CHARACTERIZATION OF PAPERBOARD, COMBINED BOARD, AND CONTAINER PERFORMANCE IN THE SERVICE MOISTURE ENVIRONMENT

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ABSTRACT

Corrugated container performance has traditionally been measured under static loading and environmental conditions but not under the cyclic moisture conditions often imposed in the shipping environment. Feasible methods have been developed to measure paper properties under the loading and environmental influences expected in service. These new testing methods for paperboard, corrugated board, and containers will permit evaluation of the creep-rupture and hygroexpansive behaviors under a wide range of environmental conditions.

KEYWORDS

Corrugated boards, humidity, compression tests, bending tests, stacking strength, cyclic humidity

INTRODUCTION

A need exists for an industry standard for measuring or predicting the performance of corrugated containers in the dynamic relative humidity environment in which these containers are often transported and stored. At present, no methods are available to properly evaluate the performance of the board components (linerboard, corrugating medium and its combining adhesive) or combined board other than the methods at constant 50% relative humidity (RH). A cooperative research program with the USDA Forest Service. Forest Products Laboratory (FPL), and the structural paper industry is underway to develop appropriate testing and analysis methodologies to predict the performance of containers. These methodologies will undoubtedly include new standards for the evaluation and specification of corrugated board and component paperboards.

In 1963, McKee, Gander, and Wachuta developed a simplified formula for estimating top-load compression strength of corrugated boxes (1). The industry standard "McKee formula" predicts compression strength of corrugated containers based on the edgewise compression test (ECT) and bending stiffness of the combined board from which the container is made. The McKee method is perhaps the best known, most widely used technique for predicting box strength under fixed environmental conditions.

Since the 1970s. investigators have studied the behavior of converted and unconverted structural paper under dynamic environmental conditions (2, 3, 4, 5, 6, 7). Thus, we know that the load-carrying ability of paperboard, combined board, and containers is dramatically reduced by fluctuating or cycling of relative humidity conditions. Humidity changes regularly occur in the real world (8), and conversion factors are typically used to reduce the McKee value to a "design" stacking strength. These factors range from 60% (90 days of loading at 50% RH) to 11% (1 year of loading at 90% RH). Thus, corrugated containers are evaluated for their perfomance at constant 50% RH conditions without regard to how differing types of liners, mediums, or adhesives might be affected, either singly or as a system by the "true" service environment.

The objectives of the FPL cooperative cyclic moisture research program are to develop the following:

1. Tests for components of containers (linerboard and corrugated medium) that measure their dimensional stability, creep resistance, and time-to-failure properties in controlled cyclic environments.

2. Methodologies for assessing the structural performance of combined board (properties measured in controlled and simulated service environments).

3. Relationships between paperboard components, combined board. and container performance in service environments.

4. Empirical and mechanistic tools for the design of corrugated containers subjected to realistic transport and storage environments.

METHODS

The program of research underway at the FPL utilizes performance indicators for three levels of structure pertinent to corrugated containers. These three levels (paperboard, combined board, and containers) are evaluated in controlled cyclic humidity and constant environments to establish relationships between each level of structure. The approach is based on time-related measures of performance including those at fixed humidity and temperature conditions and a range of cyclic environments. These performance measures will relate deformation over time while under a fixed load to time to failure (or loss of structural integrity). It is also believed that moisture sorption rates and the dimensional stability of each structural level will be key parameters in the determination of container performance in the service environment. Evaluation methods used to characterize the cyclic humidity performance of paperboard, combined board. and containers are described and preliminary results are used to illustrate their efficacy.

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Paperboard Component Evaluations

Linerboards and mediums used in constructing corrugated boards are considered as the lowest structural level expected to be of importance to the paper industry. Evaluation of these materials for their cyclic moisture-related performance under compressive loading was reported by Considine and Gunderson (7), using an apparatus that recently was made commercially available. In the FPL cyclic moisture research program, creep tests, similar to those of Considine and Gunderson, were conducted on an apparatus consisting of a load frame, a means of lateral support, and a system for generating a controlled relative humidity in a small environmental chamber. A vacuum restraint provides the lateral support necessary to prevent buckling under compressive load and hastens the equilibration of the specimen to relative humidity changes. A microcomputer controls the applied load and chamber relative humidity, measures deformation, and stores pertinent information during testing. This apparatus also measures paperboard extensional stiffness and deformation during humidity changes, and the apparatus can be programmed to simulate a variety of environmental conditions.

Data generated from the apparatus, coined the Vacuum Compression Apparatus (VCA), illustrate a three-phase creep-rupture behavior for paperboard (Fig. 1). Figure 1 shows data from each maximum or minimum of the 50% to 90% RH sinusoidally shaped relative humidity function. The constant creep rate was successfully related to the time-to-failure behavior and was indicated as a good predictor of time to failure (Fig. 2). Additionally, extensional stiffness loss was found to clearly accompany creep deformation. Thus, the correlations of the minimum creep rate and the minimum extensional stiffness loss rate are good predictors of time to failure of a paperboard under known and controlled cyclic moisture conditions.

The paperboard compressive creep tests under cyclic humidity conditions led Considine and Gunderson to the conclusion that an acceptable load level in cyclic humidity environments was less than 30% of the short-term compressive strength measured at 50% RH (7). They also reported the result of cyclic humidity environments creating failure strains that are two to three times greater than the short-term 50% RH compressive failure strains. This method of testing paperboard has great potential for relating component material properties in controlled conditions to the performance of the material in the service environment.

Combined Board Creep Evaluations

A key component for evaluating the performance of paperboard and containers in the service environment is the behavior of combined board. Combined board provides challenges to understanding the mechanosorptive creep interactions caused by multilayer and multimaterial construction, addition of a combining adhesive, and influences of such phenomena as localized buckling of the structure. between or within, the corrugations. Also, the situation would be more readily understood if a single moisture transport process were at work that moved water through the linerboard to the flute spaces.

A research tool that assists in understanding the compression (ECT). bending (four point), and dimensional stability interactions in combined board has been developed at the FPL (9). The bending and compression tests and dimensional stability measurements were chosen because they are known to relate to top-to-bottom compression strength and deformation of containers. This research tool is a multispecimen test unit that holds 28 ECT specimens and 30 four-point-bending test specimens. Loading is achieved through dead weights acting directly or through lever arms. Deformation monitoring of the 58 test specimens is conducted robotically using a computer-controlled sensor that imparts minimal load to the specimen. An additional 20 specimens on the test unit are used to monitor parameters such as Z-direction and flute-direction dimensional changes.

Preliminary results from use of the test unit show the load-induced creep and moisture-induced deformations resulting from specimens loaded in cyclic humidity conditions (Fig. 3). Note that, in this particular case, desorption decreased the bending deformation and increased the ECT deformation during the 6-h sinusoidal-cycle excursions between 50% and 90% RH. We used two materials. A and B. (which differ only in that A has a water-resistant, starch-based adhesive and B has a pearl-starch adhesive) to illustrate the capability for differentiation possible in this evaluation. These materials have identical strength and stiffness in bending and compression at 50% RH and were loaded at the same level in the simple bending and compression evaluations.

Differentiation of these nearly identical materials was achieved in the bending tests (Fig. 4) after two full cycles. The compression tests (Fig. 5) required additional cycles to illustrate a different performance between the A and B materials. Also note that the sensitivity limits of the hardware were approximately 0.013 mm (0.0005 in.). The creep deformation being measured was quite small on these Tappi Standard 38- by 51-mm (1.5- by 2.0-in.) ECT specimens.

Container Dead-Load Testing

The final structural level to be considered is the container itself. Variables that affect the container stacking strength range from quality of the scoreline to type of end closure to flowability of the enclosed material. Thus, the container evaluations must be simple enough to allow for the minimum number of tests and to generate simple performance indicators. Top-to-bottom compression strength is such an indicator for single containers. Leake utilized entire pallets of containers for initial stack-life comparisons and then ran similar static creep load tests on combined board specimens (5). Similar behaviors were noted. However, any correlation between combined board, or paperboard. and container performance should be improved by use of controlled cyclic conditions and single containers under long-term static compression loading.

Using the same A and B materials that were used in the combined board evaluations. we tested containers in static long-term compression. A total of 36 containers were loaded singly at two load levels. 30% and 35% of the box compression strength. Conditions were between 50% to 90% RH on a 6-h sinusoidal cycle. Tests were initiated at the 50% condition. and deflections were monitored for the duration of the test (Fig. 6). The secondary creep rate was regression fit to the data and was plotted as average values (Fig. 7).

Note that creep rate is directly proportional to the time to failure. Implications of that behavior are contrary to the observations made by Leake and Wojcik (6). Although deflections to failure are not given here, they do indicate a reduced "ductility" for those containers with short lifetimes. Containers under load in the uncontrolled, open warehouse creep tests have produced limited data. More infomation needs to be collected for the service environment tests (Fig. 8) to allow a correlation to be made to the moisture content of the paperboard structure.

CONCLUDING REMARKS

The moisture response of corrugated containers is of interest to researchers and to the shipping industry because of significant economic implications. Corrugated container performance has traditionally been measured under static loading and environmental conditions but not under the dynamic and cyclic moisture conditions often imposed in the shipping environment. Moreover, our research interests must be concerned with how the service environment effects the entire family of components--liners. mediums, and adhesives, which combine to produce board and containers subjected to the rigors of the "real world." For additional justification, consider that containers are the largest end use of paper and that the time-related loss of strength with exposure to moisture is the largest reduction in compression strength for design of containers.
Feasible methods nave been developed to measure paper properties under the loading and environmental influences expected in service. These new testing capabilities for paperboard, corrugated board, and containers permit evaluation of the creep-rupture and hygroexpansive behaviors under a wide range of environmental conditions. Analytical means for modeling the moisture effects upon structural use for paper are needed to relate nonlinear material properties, creep behavior, and time-to-failure characterizations to the serviceability of containers in use.

This paper describes limited preliminary evaluations in environmental and mechanical testing facilities. The facilities are climate-controlled chambers that individually simulate profiles of changing temperature and humidity experienced in virtually any "real-world" service environment. These environmental chambers house the mechanical testing equipment that, under computer control, robotically monitor and load the paperboard, combined corrugated board, and containers to simulate actual loading conditions. In addition, containers are being monitored in open warehouse locations to provide data for realistic environments.

Evaluation methods and preliminary data are presented to elucidate the environmental cycling influence on materials combined with two starch-based adhesives to demonstrate the capability of relating component behaviors to container performance. Data collection and analyses continue with a 3-year program of research sponsored by the American Paper Institute.

This research program will build a database of properties for relating test performance to component behavior in the rigors of the simulated service environment.

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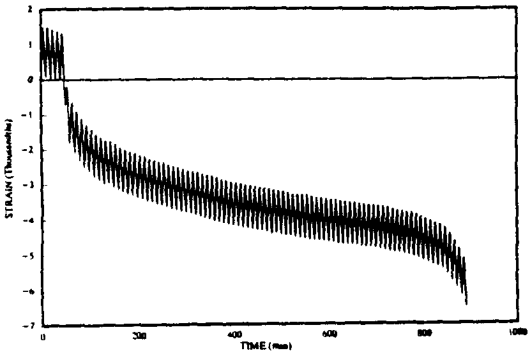

Figure 1. Example of paperboard creep strain upon application of a compressive load after five cycles of 50% to 90% RH preconditioning.

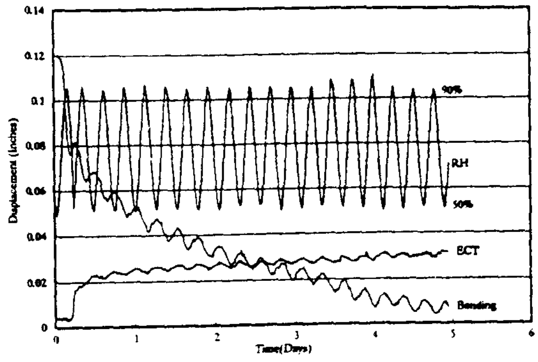

Figure 3. Typical data generated from the Combined Board Creep Apparatus includes ECT and bending deformation.

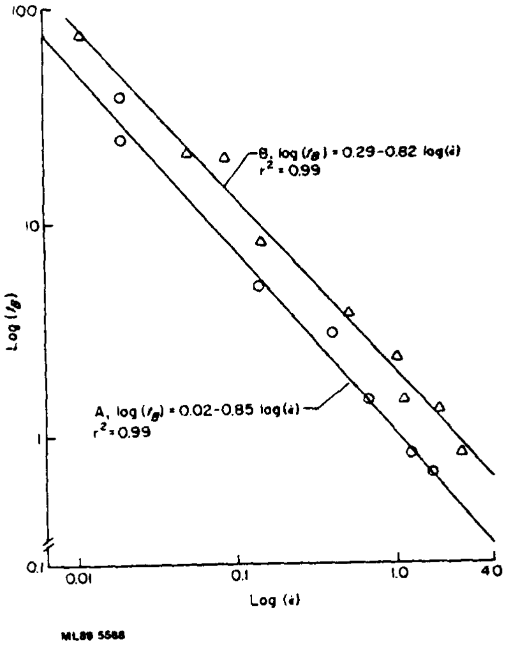

Figure 2. An accurate predictor of time to failure (t_B) resulted from use of creep strain rate ($\dot{\epsilon}$) (7).

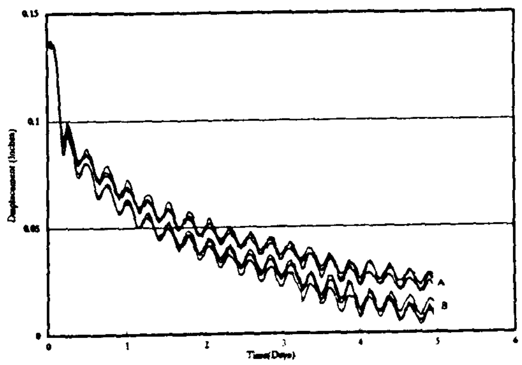

Figure 4. Bending tests in 50% to 90% RH environment of two combined board materials (A and B) illustrate distinctive performance traits.

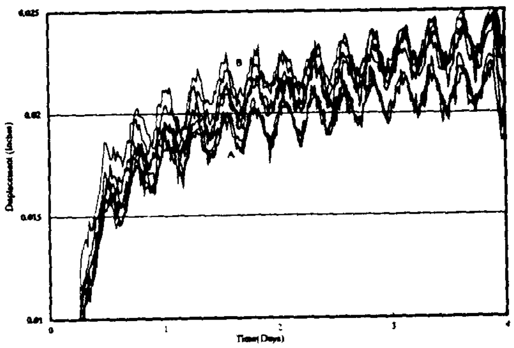

Figure 5. Edgewise compression tests of two materials in a 50% to 90% RH environment.

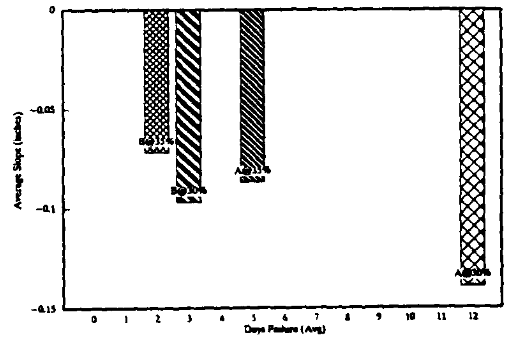

Figure 7. Minimum creep rate (average slope) is directly proportional to time to failure for these 36 container tests.

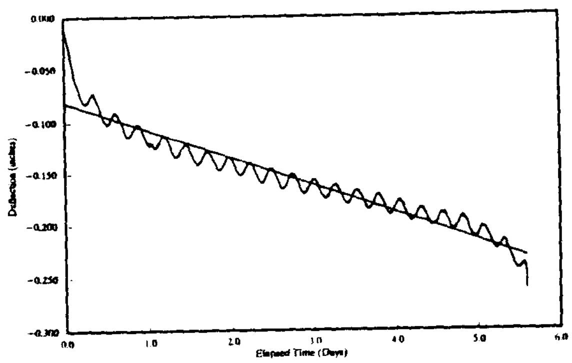

Figure 6. Single container subjected to top-to-bottom compression loading while being cycled between 50% and 90% RH.

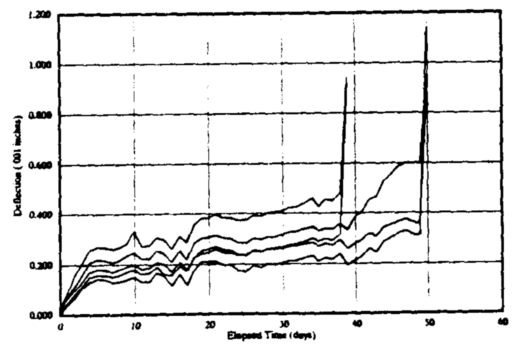

Figure 8. Single container top-to-bottom deflection behavior tested to failure in an open warehouse environment for four containers.

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Research outputs, collaborations and relationships for Forest Products Laboratory (FPL), USDA Forest Service published between 1 June 2019 - 31 May 2020 as tracked by the Nature Index.Â The table to the right includes counts of all research outputs for Forest Products Laboratory (FPL), USDA Forest Service published between 1 June 2019 - 31 May 2020 which are tracked by the Nature Index. Hover over the donut graph to view the FC output for each subject. Below, the same research outputs are grouped by subject. Click on the subject to drill-down into a list of articles organized by journal, and then by title. Note: Articles may be assigned to more than one subject area. Count. Share. The USDA Forest Service also has an extension Fungal Collective located in Madison, Wisconsin that contains material available for research and/or commercialization. The technologies below also provide a listing of the USDA Forest Service, Research & Development research capabilities and facilities available for research partnerships. Mission. The mission of USDA Forest Service is to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations. Partnerships: Partnerships are a critical component of the USDA Forest Current APA Research. USDA Forest Service Forest Products Laboratory. Research in Progress. FPL Newsline.Â The dynamic multiple-use laboratory allows scientists to perform full-scale testing of wood-framed buildings, formulate new environmentally friendly wood preservatives, develop advanced composite products in a manufacturing-friendly space, and test the durability of wood products with a one-of-a-kind weathering chamber. Learn more about FPL's Research in Progress. Contact FPL. USDA Forest Service Forest Products Laboratory One Gifford Pinchot Drive Madison, WI 53726 Phone (608) 231-9200 Email: mailroom_forest_products_laboratory@fs.fed.us Website: http://www.fpl.fs.fed.us/. Fast Facts abo US Forest Service Patent Program. Information. People & Places.Â Convinced there had to be a better way, researchers from the Forest Products Laboratory (FPL) investigated the use of remote sensing technologies to monitor the structural components of bridges and homes and transmit the findings to the internet cloud for interpretation. Early detection of termite activity could dramatically reduce the costs view Â». Topic: Forest products industry Bibliography. U.S. Forest Service Forest Products Laboratory. 107 107. Forest Products Laboratory list of publications on milling and utilization of timber products.Â Forest Products Laboratory list of publications on glue, glued products, and veneer Topics: Wood Periodicals, Forest products Research United States. U.S. Forest Service Forest Products Laboratory.