Institute of Paper Science and Technology

HIGH-TEMPERATURE STRENGTH/RUNNABILITY

Project 2696-26

Final Report

to

CONTAINERBOARD AND KRAFT PAPER GROUP

of the

AMERICAN PAPER INSTITUTE

June 4, 1991

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SUMMARY

The effects of temperature and moisture content on the MD tensile strength and stretchability of corrugating mediums have been phenomenologically investigated. The types of medium considered are recycled, caustic carbonate, green liquor and NSSC. It is suggested that two counteracting mechanisms are in effect as the temperature and moisture content of a medium are progressively altered. First, there is a "plasticizing effect," which tends to decrease the tensile strength and simultaneously enhance the stretchability of the medium. This phenomenon is attributed to the softening of the lignin and hemicellulose components of the medium. Second, there exists a "drying effect," which inclines to increase the tensile strength and simultaneously decrease the stretchability of the sheet. This phenomenon is associated with the stiffening of the sheet and generation of residual stresses in the medium. It is also suggested that for mediums of all types there exists a "critical temperature" state (typically 250°), which marks the incipient point for two distinct types of behavior. Below this critical temperature the plasticizing effect is predominant, while above the critical temperature the plasticizing effect is strongly counteracted by the drying effect. The extent of the drying effect is very much influenced by the initial moisture content of the sheet. Generally, the drying effect becomes more significant as the initial moisture content is increased. At very low levels of initial moisture content (e.g., 5%), the drying effect is almost totally absent. On the other hand, at very high levels of initial moisture content (e.g., 14%), the drying effect more than counterbalances the plastic flow. There is, generally, a complex interplay of temperature and moisture content beyond the critical temperature. Too high a temperature can stiffen the sheet, thus giving rise to high-lows and excessive flute damage or fracture during the corrugating operation. For best preconditioning effect it is suggested that the nip

temperature should be kept around the critical temperature, and moisture content should be maintained around the roll moisture of about 7-10%. It is also found that differences in the chemical composition as reflected by pulp type influence the MD tensile and stretch behavior of the medium. Although the effect of medium pulp type on high temperature tensile strength is apparent, pulp type is found to more strongly affect the stretch behavior of a medium.

INTRODUCTION

As part of a long-range plan to improve corrugator runnability, Project 2696-26 focuses on the effects of temperature and moisture preconditioning on medium strength and runnability. It has been previously demonstrated conclusively [1] that the runnability improves and high-lows diminish as the MD tensile strength and stretch of the medium increase and as the medium friction and thickness decrease, with the most significant contribution being due to stretch and caliper. These medium factors promote increases in the flute fracture corrugating speed, which in turn improve the quality of the corrugated board.

During the process of corrugation, mediums are often subjected to high levels of tension over a relatively short period of time. Furthermore, the medium may be preconditioned to a wide range of moisture contents and temperatures prior to corrugation by showers and preheaters. It is evident that high temperature medium tensile tests under a variety of preconditioning and moisture contents should prove to be of great value in explaining the observed differences in corrugator runnability under these conditions. The main thrust of Project 2696-26 has, therefore, been to develop a better understanding of the medium properties during the fluting operation by studying the tensile load-elongation properties of the medium under typical corrugator temperature and moisture conditions. Of particular interest was determination of the maximum tensile strength (measured here as peak load per unit length) and peak strain (referred to as the stretch) of four major kinds of mediums with pulping types as diverse as recycled, NSSC, caustic carbonate and green liquor. The main objective of the project was to address and attempt to explain the effects of pulp type, temperature and initial moisture content on medium MD tensile strength and stretch.

EXPERIMENTAL DETAILS

In order to conduct the tensile testing of the mediums under a variety of temperature and moisture content conditions an apparatus, the details of which are described below, was used. The device consisted of a pair of heated platens that could be pneumatically moved into position around a test specimen. The platens could be adjusted to within a few thousandths of an inch from the specimen's surface. The interval between the time that the heated platens were brought into close proximity with the specimen and subsequent loading of the specimen could be controlled and calibrated to within a tenth of a second. The test specimens were heated in the apparatus for one second just prior to testing. Specimens were foil wrapped during the heating and tensile testing procedure in an attempt to minimize moisture losses throughout the testing period. The tension tests were run at a speed of 20 in/min immediately after the heating period. Preconditioning of the mediums took place at relative humidity conditions of 30%, 50%, 70%, and 90%. It was determined that a correlation exists between the relative humidity and the percentage of initial moisture content for the typical medium considered for testing. It was found that the aforementioned relative humidity conditions corresponded to initial moisture contents of 5.6%, 7.2%, 9.1%, and 13.9%, respectively. In addition to tension tests in the control specimens at room temperature (73°F), testing was also carried out after heating the specimens with the platens at 150°F, 250°F and 350°F. It is of interest to report that previous studies have indicated that, due to rapid heating of the medium specimen by the platens, both the surface and internal temperature of the medium reach temperatures which are within 50°F of the platen temperature after one second of heating [2]. Therefore, the testing temperature range specified here, which correspond to the platen temperatures, is typically 50°F higher than the actual internal surface temperature of the specimens.

A total of 15 different mediums representing four distinct pulping processes of recycled, NSSC, caustic carbonate and green liquor were tested at the various aforementioned temperatures and initial moisture conditions. Within each distinct pulp type three different mediums of recycled, NSSC, and green liquor, and six different mediums of caustic carbonate were tested. Additionally, the results were recorded for ten different specimens of each medium type. The results of the experiments are presented in the next section. For each condition of platen temperature and initial moisture content and for every medium pulp type these results represent an average of 30 tensile tests for the recycled, NSSC, green liquor, and an average of 60 tensile tests for the caustic carbonate pulping type.

DISCUSSION OF THE RESULTS

THE EFFECTS OF TEMPERATURE AND INITIAL MOISTURE CONTENT ON MEDIUM TENSILE STRENGTH

The results of tensile peak load (lb/in) versus temperature for the various conditions of initial moisture content are shown in Fig. 1 through Fig. 4. Fig. 1 indicates that at low values of initial moisture content (e.g., 5.6%), tensile strength decreases continuously with increasing temperature. This phenomenon of tensile strength reduction may be attributed to the softening of the lignin and the hemicellulose components of the medium as a result of increased temperature.

Under the applied tensile loading, the plasticized medium begins to flow, thus creating a flattening in the stress-strain curve and, in turn, inducing a reduction in the peak stress. This phenomenon will subsequently be referred to as the "flow" or the "plasticizing effect." The results of the experiments (Figs. 2,3) indicate that at high values of initial moisture content (e.g., 7.2 - 9.1%) a similar trend is initially followed, but in a temperature regime beyond a certain higher (critical) temperature (e.g., 250°F) the extent of strength reduction decreases, and the tensile strength levels off to an almost constant value. These results, therefore, suggest the existence of an adverse (or strength gaining) phenomenon, which tends to counteract and somewhat counterbalance the flow effect. It may be conjectured that the resulting strength enhancement occurs due to the advent of local residual stresses within the medium, which in turn may be attributed to the drying and the consequent stiffening of the sheet under high temperatures. This phenomenon of

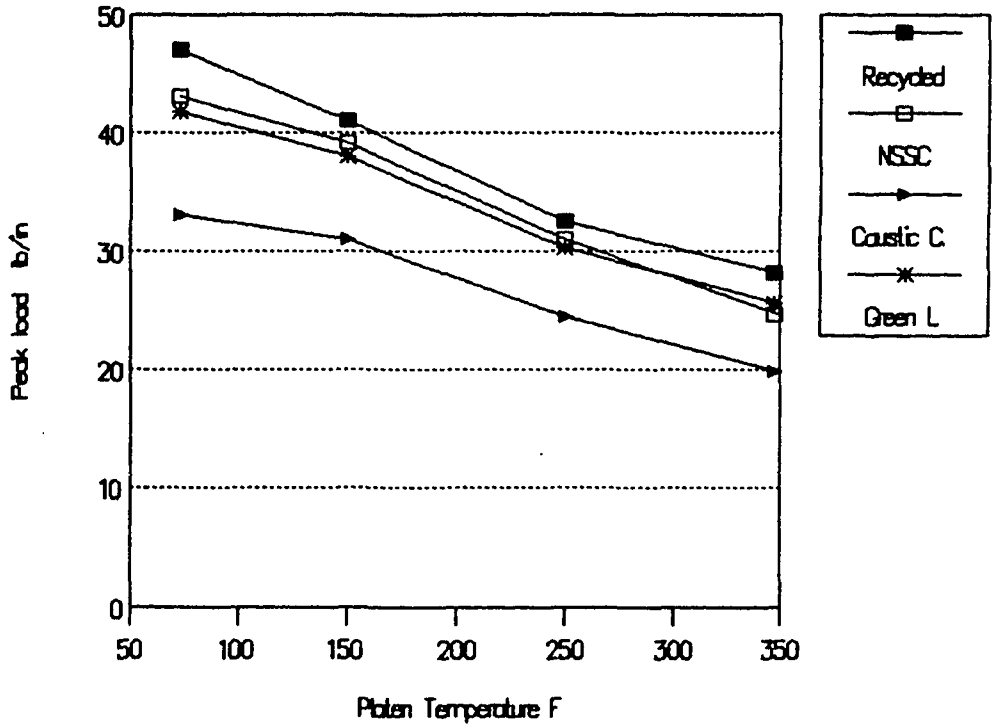

Figure 1. The tensile peak load (lb/in) representing the tensile strength of the medium versus platen temperature at the initial moisture content of 5.6% for the four kinds of medium pulping types.

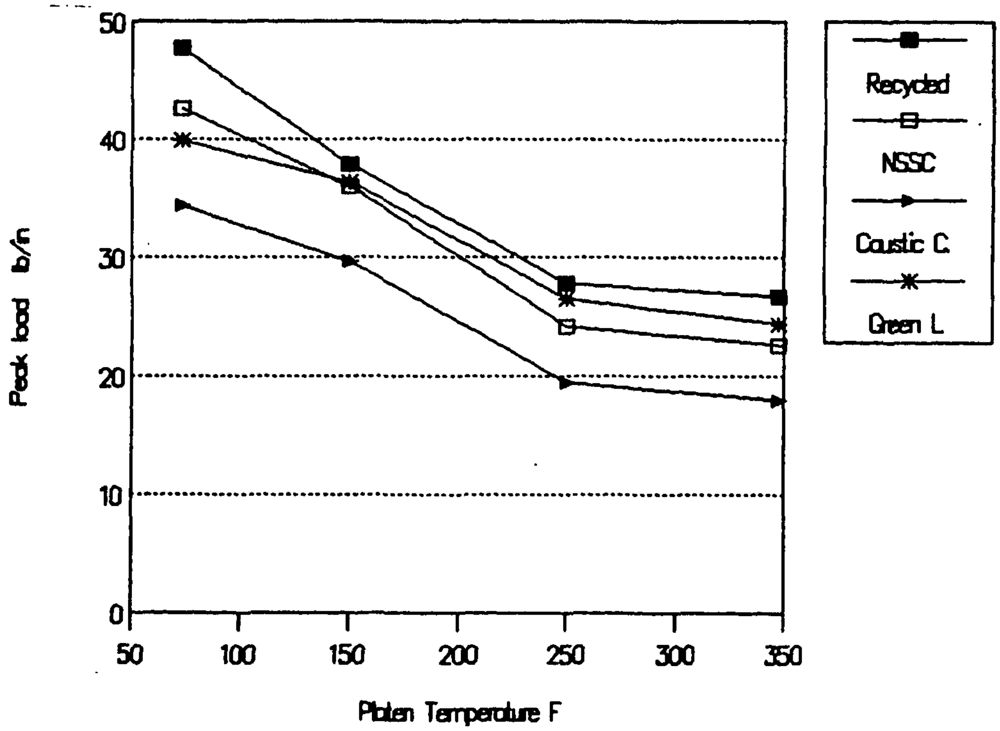

Figure 2. The tensile peak load (lb/in) representing the tensile strength of the medium versus platen temperature at the initial moisture content of 7.2% for the four kinds of medium pulping types.

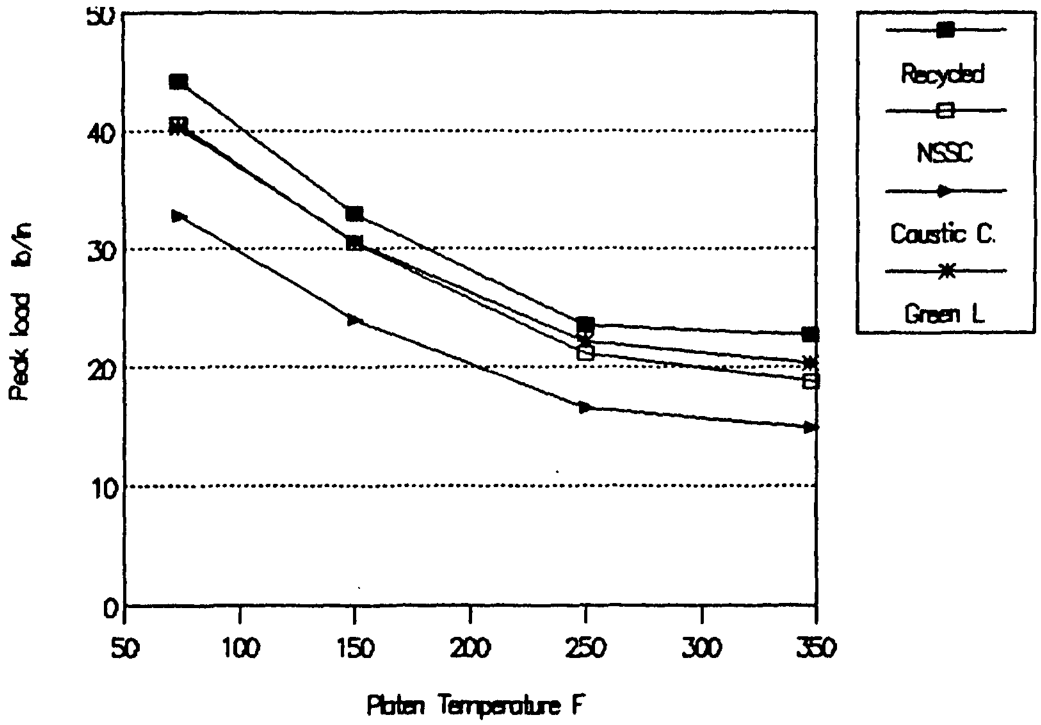

Figure 3. The tensile peak load (lb/in) representing the tensile strength of the medium versus platen temperature at the initial moisture content of 9.1% for the four kinds of medium pulping types.

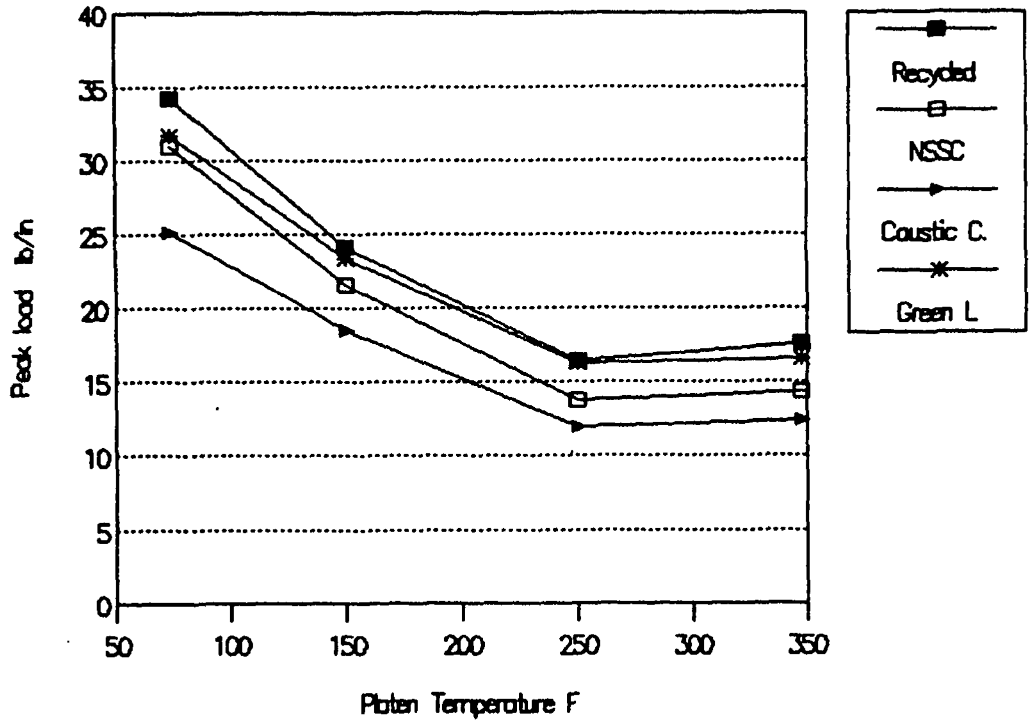

Figure 4. The tensile peak load (lb/in) representing the tensile strength of the medium versus platen temperature at the initial moisture content of 13.9% for the four kinds of medium pulping types.

strength enhancement will be referred to as the "drying effect." It is evident that at very low levels of initial moisture content (e.g., 5.6%) one might expect a more slight contribution or even total absence of the drying effect. It is, therefore, not surprising that at the initial moisture content of 5.6%, the tensile strength of the medium decreases continuously due to increased temperatures under a condition that may be regarded as being predominantly due to the flow effect. On the other hand, at very high levels of initial moisture content (e.g., 13.9%), the drying effect may more than counterbalance the effect of plastic flow, thus increasing the overall tensile strength of the sheet in the temperature range beyond the critical temperature (i.e., beyond 250°F). It is evident that during heating moisture is being lost as the platen temperature is increased, thus giving rise to a drying effect that is more significant at very high levels of initial moisture content.

The results of the experiments have been replotted in Fig. 5 through Fig. 8 for the mediums of the four pulp types as a function of initial moisture content at various platen temperatures. For most cases these results confirm the notion that at any given temperature, the tensile strength decreases as the initial moisture content increases at various platen temperatures. This is consistently true for the NSSC and green liquor pulp types of medium at any given temperature, with the highest tensile strength corresponding to the initial moisture content of 5.6% and the lowest tensile strength being associated with the initial moisture content of 13.9%. However, curiously peculiar results were recorded for certain mediums of the recycled and caustic carbonate at 73°F. Namely, at 73°F, on average the strength of the recycled and caustic carbonate types were found to be actually slightly higher at the initial moisture content of 7.2% than 5.6%. This phenomenon remains to be explained.

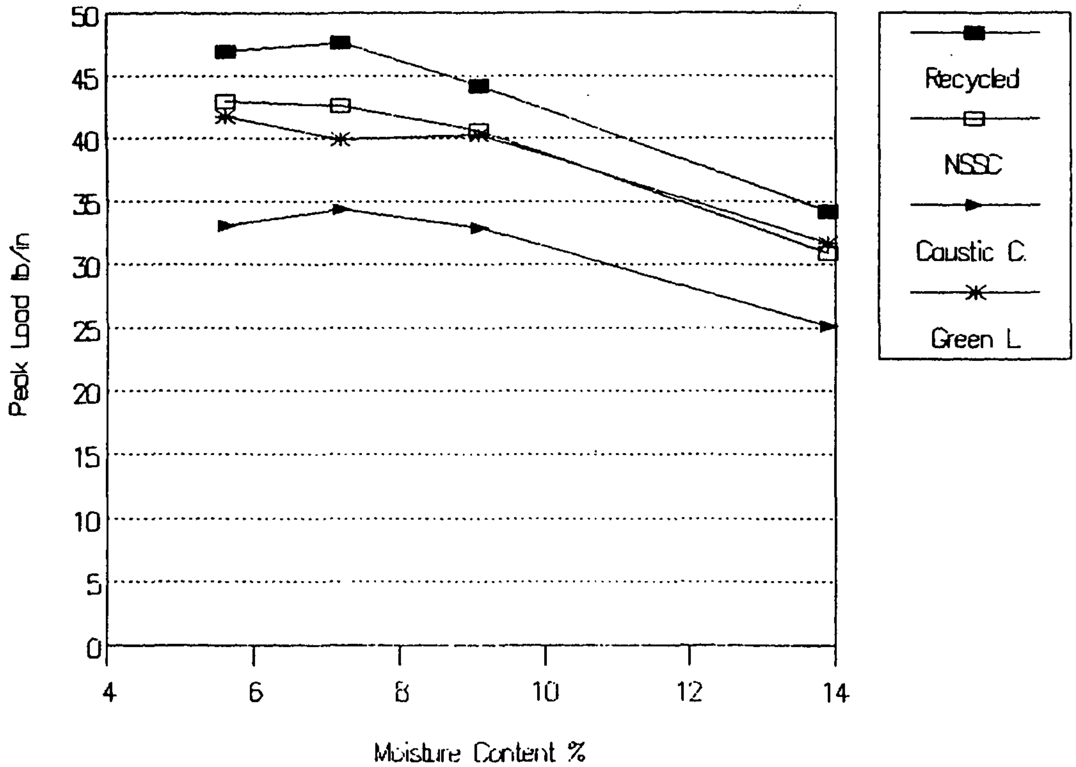

Figure 5. The tensile peak load versus initial moisture content at the platen temperature of 73°F for the four kinds of medium pulping types.

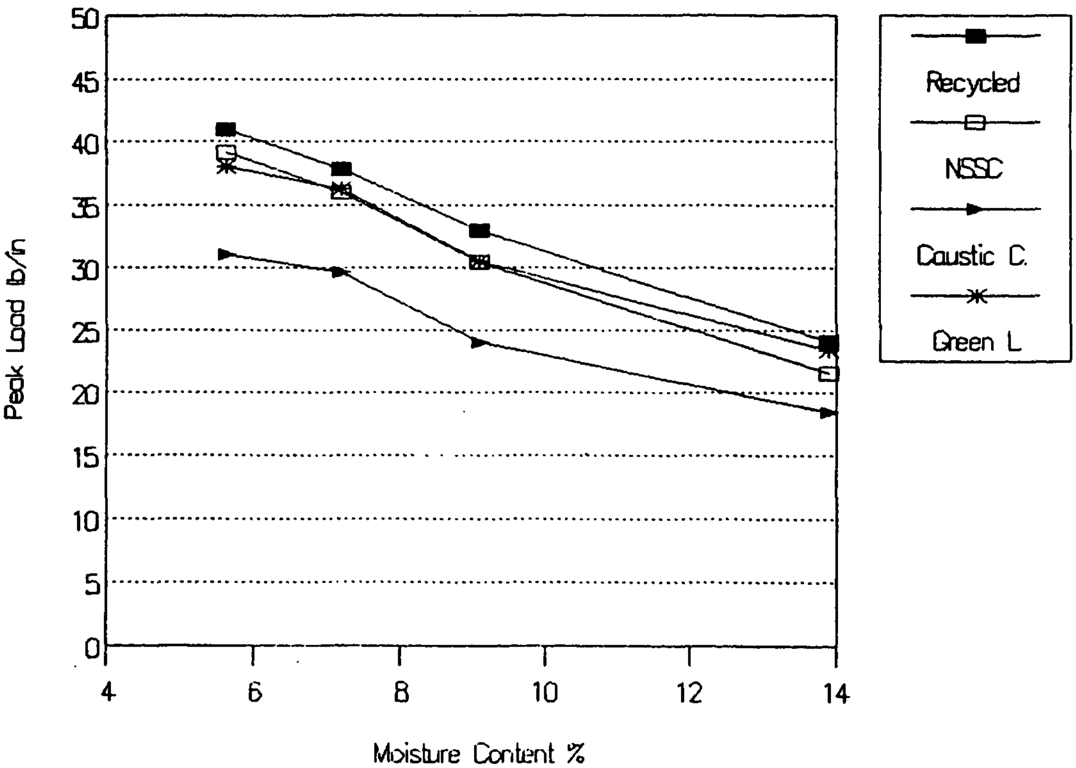

Figure 6. The tensile peak load versus initial moisture content at the platen temperature of 150°F for the four kinds of medium pulping types.

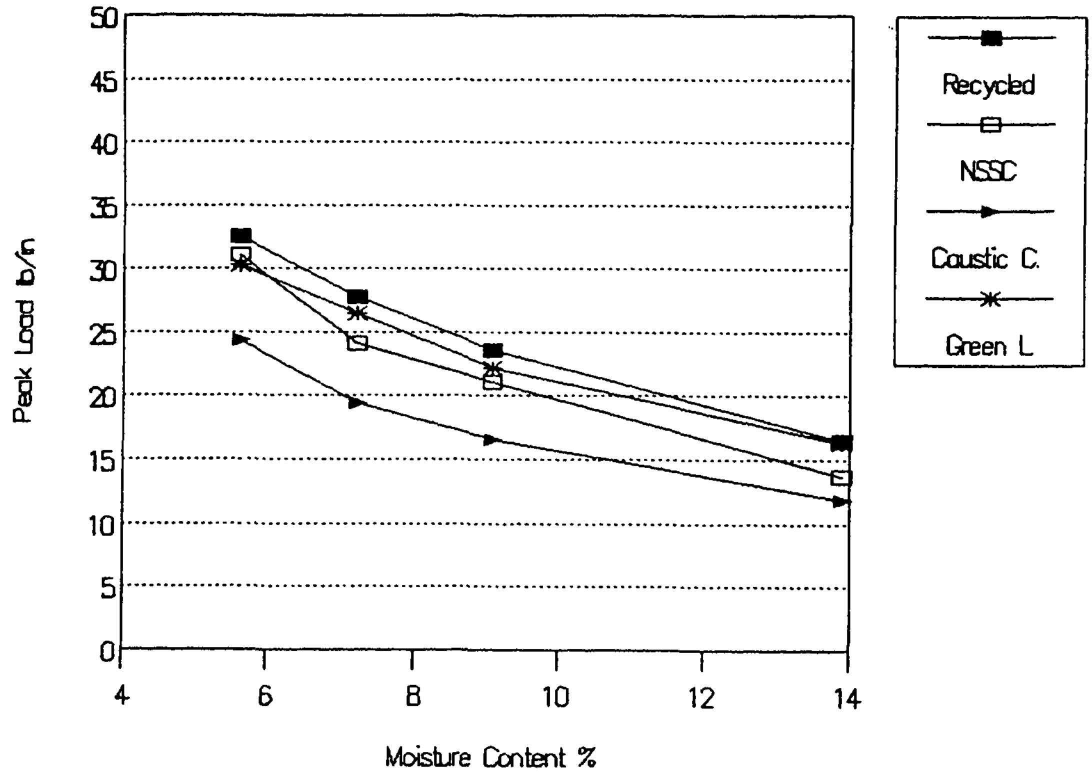

Figure 7. The tensile peak load versus initial moisture content at the platen temperature of 250°F for the four kinds of medium pulping types.

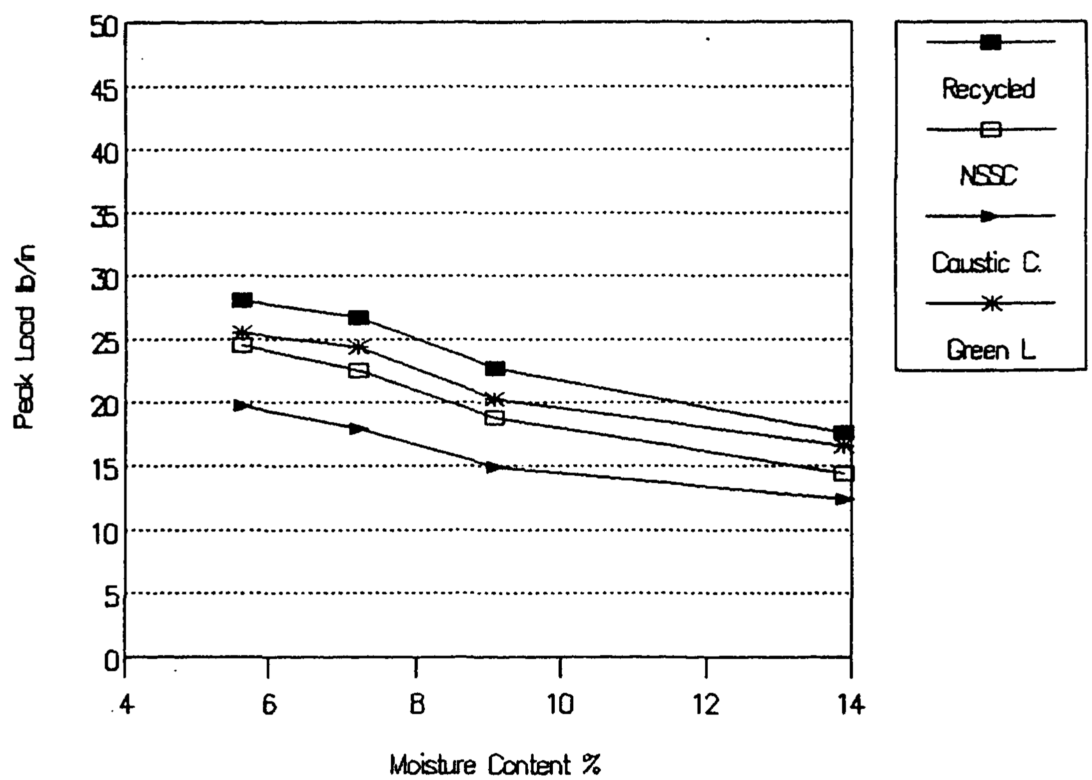

Figure 8. The tensile peak load versus initial moisture content at the platen temperature of 350°F for the four kinds of medium pulping types.

THE EFFECTS OF TEMPERATURE AND INITIAL MOISTURE CONTENT ON MEDIUM STRETCH

The stretch results versus the platen temperature for the four pulp types at various levels of initial moisture content are plotted in Fig. 9 through Fig. 12. These results indicate that the stretch values for the mediums of all pulp types at all levels of initial moisture content consistently reach a maximum at a critical temperature of about 250°F. Therefore, a critical temperature (the same critical temperature as that recorded for the case of tensile strength) marks the incipient point for a distinct mode of behavior for all mediums of different pulp types. Below this critical temperature, the medium stretch is seen to consistently increase with increasing temperature, a phenomenon which may be attributed to the plasticizing or the flow effect. On the other hand, above this critical temperature, the stretch continuously decreases with increasing temperature, with the stretch losses being significantly larger at higher levels of initial moisture content. Again, it is suggested that in the temperature regime beyond the critical temperature, the effect of plastic flow is strongly counteracted by the drying effect of the sheet, with the drying effect being more prominent at higher levels of initial moisture content. On the other hand, at very low values of initial moisture content, the effect of residual or drying stresses almost entirely counterbalances the plasticizing effect, thus giving rise to an almost constant stretch beyond the critical temperature. As the initial moisture content is increased, however, the slope of the stretch-temperature curve representing the extent of stretch losses increases, indicating that a more prominent drying behavior is in effect.

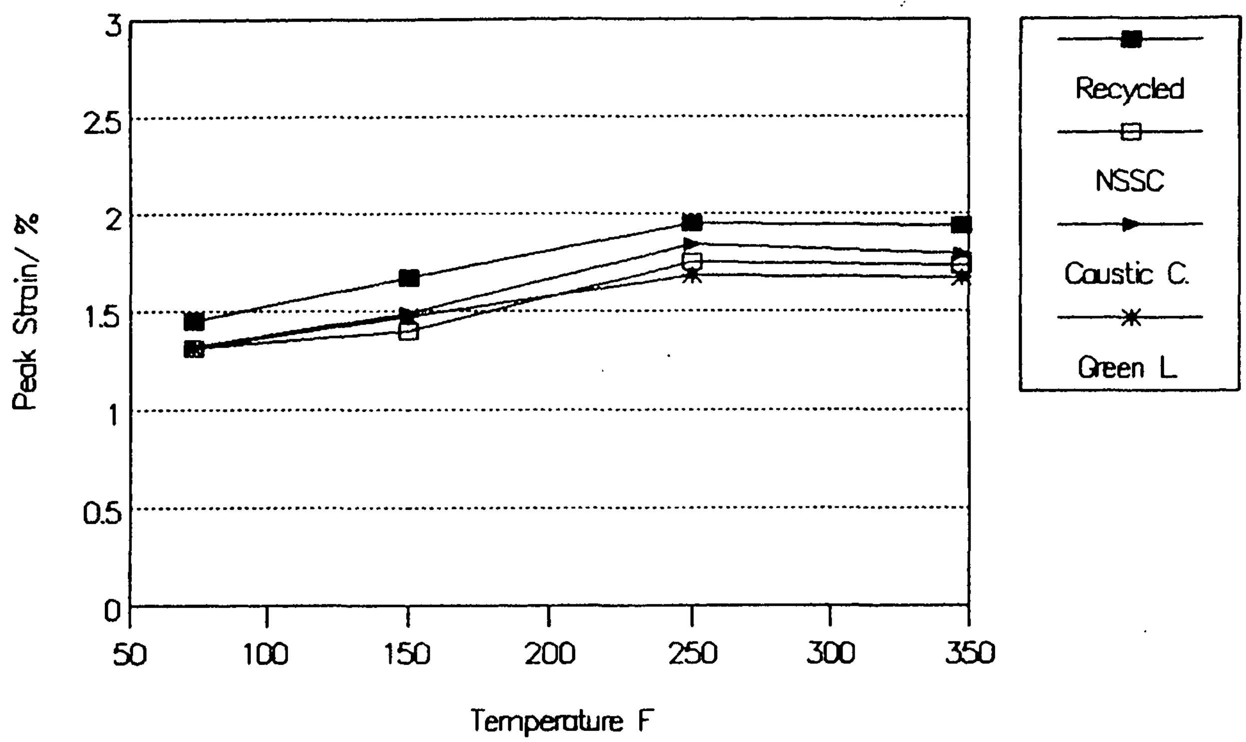

Figure 9. The peak strain (stretch) versus the platen temperature at the initial moisture content of 5.6% for the four kinds of medium pulping types.

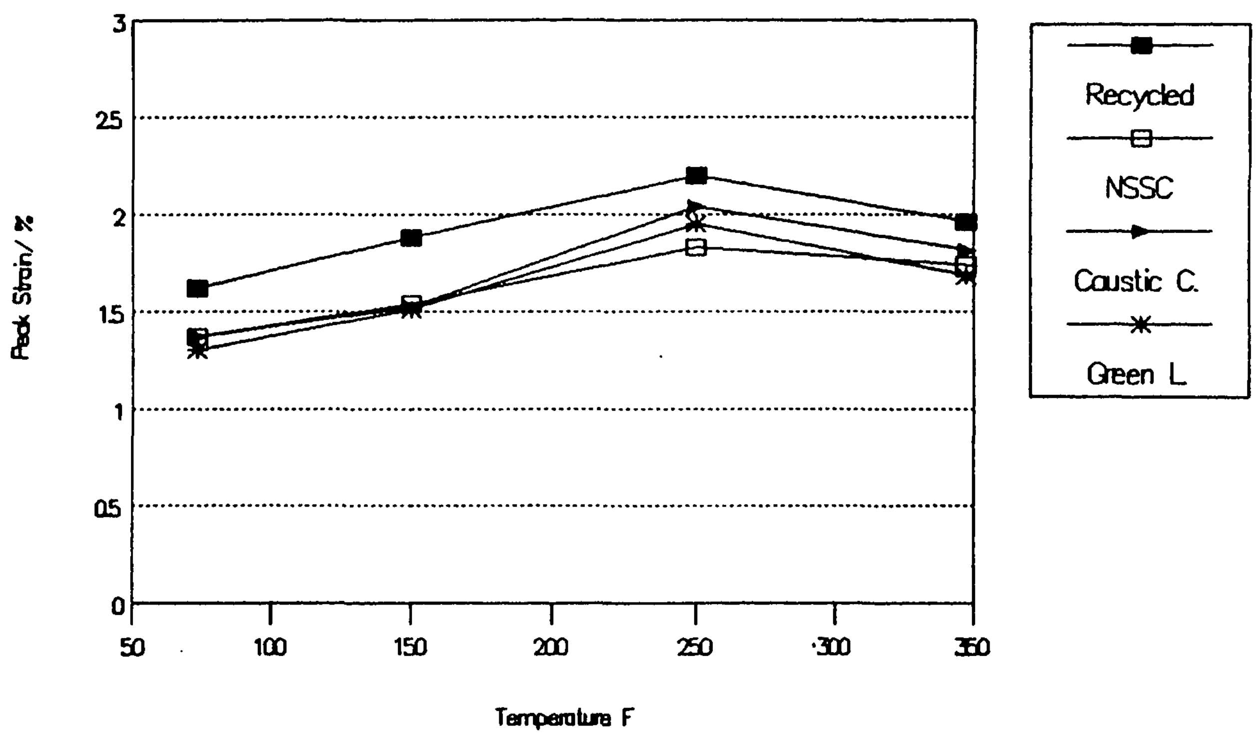

Figure 10. The peak strain (stretch) versus the platen temperature at the initial moisture content of 7.2% for the four kinds of medium pulping types.

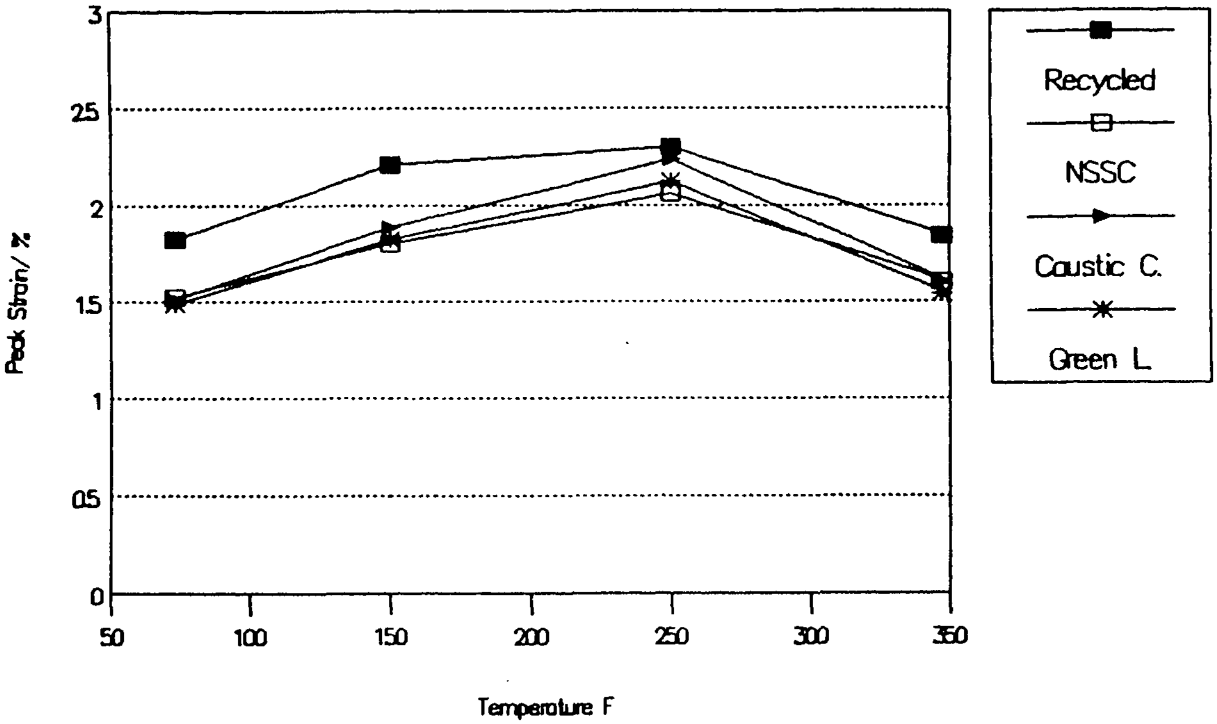

Figure 11. The peak strain (stretch) versus the platen temperature at the initial moisture content of 9.1% for the four kinds of medium pulping types.

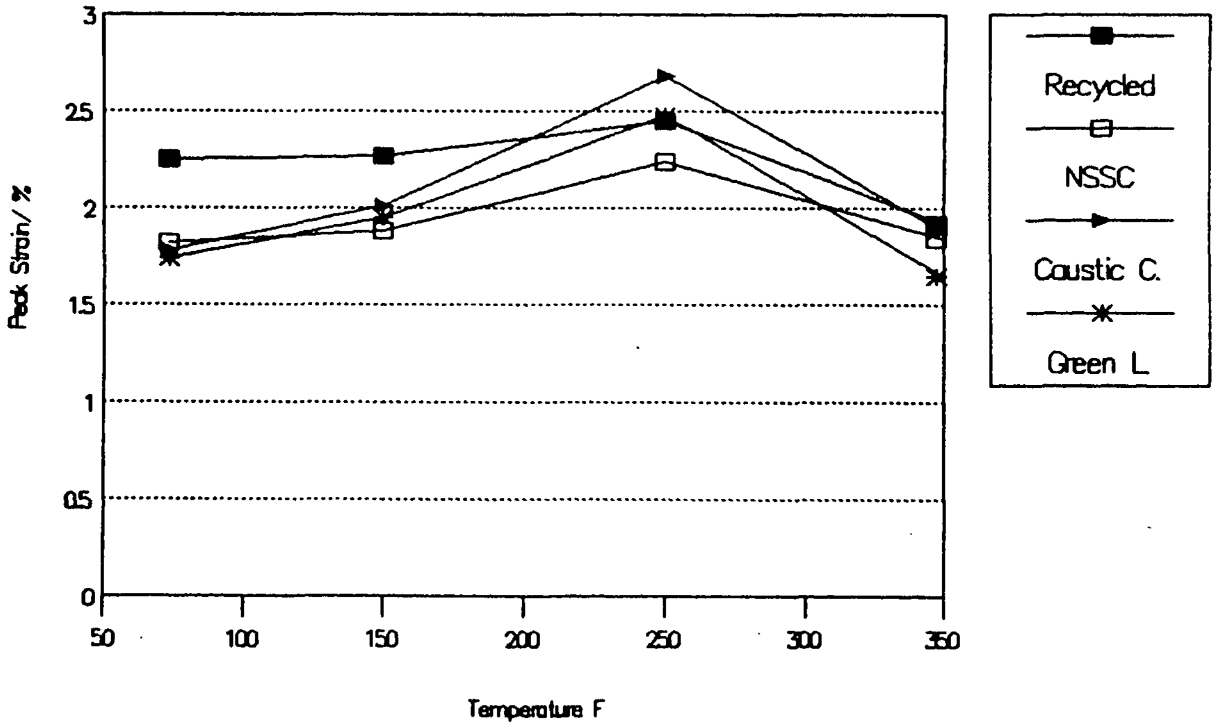

Figure 12. The peak strain (stretch) versus the platen temperature at the initial moisture content of 13.9% for the four kinds of medium pulping types.

The results of the peak strain versus initial moisture content for the four medium pulp types at various platen temperatures have been replotted in Fig. 13 through Fig. 16. These graphs indicate that at a given temperature at or below the critical temperature of 250°F, the stretch consistently increases as the initial moisture content is increased, with the lowest stretch corresponding to the initial moisture content of 5.6% (30% RH), and the highest stretch being associated with the initial moisture content of 13.9% (90% RH). On the other hand, a distinctly different behavior is observed for the mediums of all pulp types as the initial moisture content is increased at the platen temperature of 350°F. In this case, the stretch versus the initial moisture content curves follow a somewhat see-saw pattern, with the stretch first being almost constant, then decreasing and subsequently increasing as the initial moisture content is increased from 5.6% to 7.2% to 9.1% to 13.9%, respectively. Furthermore, it is seen that at such high temperatures the specimen preconditioned at 90% RH (initial moisture content of 13.9%) experiences almost the same stretch as a specimen preconditioned at 30% RH (initial moisture content of 5.6%). These results indicate that the tensile characteristics of the mediums of all pulp types are governed by distinctly different modes of behavior at very high temperatures (i.e., beyond the critical temperature) and at very high levels of initial moisture content (e.g., 13.9%). Although from the standpoint of achieving high tensile strengths it would seem beneficial to keep the corrugator nip temperature at very high temperatures (i.e., beyond 250°F) when working with excessively high levels of initial moisture content (e.g., 90%), because of the problems associated with excessive stretch losses at such temperatures, it is best to work with somewhat lower temperatures (e.g., 250°F) and lower levels of initial moisture content (e.g., 7 - 10%). In fact, these results suggest the existence of an optimum medium moisture content and temperature level for flute formation without excessive damage or high-lows.

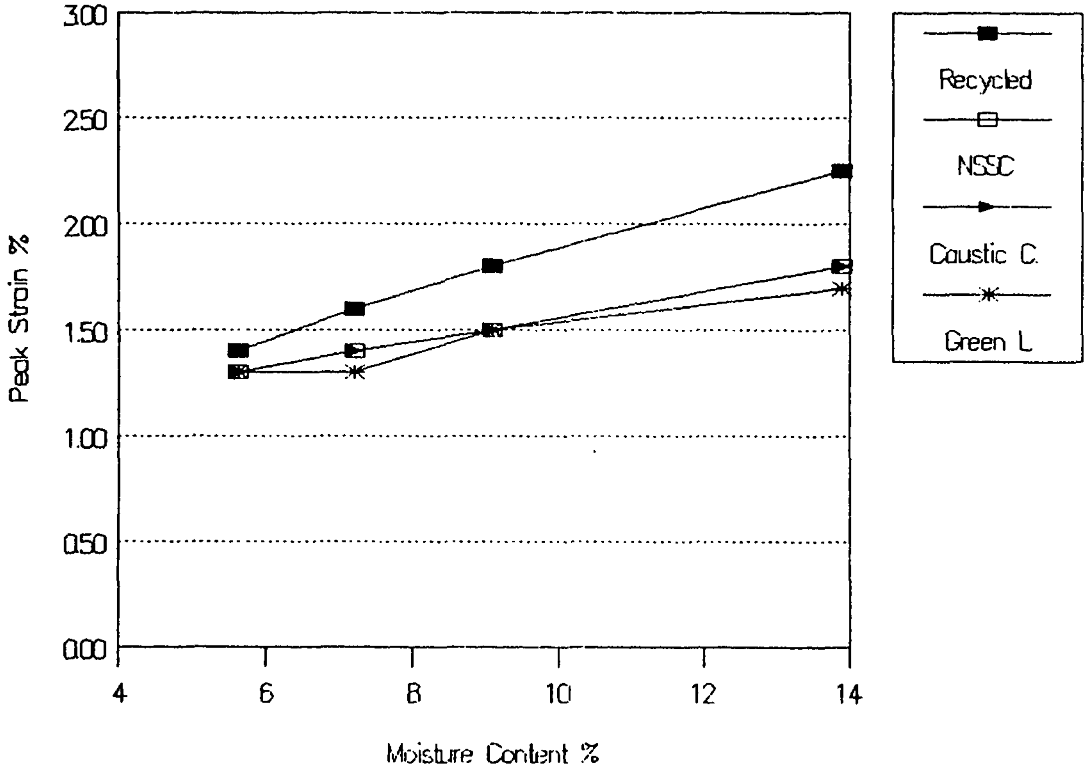

Figure 13. The stretch versus initial moisture content at the platen temperature of 73°F for the four kinds of medium pulping types.

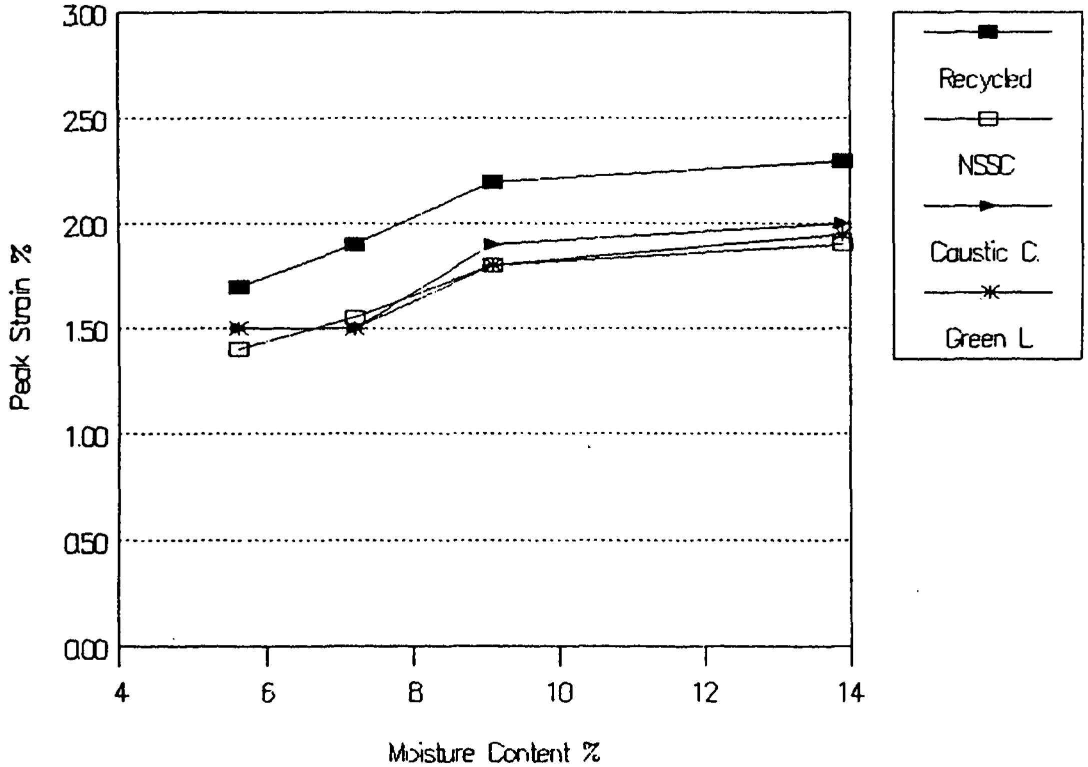

Figure 14. The stretch versus initial moisture content at the platen temperature of 150°F for the four kinds of medium pulping types.

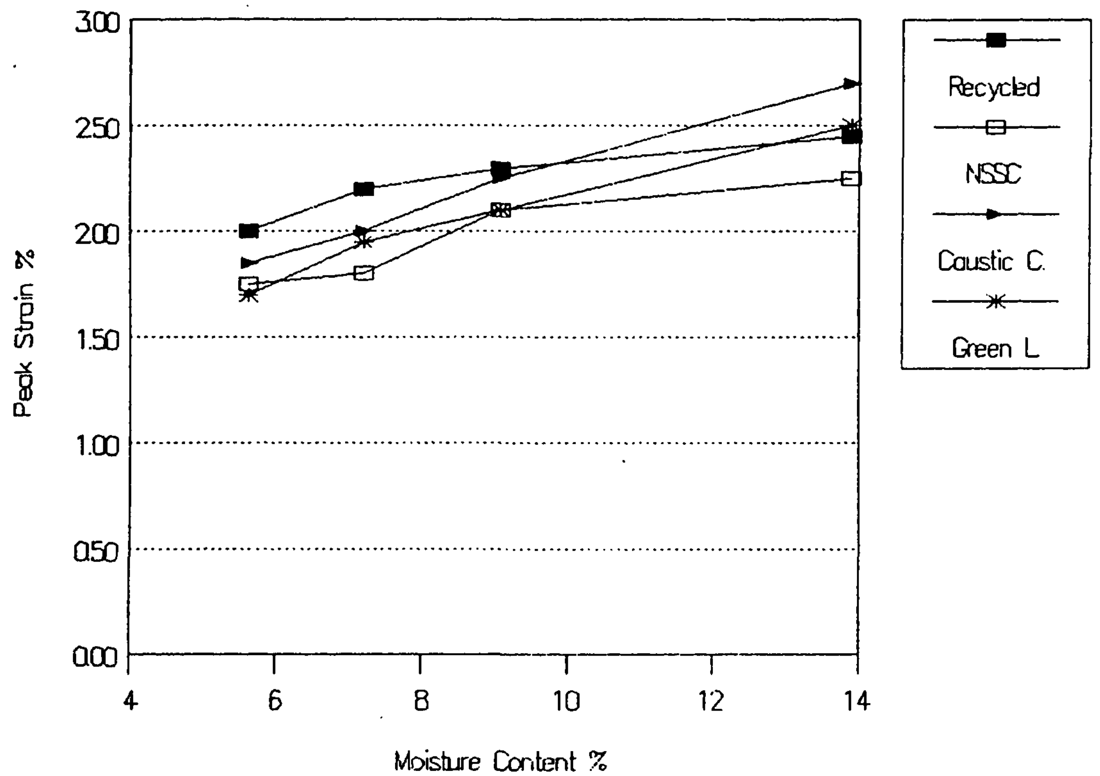

Figure 15. The stretch versus initial moisture content at the platen temperature of 250°F for the four kinds of medium pulping types.

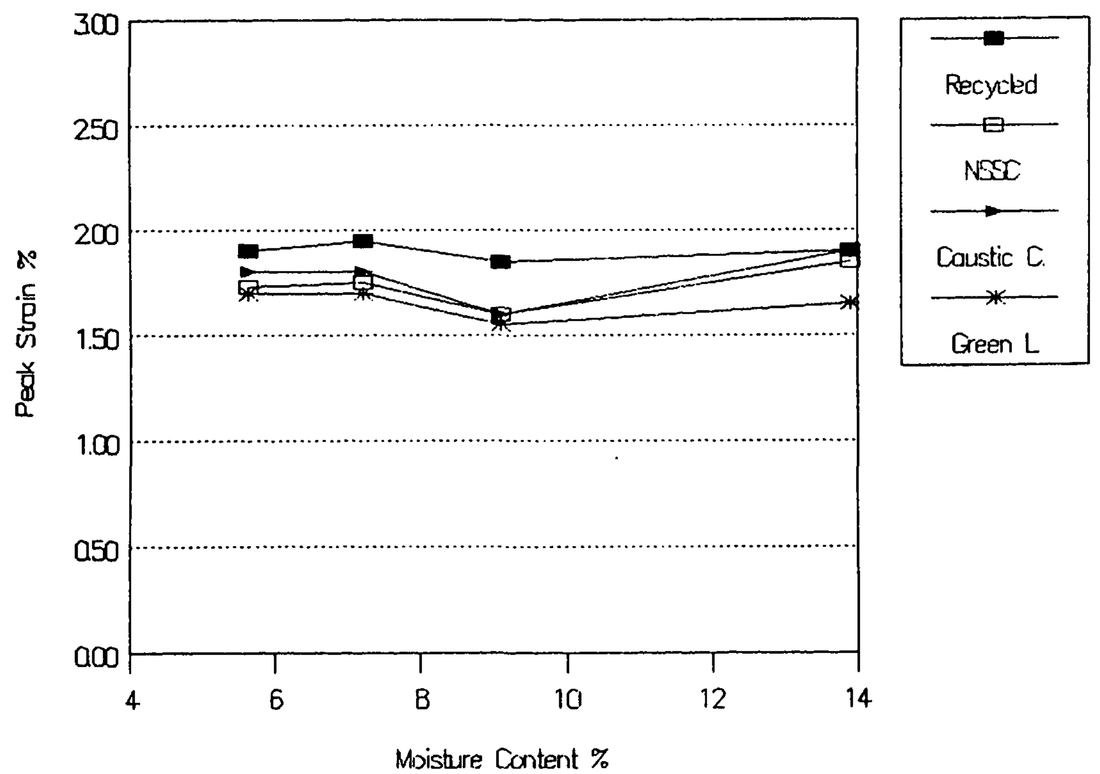

Figure 16. The stretch versus initial moisture content at the platen temperature of 350°F for the four kinds of medium pulping types.

Generally speaking, a dual system is in effect with each constituent counteracting the other. The experimental results indicated that, at a given level of initial moisture content for mediums of all pulp types, as the temperature is increased in a temperature regime below a certain critical temperature, a decrease in tensile strength is accompanied with an increase in the stretch. This, as was pointed out earlier, is believed to be due to the softening of the lignin and the hemicellulose components of the medium, which was referred to as the "plasticizing" or the "flow effect." This phenomenon is very much in accord with a universal trend for mechanics of all deformable solid materials, i.e., if the material does not deform under the action of applied stress, it resists the applied loads, thus effectively increasing its overall strength. On the other hand, when the material cannot resist the imposed loads, it deforms first elastically and then inelastically, thus creating changes in its microstructure which ultimately damage the material to the point of macroscopic failure. This progressive damage reduces the ultimate load carrying capacity (or strength) of the material.

The results of these experiments also indicate a complex interplay of temperature and initial moisture content beyond a critical temperature level, which is believed to offset the equilibrium moisture content of the medium. What is interesting is that in all of the experiments performed for various mediums of the four major pulp types, and for all levels of initial moisture content, this critical temperature has a constant value. As this temperature is reached, the increased influence of initial moisture content becomes apparent, i.e., beyond this temperature, the behavior of the system under increased temperature drastically changes depending on the initial levels of moisture content. When the initial moisture content is very low for mediums of all major pulp types, as the critical temperature is approached, the stretch reaches a saturation or constant value, while the tensile strength continues to decrease upon increasing the temperature. For higher levels of initial moisture content, on the other hand, the stretch decreases more drastically, while the tensile strength remains almost constant. From a physical point of view, it is evident that the existence of a critical temperature state, as well as the reversed roles of the tensile strength and stretch at low and high levels of initial moisture content beyond the critical temperature, are important phenomena which merit detailed investigation in the future.

THE EFFECTS OF PULP TYPE ON TENSILE BEHAVIOR

The percentage reduction in tensile strength due to increased temperature at various levels of initial moisture content compared to a standard condition with a platen temperature of 73°F and an initial moisture content of 7.2% has been shown in Fig. 17 through Fig. 20 for the four major medium pulp types. These graphs indicate that all mediums of the tested pulp types exhibit somewhat similar tensile losses as the test temperature or the initial moisture content is altered. These results suggest that the difference in the chemical composition as reflected by distinct pulp types does cause changes in the tensile strength of the medium at high temperatures, but such changes are not very significant. In other words, there is some effect of medium pulp type on high temperature tensile strength, but it is not very significant.

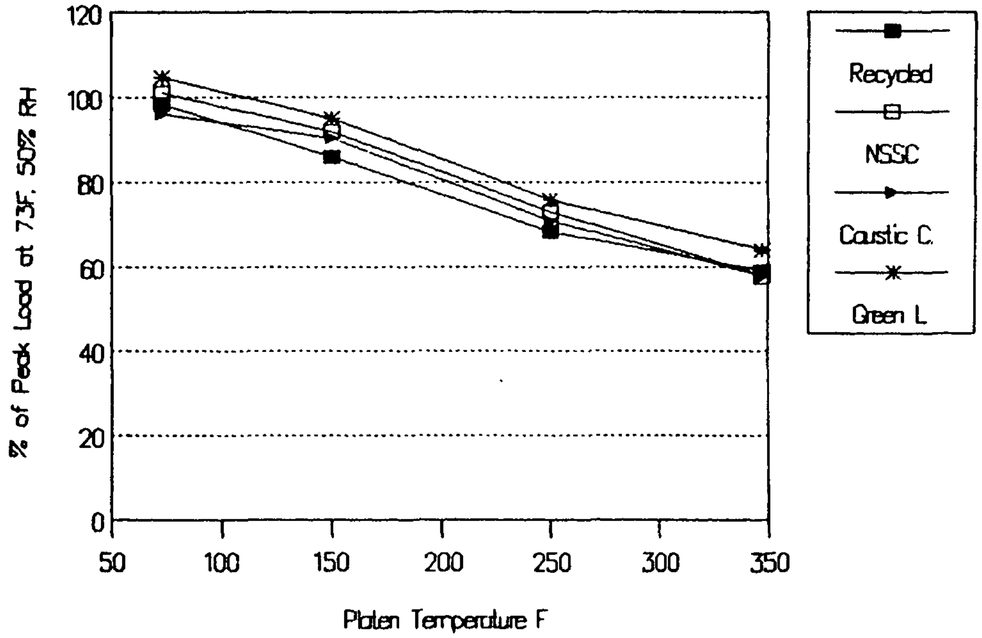

Figure 17. The percentage change in peak load as a function of temperature for the four medium pulping types at the initial moisture content of 5.6% when compared to a standard test with a platen temperature of 73°F and initial moisture content of 7.2%.

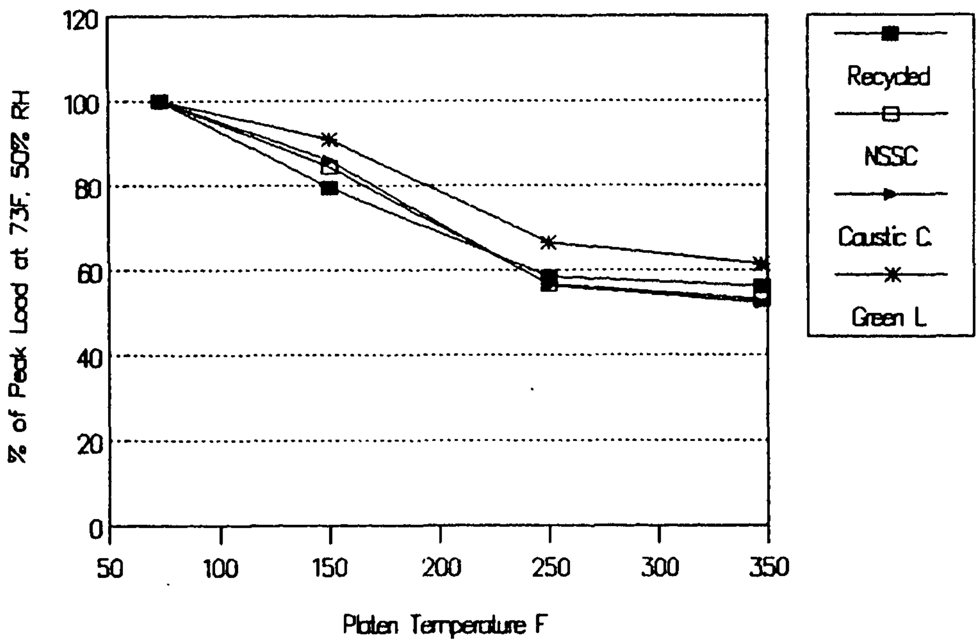

Figure 18. The percentage change in peak load as a function of temperature for the four medium pulping types at the initial moisture content of 7.2% when compared to a standard test with a platen temperature of 73°F and initial moisture content of 7.2%.

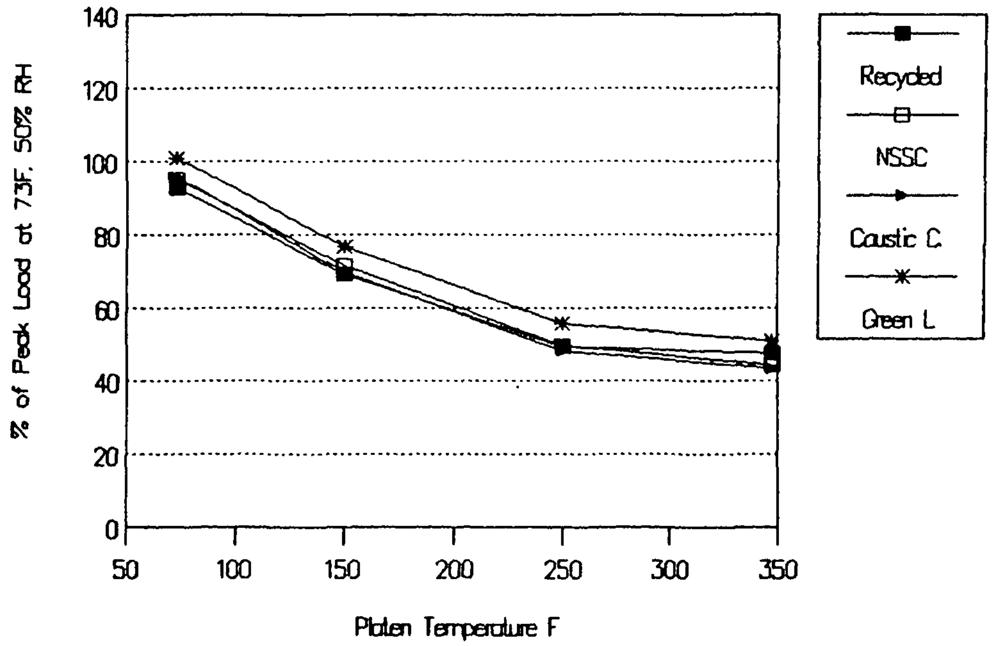

Figure 19. The percentage change in peak load as a function of temperature for the four medium pulping types at the initial moisture content of 9.1% when compared to a standard test with a platen temperature of 73°F and initial moisture content of 7.2%.

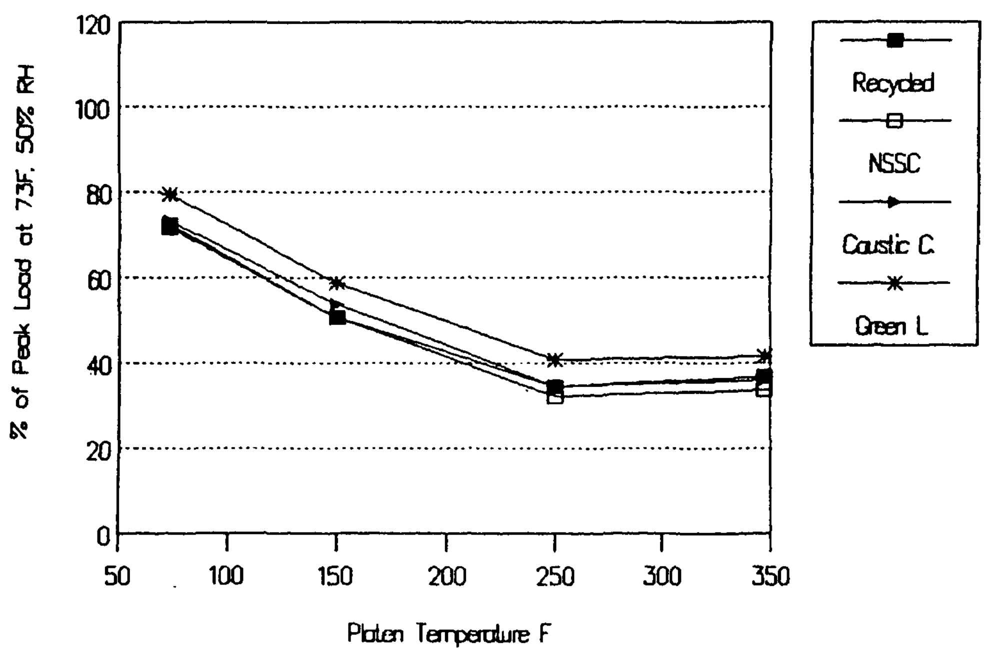

Figure 20. The percentage change in peak load as a function of temperature for the four medium pulping types at the initial moisture content of 13.9% when compared to a standard test with a platen temperature of 73°F and initial moisture content of 7.2%.

The percentage changes in peak strain (stretch) due to increased temperature at various levels of initial moisture content (when compared to the standard test condition with a platen temperature of 73°F and an initial moisture content of 7.2%) for all four major medium pulp types are shown in Fig. 21 through Fig. 24. It is quite apparent from these curves that there is a significant difference in stretch behavior for mediums of distinct pulp types as the conditions of temperatures and initial moisture content are changed. These results indicate that the caustic carbonate medium exhibits the largest stretch increases at 250°F followed closely by green liquor and then NSSC and recycled mediums, respectively. It is therefore concluded that medium pulp type is responsible for the way stretch is influenced by high temperature and initial moisture content. In other words, apparently pulp type strongly influences the high temperature stretch behavior of medium.

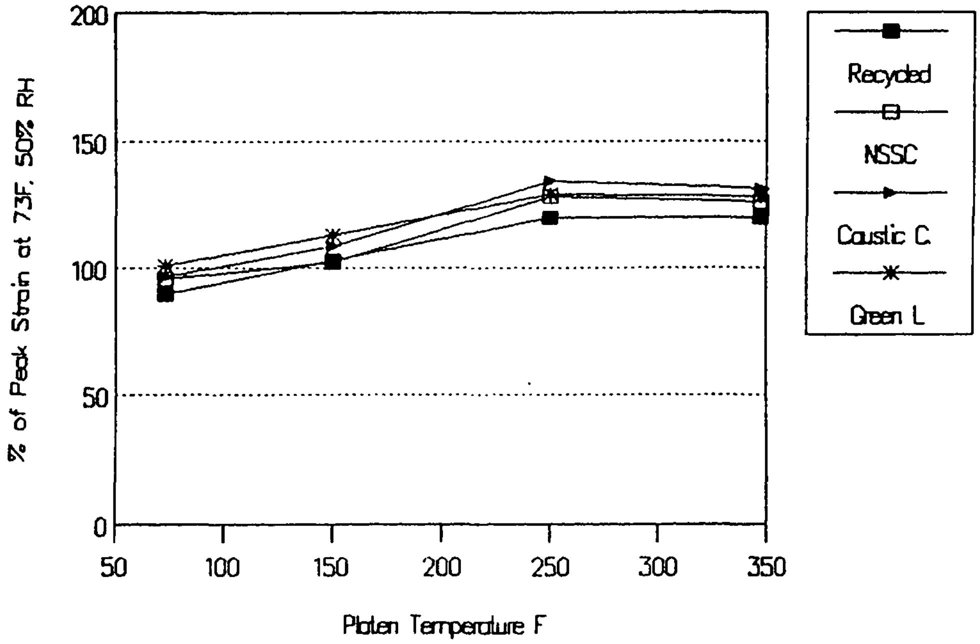

Figure 21. The percentage change in peak strain as a function of temperature for the four medium pulping types at the initial moisture content of 5.6% when compared to a standard test with a platen temperature of 73°F and initial moisture content of 7.2%.

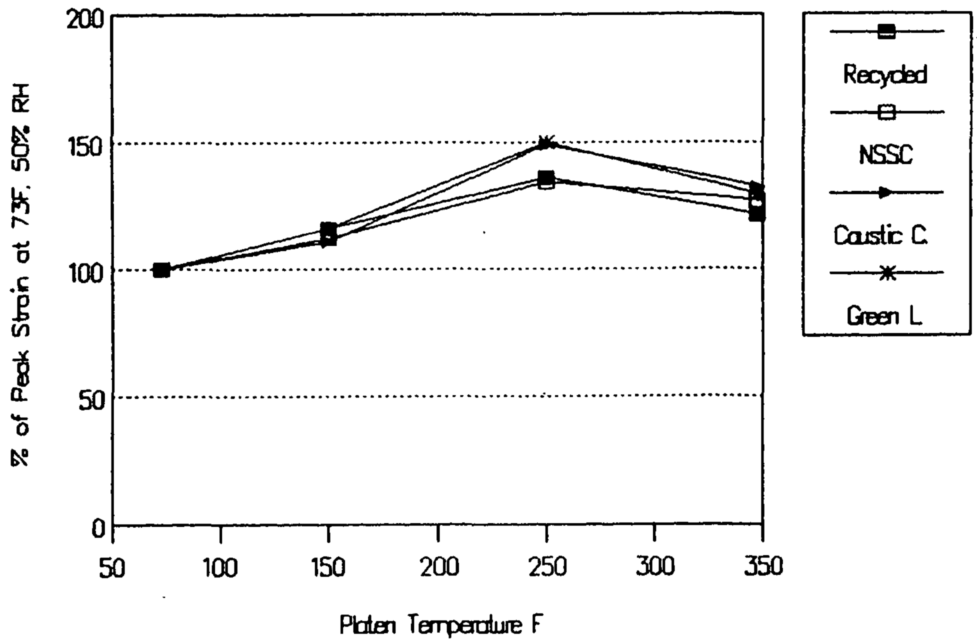

Figure 22. The percentage change in peak strain as a function of temperature for the four medium pulping types at the initial moisture content of 7.2% when compared to a standard test with a platen temperature of 73°F and initial moisture content of 7.2%.

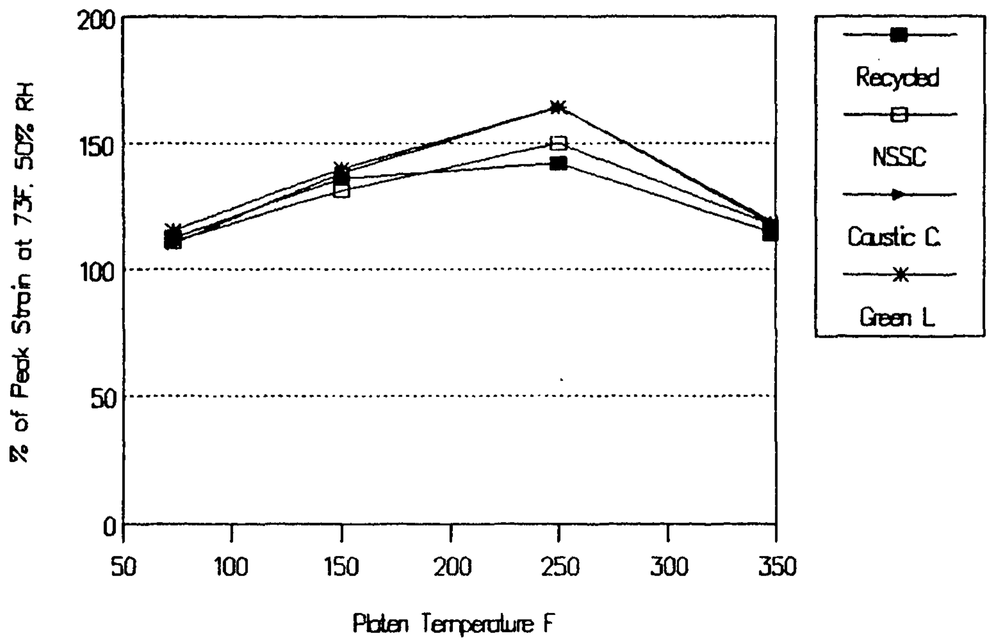

Figure 23. The percentage change in peak strain as a function of temperature for the four medium pulping types at the initial moisture content of 9.1% when compared to a standard test with a platen temperature of 73°F and initial moisture content of 7.2%.

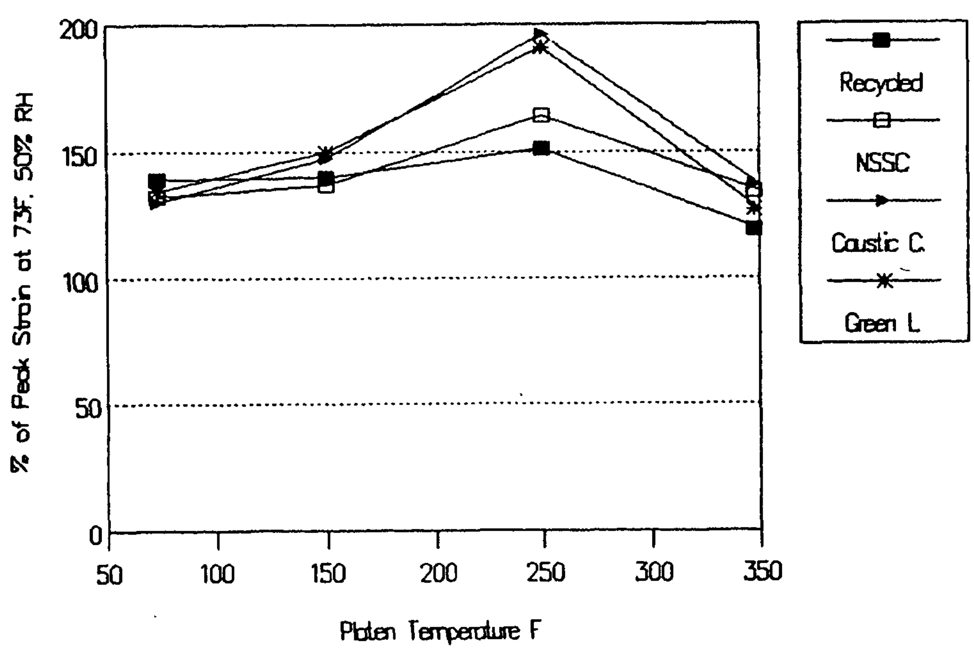

Figure 24. The percentage change in peak strain as a function of temperature for the four medium pulping types at the initial moisture content of 13.9% when compared to a standard test with a platen temperature of 73°F and initial moisture content of 7.2%.

CONCLUSIONS

To summarize the effects of temperature and initial moisture content on MD tensile strength and stretch it may be concluded that:

1. Temperature has two counteracting effects on tensile behavior of the medium: A plasticizing effect which tends to increase the stretch and reduce the tensile strength, and a drying effect which tends to decrease the stretch and increase the tensile strength of the sheet.

2. For the different mediums of the four major pulp types tested at various levels of initial moisture content, there exists a critical temperature below which the plasticizing effect is dominant and above which the plasticizing effect is strongly counteracted by the drying of the sheet.

3. The extent of drying effect at temperatures beyond the critical temperature is strongly influenced by the initial moisture content of the sheet. The drying effect becomes more significant as the initial moisture content is increased.

4. At very low levels of initial moisture content (e.g., 5.6%) the drying effect is either negligible or totally absent. At temperatures below the critical temperature (i.e., below 250°F) a nearly linear decrease in tensile strength is accompanied by an almost linear increase in stretch for mediums of all pulp types. At temperatures beyond the critical temperature the stretch reaches a constant saturation value, while the tensile strength continues to decrease almost linearly.

5. The influence of drying and plasticizing effects on tensile strength and stretch are totally different. In the case of tensile strength, the drying effect almost counterbalances the plasticizing effect, thus giving rise to an almost constant tensile strength beyond the critical temperature. On the other hand, the drying effect is more dominant for stretch, thus decreasing the stretch beyond the critical temperature regime. The extent of stretch losses becomes more significant at high levels of initial moisture content.

6. There exist optimum conditions for temperature and moisture, for which the increase in stretch values more than compensates for decreases in tensile strength. Such optimum conditions should result in better corrugated runnability, thus reducing high-lows and fluting damage. The results of these experiments indicate that it is best to keep the nip temperature and moisture contents at about 250°F (the critical temperature) and 7 - 10%, respectively.

7. The pulp type is found to strongly influence the stretch behavior and, to a lesser extent, the MD tensile strength of a medium.

ACKNOWLEDGMENTS

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Mohsen Paul Sarfarazi
Assistant Professor
Engineering and Paper Materials Division

Richard Ellis
Director,
Engineering and Paper Materials Division