MECHANICAL PROPERTIES OF SPACEBOARD PANELS AND PALLETS MADE FROM RECYCLED LINERBOARD MILL SLUDGE.

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ABSTRACT

Every day, paper mills landfill or burn 3 to 50 metric tons of fiber that might otherwise be used for value-added structural packaging products. Sludge from a recycled linerboard mill was used to form Spaceboard subpanels for Conversion Technologies Industries, Inc.. The sludge was used "as is" without any pre-processing or chemical additives or adhesives. The subpanels can be described as fiber-formed, three-dimensional, high-density structures having an integral rib and face structure. These subpanels were combined into a sandwich structure 2.0 cm thick by bonding the ribs together. Edge cursh, center point bending, and flat cursh tests were conducted to investigate initial mechanical properties of the sludge panels and to assess the potential use of such panels in a structural product, specifically a standard 101.6 by 121.9 cm (40 by 48 inch) four-way entry pallet. Nine pallets of three preliminary configurations were tested to determine bending strength properties based on the Australian Standard AS 4068. This paper discusses the measuredpanel strength properties and the results from the initial pallet tests. These preliminary tests show sludge material has the potential for use in structural panels and structural product applications.

INTRODUCTION

Every day, paper mills in the United States generate 3 to 50 metric tons of unwanted material generally referred to as mill rejects or sludge. Although, the exact content of the material varies from mill to mill, a significant amount of usable long fiber along with plastics, styrofoam, and other contaminants associated with machine screen rejects are discarded to the land fill or burned. In 1990, U.S. pulp and paper mills generated 4.2 million oven dry metric tons of sludge (1). Of that, 1.4 million metric tons could be classified as long fiber, and the remaining 2.8 million metric tons was fiber fines, ash, and debris, of which 1.1 million metric tons was ash. There is a ned to develop a process that can utilize a portion of this material to produce value-added products and divert it from landfills.

The USDA Forest Products Laboratory (FPL) has developed a three-dimensional forming process (2, 3) that can be used to process fibrous material into structural panels. The process involves forming a fibrous mixture over a three-dimensional resilient mold. The mold and fibers are then pressed and dried under heat and pressure to produce Spaceboard, a fiber-formed, three-dimensional, high-density structure having an integral rib and face structure. The process can be modified to alter the performance characteristics of the product.

If a product could be formed, the economic value for sludge diverted from the landfill would yield in Spaceboard terms approximately $500/metric ton (dry weight) in revenue. This assumes that a 12.7 kg pallet made from Spaceboard sells for $6.00. The revenue estimate also includes the avoided landfill cost of $34/ metric ton. (4)

This study was initiated by Conversion Technologies Industries, Inc., a Spaceboard sub-licensee, to investigate the structural performance of Spaceboard from an industrial sludge material.

EXPERIMENTAL PROCEDURES

Furnish

Two shipments of sludge from a recycled linerboard mill were recieved and used "as is" without processing or chemical additives. Results of a fiber analysis of the first shipment are shown in Table 1, along with comparative results for recycled corrugated and mixed office waste paper.

The fiber length was determined by the Kajaani FS 100 fiber length analyzer. A large portion of the ash content can be attributed to sand or glass particles. There were also some styrofoam beads in the sludge material.

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[1] The Forest Products laboratory is maintained in cooperation with the University of Wisconsin. This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain and not subject to copyright.

Table 1. Fiber Analysis Results.

	Sludge	Recycled Corrugated*	Mixed Office*
Freeness (CSF)	717	657	382
Average Fiber Length (mm)	2.47	2.89	1.93
Ash Content (%)	12.9	1.34	3.83

* Comparative Sample

Spaceboard Mold

A 132 by 284.5 cm Spaceboard mold was used to form a series of subpanels from 100% sludge. A subpanel is defined as a single sheet of Spaceboard with an integral rib and face structure (Figure 1). These subpanels were bonded rib-to-rib (combined subpanels are called panels) for material testing and also bonded together in three configurations for pallet testing. The mold has a 2.54 by 2.54 cm square rib pattern capable of forming approximately 10.4 mm thick subpanels.

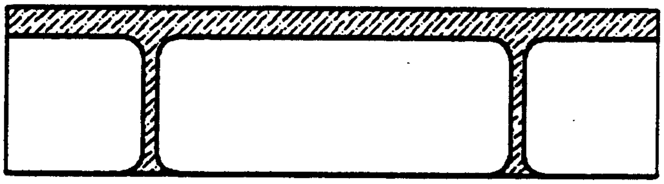

Fig. 1. Subpanel cross-section with an integral rib and face structure.

Spaceboard Process

The sludge was shipped to FPL in wet-pressed form and used as shipped. No pre-processing, chemical additives or adhesives were added for this initial test series. Sludge consistency as recieved was 32%. Two target subpanel weights were selected: 7.26 kg and 10.43 kg. For each subpanel, an appropriate amount of sludge was mixed with water and brought to a consistency of 0.9%. The sludge was pumped into the deckle box and additional water added to reduce the consistency to approximately 0.5% for forming. Once the forming height was reached, a vacuum valve was poened to pull the water through the mold depositing the sludge material around and above the silicone pads to for a three-dimensional fiber mat. After formation, the wet-formed mat and mold were then transferred to a hot press to be pressed-dried. All the subpanels were pressed at approximately 1.03 MPa and 170 C.

Each dried subpanel was cut into three pieces. Two pieces were used for fabricating pallet parts while the remaining trim piece was used for material properties testing of the sludge formed panels. Eight trim pieces were combined to form four test panels. The subpanels were combined rib-to-rib using a water-based polyvinyl acetate adhesive (carpenters glue). Test specimens were cut, conditioned, and prepared according to standard ASTM procedures.

An additional four high-density flat sheets were also formed from the sludge material and press-dried at 1.03 MPa and 170 C to a nominal 3.0 mm thickness. These flat sheets were used for pallet bases.

Pallet Fabrication

Three pallet configurations (Figure 2) having standard 101.6 by 121.9 cm (40 by 48 inch) base dimensions were selected to investigate preliminary bending strength and creep response in the short and long dimensions. The pallets were designed to have four-way entry, nine feet, and a four-hole bottom. The pallet tops for configurations 1 and 2 were cut from full panels. Figures 3 and 4 show the top and bottom views of pallet conviguration 1. The pallet top for configuration 3 had three subpanel layers bonded together, two rib-to-rib third bonded rib-to-face.

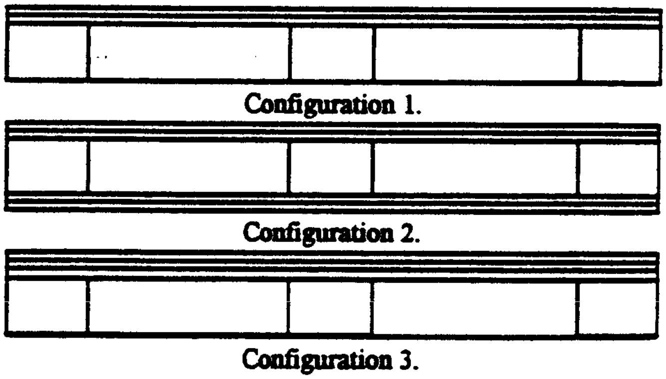

Fig. 2. Pallet Configurations used in this study.

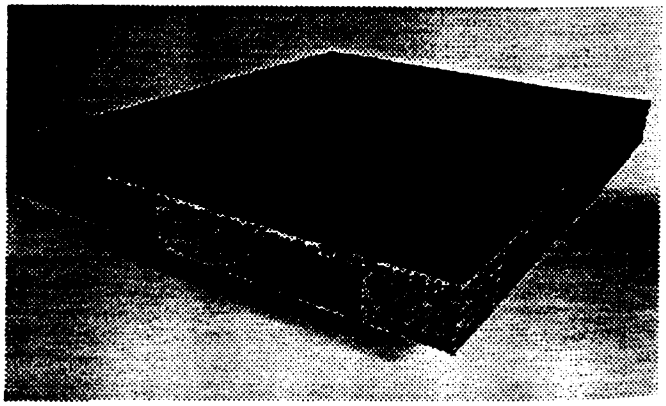

Fig. 3. Pallet configuration 1, top view, made from Spaceboard sludge panels.

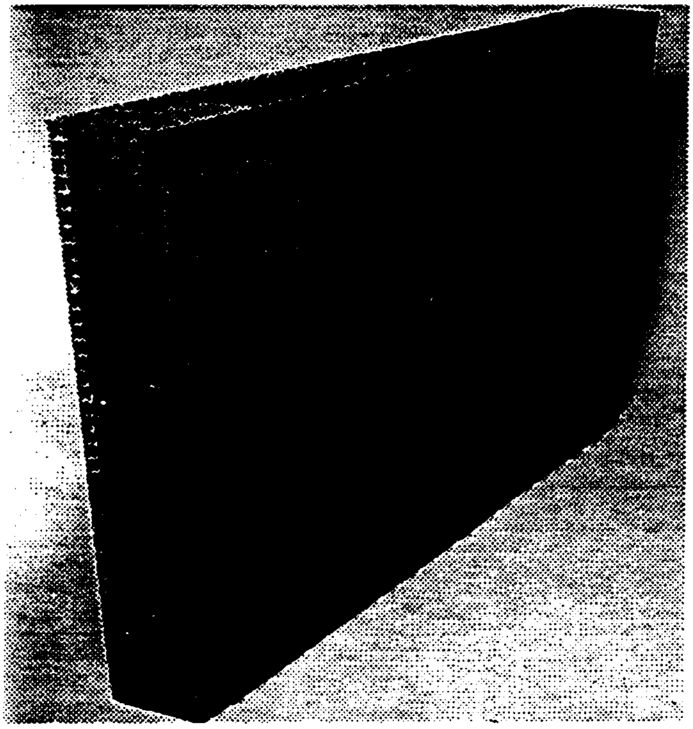

Fig. 4. Pallet configuration 1, bottom view, made from Spaceboard sludge panels.

The pallet feet were also made from Spaceboard sludge subpanels. The feet were 15.2 by 15.2 cm by 10.2 cm tall and were 16 layers thick. The feet were cut such that the facings of the subpanels were in the vertical direction (on edge) relative to the pallet top and bottom.

For pallet configurations 1 and 3, the nominal 3.0 mm flat sheet was used for the bases. Configuration 2 used Spaceboard panels as a base. Four holes, 27.9 by 30.5 cm, were cut into all the bases to provide floor access when floor jacks are used. Table 2 lists the physical dimensions and weights of the pallets tested.

MATERIAL PROPERTIES TESTING

Strength tests were conducted to assist in evaluating the performance of the sludge material for structural packaging products such as pallets. The tests include; 1. Edge crush test (ECT) in two relative humidity (RH) conditions, 47% and 90% RH; 2. Mid-point bendidng test; and 3. Flat crush test (FCT).

Table 3 lists the subpanel combinations and the physical dimensions of the test specimens.

Table 2. Pallet Measurements and Assembly Information.

Pallet	Pallet Configuration (No.)	Weight (kg)	Total Thickness (cm)	Pallet Top Thickness (cm)	Base Thickness (mm)	Test Span (cm)	Max Load (kN)	Max Deflection (cm)
AZ	1	16.0	12.7	2.16	3.29	121.9	5.27	2.27
BZ	1	14.9	12.7	2.14	3.17	101.6	5.66	1.88
CZ	1	15.5	12.5	2.18	2.74	101.6	Creep Test	NA
DZ	2	15.8	14.3	2.00	19.8	121.9	5.52	2.95
EZ	2	14.2	14.2	1.96	19.5	101.6	6.97	1.96
FZ	2	14.8	14.2	1.97	19.9	101.6	Creep Test	NA
HZ	3	16.0	13.6	3.07	2.64	101.6	8.39	2.27
IZ	3	16.1	13.6	3.04	2.72	121.9	6.87	2.27

Table 3. Subpanel Combinations and the Physical Dimensions of the Test Specimens.

Subpanel Combination	Subpanel No. 1 Face Thickness* (mm)	Subpanel No. 2 Face Thickness** (mm)	Panel Weight per Area (kg/m^2)	Panel Thickness (mm)	Panel Specific Gravity
PS 02/07	1.41	2.29	5.61	21.3	0.263
PS 08/01	1.97	1.36	5.13	21.4	0.239
PS 09/04	0.91	1.24	3.75	20.5	0.183
PS 10/05	0.98	1.75	4.49	20.5	0.219

*Corresponds to the first number of the subpanel combination.
**Corresponds to the second number of the subpanel combination.

Edge Crush Test

From each panel, five 10.2 by 10.2 cm specimens were edge crush tested. The ribs for all the specimens were oriented orthogonal to the specimen dimensions. The top and bottom edges of each specimen were dipped in epoxy resin to stiffen the edges and force failure to the center section of the samples. Three specimens were pre-conditioned at 47% RH and two at 90% RH prior to testing. The specimens were tested according to ASTM Test Standard C364 (5). Load vs. cross-head movement (1 mm/min) data were recorded. Panel and face stress vs. strain calculations were made. Table 4 lists the maximum calculated values for panel stress, panel modulus of elasticity (MOE), face stress, face MOE, and panel load at 47 and 90% RH. Panel stress is defined as the load divided by the panel cross-sectional area. Face stress is defined as the load divided by the cross-sectional area of the two faces only. MOE for both the panel and face were obtained using a linear regression from the straight portion of the stress-strain curves. Figure 5 plots panel load values vs. panel weight.

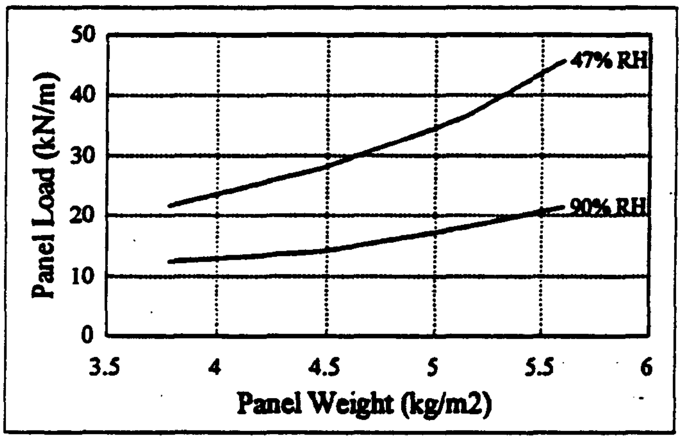

Fig.5. Edge crush test.

Strength retention comparisons between the two RH values for the calculated values are listed in Table 4. Strength retention is defined as the value at 90% RH divided by the 47% RH value.

Bending Test

From each panel, eight 10.2 by 50.8 cm specimens were cut and conditioned for bending tests with the faces perpendicular to the loading direction. The ribs for all the specimens were oriented orthogonal to the specimen dimensions. The specimens were cut lengthwise such that four ribs were centrally located in the middle of trhe 10.2 cm width. Five specimens were conditioned at 47% RH and three were conditioned at 90% RH. Of the five specimens, three were tested with the same Spaceboard subpanel up and the other two specimens were tested with the other subpanel facing up. The specimens were tested at mid-span according to ASTM Test Standard C393 (6).

The cross-head rate was 5 mm/min for the horizontal specimens. Load vs/ cross-head movement data were recorded. Area moment of inertia (MOI) for each specimen was calculated based on the thickness of the panel and the thickness of the two faces. The MOI for the ribs represent a very small portion of the total, so they were not included in the calculations. The specimens top and bottom face thicknesses were not equal, therefore the neutral axis location varied and was calculated for each specimen. From the MOI and neutral axis calculations, MOE and modulus of rupture (MOR) were calculated. Panel load, MOE, and MOR for 47 and 90% RH conditions are reported in Table 5. Strength Retention is also listed in Table 5.

Flat Crush Test

From each panel three 10.2 by 10.2 cm specimens were cut and prepared for flat crush testing. The ribs for all the specimens were oriented orthogonal to the specimen dimensions. All the samples were pre-conditioned at 47% RH prior to testing. The specimens were tested according to ASTM Test Standard C365 (7). The cross-head rate was 0.5 mm/min. Load vs cross-head movement data were

Table 4. Edgewise Compressive Strength of Flat Sandwich Construction.

Subpanel Components	47%RH						90%RH						Strength Retention				
	Test Load (N)	Panel MOE (GPa)	Face MOE (GPa)	Panel Stress (MPa)	Face Stress (MPa)	Panel Load (kN/m)	Test Load (N)	Panel MOE (GPa)	Face MOE (GPa)	Panel Stress (MPa)	Face Stress (MPa)	Panel Load (kN/m)	Panel MOE (%)	Face MOE (%)	Panel Stress (%)	Face Stress (%)	Panel Load (%)
PS 02/07	4659	0.515	2.88	2.15	12.4	45.8	2184	0.235	1.33	1.00	5.8	21.4	45	46	47	47	47
PS 08/01	3710	0.401	2.40	1.70	10.6	35.4	1855	0.187	1.17	0.85	5.5	18.1	49	49	54	53	54
PS 09/04	2196	0.305	2.71	1.05	10.0	21.5	1259	0.143	1.45	0.61	5.7	12.4	46	51	58	55	58
PS 10/05	2824	0.342	2.62	1.35	10.2	27.8	1424	0.161	1.21	0.68	5.1	14.0	51	50	54	54	54

Table 5. Bending Properties of Flat Sandwich Construction.

Subpanel Components*	47% RH				90% RH				Strength Retention			
	Load (N)	MOE (GPa)	MOR Top Compress (MPa)	MOR Bottom Tension (MPa)	Load (N)	MOE (GPa)	MOR Top Compress (MPa)	MOR Bottom Tension (MPa)	Load (%)	MOE (%)	MOR Top Compress (%)	MOR Bottom Tension (%)
PS 02/07	323	2.90	11.7	9.21	207	1.69	7.84	5.75	64	58	67	62
PS 07/02	359	3.04	10.5	14.90								
PS 08/01	374	3.42	10.8	13.60	250	1.91	7.63	9.80	67	56	71	72
PS 01/08	349	3.50	13.7	10.50								
PS 09/04	157	3.10	8.4	6.03	109	2.03	6.21	4.37	69	66	74	73
PS 04/09	233	3.37	8.9	12.40								
PS 10/05	175	3.43	9.1	6.36	117	1.94	6.18	4.10	67	56	68	64
PS 05/10	260	3.34	9.5	13.80								

*The first number listed indicates which subpanel was positioned on top during the bend test.

recorded Core stress vs strain calculations were made and the data plotted. Flatwise core stress is defined as the load divided by the panel surface area. Flatwise core MOE is a structural property of the panel and not a material property of the sludge. The MOE was obtained using a linear regression from the straight portion of the stress-strain curves. Table 6 lists the maximum calculated values for flatwise core stress and flatwise core MOE at 47% RH.

Table 6. Flatwise Compression Strength of Sandwich Cores, 47% RH.

Subpanel Components	Test Load (N)	Flatwise Core Stress (kPa)	Flatwise Core MOE (kPa)
PS 02/07	1424	137	6049
PS 08/01	1913	185	6861
PS 09/04	1836	178	7479
PS 10/05	1860	180	7332

PALLET TESTING

The nine pallets assembled were tested in third-point bending, following the Australian Test Standard AS-4068 (8). One of each pallet configuration was tested to failure using the short side (101.6 cm) as the span. Similarly, one of each configuration was tested to failure using the long side (121.9 cm) as the span. The last three pallets were tested for creep using the short span (101.6 cm).

Pallet Load-to-Failure Tests

All the pallets were conditioned at a 50% RH, 21 C room for over 1 week. All the pallets tested except for the creep test pallets, remained in the conditioned environment and were exposed to the daily environment for a maximum of 30 minutes prior to testing. An initial load equal to 2 kN was held for 1 minute to collect the datum loading deflections. After 1 minute, the load was steadily increased until failure occurred. The failure load was reached in less than 5 minutes. Figure 6 shows the pallet load for each pallet configuration for the short and long span orientations Table 2 lists pallet configuration type and pallet loads.

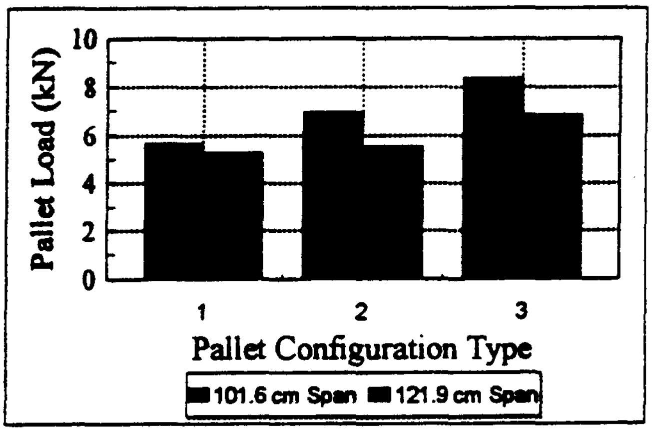

Fig. 6. Pallet load for each pallet configuration for the short and long span lengths.

Pallet Creep Tests

The pallets were set up as in the load-to-failure tests and loaded to 2 kN. The load was held for 1 minute and then increased to 50% of the estimated failure load determined from the load-to-failure test results of a similar pallet configuration. The load was held here for 1 hur and then increased to 75% of hte estimated failure load. The load was held for another 1 hour after which it ws reduced to 2 kN for 5-10 minutes. Figures 7 and 8 show pallet creep responses for pallets CZ and FZ. Palllet GZ creep data for configuration 3 were not recorded due to a collection error.

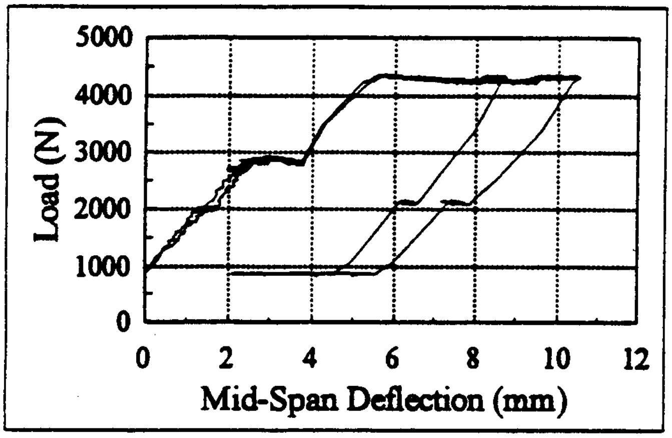

Fig. 7. **Bending creep test, 101.6 cm (40 inch) span, configuration 1. The two curves represent the deflection recorded for either end of the pallet.**

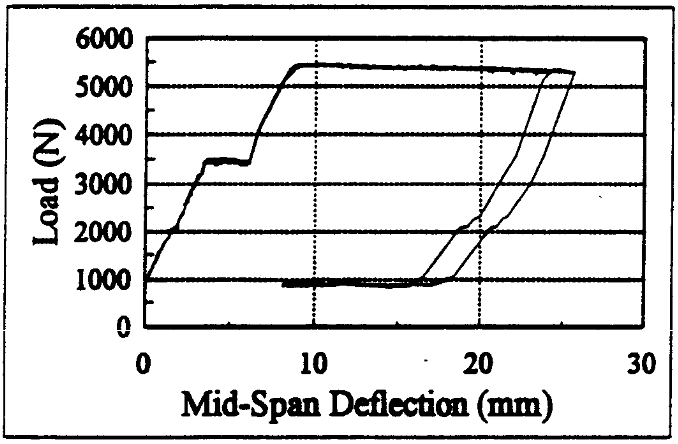

Fig. 8. **Bending creep test, 101.6 cm (40 inch) span, configuration 2. The two curves represent the deflection recorded for either end of the pallet.**

ANALYSIS AND OBSERVATIONS

The following describes the test data analysis plus some observations from forming the subpanels, panel testing, and pallet testing

Furnish

The furnish as recieved, wet-pressed, was easily repulped with minimal agitation in our stock tank. No other processing treatment, chemical additive, or adhesive was used to modify the furnish. At about 1% consistency in the stock tank, a portion of sand and grit fell out of suspension to the bottom of the tank. However, a signigicant portion of sand, glass, and grit was still pumped to the deckle box and distributed in the Spaceboard sheets. The high ash content primarily sand and grit, represents non-bonding material that gives lower strength values per unit panel weight.

Special cleaning equipment or settling traps would be necessary in the stock preparation to eliminate grit wear on pumps and piping systems.

The furnish also cintained a some small styrofoam beads that melted during drying. The melted beads were absorbed into the surface fibers with minimal transfer to the top screen in the press. The melted beads did not have any noticeable effect on board strength. The melting and heating of the styrofoam beads may need to be examined to determine if any harmful off-gassing occurs during the drying process.

Spaceboard Process

During the initial forming/agitation stages of the forming process, a disproportionate amount of "heavier" non-bonding grit material was deposited into the ribs sections. This could significantyl weaken the Spaceboard ribs.

The grit in the dried subpanels also caused problems when fabricating components for the pallets. Three saw blades were dulled while cutting only a relatively few panels for the pallet feet. However, the goal of the Spaceboard process is to produce a structural panel to final for-fit-and-function. This means that the fibrous material, along with any grit or contaminant, is processed to its final shape and form directly, thus bypassing secondary processing steps, e.g., cutting or sawing, and eliminating wear and tear on cutting tools.

Edge Crush Strength

The edge crush test shows that strength increases in proportion to board weight, which corresponds to increase face thickness. The face stress, which is an indication of the sludge material basic properties, shows lower strength compared to recycled corrugated Spaceboard panels in another study (9). For example, the maximum face stress in this study was 12.4 MPa, which is 16% lower than the face stress value of 14.8 MPa for recycled corrugated Spaceboard panel.

The maximum panel stress values at 47% RH (Table 4) indicates the potential for vertical load-carring capacity for panels on edge. For example, the feet on the pallet were made from vertically oriented panels. They had 16 subpanels (8 panels) thick and were 15.2 cm long. Based on panel load per length values from the ECT tests, the combined potential load capacity for the nine feet on the pallet would be 45.8 kN/m × 8 panels × 0.152 m × 9 pallet feet = 501 kN of force or 51,000 kg load. In our preliminary pallet designs, the pallet top could not withstand this type of loading without compression failure in the ribs. A future pallet design might attach the feet directly below the face sheet for full transfer of the verticle load.

Flexural Strength

The flexural test shows that MOE and MOR values of the sludge formed panels arc 39% and 42% lower than comparable Spaceboard panels (9) made from recycled corrugated fibers (MOE = 3.3 MPa vs 5.4 MPa and MOR 14.0 Mpa vs. 24 MPa, respectively). It is also interesting to note that the higher flexural strength were obtained with the panels oriented with the thicker face on top (Tables 3 and 5). The predominant failure for the Spaceboard panels was in compression along the rib lines. As the face thickness increased on the compression of the test specimen, the load-carring capacity also increased.

The Spaceboard mold design also influences the fiber density along the rib lines (rib-face intersection). Improving the mold design to increase the fiber density at the intersection would increase the overall strength of a Spaceboard panel.

Flat Crush Strength

The flat crush test (Table 5) shows that the current mold design for the pallet top for all the pallets and bottom for configuration 2 would withstand a vertical load of 185 kPa × 0.152 m × 0.152 m × 9 pallet feet = 38.5 kN or 3,922 kg of load. This assumes that only the area above the feet carry the load. This assumes that the compressive failure is catastrophic. However, from the load vs. deflection curves, not shown, the load peaks and then falls off to 80% to 90% of maximum and then maintains load during continued deformation. In this and other studies, the flat crush failure of Spaceboard reaches a peak then plateaus at a reduced value, but it is not catastrophic due to the vertical rib orientation.

Higher flat crush loads could be obtained if the pallet tops were specifically designed for increased rib strength and/or designed, as mentioned above so the pallet feet could be inserted directly bclow the face of the pallet top. A variety of designs are possible when forming directly with the sludge material.

Pallet Strength

The highest bending load achieved was 8.9 kN by pallet HZ, configuration 3 (Figure 6 and Table 2). This pallet had a three-layer Spaceboard deck, a flat sheet bottom, and was tested using the short(101.6 cm) span. During loading, the pallet section above and below the legs did not have any curvature, whereas the sections between the feet did. The loaded pallet took an S-shape curvature near the faillure load.

The failures in these tests all appear in two places, ribs and face. It is hard to determine which came first, but significant rib shear was noted and buckling in hte upper face of the pallet top. It is possible that shear strength of the ribs is low due to higher amounts of grit (non-bonding material) as well as fiber orientation along the plane of the pallet top. Face buckling occurred parallel to the load applicators, along the rib interface lines. These rib interface lines are regions of low density, hence low strength. Improved mold design, higher pressures, and thicker faces all help to increase the density, and hence the strength, in these areas.

The pallet feet were over designed and could be made with less fiber. The nine feet together weighed 4.5 kg representing abput 33% of the total pallet weight. As evident in the edge crush values, the amount of fiber in each pallet feet could be reduced by 50%, thus reducing the pallet weight by 16% without diminishing pallet strength

Pallet Bending Creep Strength

The pallets were creep tested at 50% of the estimated failure load for 1 hour and then at 75% of the estimated failure load for another hour. The midpoint deflections of were measured for the duration of the test. Pallets FZ and GZ failed at a sustained load of 75% of the estimated maximum load capacity. Pallet CZ was the only pallet that did not have visible face buckling after this test, but there was a visible deflections set.

CONCLUSIONS

The results from this initial study that a reject material, sludge, from a commercial mil has significant promise for fabrication into a structural packaging product.

The sludge material processing in this study was not optimized. The material was used as is without any preprocessing or additives. It had 12.9% non-bonding sand and grit, which lowered its potential strength compared to other fiber furnishes at equal board weight. Some simple separation techniques just prior to forming could remove a significant portion of this non-bonding material to increase board strenagth per unit panel weight. Additional strength improvements could be obtained with chemical additives or adhesives.

The material strength of the panels using this mold had less strength than previously made panels formed from rercycled corrugated. The Spaceboard mold design was not optimized for this sludge material nor was it optimized for fabricating a pallet. It is possible to refine the mold and pallet designs to optimize strength for this specific application or other structural packaging product(s).

The pallet tests show that significant loads can be carried with this preliminary pallet design. The Spaceboard process lends itself to forming a structural panel to its final form, fit, and function directly from the fibers, thus eliminating secondary operations such as post-fabrication and cutting

Effects from high moisture environments need to be addressed when designing a structural product. The sludge material used in this study as well as other cellulosic materials lose strength in high humidity environments. We found the panels lost about 50% strength going from a 47% to a 90% RH environment

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