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MEASURING THE MECHANICAL BEHAVIOR OF PAPERBOARD IN A CHANGING HUMIDITY ENVIRONMENT

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MEASURING THE MECHANICAL BEHAVIOR OF PAPERBOARD IN A CHANGING HUMIDITY ENVIRONMENT

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ABSTRACT

Both the strength and stability of compressively loaded paperboard are known to be adversely affected by cyclic changes in relative humidity. Current research at the Forest Products Laboratory (FPL) seeks to observe and explain this phenomenon and to develop a simple, practical test to determine allowable "working loads" in cyclic moisture environments. A new research apparatus has been developed to measure creep strain, stiffness, and strength in constant and changing humidity environments. Early results link cyclic change in relative humidity with significant loss in compressive strength and suggest the existence of a critical load value above which cyclical humidity changes are progressively destructive to the integrity of the web structure. Current efforts are directed toward evaluating the relationship between strength loss, creep load, rate of humidity change, and number of humidity cycles. We anticipate this work will result in a method for "derating" the compression strength of paperboard when used in applications involving changes in moisture content.

INTRODUCTION

Recent experiments conducted by Laundrie at the FPL (1) dramatically illustrate the effect that exposure to cyclic relative humidity (RH) can have in reducing the stacking life of corrugated containers. Laundrie applied a top-to-bottom compressive load at 25% of the machine compressive strength (based on 23°C, 50% RH) to corrugated containers measuring 470 mm by 320 mm by 360 mm.

Laundrie's containers were made from common 42-26-42 singlewall corrugated board using a water-resistant adhesive. Containers subject to constant 80% RH storage carried load for 72 d on average. Those exposed to a 30%-80%-30% RH cycle, on a 24-h period, had an average deflection rate nine times that of the containers held at constant 80% RH conditions--and failed in only 4 days! Dramatic as these results are, they are not unexpected.

Byrd at FPL (2) reported accelerated creep in corrugated board specimens subject to cyclic RH in 1972. Since that time, several papers by Byrd and Back, et al. at the Swedish Forest Products Laboratory have reported the effects of moisture change on the strength and elastic properties of corrugated board and component paperboards. Byrd has shown that creep rate varies with furnish, that cyclic creep rates can exceed rates at constant RH by as much as a factor of nine, and that creep rates for corrugated boards significantly exceed those for the component paperboards (3-4).

Back, Salmén, and Richardson report that there is a measurable transient reduction in tensile strength and stiffness during the sorption process as moisture content is increased and decreased (5-6). Back has also shown that compressive strength and extensional stiffness are more sensitive to changes in moisture content than is tensile strength (7).

Both Byrd and Back have stated that the magnitude of these effects is directly related to the rate of moisture sorption. It is clear that we should anticipate reductions in container stability, strength, and duration of load in transient moisture conditions. But it is not yet apparent how our current knowledge can be used to evaluate strength and duration-of-load performance in a way that is useful to papermakers and the packaging industry.

The objective of ongoing work at the FPL is to observe the structural behavior of paperboard under conditions of cyclic RH change and long-term loads, and to develop a simple, practical measure of paperboard strength under changing moisture conditions experienced in the end use environment. This report is an overview of our work to date.

APPARATUS

We have begun by developing an apparatus that permits us to measure creep strain, stiffness and compressive strength of paperboard under static and changing humidity conditions. A previously developed vacuum restraint method provides the lateral support necessary to prevent buckling under compressive load (8) and hastens equilibration to changes in humidity. We are, therefore, able to evaluate response to humidity changes with very short cycle times (nominally 10 min per cycle) as well as the much longer cycle periods normally experienced in actual storage conditions.

[1]Maintained at Madison, WI, in cooperation with the University of Wisconsin.

Fig. 1 illustrates the system for flexible control of relative humidity. Air is drawn into the test chamber through a flow control valve which proportions the "mix" of ambient and saturated air. A humidity sensor in the chamber monitors RH and provides continuous instructions to a programmable stepper-motor to produce specified cyclic RH profiles. Sinusidal RH profiles from 10 min to 4 h in duration can be produced. Other profiles such as linear, ramp, sawtooth, and step can be generated if desired. Temperature is constant at 23°C.

Fig. 2 depicts the functions of electrical and mechanical devices used to apply a constant creep load to the paperboard specimen and to create a sawtooth load pulse for periodic stiffness measurements. Creep load is applied to the specimen by a spring. Electrical solenoids apply supplemental, tensile and compressive load excitation. A load cell measures the force applied by the solenoids and returns a signal to the difference amplifier which, in turn, adjusts the solenoid current to achieve a precise match between the specified and actual load.

The solenoid armatures float in response to shrinking and swelling of the specimen as its moisture content changes. An extensometer (not shown) riding on the specimen measures strain caused by moisture change, creep, and stiffness-measurement excitation. The solenoids can be used to apply creep load in lieu of the spring, if stiffness measurements are omitted during the creep test.

This setup can also be used to obtain load deformation curves by omitting the spring and changing the specified load signal to achieve a ramp load through the solenoids.

TEST OPTIONS

The apparatus of Figs. 1 and 2 provides the flexibility necessary to conduct a variety of vital experiments. Test sequencing and data collection are performed by a personal computer. The current repertoire of tests performed with this apparatus includes measurementof

-- Compressive strength at specified load rates and RH.

-- Deformation in response to change in relative humidity (dimensional stability).

-- Creep deformation at fixed load in cyclic and constant RH environments.

-- Stiffness change during creep deformation--cyclic and constant RH environments.

-- Creep response to increasing load in a cyclic RH environment.

-- Equilibration rates for strain and stiffness in response to humidity change.

RESULTS

Load deformation curves for a handsheet of mixed hardwood furnish equilibrated at 23°C,

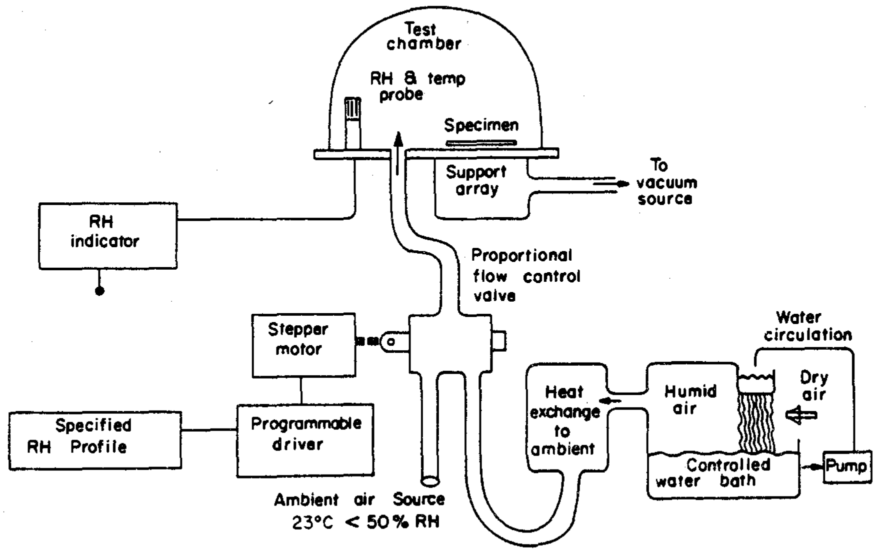

Fig. 1 Specimen support and humidity control system. Cyclic RH profiles from 10 min to 4 h in duration are available. (ML86 5199)

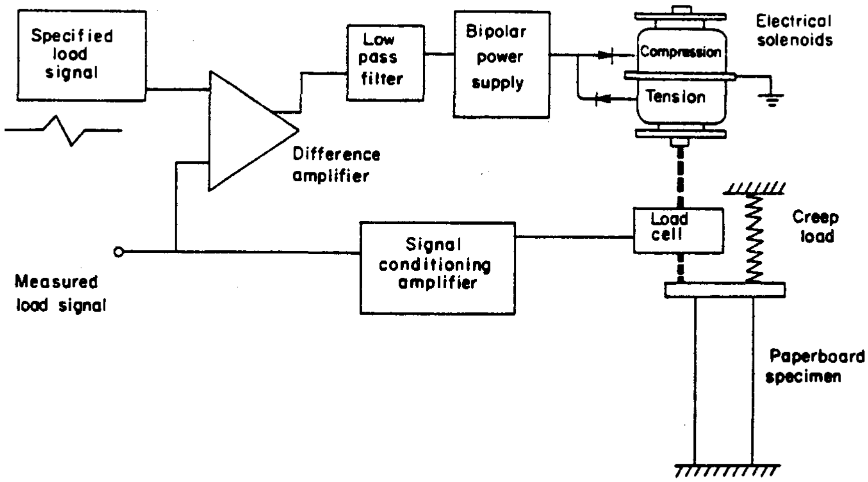

Fig. 2 Configuration for continuous application of creep load and intermittent excitation for stiffness measurement. (ML86 5200)

50% and 90% RH are shown in Fig. 3. These curves depict the loss in stiffness and compressive strength we anticipate from an increase in the ambient RH. It is interesting that, in compression, the increase in RH does not result in a large increase in strain to failure as is seen in tensile tests (9).

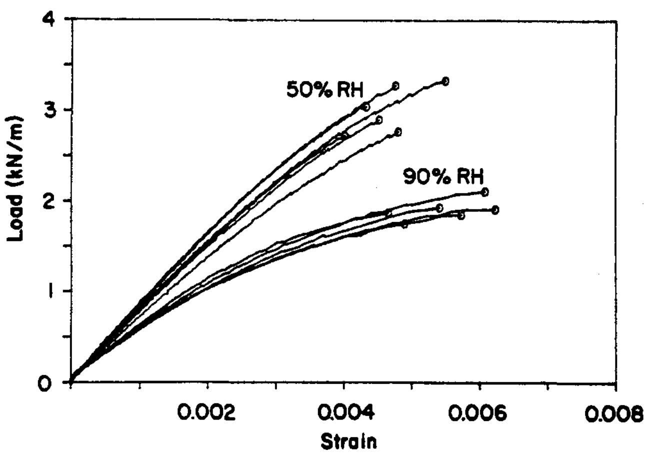

Fig. 3 Compressive load-deformation behavior of a mixed hardwood handsheet at 23°C, 50% RH and 90% RH. Basis weight 133 g/m², density 556 kg/m³. Six replicates at each moisture level are shown. (ML86 5201)

When paperboard specimens are subjected to a constant compressive load in an environment where the humidity cycles between 50% and 90% RH, however, we find that the load carrying ability is actually far less than the strength measured at 90% RH. This is evident in our tests of paperboard endurance at fixed compressive load.

Figs. 4 and 5 show compressive creep strain and stiffness change, as a function of time, for a compressively loaded softwood handsheet specimen in a 50%-90% cyclic RH environment. The load applied to the specimen is 22% of the measured compressive strength at 50% RH. The humidity is cycled nine times prior to the application of load at point "A." Failure occurred in the 27th cycle under load. Compressive creep strain at the time of failure was nearly twice the strain to failure measured for this material in a conventional, constant-rate-of-load, compression test at 50% RH.

Fig. 5 shows the rapid decline of extensional stiffness, characteristic of those cyclic RH creep tests which end in early failure. Figs. 6 and 7 show the compressive strain and stiffness change for the same material at a lower load level (17% of the compressive strength at 50% RH). In Fig. 6, we see the rate of creep strain moderating throughout the test so that the creep rate after 40 h of test is far less than that initially observed. We also see extensional stiffness stabilizing as the test progresses (Fig. 7).

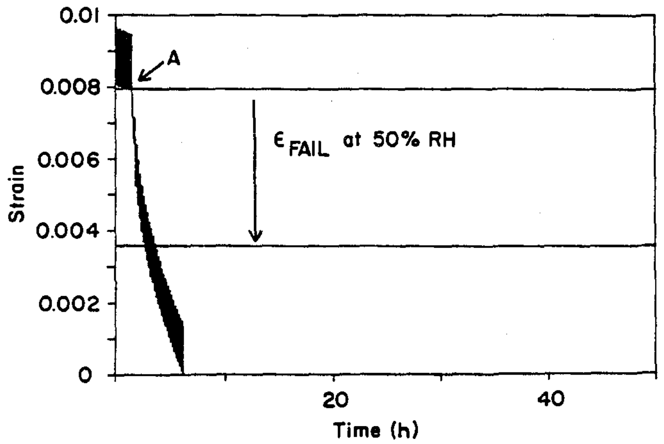

Fig. 4 Compressive creep stain at 22% of compressive strength. Moisture cycles 50%-90% RH, 10-min period. Softwood handsheet; basis weight 123 g/m², density 323 kg/m³. Load applied at point A. Specimen failed under load at 27 moisture cycles. Plotted on 50-h time scale for direct comparison with Fig. 6. ε_{FAIL}= strain to failure. (ML86 5202)

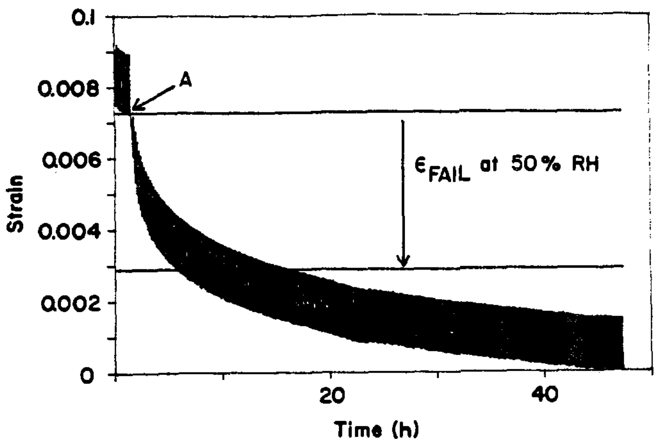

Fig. 6 Compressive creep strain at 17% of compression strength. Moisture cycles 50-90% RH, 10-min period. Softwood handsheet; basis weight 125 g/m², density 323 kg/m³. Test terminated at 274 moisture cycles without failure. ε_{FAIL} = strain to failure. (ML86 5204)

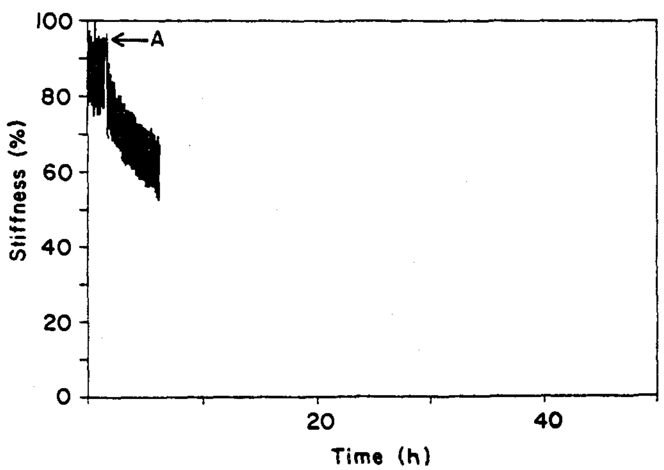

Fig. 5 Extensional stiffness change for cyclic RH creep specimen of Fig. 4. Load applied at point A. Stiffness shown as percent of pre-load stiffness. Plotted on 50-h time scale for direct comparison with Fig. 7. (ML86 5203)

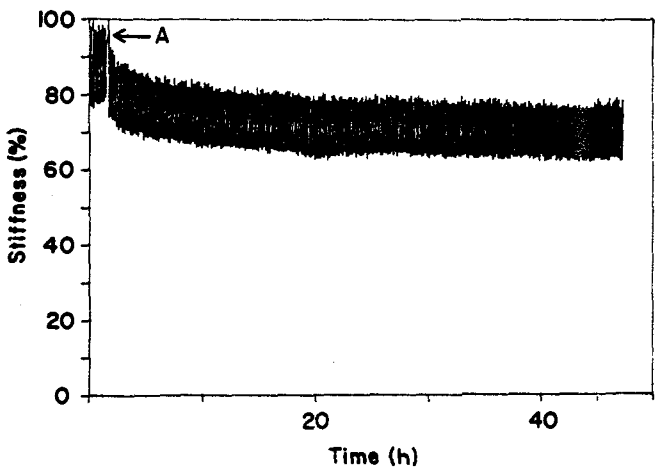

Fig. 7 Extensional stiffness change for cyclic RH creep specimen of Fig. 6. Stiffness shown as percent of pre-load stiffness. (ML86 5205)

Later humidity cycles apparently have little effect on the structural integrity of the web at this load level. From these two sets of figures, we observe that (a) in the cyclic-RH environment this specimen failed rapidly at just 22% of its compression strength, and (b) a reduction in load from 22% to 17% of maximum yields a dramatic increase in durability.

These results, typical of our experience with several paperboards, suggest that there is a critical load level above which the cyclic RH creep process is progressively destructive; but below which creep and stiffness stabilize to develop long durations of load. If our inference is correct, and there is a critical load value which marks the transition from benign to destructive creep, that value has practical significance as the "working strength" for paperboards used in changing humidity environments.

Working strength could be determined by conducting a large number of creep tests at various constant loads. A more efficient approach, however, appears to be one in which the creep-load applied to a given specimen is gradually increased, at intervals, during repeated moisture cycles, as illustrated in Fig. 8. Below critical load, moisture cycles would be expected to cause creep but would not degrade the structural integrity of the specimen. Above the critical load, humidity cycling would damage web structure, reduce stiffness, accelerate creep rate, and rapidly lead to failure.

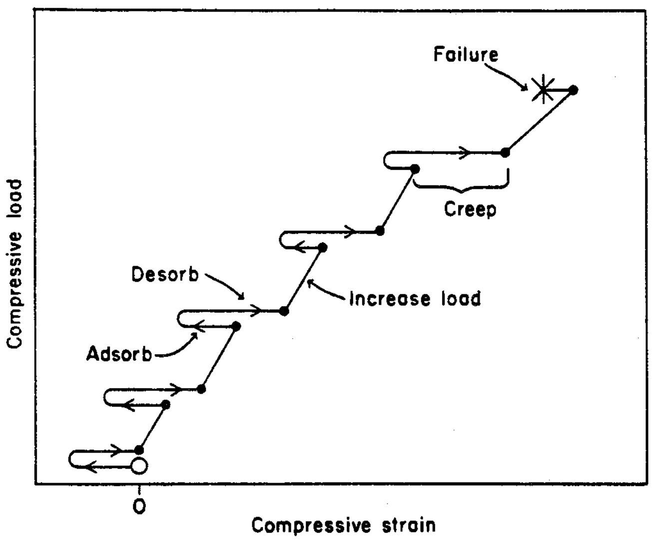

Fig. 8 Load-deformation "curve" illustrating concept for incremental increase in load applied to specimen during cycle RH creep tests. Load increases coincide with 50% RH conditions. (ML85 5206)

The creep curve in Fig. 9 shows the response of a softwood handsheet specimen to a gradually increasing load. Load has been increased in ten steps from 0 to .945 kN/m. RH is cycled between 50% RH and 90% RH ten times at each load. Rate of strain increases exponentially just prior to failure. Failure occurs at 32% of the known compressive strength at 50% RH, equivalent to 42% of the strength at 90% RH.

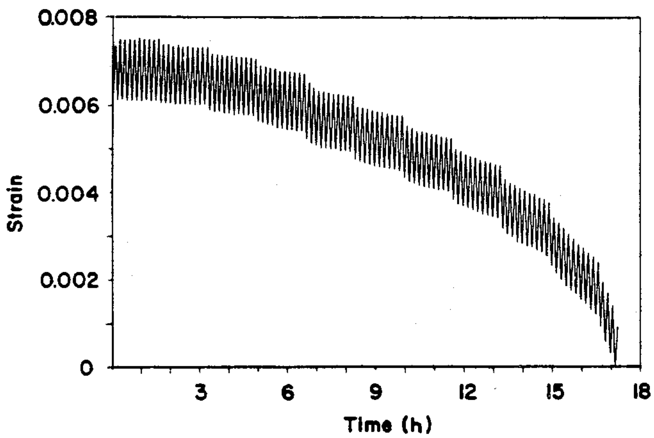

Fig. 9 Creep strain response to increasing load in a cyclic RH environment (50%-90% RH). Ten RH cycles at each load value. Failure at 32% of compression strength after 103 cycles. Softwood handsheet, basis weight 129 g/m^2, density 566 kg/m^3. (ML86 5207)

Our experience with this method of cyclic RH testing indicates that the failing load is a fraction of the compressive strength measured at a constant 50% RH and is relatively insensitive to the number of humidity cycles repeated at each load.

STATUS AND FUTURE WORK

Three characteristics of results obtained thus far suggest consideration of a derated, working strength value for paperboards used in cyclic RH environments:

1. Cyclic RH endurance (defined as the number of RH cycles possible at a given load) drops precipitously at a critical load level well below the compressive strength at 90% RH. (We propose to call this lower load level the "working strength.")

2. Web stiffness declines with repetitive RH cycles when applied load exceeds the working strength--but tends to stabilize at lesser loads.

3. When creep load is applied gradually in a cyclic RH test, rate of strain increases exponentially as applied load approaches the working strength--and failure quickly follows.

We think the working strength concept (if verified in future tests) could be a most useful approach to dealing with the load-carrying ability of corrugated containers in real-world environments. We have a versatile and reliable test apparatus "in-hand." Further work will examine the effect of changes in cyclic RH rate and period on working strength, and evaluate. the adequacy of this concept as a means to explain and predict duration-of-load behavior.

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