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EVALUATION OF THE COMPRESSION STRENGTH OF CORRUGATED SHIPPING CONTAINERS HELD IN FROZEN FOOD STORAGE

By

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ABSTRACT

EVALUATION OF THE COMPRESSION STRENGTH OF CORRUGATED SHIPPING CONTAINERS HELD IN FROZEN STORAGE.

By

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Set-up corrugated boxes were stored in frozen environment for a period from 1 to 92 days. Boxes were removed and evaluated for compression strength. Compression strength of boxes held at 23°C, -31.7°C and -40°C storage were determined. Compression strength and moisture content of wax-coated boxes and uncoated boxes filled with vegetables were also determined at -31.7°C. The effects of thawing and freeze-thaw cycling on compression strength of boxes were determined.

Compression strength of boxes was greater under frozen condition than at 23°C. Frozen moisture partially contributed to increased compression strength. Change in physical structure during freezing was suggested as a possible contributory factor in increased compression strength. Wax-coated boxes held in frozen storage substantially increased in compression strength. Thawing of frozen boxes reduced compression strength with less reduction found for

wax-coated boxes. Boxes tended to regain strength when refrozen. Freeze-thaw cycling did not affect compression strength of frozen boxes.

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Dedicated to

my parents for their continued

support and prayer for my

success in life.

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INTRODUCTION

The properties of corrugated fiberboard have been studied extensively in order to predict behavior in usage. Despite generation of a broad data base on the mechanical properties of corrugated containers under ordinary conditions of storage, little research has been made on what happens when the board is put in use under frozen conditions, as in the frozen food industry.

The compressive strength of shipping containers is an important factor during storage and distribution of frozen food. This property is affected by moisture content in the board, which also is a function of the relative humidity and temperature of storage and distribution, equilibrium moisture interaction between box and product inserts, and exposure (position) of the box within a pallet load. During distribution, loads are exposed to loading and unloading from warehouse to truck and truck to warehouse for varying periods of time. Water condensation/absorption on corrugated boxes when unfrozen or thawed often make the cases soggy resulting in loss in stacking strength. This condition is most undesirable especially for products which do not contribute to the overall stacking strength. This can cause economic losses to warehouse operators, transporters and retailers.

Under frozen conditions, it is speculated that the moisture in boxes will become frozen, thereby, increasing stacking strength of boxes. If stacking strength increases, then it may be economical to reduce the stacking strength requirement for boxes used in the frozen food industry. This could then be a cost saving to the industry.

Evaluation of compressive strength of corrugated fiberboard shipping containers is a common test usually done on empty containers conditioned at standard Tappi (Technical Association of Pulp and Paper Industry) conditions $70 \pm 3^{o}F$, $50 \pm 2\%$ R.H. Little information is available on the compressive strength and performance characteristics of corrugated containers in a frozen distribution environment. Paper, paperboard and corrugated board are sensitive to ambient atmospheric conditions. The cellulosic fibers absorb water, swell and weaken at high relative humidities (R.H.) and release water and stiffen at low relative humidities. This characteristic contributes substantially to box compressive resistance, a measure of the performance character of the finished package and a principal criterion of measurement for the shipper. The greater the compressive strength of shipping containers, the heavier can be products to be packaged in it, and with higher stacking heights.

An important function of the package is to protect and support its content (stacking strength) in warehousing, transportation and distribution. Each of the components of the total package contributes to the strength of the whole, but it is the primary (or consumer) package and its content that must arrive at the end-point, damage free.

Traditionally, design of the shipping boxes has been based upon experience and/or trial and error methods. A safety factor system is based on experience or on what seems to work. Using this system, the weight that a box of product must withstand in a static load at the bottom of a stack is calculated. A package is then designed to that load multiplied by a judgement safety factor. Current emphasis on quality and more effective communication to identify damage has proved this system to be of limited utility.

The introduction of commercial distribution of frozen foods brought with it a unique set of problems to the packaging industry. In the case of ambient packaging, the primary requirement is exclusion of moisture vapor to maintain the product in fresh condition. In frozen foods, protection is required internally and externally. One of the most important problems in the storage and distribution of frozen foods is the change in the moisture content of both the packaging material and the food being protected. The moisture content of corrugated board affects the compression strength of the corrugated box. Moisture content of container boards tend to be in equilibrium with the relative humidity of the environment. Temperature of the environment is an important factor in the rate of moisture absorption by the corrugated fiberboards which are hygroscopic materials. These factors are becoming more important to the warehouseman, processor and retailer because of rapid changes taking place in food processing, refrigeration, transport, and distribution. These people are concerned with contributory factors dealing with package failure to minimize losses. Package failure causes loss because of: added labor cost for rehandling, damage to the product, spillage, and large pilferage losses.

OBJECTIVES OF STUDY

1. To evaluate changes in compression strength of corrugated boxes as a function of storage time in a frozen environment (-25°F). Comparison to be made to boxes held at standard (73°F, 50% R.H.) testing condition. -25°F is the temperature of refrigerated storage room available for this study.
2. To evaluate compression strength changes of boxes subjected to thawing and freeze-thaw cycles, typical of a frozen food distibution channel. This will provide guidelines for handling and management in the frozen food distribution system.

3. To determine whether moisture absorption or desorption occurs in corrugated boxes held at frozen storage temperatures for varying periods of time.
4. To compare box compression strength and moisture changes in wax-coated boxes under frozen storage conditions.
5. To determine if a relationship exists between moisture change and compression strength of corrugated shippers under frozen storage conditions.
6. To determine if moisture transfer occurs between boxes and product packed inside under frozen storage conditions.

LITERATURE REVIEW

FROZEN FOOD STORAGE

Beardsell (1961) stated that the cheapest container for frozen food may in the long run turn out to be the most expensive. This is because the least costly product almost certainly will not stand up to the stresses and strains put upon it during transportation and storage. Many of the container boxes now used in the frozen food industry were originally made for canned goods and other non-frozen products. Since these cartons were not designed for the conditions which prevail in a refrigerated warehouse, truck or box-car, an appalling number of them fail.

Beardsell (1961) listed some conditions which could cause box failures:

1. Substantial changes in the temperature, humidity and vapor pressure to which the container is subjected during storage, handling and movement from place to place.
2. Vibration of a pummelling nature which takes place aboard trucks and railroad cars.
3. Low temperatures and high air velocities which prevail when a product is rapidly cooled in a blast freezer.
4. Condensation which results from changes in temperature

and humidity, for example, when the door of the freezer is opened and warm air is admitted from outside.

5. The weight of stacking. This is the compressive loads due to stacking that must be supported by the bottom box.
6. Uneven length of storage finished products received at different times for storage at the warehouse.

It is not unusual for a palleted stack of containers to topple causing breakage. Not only are the products lost but labor is required to restack the containers and clean up the mess.

Beardsell (1961) also described some special problems when handling frozen foods:

1. The expansion of the food, as it is frozen exerts a considerable pressure on the sides of the container. The package must be equal to the job of meeting that pressure.
2. The packing of low-density, low strength items like frozen broccoli is far different from the packing of cans of tomatoes. The cans are strong and can support a great weight. The broccoli is not, even when frozen. Therefore, the container must do the job without the help of its contents. Prepared dinners and precooked frozen pie are examples of products which virtually have no inherent strength and must be packed

accordingly.

3. Irregularly shaped merchandise such as frozen chickens and turkeys present a problem. Necessarily, one finds a good deal of air space in the container holding several such birds. The container, therefore, has to be strong enough to stand up, in-spite of the voids inside.

4. At high temperature, and high humidity, moisture works its way into the paperboard fibers and the box rapidly loses much of its structural strength. During freezer defrosting, humidity changes have a particularly damaging effect on paperboard. Even when a paperboard container full of frozen food is stored at -17.8^{o}C (0^{o}F) or lower, moisture gets into the structure. The fact that it is frozen does not protect it from the problems associated with high relative humidity. A container must be chosen with due consideration for these factors.

5. Even-though frozen foods are not supposed to be permitted to thaw, lapses do happen. A careless driver may leave a load of food on the sidewalk, long enough for the container to defrost, sometimes long enough for the contents to warm up. The warming process and subsequent refreezing weakens the paperboard. If the thawing releases acids or fats from fruits, meat, etc., such agents may also contribute to paperboard failure.

TYPICAL DISTRIBUTION CYCLE

Guins (1975) stated that, in its simple form, the distribution environment for frozen food consists of the following steps:

1. Product assembly and packaging.
2. Transfer to warehouse.
3. Storage at manufacturer's warehouse.
4. Transfer to transportation vehicle (loading), truck or railroad.
5. Transportation to district or wholesale warehouse.
6. Transfer to retailers (usually by truck).
7. Handling at retailers (small truck).
8. Delivery to final consumer.

Each step has its own characteristics that individually and collectively constitute the distribution environment. Appendix 2 shows some average lengths of time used for loading and unloading (unpublished information obtained from Pillsbury Company). It is important to understand the collective effect of this environment on the performance of shipping containers and what protection products will need through distribution.

CORRUGATED SHIPPING CONTAINERS

By far, the most widely used shipping container is the corrugated box. Maltenfort (1970) summarized its functions as follows:

1. Protection. The corrugated shipping container protects the product from damage and soiling as it moves through the transportation and handling environment from producer to consumer.
2. Storage. It offers a convenient and safe method of storing a product until it is sold.
3. Advertising. It can function as an advertising billboard for the User's product while the container is in transit, storage, or display.
4. Economics. It performs the above functions at a minimal cost.

Showell (1974) described three fundamental principles of packaging to include; protection of product, maintainance of product quality and provision of attractiveness either visually or by printing or both. He said that frozen food package has one further criteria: that the material must withstand cold storage conditions without deterioration. Anon (1975) stated that an advantage of using corrugated boxes for frozen food packaging is its printability for distribution and merchandising. Janson (1974) estimated that ten to forty percent of the total physical distribution cost is costs for packaging material.

Tanaka et al (1971) compared freezing times for package forms of metal, plastic and water resistant corrugated fiberboard boxes. It was found that corrugated boxes had the shortest freezing times, particularly at high air velocities where the thermal conductivity between the coil and the box has a lesser effect on the freezing rate. He also found that tests with wooden boxes gave results similar to the corrugated fiberboard boxes.

Maj. et al (1972) reported on a method which could be used to improve strength of corrugated boxes for transport packages. These included using different starch glues with an addition of synthetic resin hardened in an acid or alkaline medium or plastic glues, for joining the board layers.

COMPRESSION STRENGTH

Box compression strength can be used as a measure of performance of the finished package and is a major criterion for the shipper. High compressive strength permits heavier product to be packaged with higher stacking heights possible.

Guins (1975) reported that compression loads during transportation and storage can be estimated based on the maximum loading height in the various vehicles and storage facilities. During storage, it is common practice to stack packages in order to more efficiently utilize available storage space. A maximum stacking of approximately 16 feet appears to be justified based on current heights of warehouses and the stacking height of a conventional fork-lift truck. Guins further stated that to verify stacking integrity of most types of packages, it is necessary to test their performance under normal stacking loads and conditions.

Kellicut and Landt (1951) conducted tests to determine the influence of storage time upon the behavior of corrugated boxes in a stack. Their results indicate that long term failure can be significantly less than the failure seen from a suddenly applied compressive force. They derived a relationship between failure load as a function of the load duration. Kellicut and Landt (1951) investigated influence of humidity upon static load tests of corrugated containers. They related the compressive strength of moist packages to dry packages by the relationship

$$P=P_o 10^{-3.01\,x}$$

where P is the compressive strength, P_o the compressive strength at 0 moisture content and x the moisture content of the corrugated material.

A simplified formula for top-load compression strength of corrugated boxes was developed by McKee, Gander and Wachutta (1963) of the Institute of Paper Chemistry, Appleton, Wisconsin. The formula is as shown below:

Top to bottom compression = 5.8745 Pm $h^{0.5076}$ $Z^{0.4924}$ where Pm = column crush in lb/inch; h = caliper of board in inches, and Z=box perimeter (2L + 2W) in inches. The formula applies only to standard conditions, 73°F (23°C), 50% R. H.

Levans (1977) stated that conversion of dynamic compression strength values for corrugated shipping containers obtained by testing boxes, to static compression strength, which indicates its load-carrying capability is accomplished through the use of a conversion factor. This factor is in the form of a percentage of the dynamic strength value, which is very much dependent on the ambient relative humidity and somewhat less on duration of storage. The conversion factors have recently been more precisely defined through an Institute of Paper Chemistry study (1972), (Appendix 3). In the study by Levans (1977) it was found that boxes respond very slowly to a sharp increase in the ambient relative humidity, irrespective of the position of the box in a pallet load. It was concluded from the study, that in a natural environment with constantly fluctuating relative humidity, a palletized box assumes a moisture content closely related to the average percent relative humidity in the environment. The rate at which this occurs depends on the contents of the box, as well as on the limits of the extremes of humidity. He further stated that brief periods, in terms of 12-24 hours of very high humidity should not generally reduce the stacking strength to critical levels.

Easter (date unknown) noted that compression strength is an indication of proper fabrication and material components. This necessitates an understanding of the factors that influence compression strength. Some factors include: fatigue, moisture (including relative humidity), board construction, printing and spotting, and allignment of pallet layers. Corrugated fiberboard containers designed for long-term storage of goods must withstand and support customary superimposed loads in the warehouse. The question is, how much design strength should these containers have? Package designers have made such designs on the basis of design curves such as the one by Kellicutt and Landt (1951), past experience, trial and error, and guesswork. Kellicutt and Landt (1951) stated that "in general, for dead loads that are less than 75 percent of the machine test load, each decrease of about 8% points in the ratio of the dead load to the static compressive strength results in extending the time of failure by about 8 times". They based their relationship on the average machine compressive strength of the container after exposure at a specified temperature and humidity. All tests were conducted with single, empty containers made from either solid or B flute fiberboard and conditioned at 73°F (23°C), 50% R.H.

Scott (1959) also studied the creep characteristics of corrugated fiber tubes including tubes conditioned to various moisture contents ranging from 5.5 to 19.2%. Close agreement with Kellicutt was found for tests made on tubes having a moisture content of 10%, but a lower level relationship was found as moisture content increased, indicating that basing the percent dead load on the average machine compressive strength (determined at higher moisture content) was not sufficient to account for the effect of moisture at lower levels.

Peterson et al (1980) reported on a theory to demonstrate how boxes fail in compression. The authors studied the compressive failure morphology of liners so as to develop an understanding of what could be done to improve the compressive strength. Physical examination of linerboard cross-sections, that had failed while under compressive loads, revealed that on occasion the board delaminated as if it were made of many layers. The bonds between the layers ruptured when loaded. Other samples observed within the failure zone showed buckling or delamination of fibers. purther examination of the compressive strength of liner as a function of bonding strength indicated fiber layer bonding and stiffness as two distinct mechanisms contributing to liner failure. Peterson et al (1980) concluded that interfiber bond strength and fiber stiffness are the most important variables related to linerboard compressive strength.

ENVIRONMENTAL FACTORS

Most of the reported work dealing with the effect of environmental factors (humidity, temperature and conditioning time) have been concerned with paper. Little has been published with regard to frozen storage of corrugated board and boxes. Brooks (1967) studied sorption-desorption of water vapor in paper; Nordman and Aaltonen (date unknown) studied the effect of humidity on properties of various papers and board. These authors found an optimum in several mechanical properties in the range of 60-70% relative humidity. Schiel (1966) studied the influence of humidity on corrugated fiberboard and its effect on board quality. He reported that bursting resistance is clearly dependent on humidity, as are puncture resistance, flat crush resistance and compression resistance. He concluded that storage conditions determine the quality of the corrugated board. Henzi (1971) stated that high relative humidities are a major concern only when associated with warm or hot temperatures. He further suggested that although most cold climates do have humidities tending towards saturation, the absolute humidity in grains of moisture per pound of air is very low. He found relative humidity to be as high as 90-95% with low absolute humidity. In the warm and hot climates, however, high relative humidities are accompanied by high moisture content (i.e. absolute humidity).

Benson (1971) reported that a basic relationship exists between specimen equilibrium moisture content (EMC) and tensile properties of linerboards. He found that tensile strength and modulus of elasticity appear to be linear between 4 and 13% EMC.

MOISTURE ABSORPTION

Moisture absorption by hygroscopic packaging materials can contribute to the surface desication of frozen foods, depending on the amount and rate of absorption. Brown and Lentz (1956) found that below 32^{o}F, the saturation moisture content of wood and cardboard decreased with decreasing temperature, the value at 0^{o}F being about half that at 40^{o}F. Most of the other information published on the amount and rate of water absorption by cellulosic materials deals only with above-freezing temperatures. At above temperatures, the amount of moisture absorbed by these materials decreases with decreasing temperature and increasing with relative humidity. Brown et al (1956) stated that the rate of moisture absorption depends on the nature and thickness of the material and on the direction of moisture movement in it. Applicable information on drying indicated that the rate of moisture absorption is also a function of the initial and final moisture contents of the material and depends on air velocity. Brown et al (1956) found that the time for initially dry wood to reach a saturation moisture content at $0^{o}F$ ($-17.8^{o}C$) and 98-100% relative humidity varied by as much as 10-15 times depending on species and direction of grain.

Beardsell (1960) reported on work done by Simons and Kayan of the Refrigeration Research Foundation Scientific Advisory Council. These authors reported that the capacity of surfaces to hold moisture vapor is particularly dentrimental to containers constructed of an organic or fiberous nature. The fibers are natural capillaries and the surface moisture diffuses through these capillaries along a moisture gradient to the point of low concentration. Thus moisture in high humidity rooms readily moves into the fibers. They found that organic fibers change in length with moisture content. The higher the moisture, the longer the fibers become. In general, the fibers soften as they lengthen, thus losing strength. Adding a new load of dry material or a load of wet material into the storage room will lower or raise the relative humidity, resulting in a change in fiber length. This continued expansion and contraction can weaken the fibers to the extent of structural failure. Also, in a tightly stacked pile of containers, the quantity of moisture available to the fibers on the outside of the stack is different from that within the stack. There is a differential gradient of strength across the containers. They concluded that this strain could result in a part of the pallet load failing due to lack of uniformity, and toppling of the stack.

TIME, TEMPERATURE CONSIDERATION

Studies by Klose _et al_ (1959) showed that the beneficial effects of good packaging are much more evident at higher temperature than at -17.8^{o}C (0^{o}F) or lower, and adverse effect of poor packaging are minimized by storage at lower temperatures. He further stressed that the type of package used was found to be of greater importançe than storage temperature in the range of -12.2 to -23.3^{o}C (10^{o} to -10^{o}F) for retention of quality of most foods.

Munter, Byrne and Dykstra (1953) did a survey of times and temperatures used in the transportation, storage and distribution of frozen food. In the public frozen warehouses surveyed, temperatures ranged from -27.8^{o}C to -11.1^{o}C (-18^{o}F to 12^{o}F). Average temperature was -18.8^{o}C (-1.8^{o}F). Products were found to be in storage for periods varying from a few days to one year or more. They concluded that because storage in these rooms was invariably in excess of a few days, room temperature was a good index of product or box temperature. Munter _et al_ (1953) observed that incoming shipments were usually handled rapidly and efficiently. They observed shipments unloaded in the warehouse in a minimum of 8 hours. The maximum time merchandise was left unprotected on platforms was 1 1/2 hours.

Sparnon (1979) reported that if frozen foodstuff could be maintained at $-30^{o}C$ throughout distribution, quality loss by physical, biochemical and microbiological processes of deterioration would be negligible. The author recommended strict temperature control towards the end of distribution and particularly that at the retail cabinet. Wares (1973) reported that in United Kingdom producers of frozen foods run factory cold stores at $-29^{o}C$ ($-20.2^{o}F$) and distribution cold stores at $-24^{o}C$ ($-11.2^{o}F$) with delivery to retailers at not higher than $-18^{o}C$ ($-0.4^{o}F$). He further stated that integrated mean temperature of test packs should not be warmer than $-15^{o}C$ ($5^{o}F$) nor rise above $-12^{o}C$ ($10.4^{o}F$) during automatic defrosting.

Another survey of test methods for simulation of the transportation environment was done by Henzi (1971). He reported that if time dependent effects are deemed to be important in temperature testing of a particular package, the package should be tested for a duration equal to the maximum expected storage time. If, however, time is not of much importance, it should be necessary only to maintain the extreme temperature until the temperature and the package stabilize. Two or three days should probably be sufficient.

Benson (1971) investigated temperature effects on the tensile properties of linerboards. He stated that temperature and moisture interrelationships and their combined effects on tensile strain need to be considered. A factor that may be of significance is the absolute vapor pressure. Its effect on the mechanism by which moisture is absorbed and distributed within the fibrous system may relate to anomalous strain behavior exhibited under tensile loading at simultaneously varying temperature and relative humidity conditions at constant equilibrium moisture content. The author concluded that temperature has a large effect on tensile properties of fibrous materials and that the narrowing of the Tappi standard temperature range ($23 \pm 1^{o}C$) was a highly desirable change.

CONDENSATION

Condensation is another factor in the distribution of frozen food. Henzi (1971) stated that condensation on shipping container surfaces usually occurs when packages are removed from cold stores to the ambient environment or environment of higher temperature and higher absolute humidity. This will happen when the dew-point of the air is higher than the surface temperature of the packaging material.

According to Benson (1971) a pallet load of packages can be covered until it warms to above the dew-point of the surrounding air, thus avoiding condensation. Condensation weakens corrugated shipping containers.

Nethercotes (1971) study on condensation, found that condensed moisture is a major factor in the deterioration of corrugated fiberboard containers carrying chilled or frozen products. In such containers, moisture is absorbed faster from warm humid atmospheres than with empty containers.

COATINGS

Brooks (1967) studied the effect of coating materials on the moisture sorption by papers. He reported that coating on materials (newsprint) picked up moisture, but at a lower rate than the cellulose fibers of the paper. The coated papers picked up more water by weight caused by the coating, the percent moisture increase was less. The coating, evidently blocked some of the pores in the paper and reduced kinetic hysteresis. He concluded by saying that diffusion through the coating must take place before sorption on the fibers can occur. Brooks (1967), reporting on uncoated papers stated that integral kinetic hysteresis in a range of relative humidities of 11.1 - 92.5%, cracking stresses (loosening of fiberbonds) are produced in the fibers which increase subsequent gain and loss rates of moisture in uncoated papers. In coated papers, this difference between first and later humidity cycles was smaller. Coatings can do much to stabilize paper structure on exposure to environments of fluctuating water content.

Anon (1970) reported on Hycote coatings by Hygrade Packaging Corporation which provide board and carton with glossy, scuff and moisture-resistant coating. It was found that the tendency of the carton board to soften under high relative humidity is eliminated. The coatings were particularly suitable for frozen food packaging.

FILLED BOXES VS UNFILLED

The packing of solid contents into corrugated fiberboard shipping containers, especially when frozen, keep the panels of the sides and ends from bending and bowing in a normal manner when a crushing load is applied. This definitely increases the strength of boxes. Kellicutt (1963) found that boxes with contents were stronger than empty boxes when stacks of each were tested between flat patterns.

Usually products for frozen distribution storage are food materials with high moisture content. When conditioned in frozen storage, most of the water becomes crystalline making the food material solid. This can contribute considerable strength to the compressive strength of the whole package. At the same time, moisture can be transferred to the corrugated board, according to Kellicutt. This moisture when thawed can cause a severe loss of compressive strength of the container. This makes it more imperative that packaged frozen food items should not be left to thaw. Care should be taken throughout the distribution chain to prevent thawing of frozen food packages.

According to Beardsell (1960), stresses and strains on packages caused by external atmospheric conditions and by internal chemical or other reactions of the contents of the container are a prime source of trouble in the warehouse.

EXPERIMENTAL PROCEDURE

TEST SAMPLE MATERIALS

The test samples used for this study were constructed of singewall B-flute corrugated board and were of an R.S.C. (Regular Slotted Container) type.

UNCOATED BOXES

Box Specification:

Type - B flute, double faced corrugated.

Medium - B flute, wet strength virgin kraft.

Dimension - 15 1/4" x 6 1/16" x 4 5/8" (L x W x D)

Bursting Strength - 125 lbs per sq. inch.

Min. combined wt. facings - 52 lbs per M sq. ft.

Board component include two (2) 26 lb/MSF liners, regular 26 lb/MSF medium and regular adhesive.

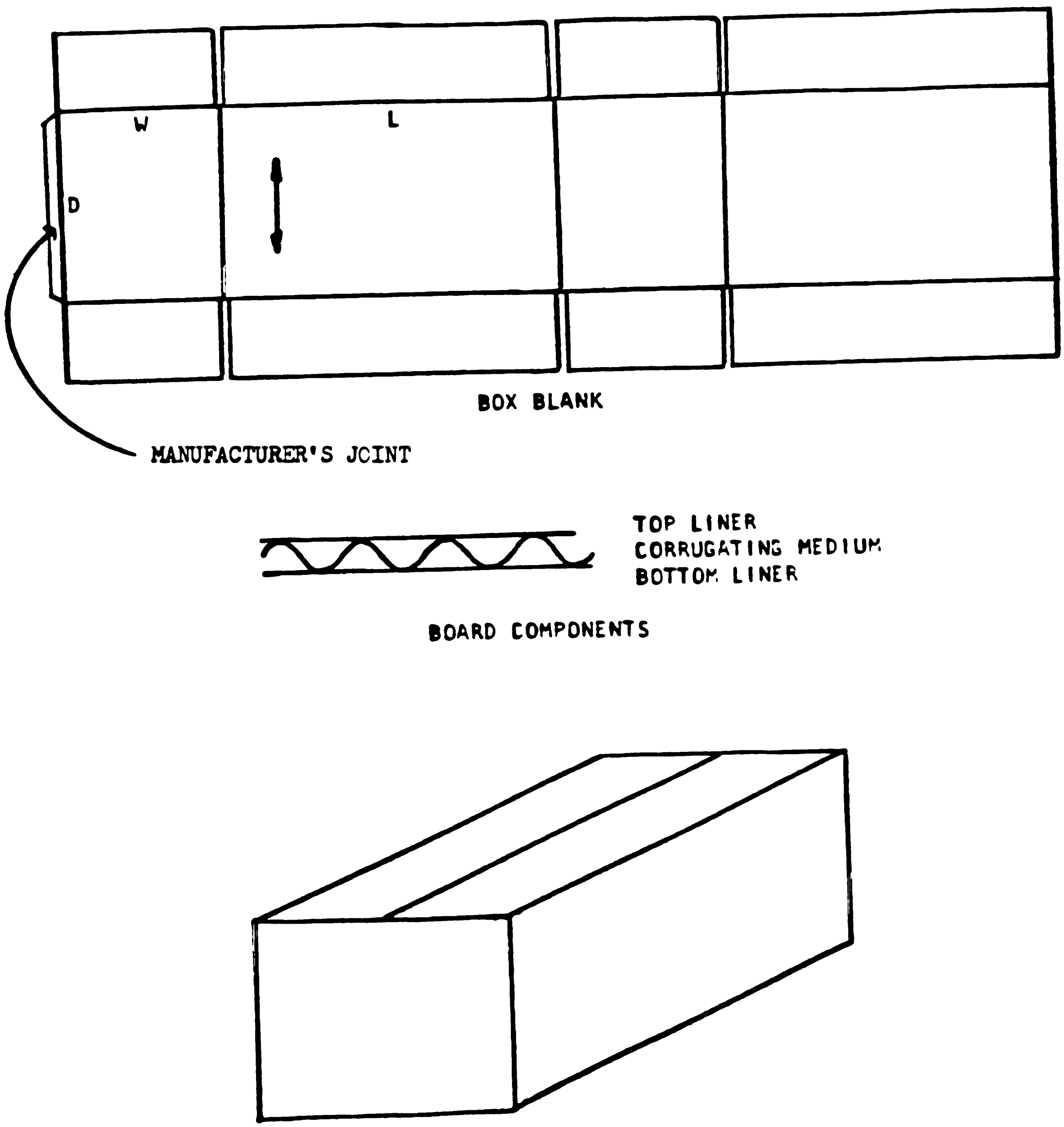
Uncoated boxes were manufactured by Weyerhaeuser Company for the Pillsbury Company.

WAX-COATED BOXES

Wax-coated boxes were also tested and were obtained from Champion International Corporation to meet specifications of sample test materials (above) as close as

FIGURE 1

TYPICAL CORRUGATED BOX FOR DISTRIBUTION OF FROZEN VEGETABLES



possible.

Specifications:

Dimension - 15 1/4" x 6 1/16" x 4 5/8"

Bursting strength - 125 lbs per sq. inch.

Type - B flute wax coated board.

BOX SET UP AND STORAGE CONDITIONS

Knocked-down boxes with manufacturer's joint attached (glued) were obtained from the Pillsbury Company. The boxes were set-up and sealed top and bottom with a hot melt adhesive. The adhesive is a solid plastic polyolefin in stick form made by the 3M Company and applied using an electrically heated dispensing polygun through a nozzle device.

Sample Conditioning

After box set-up, samples were conditioned at standard conditions of 22.8$\pm$ 1.6^{o}C (73$\pm$3^{o}F), 50$\pm$2% R.H. (Technical Association of the Pulp and Paper Industries (TAPPI) for at least 48 hours before transfer to storage conditions. Standard and frozen storage conditions of -31.7^{o}C (-25^{o}F) were used in this study. Standard conditions were measured and monitored using a Hygro-thermograph model number 594 recording instrument, which records both relative humidity and air temperature.

This study was mainly concerned with frozen storage.

Frozen storage was in a mechanically refrigerated room maintained at $-37.7^{o}C$ ($-25^{o}F$). Although, the author understands that frozen vegetables are usually stored at $-17.8^{o}C$ ($0^{o}F$), the only refrigerated storage room available, large enough to contain test boxes is that of a commercially operated ice-cream storage room maintained at $-31.7 \pm 2.8^{o}C$ ($-25 \pm 5^{o}F$). Relative humidity of the frozen storage room was not measured because there was not instrument available to measure it at such low temperature. Relative humidity could be as high as 90-95% R.H. with low absolute humidity (Henzi 1971). Boxes were left at $-31.7^{o}C$ for a period ranging from 1 day to 92 days.

A chest style freezer with temperature range of -17.8^{o} to $-20.6^{o}C$ (0^{o} to $-5^{o}F$) was also used. A dry ice-packed box with a temperature range of -40^{o} to $-45.6^{o}C$ (-40^{o} to $-50^{o}F$) was also used to compare the temperature effect on compression strength and moisture absorption by boxes.

TEST METHODS

Compression Strength

Compression strength was evaluated on boxes held under standard and frozen storage conditions using the Instron Universal Tester Model TTC 2344642. Before testing, boxes were transported over a distance of 200 meters because of the location of the freezer. The freezer temperature used was maintained by transporting the boxes (5/chest) in an insulated styrene foam chest, packed with dry ice. Two styrene foam chest were used during each trip. Dry ice was put in the chest freezer (located next to the Instron) and into the insulated styrene foam chests before entering the frozen storage room. Approximately 5 minutes were needed to pack-in the 10 boxes in two styrene foam chests and close with cover. Another 10 minutes was used to move (by car) the two styrene foam chests with boxes from the storage room location to the Instron location site. About 2 minutes were used to get the styrene foam chests moved from the car to the chest-style freezer (Instron location) and boxes removed into the freezer. These actions were accomplished by two people. The freezer temperature was maintained at a temperature between -28.9^{o} to -34.4^{o}C (-20^{o} to -30^{o}F) with dry ice added. Boxes were allowed to condition at this temperature for about 20-25 minutes for compression strength. At the end of 20-25 minutes conditioning time, one box at a time was removed and placed on the testing platens of the Instron and tested for compression strength. The test was usually completed within 10 seconds of removal from the -31.7^{o}C chest.

Each compression test value reported is an average value obtained from 20 boxes. The same testing procedure was observed for wax-coated boxes. Boxes stored at standard conditions were tested in the room where the Instron is located. Boxes at -17.8^{o}C (0^{o}F) were placed into the chest

Figure 2. Instron Universal Testing Machine Model TTC 2344642 with test sample box on platten.

style freezer located next to the Instron, therefore no transportation was required.

Figure 3 is a typical example of a force-deflection curve as recorded for compression tests on the boxes. Cross-head speed of the Instron (compression tester) was run at 20 inches per minute while the chart-speed was 50 inches per minute. The yield strength is the highest point on the force-deflection curve. The yield strength is the maximum force applied beyond which the box failed and collapsed. This force corresponds to the maximum force in the force-deflection curve. The failure point used in this study was taken to correspond to the yield strength. The maximum yield strength at failure and its corresponding deflection were read off the curves and the average values for 20 boxes calculated and reported as a point value for the boxes being tested.

MOISTURE CONTENT

Moisture content (M.C.) of boxes was determined for boxes tested for compression tests. Immediately after testing for compression strength, each box was returned to the chest freezer to allow time for testing of remaining boxes. Samples were removed from side and top walls of 10 boxes immediately upon completion of compression tests. American Society of Testing Materials (ASTM) test method D 644 was used for determination of moisture content.

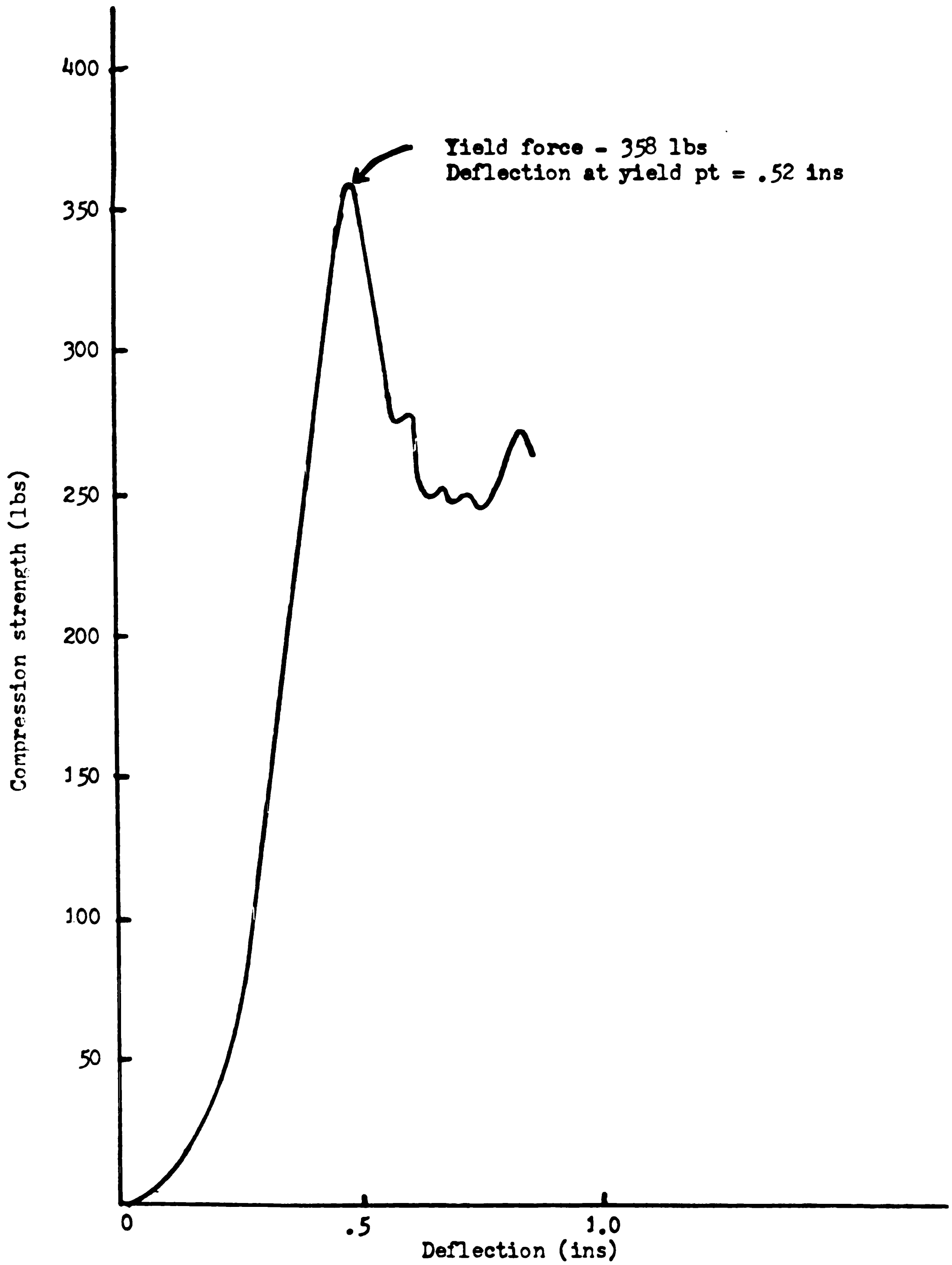


Figure 3 Example of force-deflection curve of box compression strength testing

(Appendix 4).

Box moisture content was determined for -31.7°C (-25°F) and standard condition samples. Moisture content was monitored over the entire length of frozen storage. Ten samples from five to ten boxes were used for moisture determination with averages reported.

<u>Variables Affecting Compression Strength of Uncoated and Coated Boxes</u>

1. Compression strength at standard conditions and moisture content (M.C.) of boxes.
2. Compression strength and moisture content of boxes held at -31.7°C (-25°F) as a function of time (in days) ranging from 1 day to 92 days.
3. Freeze-thaw and freeze-thaw cycling on compression strength of boxes. Freeze-thaw is the exposure of frozen boxes into standard conditions of 22.8±1.6°C (73±3°F), 50±2% R.H. for periods of 15 minutes, 30 minutes, 1 hour, 2 hours and 3 hours, following by testing of boxes for compression strength and moisture content. Ten boxes were used in each situation. Average test values for compression strength and moisture contents are reported for each freeze-thaw test.

   Freeze-thaw cycling was done for 1, 2, 3 and 4 cycles. A cycle is the thawing of 10 frozen box samples for a period of 1 hour, refrozen at -31.7°C for 45 minutes, and then tested. All boxes were tested frozen and the average compression strength reported for each test. Samples were obtained from tested boxes for the determination of moisture content. Wax-coated boxes were tested in the same way.

4. Filled boxes with mixed and whole-piece vegetables were tested for moisture content after storage at -31.7°C for 60 days. Frozen consumer unit packages of vegetables from Pillsbury Company were packed in test sample boxes and sealed, top and bottom with hot-melt adhesives. Ten boxes were tested for each mixed and whole-piece (corn) sample.

5. Box compression strength and moisture content at different temperatures of storage: Twenty boxes each were stored for at least 1 hour at 22.8°C (73°F), -17.8°C (0°F), -31.7°C (-25°F) and -40°C (-40°F) and tested for compression strength. Average compression strength for boxes was reported for each temperature.

RESULTS AND DISCUSSION

Over 650 corrugated boxes were used for the collection of data on compression strength and moisture content. Boxes were held in frozen (-31.7^{o}C) storage for up to 3-months. The effect of thawing and freeze thaw exposure was evaluated. Compression strength and moisture content of wax-coated boxes were also evaluated. The effect of storage temperature on compression strength and moisture content was determined.

FROZEN STORAGE AT -31.7^{o}C (-25^{o}F)

Table I shows the average compression strength of boxes held at 23^{o}C (73^{o}F), -17.8^{o}C (0^{o}F), and -31.7^{o}C (-25^{o}F). Each value is an average of 20 test samples. Conditions used were 22.8$\pm$1.6^{o}C (73$\pm$3^{o}F) and 50$\pm$2% R.H. The -17.8^{o}C (0^{o}F) storage condition was achieved by using a chest style freezer with a range of -17.8^{o} to -20.6^{o}C (0^{o} to -5^{o}F). A mechanically refrigerated room was used for most of the study and maintained at -31.7$\pm$2.8^{o}C (-25$\pm$5^{o}F).

The data from Table I shows that there was an increase of about 20% in compression strength for boxes stored at -31.7^{o}C within 1 day of storage. This was found to be significant by the least significant difference method at a 5 percent level (L.S.D. .05)=9.9 lbs (see appendix 5). Any

TABLE 1

Compression Strength of Uncoated Boxes Held at 23°C, -17.8°C and -31.7°C

Compression Strength (lb)

Storage Condition	Storage Time (Days)	Compression Strength (Lbs)	Standard Deviation	% Change in Compression Strength vs 22°C
23°C	2 days	286	15.1	----
-31.7°C				
	1 day	344 *	18.5	20
	2 days	350 *	17.5	22.4
	5 "	346 *	16.1	21
	7 "	361 *	24.4	26
	14 "	363 *	26	27
	21 "	342 *	32	20
	28 "	365 *	27	27.3
	49 "	357 *	19.6	24
	56 "	388 *	20	35
	71 "	356 *	24	24.4
	78 "	360 *	22.6	25.4
	92 "	354 *	25.2	23.7
-17.8°C	14 "	315 *	21.3	10.1
	LSD.05	(9.9)		

Standard Condition = 22.8±1.6°C (73±3°F), 50±2% R.H.

LSD.05 = Least significant difference at 5% significant level.

* Significantly different from compression strength at standard condition at LSD.05.

difference between compression strength (lbs) at 22°C and compression strength at -31.7°C larger than L.S.D. (.05)=9.9 lbs was significant. Data also showed a significant increase (LSD .05=9.9) of 10.1% at -17.8°C (0°F) storage. Maximum percent increase in compression strength (at -31.7°C) of 35% was achieved at about 56 days of storage. This increase in compression strength resulted in an average increase of about 25% during the 3-month study.

Table 2 shows the percent moisture increase in boxes stored at -31.7°C. Moisture increased from 8.2% to 8.9% (actual values) within 1 day. In 5 days, moisture content had increased by about 70% (by absorption from the high relative humidity environment) with an increase in compression strength of about 21%. Moisture levels continued to increase reaching a maximum moisture content of 16.3%, subsequently followed by slow dehydration. No correlation existed between box moisture content and compression strength (see appendix 7) after the first day of frozen storage. For correlation to exist, the absolute correlation value must be greater than 0.8. Boxes held at -17.8°C (0°F) for 14 days showed a 10.1% increase in compression strength, while the increase in moisture content was 54.9%.

Table 3 shows compression strength for boxes frozen at -40°C by packing a chest style freezer with dry ice. An increase of 21% in compression strength was achieved within

TABLE 2

Moisture Content of Uncoated Boxes Held at 23°C, -17.8°C (0°F) and -31.7°C (-25°F) Storage Conditions

Storage Condition	Storage Time	Moisture Content (%)	S.D.	% Increase in M.C. vs. Standard
23°C	2 days	8.2	0.9	---
-31.7°C (-25°F)	1 day	8.9	1.4	8.5
	2 days	12.1	1.5	47.6
	5 "	13.6	1.6	70.7
	7 "	14.2	2.3	73.2
	14 "	14.3	1.6	74.4
	21 "	16.1	1.7	96.3
	28 "	16.3	1.8	98.8
	49 "	16.2	1.1	97.6
	56 "	16.1	.9	96.3
	71 "	14.9	1.5	81.7
	78 "	14.7	1.8	79.3
	92 "	14.6	1.3	78.0

$LSD_{.05}$ = .9 any difference between two values (M.C.) would have to be larger than .9 (LSD-least significant difference) to be significant.

TABLE 3

Compression Strength and Moisture content of Uncoated Boxes as a Result of Freezing at -40°C.

Time of Freezing	Compression Strength (Lbs)	S.D.	% Increase in Compression vs Standard	M.C.	% Moisture Increase
15 mins	367*	16.2	21.5	8.2	3.8
30 mins	383*	16.6	27	8.4	6.3
1 hr	396*	25.1	31.1	8.6	8.9
2 hr	393*	27	30.1	8.8	11.4
3 hr	393*	24	30	8.8	11.4
	LSD.05 (19.5)				

Boxes were frozen using dry ice in the chest style freezer. Temperature was -40°C (-40°F).

* Significantly different from compression strength at standard condition by LSD.05 = 19.5>

15 minutes with a corresponding 3.8% increase in moisture. This represents a significant difference in compression strength, (LSD.05=19.5 lb). Compression strength after freezing for 30 minutes, 1 hour, 2 and 3 hours at -40°C did not show further substantial change. Substantial increase in compression strength occured within 15 minutes of freezing at -40°C, this shows that the increase in compression strength is more dependent on the physical change in box structure than increase in box moisture content or box storage time. Greater fiber layer bonding and stiffness of fibers were suggested as two main physical structural changes in board as was found by Peterson and Fox (1980).

Figures 4, 5, and 6 are graphs showing the changes in compression strength and moisture content of uncoated boxes at -31.7°C for a period of 3-months. There was a sharp increase in compression strength within 1 day of storage. Thereafter slight increases in compression strength occured. Compression strength tended to level off after about 8 days storage time. This occured at a level about 25% higher than found at 23°C. Moisture content of boxes held at -31.7°C (figure 5) showed a steep rise during the first 5 days of storage. Beyond this period, rate of increase in moisture content slowed until reaching its maximum at about 28 days, thereafter it levelled off. There appeared to be slight dehydration (but not significant) beyond 2 months of

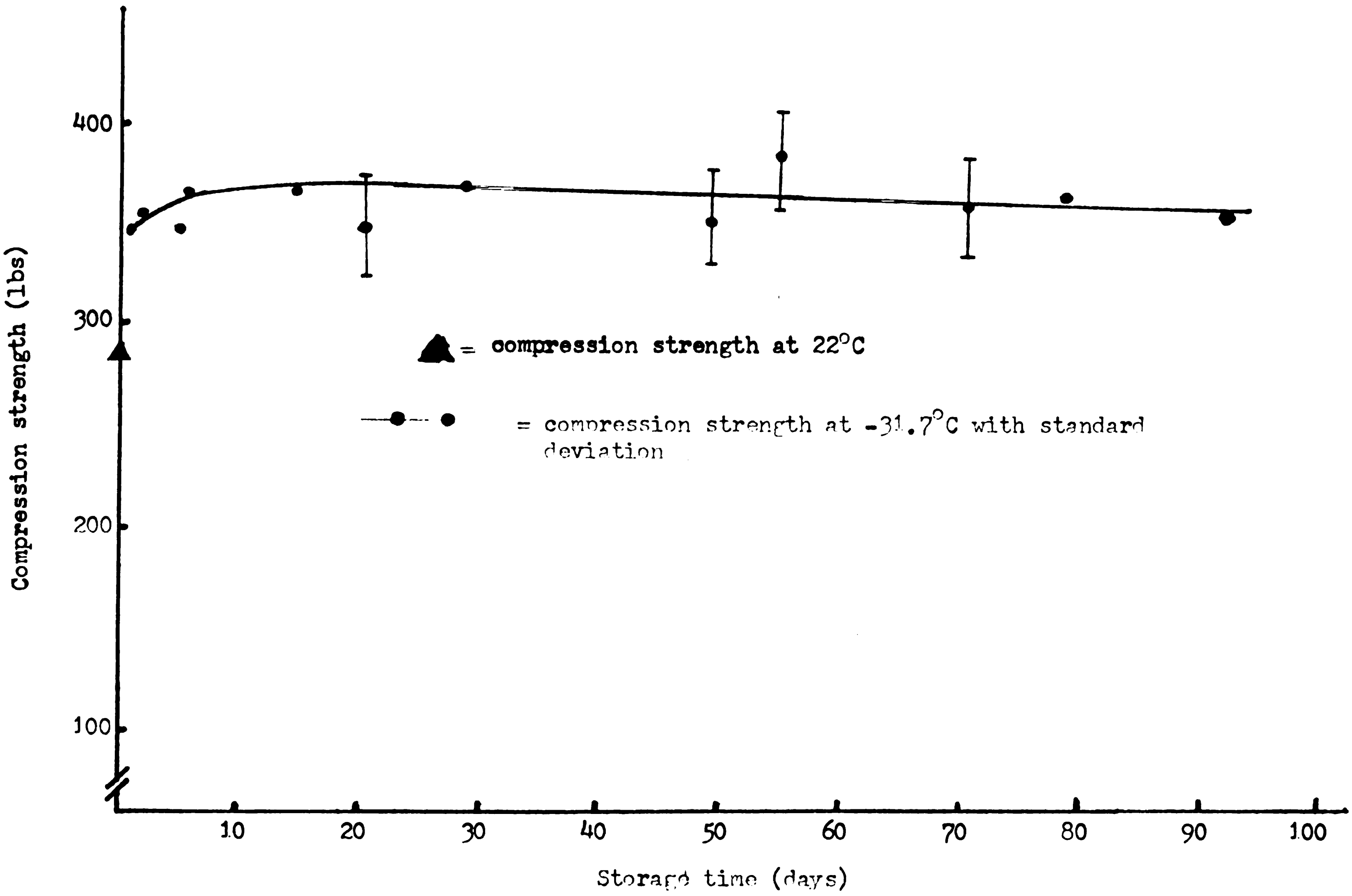


Figure 4 compression strength of uncoated corrugated boxes held at -31.7°C

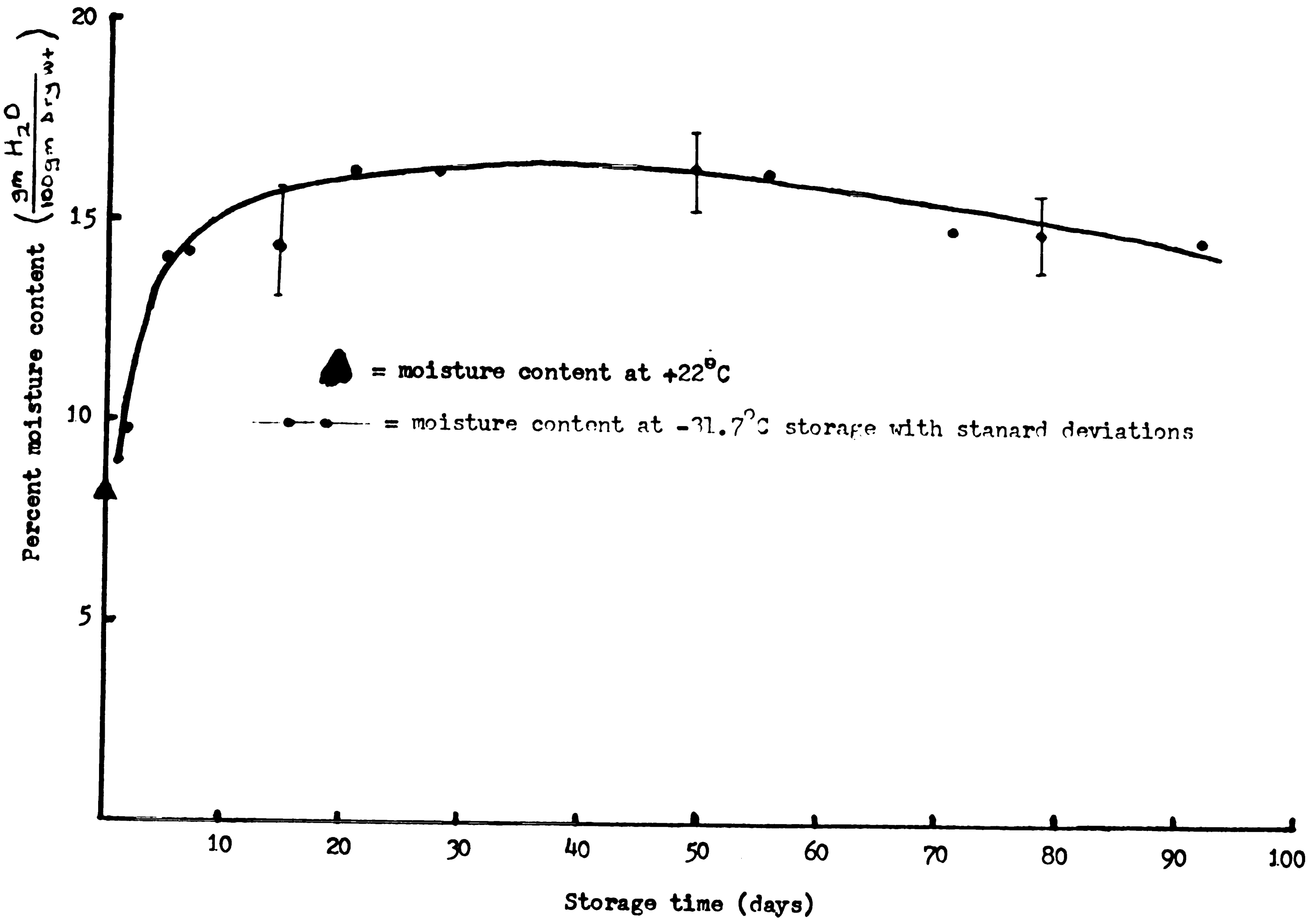


Figure 5 Moisture content of uncoated corrugated boxes held at -31.7°C

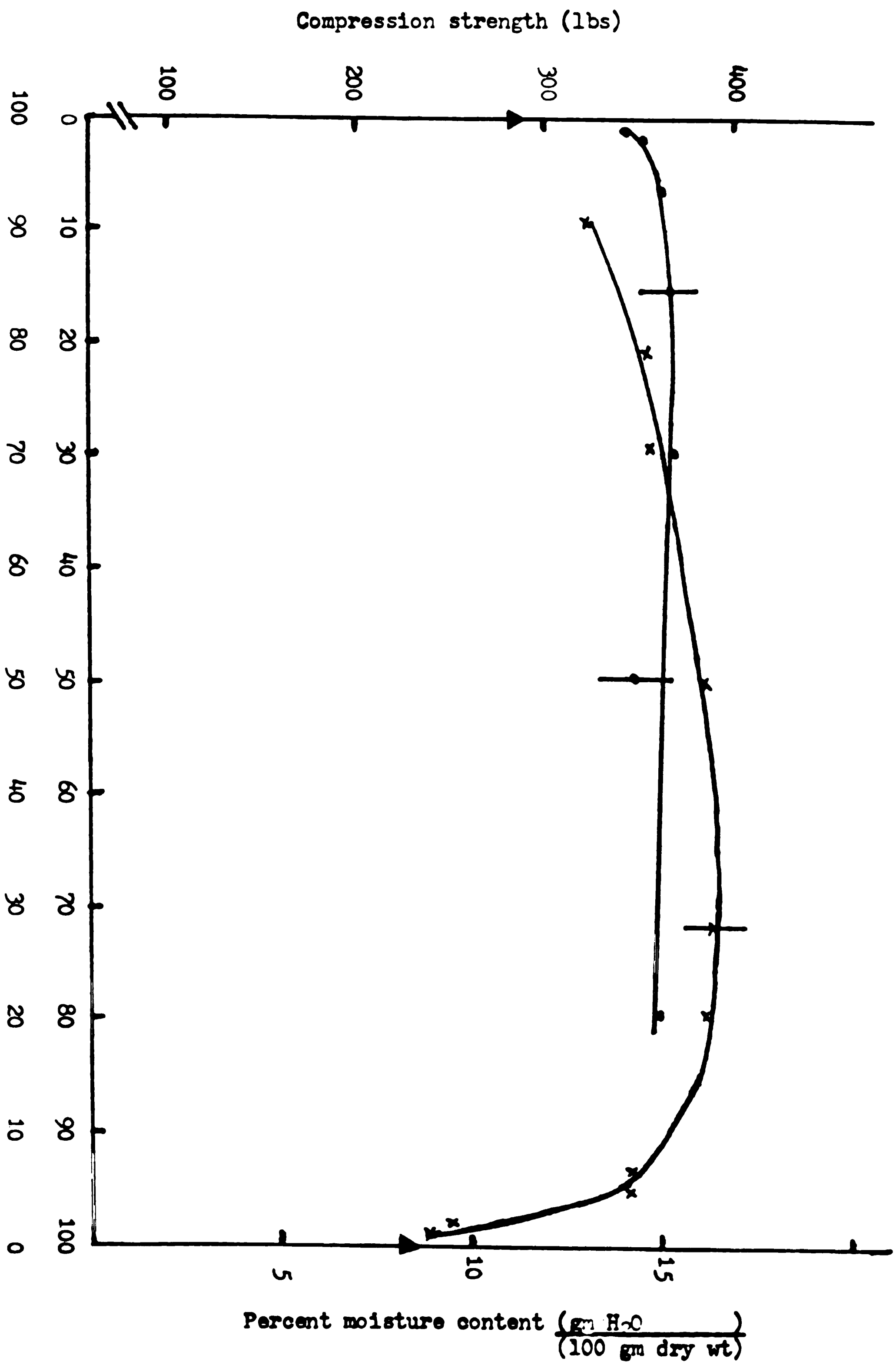


Figure 6 Compression strength and moisture content of uncoated corrugated boxes held at -31.7°C

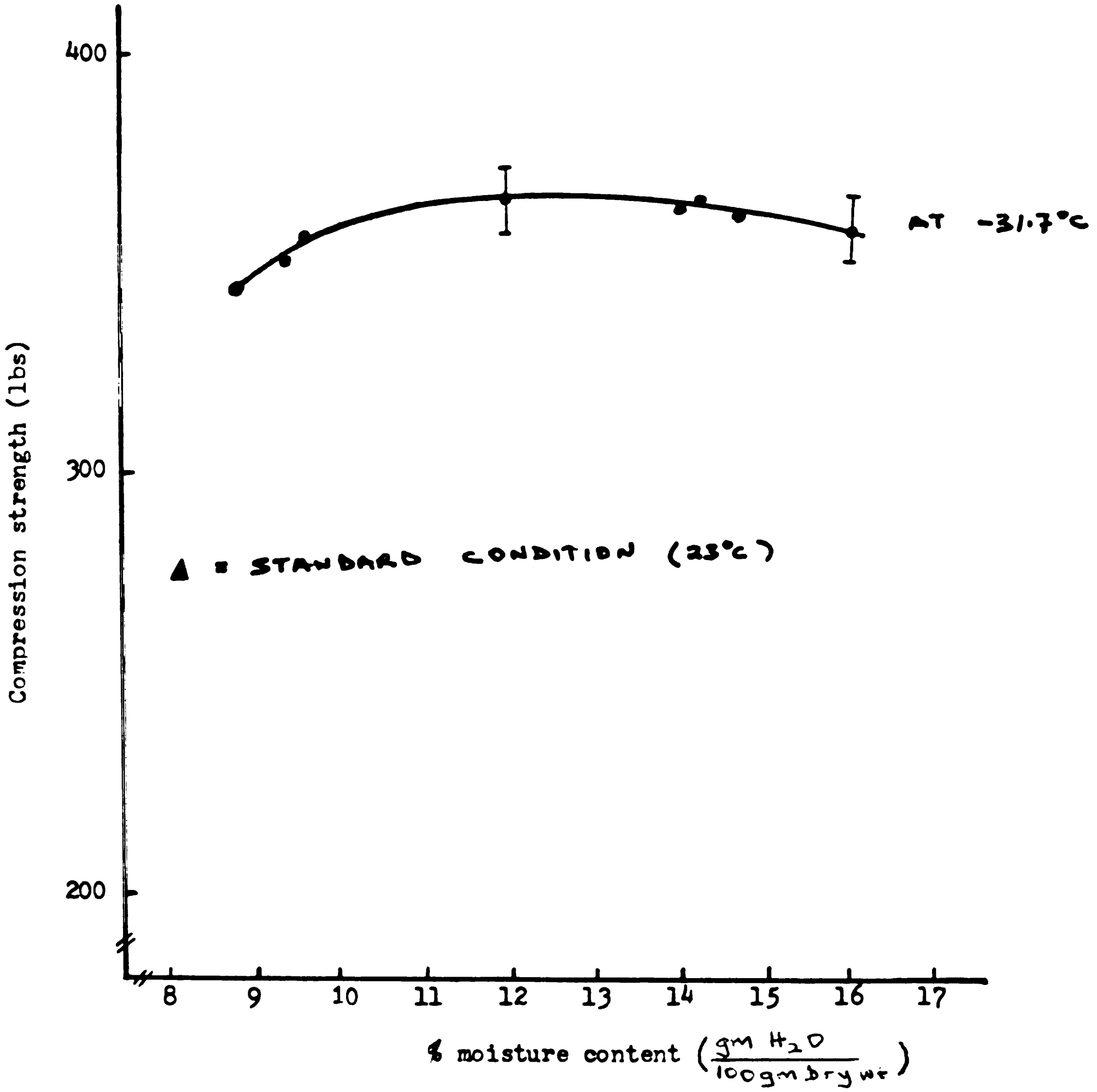


Figure 7 Relationship between compression strength and moisture content of uncoated boxes

storage. Figure 6 shows graphs of compression strength and moisture content overlayed. Figure 7 shows the relationship which exists between compression strength and moisture content of uncoated boxes. The graph indicates that increase in compression strength due to increase in box moisture content occured during the initial stage of moisture increase (8.2% to 12.1% M.C.). From figure 5, this increase in moisture content occured within 2 days of storage at -31.7°C.

The results indicate that increase in moisture content of boxes at frozen conditions (-17.8°C, -31.7°C, and -40°C) contributed to increase in compression strength. This can be explained by the fact that the moisture in the board is frozen, contributing to the increase in strength. Most of the increase in compression strength was achieved with a small increase in moisture content (3.8%) within the 15 minutes of freezing. No substantial further increase in compression strength occured, though the moisture content in the boxes continued to increase by about 70%. Therefore, the increased water content of boxes in the frozen state cannot be the only contributory factor leading to the increase in compression strength. Other factors must be responsible for this increase in compression strength. It is suspected that increase in compression strength could be attributed to greater fiber layer bonding and stiffening of board fibers as hypothesized by Peterson and Fox (1980).

Table 4 shows compression strength values for wax-coated boxes at -31.7°C. When frozen for 14 days, there was a 70.9 percent increase in compression strength, significant by L.S.D.05=20.2 lbs, and a 12.7% increase in moisture content. Compared with uncoated boxes, (from Table 1) frozen storage at 14 days produced a 27% increase in compression strength with as much as a 74.4% increase in moisture content. After 21 days in storage, wax-coated boxes had a 80.4% increase in compression strength and a 17.1% increase in moisture content. Uncoated boxes had a 20% increase in compression strength and 96.3% increase in moisture content. This result also lends evidence to the assumption that eventhough frozen moisture in board contributes to increased compression strength, other factors such as the stiffening of fibers and fiber layer bonding play an important role (Peterson and Fox, 1980). In the case of wax-coated boxes, hardening of the wax probably contributes to the greater increase in compression strength. This was observed during test by the flaking off of wax and cracking noise produce during testing of compression strength. This was also reported by Brooks (1967).

Effect of Storage Temperature

Table 5 depicts compression strength for both uncoated

TABLE 4

Box Compression Strength and Moisture Content for Wax-Coated Boxes at -31.7°C (-25°C)

Storage Condition	Storage Time	Compression Strength (Lbs)	S.D.	% Increase in Compression Strength	Moisure Content (%)	% Increase in M.C. vs Standard
(22.8°C, 50% R.H.)	5 days	460	21.9	----	7.0	----
-31.7°C (-25°F)	14 days	786*	31.2	70.9	7.9	12.9
	21 days	829*	36.5	80.4	8.2	17.1
LSD.05		(20.2)				

* Significant increase from compression strength at standard condition by LSD.05 = 20.2.

boxes and wax-coated boxes at different storage temperature. The data shows a substantial increase in compression strength as the storage temperature was lowered. At -17.8^{o}, there was an increase in compression strength of 10.1% over the uncoated boxes at $23^{o}C$. At $-31.7^{o}C$, the compression strength increased by 15.2%, which increased to 35.3% at $-40^{o}C$ (dry ice packed). Compared with wax-coated boxes, an increase of 51.4% (vs $23^{o}C$) was obtained. This increased to 70.9% under frozen ($-31.7^{o}C$) storage and finally 80.4% at $-40^{o}C$. These increases can be attributed to increased stiffening of fibers and wax-coatings as temperatures were lowered.

MOISTURE ABSORPTION RATE

Figure 8 presents the results of a study comparing the moisture absorption rate of uncoated and wax-coated boxes at $-31.7^{o}C$ ($-25^{o}F$) (data found in Table 10). Both types of boxes showed increase in moisture content. Uncoated boxes initially absorb moisture much faster than the wax-coated boxes, especially during the first four days of storage. In four days, uncoated boxes had increased 57.3% in moisture content while moisture content in wax-coated boxes increased by only 2.9%. At 22 days of storage, the uncoated boxes reached a maximum moisture content of 16.3% (96.3% increase). The wax-coated boxes did not reach a maximum moisture content during the one-month study. A 21.4 percent

TABLE 5

The Effect of Storage Temperature on Compression Strength of Uncoated and Wax-Coated Boxes

	Uncoated Boxes		Wax-Coated Boxes	
Temperature of Test	Average Compression Strength (Lbs)	% Increase in Compression Strength vs Standard	Average Compression Strength (Lbs)	% Increase in Compression Strength vs Standard
(22.8°C)	286	----	460	----
-17.8°C	315 (a)	10.1	696 (d)	51.4
-31.7°C	363 (b)	15.2	786 (e)	70.9
-40°C	387 (c)	35.3	829 (f)	80.4

(a) and (d) 14 days in storage

(b) and (e) 28 days in storage

(e) and (f) 1 day in storage

increase in moisture content was achieved by wax-coated boxes in 30 days. The difference in the absorption rate is due to the fact that wax coating protects the fibers of boxes from rapid absorption of moisture. Paper fibers being hygroscopic in nature, tend to absorb moisture rapidly. Broods (1967) illustrated that some moisture can still get into fibers in wax-coated papers through creases and unprotected area, thereby causing an increase in moisture.

THE EFFECT OF PRODUCT LOADING ON BOX COMPRESSION STRENGTH

Table 6 shows the effect of box loading with mixed and whole corn vegetables on the moisture content of board. Frozen storage at -31.7°C was for two months. The moisture content of boxes containing flexible pouches of mixed vegetales increased to 14.7%, and 16.9% for boxes containing folding cartons of corn. This was not significantly different (LSD.05=1.8) from the moisture content of empty boxes at 56 days held in frozen storage. Apparently, there was little, if any, permanent interchange of moisture from product to box.

THAWING AND FREEZE-THAW CYCLING

Frozen box samples were subjected to a period of thawing and freeze-thaw cycling. Table 7 shows the results

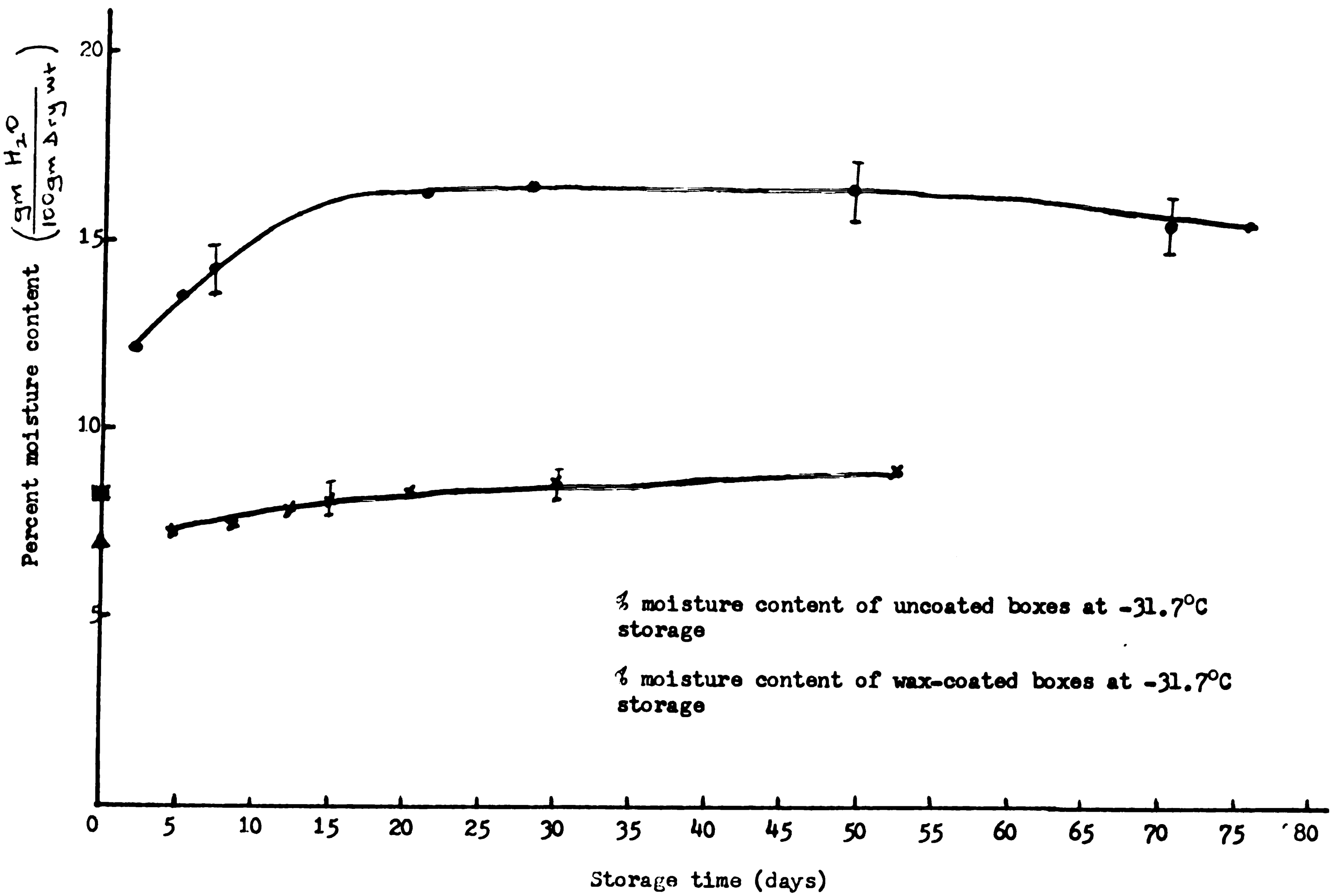


Figure 8 Percent moisture increase of uncoated and wax-coated boxes at -31.7°C

TABLE 6

Moisture Content of Uncoated Boxes Containing Frozen Vegetables at -31.7°C (-25°F) for 2 Months

Type of Product in Box	Storage Time	Moisture Content of Box (%)	Standard Deviation
Empty	56 days	16.1	.9
Empty	71 days	14.9	1.5
Flexible Pouch (a)	60 days	14.7+	.64
Folding Carton (b)	60 days	16.9+	1.79
		LSD.05 1.8	

(a) Mixed vegetables
(b) Corn in pouch and packed in folding carton (consumer package)
\+ Not significantly different from moisture content of empty boxes

TABLE 7

Compression Strength and Moisture Content of Uncoated Boxes Held at -31.7°C, Subjected to Thawing at 23°C, 50% R.H.

Day of Storage	Time for Thawing	Compression Strength (Lbs) at -31.7°C	S.D.	% Reduction in Compression (STD) vs Initial (-31.7°C)	% M.C.	% Reduction (From -31.7°C) in M.C. by Thawing
5 days	----	(346)	16.1	----	----	----
5 days	15 min	278*	22	20	10.6	22.1
5 days	30 min	291*	24	15.9	10.2	25.0
5 days	1 hr	289*	18	16.3	9.1	33.1
5 days	2 hrs	280*	13.9	19	8.5	37.5
71 days	----	(356)	----	----	----	----
71 days	3 hr	292*	22	17.9	10.3	30.9
		LSD.05 (13:3)				

( ) Compression strength values at -31.7°C at -31.7°C before thawing test.
* Significantly different from compression values at -31.7°C by LSD.05.
Thawing temperature was 22.8°C, 50% R.H., box place on table by end-side.

of 10 samples subjected to a period of thawing and then evaluated for compression strength and moisture content. Table 8 shows the results for compression strength and moisture content for 10 samples after undergoing a number of freeze-thaw cycles. Tests for compression strength were done after the final freezing period. Also in Table 8 are results of thawing and freeze-thaw cycling of wax-coated boxes. When boxes were allowed to thaw for 15 minutes, compression strength was reduced by 20% from a value of 346 lbs frozen to 277.6 lbs thawed (statistically significant by LSD.05=13.3 lbs). This value (277.6 lbs) is not significantly lower than compression strength of box at standard conditions (286 lb). Thawing of boxes for 15 minutes reduced the moisture content of box from 13.6% to 10.6%. Thawing was carried out at 22.8^{o}C (73^{o}F), 50% R.H. Following 15 minutes of thawing, moisture content of box changed from 13.6% to 10.6%, which is a 22.1% reduction. Further reduction in moisture content occured as the thawing time increased. This corresponds to slight increase in compression strength. This is indicated by the 30 minute, 1 hour thawing times. Figure 9 is graph showing effect of thawing on uncoated boxes. It shows a substantial reduction in compression strength within 15 minutes of thawing. Longer thawing time did not show much further change in compression strength.

TABLE 8

Compression Strength and Moisture Content of Uncoated Boxes Held at -31.7^{o}C Subjected to Freeze-Thaw Cycling at 22^{o}, 50% R.H.

Number of Cycles	Compression Strength (Lbs) at -31.7^{o}C	Compression Strength at -31.7 After Cycling (Lbs)	S.D.	% Change in Compression Strength	% M.C. at Test	% Reduiton in M.C. -31.7^{o}C at End of cycle vs Initial -31.7^{o}C M.C.
1	356	375+	26.0	+5.3	11.5	22.8
2	360	351+	21.3	-2.5	11.8	12.9
3	360	344+	15.9	-4.4	11.7	20.4
4	354	344+	16.9	-2.9	9.6	34.2
		LSD.05 = (19.8)				

( ) Compression strength at -31.7^{o}C before freeze-thaw cycling test.
\+ Not significantly different from compression strength at -31.7^{o}C (before freeze-thaw cycling) by LSD.05.

Note: 10 boxes were tested at -31.7^{o}C at end of cycle (s). 2 cycles means frozen boxes thawed (at standard condition) for 1 hour, then refrozen for 45 minutes with dry ice (-31.7$\pm$2.8^{o}C), thawed again for 1 hour and refrozen for 45 minutes and tested frozen.

The number of freeze-thaw cycles seemed not to significantly affect the ultimate compression strength. There was generally a slight reduction in compression strength due to freeze-thaw cycling. Comparing 2 and 3 cycle tests for boxes stored for the same length of time, percent reducion in compression strength varied from 2.5 to 4.6 respectively. As the number of freeze-thaw cycles increased the % moisture content left in board decreased. Thawing was accomplished for 1 hour and with refreezing for 45 minutes. Figure 10 illustrates the effect of freeze-thaw cycling on compression strength of uncoated boxes held at -31.7^{o}C storage. It did not show any substantial change or reduction from compression strength of boxes not subjected to freeze-thaw cycling.

Limitations to the Study

1. Temperature fluctuation: - Moisture absorption by board is quite dependent on the temperature of storage. The frozen storage room used for this study is that used for commercial purpose, with temperature maintained by a mechanical refrigeration system. During the 3-month storage study, temperature of the room was likely to have fluctuated. This could be caused by the mechanical system failing or by the opening and closing of the room-door, thereby allowing hot air to enter. This

TABLE 9

Compression Strength and Moisture Content of Wax-Coated Boxes Held at -31.7°C Subjected to Thawing and Freeze-Thaw Cycling

Treatment	Compression Strength (Lbs)	S.D.	% Change in Compression Strength	% Moisture Content	% Reduction in Moisture Content
Frozen	785	33.2	----	8.4	----
Thawing: (a)					
15 mins	526	18.7	-49.2	7.9	6.0
30 mins	493*	17.2	-59.2	7.5	10.7
1 hr	500*	24	-57.1	7.4	7.4
Freeze-Thaw Cycling					
1 Cycle (b)	696*	32.3	-12.9	8.0	4.8
2 Cycles (c)	802+	29.3	+ 2.1	8.2	2.4
LSD.05	(24.8)				

(a) Thawing was at standard condition and tested at end of thawing.

(b) 1 cycle freeze-thaw - test was done at end of thawing (22.8°C).

(c) 2 cycles freeze-thaw cycling - test was done by refreezing at -31.7°C).

* Significantly different from compression strength at -31.7°C by LSD.05.

\+ Not significantly different from Compression Strength at 31.7°C (before test) by LSD.05.

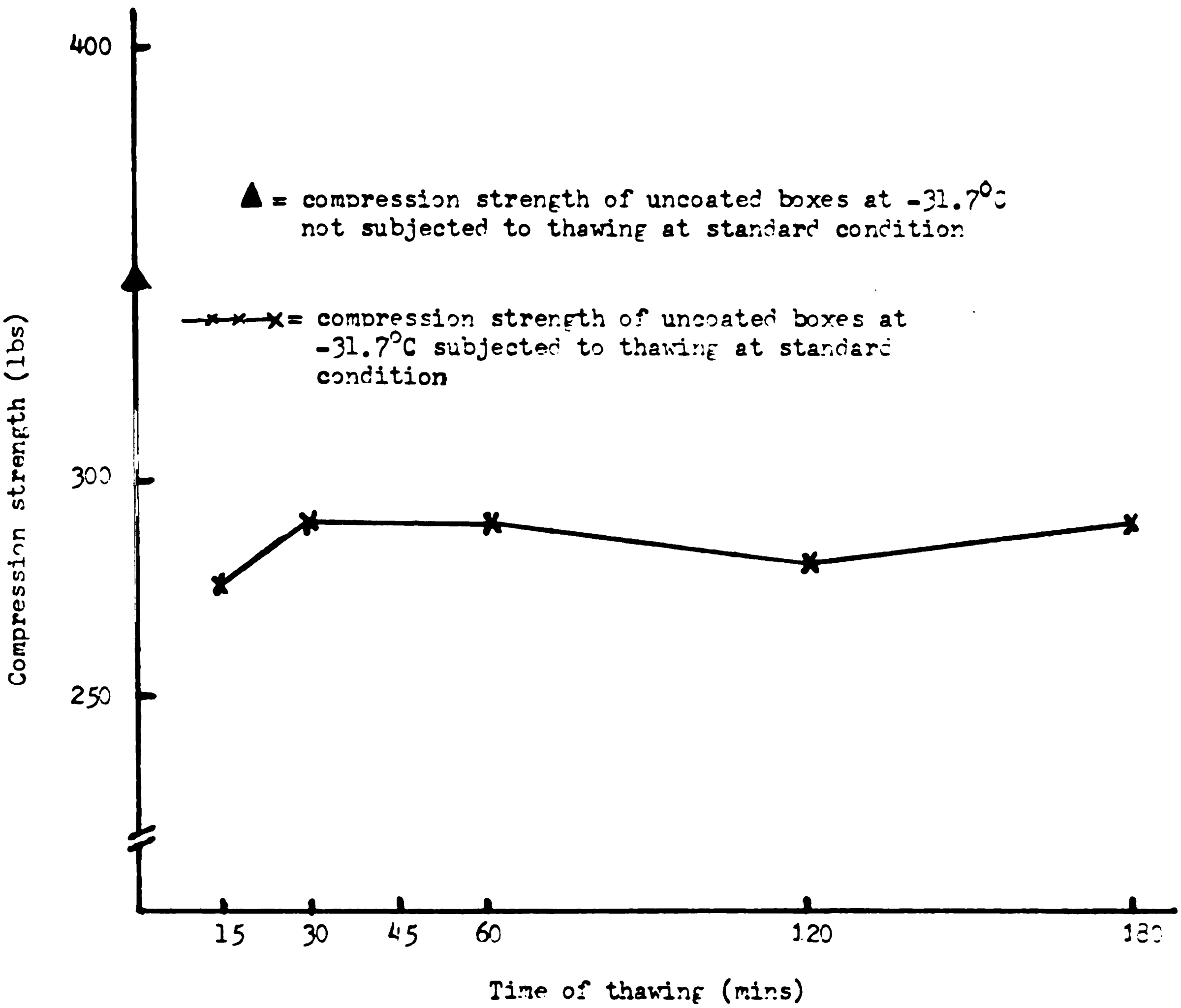


Figure 9 Effect of thawing on compression strength of uncoated boxes thawed at 23°C, 50% R.H. (Standard Tappi condition)

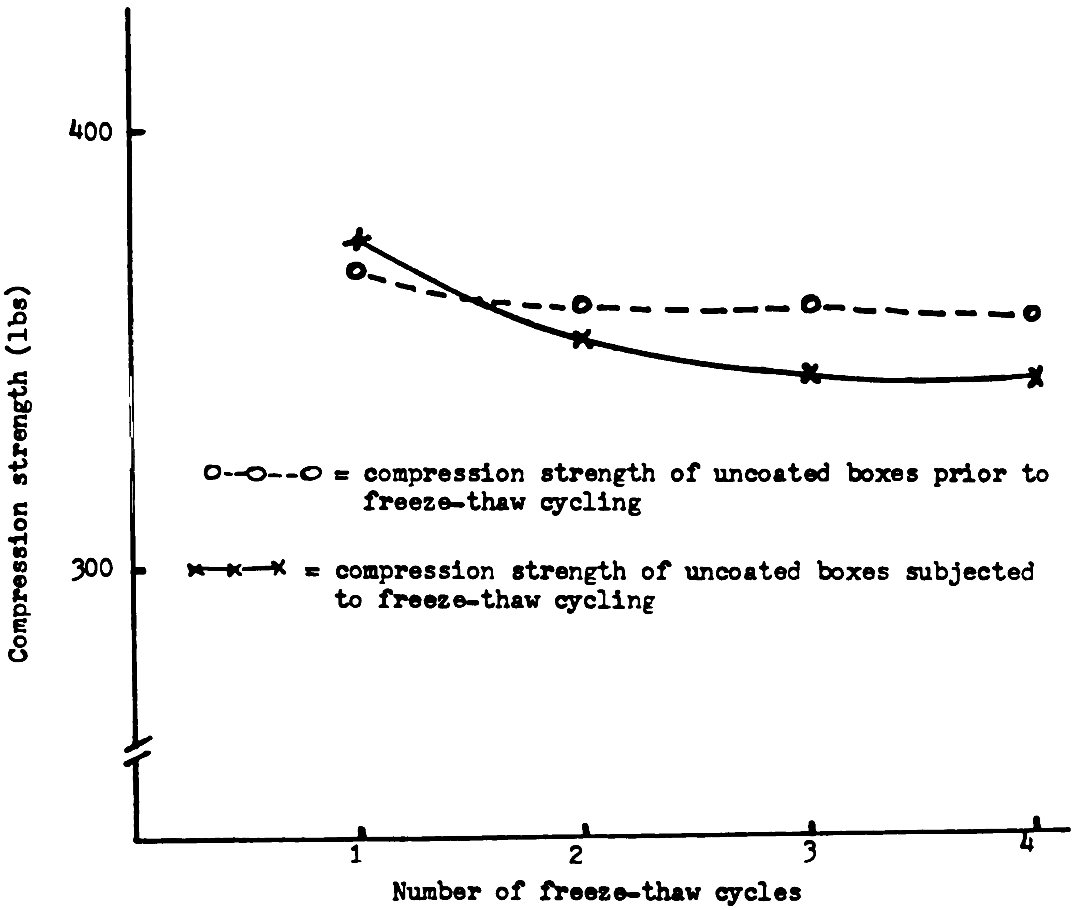


Figure 10 The effect of freeze-thaw cycling on compression strength of uncoated boxes

could have had effect the moisture absorption pattern and created errors in compression strength. During this study, no breakdown of the mechanical freezer system occured.

2. In an ideal situation compression testing should be carried out in the storage room. In this study, however, boxes had to be transported over 200 meters before testing because of the freezer location. To minimize effect of transportation, boxes were transported in an insulated styrene-foam chest packed with dry ice.
3. Factors affecting compression strength include temperature, relative humidity, box construction material, air-circulation in storage room, etc. Control of these factors by the author was not possible and was left to the operators of the commercially utilized freezer.

CONCLUSIONS OR SUMMARY

SUMMATION OF CONCLUSIONS

1. Under frozen storage, moisture content (M.C.) of corrugated boxes increased from 8.2% to a maximum moisture content of 16.3% at 28 days.
2. Generally, compression strength (C.S.) increased with increasing moisture content in frozen storage, (mostly during the first 10 days of freezing). A 20-35% increase in compression strength was found.
3. It is suspected that stiffening of board fibers contributes to increases compression strength. Wax-hardening in wax-coated boxes was considered partialy responsible for increases in compression strength in frozen storage with comparable smaller amount of moisture absorbed.
4. Thawing of frozen boxes reduced compression strength. Thawing for less than 2 minutes caused a rapid loss in compression strength. The board warmed up rapidly making board structure soggy. Thawing for more than 15 minutes showed little more effect on compression strength. This may be attributed to the evaporation of moisture from the board surface.
5. Refreezing of thawed boxes appeared to restore the

frozen compression strength of corrugated boxes. The moisture left was refrozen with fibers stiffening, demonstrating that little damage had occured to fibers during short-time thawing (1 to 2 hours).

6. Effect of freeze-thaw-refreeze cycles on compression strength appeared to be negligible for 1-4 cycles.
7. Frozen storage generally increased compression strength by about 20-30% over the compression strength at ambient condition.
8. The moisture absorption rate generally decreased with decreasing temperature of storage, and compression strength increased with decreasing temperature of storage.

The results obtained in these tests indicate that moisture absorption by corrugated shipping containers during frozen storage can contribute to increased compression strength. Moisture absorption proceeds very rapidly within the first 10 days of frozen storage, but thereafter, tends to level off, reaching a maximum moisture content (M.C.) at about 16%. There is also indication of some desication for prolonged storage beyond 2 months which had no significant effect on strength.

Results indicate that the compression strength of wax coated boxes also increased significantly in frozen storage. A 2.3% increase in moisture content was accompanied by more than a 80% increase in compression strength. This increase may also be attributed to hardening of the wax coating. There was substantial cracking of the wax during compression testing.

During thawing, waxed boxes tended to condense more moisture on board surface. This was responsible for the smaller reduction in compression strength during thawing. Moisture was unable to move into the board fibers as fast as in uncoated boxes. Wax coated boxes, therefore, retained more strength than non-coated boxes when exposed to adverse atmospheric conditions, resulting in improved box performance.

There does not appear to be any significant difference in moisture content for corrugated boxes with product inserts (folding cartons of corn vegetables and flexible pouches of mixed vegetables) compared with empty frozen boxes.

The compression strength (C.S.) of frozen boxes is of great importance to know since it is a vital part of package performance and distribution for almost all frozen food items. Design, using as little corrugated board as possible can effect considerable savings. Knowing that compression strength is increased during frozen storage would reduce the strength requirement for design of corrugated boxes and hence savings.

RECOMMENDATIONS

Major recommendations from this study are as follows:

1. There should be proper monitoring of the frozen distribution channel to determine at what point in the distribution process does exposure to standard conditions occur resulting in thawing and damage to package and product.
2. Greater compression strength under frozen condition should not result in abitrary use of low-strength boxes but should be thought of as an added assurance that the package would survive the distribution hazard. This is more important when cost of package is small relative to the product. Carpenter (1961) reported that expenditure of an additional 10 cents per carton for frozen turkeys would be more than offset by the saving in damage and handling. The increased cost would amount to 2 1/2 cents a bird, but savings would run from 5 cents to 20 cents per turkey.
3. Comprehensive pilot testing of shipping containers to predetermine if the new packages would meet requirements of performance and economy is recommended.
4. Use of moisture resistant coatings to improve moisture absorption may provide an advantage in strength.

Areas for Future Study

1. Electron microscopy: Examination of structural changes in board fiber due to freezing and freeze-thaw cycles using electron microscope. Examination of the physical state of moisture in board under frozen condition and how it affects fiber structure.
2. Pallet Load: Study of moisture movement from frozen environment into palletized boxes. Examine changes in moisture from external container surfaces to internal container surfaces.
3. Moisture Isotherm: Determining of the moisture Isotherm for corrugated board materials under frozen conditions.
4. Compressive strength study of boxes filled with products (food) under frozen condition.
5. Generation of Broad-based data to determine a safety factor to use for calculating stacking strength under frozen condition compared with that used under Tappi condition.

APPENDIX 1

Table 10 Moisture Absorption in Frozen Storage

Days of Storage	Untreated Box M.C. (%)	Untreated Box % Increase vs Ambient	Waxed Treated Boxes M.C. (%)	Waxed Treated Boxes % Increase vs Ambient
Ambient	8.2		7.0	
2 Days	12.1	47.6	7.2	2.9
4 Days	12.9	57.3	7.2	2.9
8 Days	13.1	59.8	7.7	10.0
12 Days	13.4	63.4	7.9	12.9
14 Days	14.3	74.4	8.0	14.3
18 Days	14.5	76.8	8.1	15.7
20 Days	15.7	91.5	8.3	18.6
22 Days	16.1	96.3	8.4	20.0
25 Days	15.9	93.9	8.3	18.6
28 Days	15.8	92.7	8.4	20.0
30 Days	15.6	90.2	8.5	21.4

APPENDIX 2

LOADING AND UNLOADING TIME/TEMPERATURE

TABLE 11 DISTRIBUTION CENTERS

	Average Model/(Survey)	90% Model/(Survey)
Time to unload truck	144 min. (135 min.)	300 min. (240 min.)
Truck temperature while unloading	--------- ---------	--------- ---------
Time product sits on loading dock	30 min. (15 min.)	84 min. (60 min.)
Unloading dock temperature	62°F (55°F)	88°F (75°F)
Warehouse temperature	- 3.6°F (- 2.1°F)	1.3°F (0°F, + 5°F)
Time on loading dock	21 min. (15 min.)	60 min. (60 min.)
Loading dock temperature	52°F (55°F)	78°F (78°F)
Time to load truck	98 min. (150 min.)	222 min. (240 min.)
Truck temperature while loading	55°F (55°F)	87°F (75°F)

* Obtained from Pillsbury Company.

Values in parenthesis were obtained during a second monitoring.

LOADING AND UNLOADING TIME TEMPERATURE

Table 12 CUSTOMER WAREHOUSE

	Average Model/(Survey)	90% Model/(Survey)
Time to unload truck	88 min. (160 min.)	198 min. (300 min.)
Truck temperature	---------- -(32°F)	---------- -(50°F)
Time on unloading dock	33 min. (15 min.)	96 min. (60°F)
Unloading dock temperature bimodel dostricution: (see text)	50°F (39°F)	78°F (60°F)
Warehouse temperature	-14°F (- 7°F)	- 5°F (0°F)
Time on loading dock	64 min.	(60 min.)
Temperature of loading dock	56°F (39°F)	73°F (60°F)
Time to load truck	(144 min.)	(240 min.)
Truck temperature while loading	(38°F (32°F)	58°F (60°F)

Obtained from Pillsbury Company.

APPENDIX 3

Table 13 **Mead Containers**

Compression Correction Factors
(For boxes with standard 26#/msf medium)

Test	Combination	Top-to-Bottom		End-to-End	
		Singlewall			
125#	(26-26)	73%		54%	
	(33-26)	75%		64%	
150#	(33-33)	78%		74%	
	(33-38)				
175#	(42-33)	82%		80%	
	(38-38)	95%		92%	
	(38-42)				
200#	(42-42)	100%		100%	
	(47-42)	103%		104%	
	(47-47)	111%		114%	
250#	(69-42)	123%		130%	
	(62-62)	138%			
275#	(69-69)	146%		161%	
300#	(90-90)	167%		188%	
350#	(90-90)	189%		215%	
		Doublewall			
		A/B	C/B	A/B	C/B
200#	(33-26-33)	166%	154%	109%	122%
275#	(42-26-42)	183%	171%	142%	155%
350#	(42-42-42)	198%	186%	171%	183%
	(69-33-42)	213%	201%	197%	210%
500#	(90-42-90)	286%	273%	315%	328%
600#	(90-90-90)	331%	318%	387%	399%

Table 13 (Cont'd)

Compression Correction Factors for Mediums	
26#	100%
30#	106%
33#	112%
36#	118%
40#	122%
52#	126%

Conversion Factors	
From dynamic machine strength to long term static dead load	
Variable Humidity	2 to 1
Abuse and Creep	
Altogether	4 to 1 (for production run)
	5 to 1 (for handmade)

(NST Static Compression = Three times load for one hour)

Institute of Paper Chemistry (1972).

APPENDIX 4

Table 14

EFFECT OF MOISTURE CONTENT, TIME AND COMPRESSION STRENGTH ON STACKING STRENGTH OR PALLETIZED BOXES

R.H.	Moisture Content %	Load at Standard Condition, % of Compression Strength		
		90-day Life	180-day Life	360-day Life
50	7.5	60	55	51
65	10.0	43	40	37
75	12.5	32	29	27
80	15	23	21	20
85	17.5	16	15	14
90	20	12	11	11

Uldis I. Levans (1977).

APPENDIX 5

Least Significant Difference

The LSD computes the smallest difference between two or more treatments that would be declared significant. The absolute value of each observed difference between treatments are then compared with the L.S.D. value to establish significance.

Any difference between values larger than L.S.D. is significant. For example, comparing compression strength at -31.7°C (-25°F) with C.S. at 23°C.

Procedure for L.S.D.

1. Using standard deviation of means pooled variance

$$(S^2) = \frac{S_1^{\ 2} + \ldots\ldots\ldots S_n^{\ 2}}{n}$$

Standard deviation of mean Sy = $\frac{\text{Pooled } S^2}{N}$

n = number of means.

N = number of observations for which a mean was obtained (N is equal for each mean).

2. L.S.D.05 = t.05 (d.f.) Sy

d.f. = degree of fredom (N-1) (n-1) used for the t - table.

(.05) = 5 percent significant level which is more common and practical for most scientific studies.

t = Probability level.

3. When number of observations for each mean are not the same.

$$\text{pooled } S^2 = \frac{(n_1-1)S_1^{\,2} + (n_2-1)S_2^{\,2} + \text{-----} \ (n_i - 1)\ S_i^{\,2}}{(n_i-1)}$$

Standard deviation of mean difference

$$S^{\,2}_{\ d} = \text{Pooled } S^2 \ \left(\frac{N+n}{Nn}\right) = S^2(1/N + 1/n)$$

$$\text{L.S.D.05} = t_{.05}\ Sd$$

<u>EXAMPLE:</u> using table 1.

$$\text{pooled } S^2 = \frac{15.1^2 + 18.5^2 + 17.5^2 + 16.1^2 + 24.4^4 + 26^2 + 26^2 + 32^2 + 27^2 + 19.6^2 + 20^2 + 24^2 + 22.6^2 + 25.2^2 + 21.3^2}{14}$$

$$= \frac{7119.73}{14} = 508.55$$ (14 = number of means).

$$Sy = \frac{508.55}{20} = 5.04$$ (20 = no of) (observations) (for each mean) (values)

Degree of freedom = 19 x 13 = 247 (DC)

$$\text{L.S.D.}_{05} = t_{.05(OC)}\ Sy$$
$$= 1.96 \times 5.04 = 9.9 \text{ lbs.}$$

Any difference between compression strength at $-31.7^{o}C$ and $23^{o}C$ larger than $\text{L.S.D.}_{.05}$ = 9.9 lbs is significant.

APPENDIX 6

Moisture Content Determination of Paper and Paperboard by Oven Drying. ASTM D644

Percent moisture content was determined based on oven dry weight as follows:

Temperature of oven-drying = $105 \pm 3^{o}C$.

Tare weight of bottle + cap = W_o (gms).

Weight of container + wet sample = W_1.

Original weight of sample = $W_1 - W_o = W_w$.

Weight of sample after oven-drying = $W_2 - W_o = W_D$.

$$\text{Moisture percent} = \frac{W_w - W_D \times 100}{W_D}$$

APPENDIX 7

CORRELATION THEORY

CORRELATION BETWEEN COMPRESSION STRENGTH AND MOISTURE CONTENT OF BOXES HELD AT -25°F (-31.7°C)

Y_1 = compression strength (lbs).

Y_2 = moisture content (%).

	Y_1	Y_2	Y_1Y_2
1	344	8.9	3061.6
2	350	9.5	3325
3	346	13.6	4705.6
4	361.3	14.2	5130.5
5	363	14.3	5190.9
6	343	16.1	5522.3
7	365	16.3	5949.5
8	357	16.2	5783.4
9	388	16.1	6246.8
10	356	14.9	4842.5
11	360	14.7	5292
12	354	14.6	5168.4
Sums	4287	169.2	60218.5
Mean	(357.3)	(14.1)	

Variance S_1^2 = 148.21 S_2^2 6.09

S.D. S_1 = 12.174 S_2 2.47

Covariance 60,218.5 - (4287) (169.2)/12 /11 =
S_{12} 60,218.5 - 60,044.6 /11 = 15.81

Correlation r_{12} = $S_{12}/S_1S_2 = \frac{15.81}{(12.174)(2.47)} = \frac{15.81}{30.07}$

= (.5258 Considered to be no correlation)

Absolute value should be .8 and above to establish correlation.

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