the resistance of the fibers to bending becomes considerably higher.

At deformation rates of about 80 in./sec. and higher, the compression curve is altered so much that an entirely new mechanism appears to dominate the behavior of the compression curve. Above this loading rate, not only is there insufficient time for the water to leave the structure while the pressure is being applied, but to some extent there isn't even time for the fibers to bend to a degree appropriate to the applied force!

Effect of Water Content on the Compression Curve of the Felt

The same phenomenon which gives rise to the compressive stress due to strain rate is responsible for the effect of moisture content on the compression curve. When a felt is dry, the voids are filled with air which, being a compressible gas, offers little or no resistance to the collapse of the

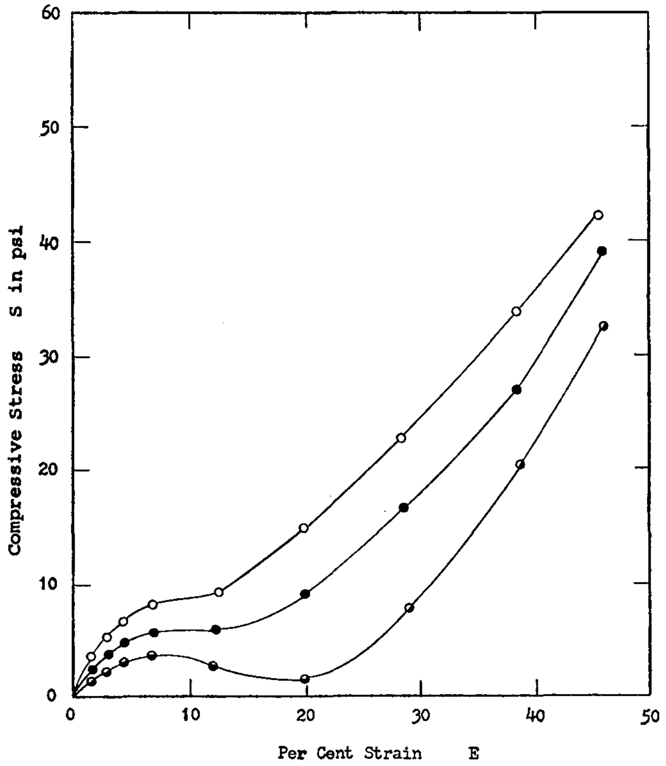

Fig. 2. Effect of moisture content on the compression curve of the felt (new, strain rate equivalent to 4000 ft./min. machine speed): (●), wet; (○), saturated; (◒), dry.

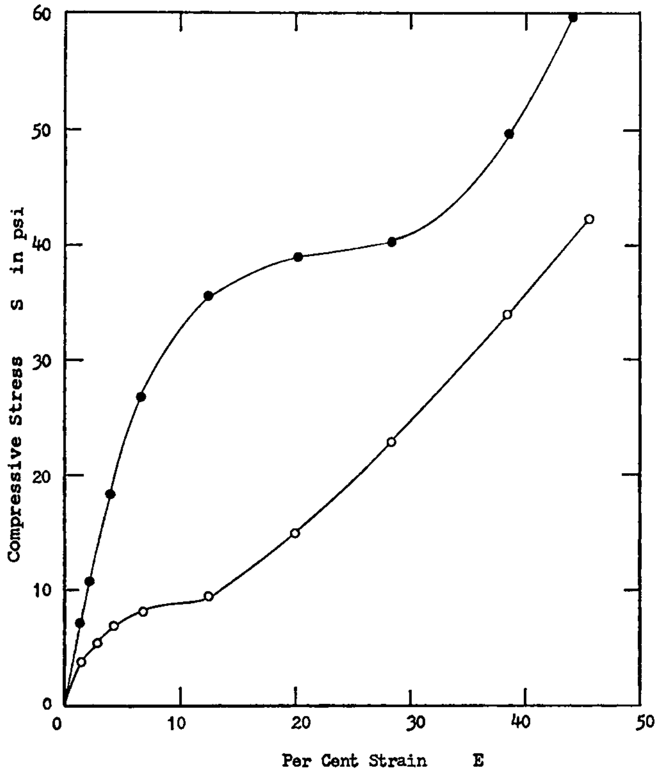

Fig. 3. Effect of wear on the compression curve of the felt (saturated, strain rate equivalent to 4000 ft./min. machine speed): (●), worn felt; (O), new felt.

void volumes. Water being a viscous fluid has more difficulty in leaving the voids, and being noncompressible, offers much more resistance to compression than the air does. This dual effect makes the presence of water a formidable barrier to the deformation of the felt. The initial part of the compressive stress-strain curve is greatly affected by the moisture content, because that is when the water particles are being accelerated and the orifices are choked up. For saturated felts at high speeds, this effect becomes so large that the felt acts almost like a solid and the initial slope of the stress-strain curve is greatly increased. Once the water has had time to leave the voids, however, the load levels off (it even drops off in some cases), and then rises again due to the bending of the fibers and the yarns. The sharp increase in the initial part of the stress-strain curve also occurs for dry felts at high speeds (deformation rate of about 80 in./sec.).

The influence of moisture content on the compression curve is demonstrated in Figure 2. The compression curve of the dry felt is smooth, with a small initial slope slightly lower than that of a wet felt. There is, however, very little or no difference between the compression curves of felts having moisture contents up to about 70%. The nap may raise the initial slope of the curve as the moisture content is increased, but the latter part of the curve is unaffected by it. Once the moisture content is increased to the saturation level, however, the initial slope is greatly increased, bringing the whole curve up. If the felt is compressed sufficiently to allow the water to

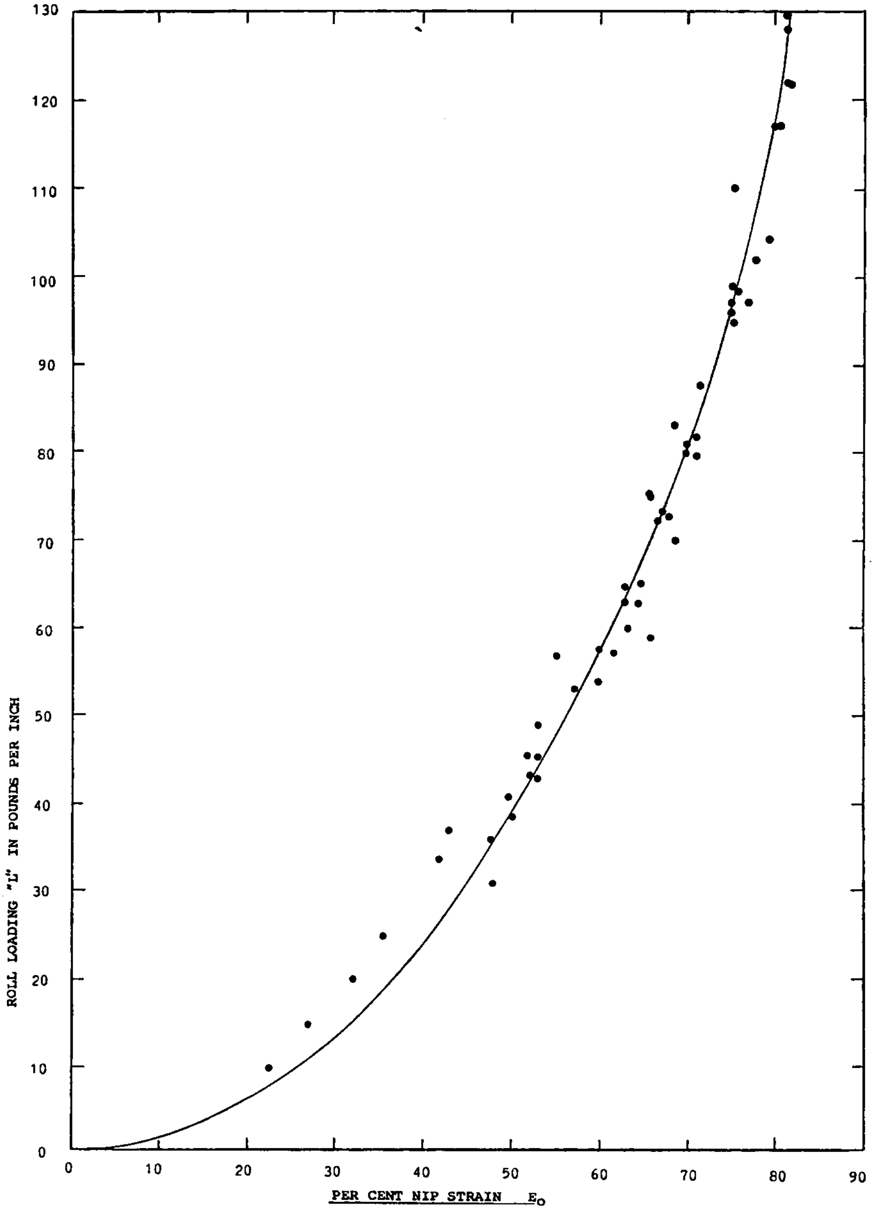

Fig. 4. A comparison of experimental results (●) with the theoretical load-nip strain relationship (—) of the plain press roll (machine speed 850 ft./min.; felt moisture content, 60%)

leave the felt, the latter part of the curve nears that of the wet felt and should ultimately join it (beyond about 80% strain).

Effect of Wear on the Compression Curve

As the felt wears out during its life on the paper machine, it loses much of its compressibility and becomes more resilient. Much of the change in the compression curve of the felt occurs in the early life of the felt, because it wears out faster at this stage. The nap which covers the felt is most severely affected by the wear, and any change in the compression curve would initially depend on the amount of the nap. The preliminary studies carried on so far on the effect of the nap in the compression curve show that it is responsible for the low initial slope of the compression curve of the dry and wet felts. This is to be expected, because bending resistance of wool fibers is much less than the compressive resistance of the yarns. When the nap is absent, however, the initial slope of the compression curve is determined by the compressive resistance of the yarns, and would, therefore, be greater for worn felts than for new napped felts.

Figure 3 shows the compression curve of a new and of a worn felt at the dry state and deformation rate equivalent to 60 in./sec. As can clearly be seen, the worn felt is harder and consistently offers more resistance to compression than the new felt does.

The Recovery Curve of the Felt

A survey of the existing literature of high speed compression tests has failed to discover any information regarding the recovery properties of felts or the existence of an apparatus that would determine. Lack of such information regarding the recovery properties of felts has forced us to make the assumption that the felt recovers at a slower rate than the back of the nip of a pair of solid rolls opens up. The agreement (Fig. 4) between experimental results and the theoretical predictions of the load-nip strain relationship of a felt tends to justify this assumption.

As this study is carried on further, the need for an apparatus to determine the recovery curve of textile structures and sheetlike materials from high speed compression becomes more and more evident. Until such time as the pertinent information or equipment for determining the recovery curve becomes available, any theoretical analysis regarding the performance of the felt, or any other deformable material, in the nip of a press section should probably be based on the assumption that the rate of recovery of the medium from compression is less than the rate at which the back of the nip opens up.

Résumé

Les proprietés de compression a vitesse élevée de fibres textiles et de matériaux en feuilles, qui passent par des rouleaux compresseurs, sont déterminants pour le programme de pression dans la région de pincement, la charge des rouleaux, et la séparation minimum des surfaces des rouleaux de pression. Les facteurs affectant les propriétés de compression à vitesse élevée de feutres (structures textiles en nappes), qui sont utilisées au transport d'un rouleau de papier humide au travers la presse d'une machine à papier, ont été examinés. Les courbes de tension-élongation par compression d'un feutre ont été obtenues en utilisant un appareil "Plastechon" à vitesse élevée en vue d'imiter un programme de tension, endéans la région de pincement de la presse de la machine à papier. Les courbes de compression de feutres nouveaux, utilisés et tissés, ont été obtenues à des vitesses de déformation de 20 pouces/sec à 100 pouces/sec, équivalentes aux vitesses de la machine à papier, qui varient de 1000 pieds à 5000 pieds/minute et à diverses teneurs en eau (sec, humide et saturé). Les résultats montrent que le feutre résiste mieux à la compression lorsque la vitesse de tension et/ou la teneur en eau croît. De façon semblable, des feutres tissés nécessitent une force plus élevée pour obtenir un degré de compression déterminé, que des feutres nouveaux en nappes. Ces courbes de compression sont utilisées pour vérifier une théorie générale de la détermination de la relation charge/tension dans la presse. Les résultats des expériences conduites dans une presse experimentale semblent confirmer la théorie, et l'importance extrème des caractéristiques de compression à vitesse élevée du matériau dans la région de pincement pour déterminer les propriétés dynamiques d'une presse.

Zusammenfassung

Das Verhalten bei Kompression mit hoher Geschwindigkeit von Textilien und blattartigen Materialien, die durch eine Reihe von Presswalzen gehen, ist der bestimmende Faktor für das Druckschema innerhalb des Einpressbereiches, die Belastung der Walzen und den Mindestabstand der Walzenoberflächen (Pressdicke) der Presse. Die Faktoren, die das Kompressionsverhalten bei hoher Geschwindigkeit von Transporttüchern (gerauaten Textilien) als Trägern eines feuchten Papierblattes im Pressbereich einer Papiermaschine beeinflussen, werden bestimmt. Die Kompressionsspannungs-Verformungskurven eines einzelnen Transporttuches werden, um das Verformungsverhalten innerhalb des Einpressbereiches der Papiermaschine wiederzugeben, mit dem Plastechon-Hochgeschwindigkeitstester erhalten. Kompressionskurven neuer, gebrauchter und abgenützter Transporttücher werden bei Deformationsgeschwindigkeiten von 20 in./sec bis 100 in./sec, entsprechend Geschwindigkeiten der Papiermaschine von 1000 ft/min bis 5000 ft/min, bei verschiedenem Wassergehalt (trocken, feucht und gesättigt) erhalten. Die Ergebnisse zeigen, dass das Tuch bei steigender Verformungsgeschwindigkeit und steigendem Wassergehalt einen höheren Kompressionswiderstand leistet. In gleicher Weise erfordern abgenützte Tücher zur Erreichung eines bestimmten Kompressionsgrades eine höhere Kraft als neue gerauhte Tücher. An den Kompressionskurven wird eine allgemeine Theorie zur Bestimmung der Belastungs-Einpressverformungsbeziehung im Pressbereich verifiziert. Die an einer Versuchspressstrecke erhaltenen Ergebnisse bestätigen die Theorie und beweisen so die grosse Wichtigkeit der Hochgeschwindigkeits-Kompressions-charakteristik des Materials im Einpressbereich für die Dynamik der Presse.

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