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Improving Engineered Wood Fiber Surfaces for Accessible Playgrounds

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Abstract

Some engineered wood fiber surfaces are uneven, tend to shift, and have low density. The goal of our research was to develop a playground surface material that cushions impact and is accessible to people with disabilities. In the initial screening phase, we evaluated a variety of *in situ* surface treatments and mixtures of wood particles combined with various binders. Engineered wood fiber (EWF) was prepared from three species, red maple, ponderosa pine, and one-seed juniper, which have a wide range of densities and bonding properties. In the scale-up phase, we evaluated commercially available EWF and several promising binding systems from the screening phase trials. Seventeen test configurations were formed in plywood boxes, using different levels of EWF compaction, fiber moisture content, surface layer thickness, and types of binders. Binder systems that show promise for surface stabilization and satisfactory impact behavior are polyurethane, latex, and silicone. These binders were chosen on the basis of processing ease, flexibility (elongation to failure), cost, and safety in application and use. In this report, we identify the strengths and weaknesses of the surface treatments, review the viability of the systems and the testing concepts we have developed, and identify further research needs.

Keywords: surfacing, impact, accessibility, ADA, composite, polyurethane, cushioning, engineered wood fiber, latex, silicone

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Background

Engineered wood fiber (EWF) products are the first choice of playground designers who wish to provide a natural or rustic-looking environment or for whom cost is a primary concern. Such products cost only 10% to 15% of the cost of synthetic rubber surfaces for full-depth playground system installations. When installed with proper drainage and well maintained, a wood fiber surface can last for 8 years or more. It can be designed to exceed Consumer Product and Safety Commission guidelines for the safety of playground surfaces.

For physically challenged children and adults who must use a wheelchair, crutches, or a walker, play areas and trails surfaced with EWF are generally suitable for short distances. However, recent research by Axelson and Chesney (1999) indicates that some EWF installations, especially when wet, might only be marginal for use on "accessible" traffic routes. As a consequence, the U.S. Architectural and Transportation Accessibility Compliance Board (known as the Access Board[1]) has been examining the appropriateness and usability of wood-based playground surface materials for outdoor environments designed to be accessible to children with disabilities (U.S. Architectural and Transportation Barriers Compliance Board 1991, 1994).

The baseline of safety performance is ASTM F1292, the Standard Specification for Impact Attenuation of Surface Systems Under and Around Playground Equipment (ASTM 1999a). The F1292 specification establishes impact attenuation requirements, when tested in accordance with Test Method F355 (ASTM 1995). The F1292 specification applies to all types of material that can be used under playground equipment. It establishes a direct means of comparison and does not imply that an injury cannot be incurred if the surface system complies with the specification.

The requirements of ASTM F1292 (and F355, Procedure C) are as follows:

1. The surface does not impart peak acceleration in excess of 1,961 m/s^2 (200 *g*) to an instrumented 4.54-kg (10-lb) head form dropped on a surface from the maximum fall height (critical height).
2. The surface must meet the head injury criterion (HIC) established in F1292 of less than 1,000 when properly installed.

The critical height of a surface material is established and published by the U.S. Consumer Product Safety Commission (1998) based on typical performance. The head injury criterion is an energy absorption measure for the entire impact event.

Axelson and Chesney (1999) researched the capability of a wide array of commonly used accessible surfaces. Accessible test courses, in compliance with the Americans With Disabilities Act (ADA) accessibility guidelines, were designed and built using three types of exterior wood-based surfaces. The firmness and stability of the test surfaces were measured using the wheelchair work measurement method and a portable surface measurement device, a rotational penetrometer. To determine energy required, persons with and without disabilities walked or wheeled across each surface.

Wheelchair work per meter values for forward movement and turning were determined for all test course surfaces under dry conditions using the wheelchair work measurement method in accordance with ASTM F1951 (formerly PS 83–97) (ASTM 1997, 1999b). The test courses were measured using a rotational penetrometer under both wet and dry conditions. The rotational penetrometer is a portable device developed by Axelson and Chesney (1999) that provides quantitative (ASTM F1951) measurements of firmness and stability on a wide variety of surfaces.

Standardized tests of physical fitness and community ambulation indicate that measures of mechanical work expended during ambulation would be a more consistent measure of surface acceptability than are subjective user assessments. In the study by Axelson and Chesney (1999), the work required to propel a wheelchair in a straight path was correlated to the firmness of the surface. The work required to propel a

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[1] The Access Board is a Federal steering group created under the Americans with Disabilities Act of 1992.

wheelchair through a 90° turn was correlated to the stability of the surface. The results indicated that the chipped brush surface and two EWF surfaces had higher work per meter values compared with that of the other surfaces tested. All exterior surfaces, except chipped brush, became less stable when wet. Axelson and Chesney recommended that these surfaces be considered moderately firm and stable and that each be rated as suitable for use in level areas for limited distances on trails and playgrounds.

Scope of Study

The study objective was to develop an EWF-based composite material, composed of a highly resilient bonded EWF surface and an unbonded EWF core, that would improve accessibility to playgrounds and other recreational surfaces for people with disabilities. In the initial screening phase, we identified several fiber processing options and evaluated several promising bonding systems. In the scale-up-phase, we performed impact cushioning tests and simulated accessibility testing using laboratory-sized full-depth surface specimens.

The screening phase included evaluation of a variety of *in situ* surface treatments and mixtures of wood particles with binder (silicone, urethane polymer resin, synthetic latex, or low molecular weight butylene co-polymer). Trials were made with several application techniques and binders to assess process and performance attributes.

A variety of potential binding agents were identified for mixing with EWF to stabilize the upper surface of a playground surface. This adhesive, filler, or matrix binding material was intended to bond or encapsulate the top surface of the EWF composite, thereby imparting a degree of resistance to wheelchair casters from penetrating the surface. A related objective was to impart upper layer stiffness so that the wheel or caster did not depress the surface. Somewhat at odds with these objectives was our desire to produce a stabilizing material that provided cushioning from falls.

Processing procedures needed to be developed for each stabilizing binder system. In each instance, we sought a system of materials with certain performance and processing attributes. The stabilizing binders were intended to be applied on site or mixed with the EWF no longer than 1 hour prior to installation. The method for mixing depended on the speed of curing, viscosity, tack, and similar attributes of the resin or binder. Costs for each type of operation was a concern as were such factors as worker safety, quality control, and performance assurance of the finished system.

Our expectations for good processing performance of a stabilizing binder were subjective but hinged on practical considerations. We sought a system that would provide impact safety and good access behavior. Impact safety (that is, energy absorption characteristics) is quantifiable by ASTM F1292 (ASTM 1999a) and preliminary tests using a portable impact test provided indication of stabilizing binder potential. Accessible surfaces are defined (by ADA) as stable, firm, and slip resistant. Accessibility of the potential surfaces was quantified using a rotational penetrometer (Axelson and Chesney 1999), which has good correlation to the wheelchair work method in ASTM F1951 (ASTM 1999b). Two cooperators provided portable test apparatuses and training in their use.

Wood Fiber Processing Trials

Wood fiber material consisted of three underutilized small-diameter species: red maple (*Acer rubrum*), one-seed juniper (*Juniperus monosperma*), and ponderosa pine (*Pinus ponderosa*). These species were selected to represent a range of density, natural durability, and geographic location to approximate the wood material used for playgrounds and trails. In addition, species were selected to achieve USDA Forest Service objectives of reducing forest fire fuel loading, improving timber quality for increased growth and forest health, and removing invasive species to restore the native ecosystem.

The fiber was processed and analyzed at the Forest Products Laboratory. Approximately 90 to 136 kg (200 to 300 lb) of roundwood was obtained for each species evaluated. The wood was maintained in the "green" condition. The processing steps were as follows:

1. Produce approximately 19-mm (approximately 0.75-in.) "pulp quality" chips.
2. Screen out oversize chips, bark, and fines larger than 3.1 mm (1.25 in.) and smaller than 0.6 mm (0.25 in.).
3. Hammermill fiber through screens to obtain an EWF mix of fiber sizes.
4. Perform sieve analysis of resulting EWF.
5. Dry to 8% to 10% moisture content.

Standard samples of EWF from two industrial suppliers were used to develop the test protocol. Visual assessment was used in the initial stages of the process. A sieve analysis was later used to generate comparative data to the EWF draft standard, which was being developed by the ASTM F08.63 subcommittee. Each sieve analysis was completed with EWF in the dry condition (approximately 8% to 10% moisture content) and repeated three times, as called for in earlier versions of the draft standard. The eventual EWF standard, ASTM F2075–01a, does not require three sample repetitions of the sieve analysis.

There are many methods for preparing EWF to meet the standard but even more ways to prepare sub-standard mixes. During our trials we found several ways to successfully prepare the ponderosa pine and red maple constituents.

However, we could not find a method for preparing juniper. When chipped and hammermilled, juniper fractured into needle-like elements that could be forced to meet the EWF standard. However, in our opinion, the use of such needle-like elements on a playground might create secondary safety hazards in the form of splinters, punctures, and other injuries.

A large sample (2 to 3 m^3 (2 to 3 yd^3)) of primarily oak industry-supplied EWF material was used to prepare full-depth specimens for impact testing and evaluation with the rotational penetrometer in the scale-up-phase. This material was donated by a manufacturer with a license for production of EWF from our cooperator, Zeager Brothers, Inc.

Bonding System Evaluations

Trials were made with several application techniques and binders to assess process and performance attributes. The techniques included several *in situ* surface treatments and mixtures of wood particles with binder. Binders were a butylene co-polymer, synthetic latex emulsion, silicone, and polyurethane polymer resin.

Process details were developed for each stabilizing binder system. In each instance, we evaluated a system of materials and sought a balance of several attributes.

Application

We sought a stabilizing binder that could be mixed on site or mixed with EWF no longer than one hour prior to application on the ground surface. The method for mixing depended on the speed of curing, viscosity, tack, and similar attributes. Options for application were as follows:

- Spray mixing in a blender (concrete mixer or augured adhesive blender)
- In-place spraying on compacted EWF with a tank or backpack sprayer
- Flood coating on compacted EWF
- Spray or flood coating with mechanical mixing onto top layer of EWF

Costs for each type of operation was a concern as well as worker safety, quality control, and performance assurance of finished system.

Curing Conditions and Behavior

Expectations for a successful stabilizing binder are not standardized. Thus, our assessment was partially subjective, but it was based on relevant practical considerations, including (1) cure or set time prior to surface use, (2) range of moisture and temperature conditions acceptable for use, and (3) fume, odor, toxicity, outgas, exotherm, or other chemical release from the binder/EWF mixture.

Preliminary screening phase evaluations were completed for 26 small specimens. The primary variables were binder type, binder content, and EWF type. Other variables included concepts of layering a surface, compaction, and surface coating. From these evaluations we selected several binders and surfacing concepts that were usable from a processing standpoint and showed potential for meeting the performance needs of an accessible playground surface.

Full-Depth Surface Specimens

Screening Phase

Bonded and unbonded specimens for the screening phase are described in Table 1. The specimens were formed in

Table 1—Specimens for screening phase

Specimen ID	Species	Chip and screen size	Adhesive matrix	Top surface thickness[a] (mm)^2	Density[b] (g/cm^3(lb/ft^3))
A	Red maple	Pulp, large screen	NA	NA	0.29 (18.3)
B	Red maple	Pulp, large screen	NA	NA	0.29 (17.9)
C	Red maple	Large, small screen	NA	NA	0.20 (12.4)
D	Ponderosa pine	Pulp, large screen	NA	NA	0.26 (16.4)
E	Ponderosa pine	Large, small screen	NA	NA	0.16 (9.8)
F	Juniper	Large, small screen	NA	NA	0.15 (9.3)
G	Juniper[c]	Large, small screen	NA	NA	0.10 (6.3)
SA	Red maple	Pulp, large screen	AllGuard	25	0.29 (18.1)
SB	Red maple	Pulp, large screen	AllGuard	50	0.28 (17.5)
SC	Red maple	Pulp, large screen	AllGuard	75	0.27 (16.7)
SD	Red maple	Pulp, large screen	3–5000	25	0.29 (17.8)
SE	Red maple	Pulp, large screen	3–5000	50	0.29 (18.3)

[a] Top surface composed of target thickness of EWF removed from specimen, then weighed and mixed with 40% (dry weight) adhesive matrix binder.

[b] Density of EWF specimen was calculated prior to addition of surface layer.

[c] Uncompacted.

450- by 450- by 300-mm (18- by 18- by 12-in.) test boxes filled with compacted EWF as defined in ASTM Standard F2075 (ASTM 2001). Bonded specimens were made from red maple chips, processed through a 38-mm (1.5-in.) hammermill screen. This material was compacted into the test box, and the filled box was weighed. Two silicone-based bonding systems were used for the screening phase preliminary tests: (1) AllGuard (Dow Corning Corp., Midland, Michigan), a masonry waterproofing formulation, and (2) 3–5000 (Dow Corning Corp.), a roof coating formulation.

All specimens were compacted to simulate the finished surface of a play area. It is standard practice to compact EWF for testing and actual installations. Given the lack of an industry, governmental, or association accepted standard for compacting EWF, we established a procedure for this study. Our intent was to simulate the amount of compaction produced by an average 10-year-old child while playing on the surface.

To compact the fiber, EWF was uniformly and evenly tamped into a 450- by 450-mm (18- by 18-in.) box using a 7.25-kg (16-lb), 57-mm- (2.25-in.-) diameter, 375-mm- (15-in.-) long steel rod. The surface was tamped 50 times. Each tamp used only the dead weight of the rod applied in evenly spaced locations over the box. This was accomplished in four stages:

1. Fill box to 300-mm (12-in.) depth with loose EWF, level, and tamp uniformly with 9 strokes of rod.
2. Refill box to 300-mm (12-in.) depth, level, and tamp 16 times.
3. Refill to 300-mm (12-in.) depth, level, and tamp 25 times.
4. Refill to 300-mm (12-in.) depth, level, and roll rod over surface once in both directions.

This technique made the test EWF 25% to 47% more dense than uncompacted EWF. The densification values were influenced by species, EWF particle configuration, and EWF moisture content.

A proportion of the compacted EWF, depending on surface thickness, was mixed with the matrix binder. Matrix binder surface was 40% (by dry weight) of EWF. This mixture was returned to the test box and allowed to cure for 5 days prior to F1292 testing (ASTM 1999a).

Scale-Up Phase

Bonded specimens were made with several new application techniques and binders to assess process and performance attributes (Table 2). Unbonded specimens provided an EWF baseline for tests in the scale-up-phase (Table 3). These new

Table 2—Bonded specimens for scale-up phase

Specimen ID	Adhesive matrix	Top surface[a]	Density[b] (g/cm^3 (lb/ft^3))
J	Polyurethane Vitriturf	25 mm (1 in.) thick, 30% adhesive, perforations[c]	0.27 (16.8)
K	Polyurethane Vitriturf	37 mm (1.5 in.) thick, 30% adhesive, perforations[c]	0.26 (16.5)
L	Polyurethane ReacTITE 8143	25 mm (1 in.) thick, 30% adhesive, geotextile[d]	0.25 (15.5)
M	Polyurethane ReacTITE 8143	37 mm (1.5 in.) thick, 30% adhesive, geotextile[d]	0.27 (17.0)
N	Latex Soil-Sement	63 mm (2.5 in.) thick, 35% adhesive, perforations[c]	0.28 (17.4)
0	Latex Soil-Sement	63 mm (2.5 in.) thick, 25% adhesive, perforations[c]	0.30 (18.6)
P	Latex Soil-Sement	63 mm (2.5 in.) thick, 25% adhesive, geotextile[d]	0.27 (17.0)
Q	Latex Soil-Sement	63 mm (2.5 in.) thick, 30% adhesive, geotextile,[d] plus 5% top coating[e]	0.28 (17.5)
R	Silicone[f] D-C AllGuard	37 mm (1.5 in.) thick, 40% adhesive, perforations[c]	0.28 (17.2)
S	Silicone[f] D-C AllGuard	50 mm (2 in.) thick, 35% adhesive, perforations,[c] plus 5% top coating[e]	0.29 (17.9)
T	Silicone[f] D-C 3-5000	37 mm (1.5 in.) thick, 40% adhesive, perforations[c]	0.27 (17.1)
U	Silicone[f] D-C 3-5000	50 mm (2 in.) thick, 35% adhesive, perforations,[c] plus 10% top coating[e]	0.28 (17.4)

[a] Top surface composed of target thickness of compacted EWF; proportion of compacted EWF removed from top surface, weighed, and mixed with measured percentage (dry weight EWF) of adhesive matrix binder
[b] Density of EWF specimen was calculated prior to addition of surface layer.
[c] Specimen perforated on 75- by 75-mm (3- by 3-in.) grid to depth of 200 mm (8 in.).
[d] Application of polyolefin geotextile under surface layer.
[e] Topcoating of adhesive matrix brushed on top of surface after cure; adhesive matrix consisted of controlled percentage of oven-dry weight of surface layer.
[f] Surface layer removed and dried to 7% moisture content prior to mixing with adhesive matrix.

Table 3—Unbonded specimens for scale-up phase

Specimen ID	Compaction	Target moisture content	Density[a] (g/cm^3 (lb/ft^3))	MC at test[b] (%)
W	Yes	Less than 10%, greater than 5%	0.20 (12.7)	7.9
X	Yes	Greater than 30%, less than 35%	0.25 (15.9)	27.0
Y	No	Less than 10%, greater than 5%	0.16 (10.2)	7.7
Z	No	Greater than 30%, less than 35%	0.19 (12.0)	28.3
XX	Yes	As for X + 5% Soil-Sement spray	0.26 (16.1)	28.0

[a] Density of entire specimen calculated on basis of weight and volume of EWF in specimen test box.
[b] Moisture content (MC) based on small sample removed from test box immediately after impact test.

techniques and binders expanded upon the options identified in the screening phase and assisted in quantifying the impact and accessibility of the novel surfaces.

The scale-up series included a variety of *in situ* bonding treatments and interfacial treatments, and several thicknesses and quantities of binder/EWF mixtures. Binders were synthetic latex emulsions, silicones, and foaming and resilient polyurethanes. Twelve modified surface test specimens were formed in 450- by 450- by 300-mm (18- by 18- by 12-in.) test boxes filled with EWF, as defined by ASTM F2075 (ASTM 2001) unless otherwise noted.

All specimens were commercial EWF obtained from a producer in Oskaloosa, Iowa (a licensee of our cooperator, Zeager Brothers, Inc.). A sieve test was completed according to the ASTM F.08.63 draft standard. The test material was placed in the test box and compacted. The weight and bulk density of the filled box was then determined.

Three bonding systems were used:

1. Silicone-based (Dow Corning Corp., Midland, Michigan)
   a. AllGuard, a waterproofing coating
   b. 3–5000, a roof coating/sealant
2. Synthetic latex, Soil-Sement (Midwest Industrial Supply, Canton, Ohio)
3. Polyurethane
   a. Vitriturf (Polmer Plastics Corp., Hauppauge New York)
   b. ReacTITE 8143 (Franklin International, Columbus, Ohio)

The full-depth surface samples were formed in 300-mm- (12-in.-) deep boxes in a manner similar to that described for screening phase specimens. The percentage of matrix binder added to the surface layer was a prescribed quantity (by dry weight) of EWF.

Two interfacial treatments, perforation and geotextile reinforcement, were used to improve the adhesion of the bonded surface to the remainder of the cushioning surface:

Perforation—After the surface layer was applied to EWF, the surface was penetrated by a 12-mm (0.5-in.) steel rod to a depth of 200 mm (8 in.) to achieve a "rough" interface between the bonded and unbonded portions of the specimen. This treatment improved surface drainage for binders that formed a non-draining film on the surface. Perforations were 100 mm (4 in.) from the edge, 125 mm (5 in.) on center, and were placed in a 3 by 3 pattern through the surface.

Geotextile reinforcement—A 450- by 450-mm (18- by 18-in.) single ply of lightweight polyolefin landscaping geotextile (100 g/m^2) was placed between the bonded layer and unbonded base of the specimen. The geotextile was intended to provide continuity for the bonded surface layer in the event that it fractured through its entire thickness. By bonding this membrane to the top layer, the fractured segments of the layer were less likely to be ejected from their original position and to pose a hazard on the remaining bonded surface.

Four identical unbonded test specimens (W through Z) were made with only EWF. These baseline EWF specimens were used to preliminarily assess variability and the effects of moisture content and compaction on cushioning. Thus, the test matrix had two levels of compaction and two levels of moisture content. To assess the effectiveness of a simple top coating on cushioning and accessibility behavior, specimen XX had only a sprayed-on coating of Soil-Sement (5% by weight of top 25 mm (1 in.) of EWF).

Test Procedures

Impact Behavior

Test specifications in ASTM F1292 (ASTM 1999a) and F355–95 test procedure C (ASTM 1995) were used at a constant test drop height of 3.0 m (10 ft) (Fig. 1). Specimens were preconditioned for a minimum of 4 days at ambient conditions (approximately 50% relative humidity and 23°C (74°F)) in a dry storage building during late summer of 2001. At least three impact tests were run in sequence on each specimen per ASTM F1292. Several specimens were

Figure 1—Impact testing set-up for 3-m (10-ft) drop using free-fall test method of ASTM F1292–99.

Figure 2—Impact head caught on rebound from EWF surface.

dropped 10 times to assess the effect of multiple drops on impact parameters.

The instrumented hemispherical impactor (Fig. 2) was dropped by a magnetic release over the drop site. The impact site was a hardened zone with a mass of approximately 4,500 kg (10,000 lb). A minimum mass of 454 kg (1,000 lb) is dictated by the standard. Results of the second and third impact tests were averaged to compare to playground surface specifications. Immediately after impact testing, samples of each species were obtained from representative boxes for moisture content determination.

The performance requirements for a tested surface to meet ASTM F1292 and F355 Procedure C are as follows:

- Test does not impart a peak deceleration in excess of 1,961 m/s^2 (200 G) to an instrumented 4.5-kg (10-lb) ANSI head form (minimum requirement) dropped on a surface from maximum fall height (critical height).
- Surface must meet the head HIC of less than 1,000 when properly installed.
- HIC is the summation of energy absorption for the entire impact event; maximum allowed fall is 3.0 m (10 ft).

Accessibility

We used a relative measure of accessibility because of the small size of our specimens. The 450- by 450-mm (18- by 18-in.) test surfaces were objectively measured using a portable rotational penetrometer supplied by Beneficial Designs Inc. (Minden, Nevada), who also provided original carpet samples (C1 and C3 without pads) for ongoing calibration of the device to the original study.

The rotational penetrometer was used to measure compacted or stabilized surface test specimens from the scale-up phase.

Figure 3—Rotational penetrometer mounted on full-depth playground surface specimen.

The rotational penetrometer was mounted atop 450- by 450- by 300-mm (18- by 18- by 12-in.) plywood boxes. All tests were performed on specimens previously subjected to impact testing. Special care was taken to avoid, to the greatest extent possible, evaluating areas damaged by the impactor or fractures resulting from the impact tests. Contact between the footpads and the surface was assured. The tests were conducted as specified by the Beneficial Designs protocol (Axelson and Chesney 1999).

Surface firmness was measured by a rotational penetrometer, which applied a standard force (approximately 15 kg (33 lb)) to a pneumatic wheelchair caster. This permitted measurement of the downward displacement of the surface and the caster (Fig. 3). After the force was applied, the penetrometer was rotated 90° to the left and right for two sequences, for a total 360°. The final depth of penetration was then measured, representing the stability of the surface (Fig. 4).

The criteria for acceptable accessibility performance have not been embodied in a consensus test standard or guideline. However, the correlation of the rotational penetrometer measurement to the wheelchair work measurement with realistic subjects provides a guideline for firmness and stability within definitions set by the ADA Accessibility Guidelines.

Three recommended levels of performance for firmness and stability (Axelson and Chesney 1999) were analyzed (Table 4). According to these recommendations, "moderate" ratings are acceptable for areas such as playgrounds where the slope is less than 3% and the distance traveled is less than 160 m (525 ft).

Figure 4—Disturbed EWF at contact point of rotational penetrometer after caster performed 360° rotation sequence.

Table 4—Firmness and stability levels recommended for accessible surfaces[a]

Property	Performance level	Depth of penetration[b] (mm (in.))
Firmness	Firm	≤7.6 (≤0.3)
	Moderately Firm	>7.6 (>0.3), <12.7 (<0.5)
	Not Firm	≥12.7 (≥0.5)
Stability	Stable	≤12.7 (≤0.5)
	Moderately Stable	>12.7 (>0.5), ≤25.4 (≤1.0)
	Not Stable	>25.4 (>1.0)

[a] Axelson and Chesney (1999).

[b] Penetration of rotational penetrometer into specimen surface.

Results and Discussion

Wood Fiber Processing

During preliminary evaluations, we studied many types of EWF and several potential binders for accessible playground surfaces. Many of those evaluations were qualitative and reflected our knowledge at the time. The EWF production process used in the industry has not been standardized and could conceivably have many processing variants. Nevertheless, there is a prescriptive standard for EWF material that is a tentative step toward a performance standard. We undertook the systematic development of the appropriate process for converting pulp-size chips to EWF. We found that the range of particle sizes in EWF was appropriate for our concept of a bonded playground surface.

Ponderosa pine and red maple did not present any bonding problems or special concerns. Both of these species bonded well and produced good EWF, as defined by sieve analysis. On the other hand, we encountered significant and ultimately insurmountable challenges in making EWF from one-seed juniper. Hammermilling and chipping of juniper produced needle-like particles that would be inadequate for cushioning and would be a hazardous surface for a playground.

Commercially available EWF was used for scale-up tests. Because this fiber is usually composed of mixed hardwoods, we expected it to have moderate to good durability. The EWF for our tests was primarily composed of hickory, red and white oak, and slippery and American elm, with lesser amounts of lower density species (aspen, silver maple, and cottonwood). Upon delivery, EWF moisture content was 42%. Sieve analysis indicated that the EWF met the F2075 Standard Specification when tested oven dry. We decided to conform to existing material practices rather than develop a new or radically different wood-based particle or configuration for the purpose of evaluating the stabilized playground surface concept.

Bonding System

Given the preliminary nature of this conceptual study, we could not justify the development of a new adhesive or binder system. Instead, we considered many existing formulations and adopted several without modification. Although we limited the number of variables by using available binders, we were able to change the binder type and quantity, surface layer thickness, EWF moisture content, and the application method. Nearly all the binders, when cured and fully reacted, were considered benign from a toxicological standpoint. The exceptions are discussed in the following text.

Four classes of stabilizing binders were considered; three classes were taken to the scale-up phase. We excluded the butylene co-polymer because its hydrophobic nature and low matrix strength resulted in a mat with diminished inter-fiber bonding and a slippery glaze. Considering the low coefficient of friction imparted to the fiber-to-fiber matrix, this “hot melt” type of adhesive would certainly have reduced the traction of the system and hence accessibility, with little effect on cushioning behavior.

The polyurethane class of adhesives offered a wide range of viscosities, foaming potential, and cured resin flexibility. Vitriturf is presently used in the recreational surfaces industry for bonding rubber particle surfaces. This class of adhesives bonds well to wood and can fill interstitial spaces. Even at low application rates, some mat bonding occurs. The cost for polyurethane adhesives is in the middle of those we investigated. A special formulation for stabilized EWF surfaces would enhance the cost competitiveness of the system. Before it is cured, the sprayed resin can cause allergic reactions, so care must be taken to protect breathing and skin contact during mixing and application. Once the adhesive is cured, it is considered benign.

Silicone was initially considered a good candidate because of its potential for highly elastic behavior and ability to perform in high ultraviolet light and moist environments. However, the hydrophobic nature of silicone produces poor bonding to wood and requires a high application rate. We found that the silicone matrix needed to be continuous to be effective in holding the EWF together as a unit. In addition, we expect the unit cost to be somewhat higher than that of most resins. In the cured state, the 3–5000 roof coating forms methyl ethyl ketoxime (MEKO) upon contact with water. Recommendations are to minimize exposure to MEKO because high levels of exposure have been shown to result in liver cancer in rodents. No such concerns have been noted for the AllGuard silicone used in our study.

Synthetic latex was considered because of its acceptance in the soil stabilization industry for trails, embankments, and other landscaping applications. It remains flexible after application and becomes stiff only after an extended period of exposure. One concern is that synthetic latex is tacky to the touch for an extended period after application, depending on local temperature and humidity. An application rate of 20% to 25% produces a moderately well-bonded EWF mat. The low cost of this system and its present large-scale use in the landscaping industry make synthetic latex a good candidate for further development. A drawback is its leachability and biodeterioration, which would require rejuvenation of the surface at regular intervals (6 to 24 months). Rejuvenation of the latex binder could be part of regular playground maintenance.

Impact Behavior

Data gathered from impact testing (Tables 5 to 8) included maximum deceleration and HIC according to ASTM F1292 (ASTM 1999a) and ASTM F355 (ASTM 1995). Specimen

Table 5—Results of screening phase impact tests for unsurfaced specimens

Specimen ID	Drop number	Peak deceleration (G)	HIC
A	1	62	252
	2	74	272
	3	89	372
	4	96	428
	5	102	464
	6	110	549
	7	113	593
	8	116	573
	9	115	593
	10	114	581
B	1	77	321
	2	94	415
	3	99	448
C	1	59	174
	2	78	316
	3	91	451
D	1	56	228
	2	75	329
	3	91	393
E	1	69	251
	2	80	346
	3	84	368
F	1	70	258
	2	88	411
	3	98	520
	4	110	620
	5	117	678
	6	131	811
	7	131	809
	8	145	917
	9	153	1,015
	10	156	997
G	1	66	121
	2	109	485
	3	142	774
	4	194	1,351
	5	250	2,078
	6	259	2,157
	7	272	2,381
	8	318	3,119
	9	260	2,059
	10	320	3,028

Table 6—Results of screening phase impact tests for surfaced specimens

Specimen ID	Drop number	Peak deceleration (G)	HIC
SA	1	64	294
	2	72	322
	3	79	399
SB	1	58	231
	2	60	294
	3	69	362
SC	1	72	241
	2	57	252
	3	52	246
SD	1	55	229
	2	67	306
	3	64	248
SE	1	63	277
	2	53	241
	3	53	212

weight, density, and moisture content were measured. The impact criteria for playground surfaces require that deceleration not exceed 200 and HIC not exceed 1000. In the F1292 Standard, the critical tests are the second and third drops only. The first drop is primarily for compacting the impact site. Using these criteria, all test configurations from the screening and scale-up phases passed the requirements for the 3-m (10-ft) height used in this assessment. Thus, critical height for all configurations was in excess of 3 m (10 ft).

EWF Density and Compaction

Cushioning capacity of all test specimens was reduced by successive impacts. This effect was particularly evident for specimens A, F, and G, which were subjected to 10 drops. The level of compaction (density) had a marked effect on cushioning effectiveness (Figs. 5 and 6). Specimens A and G represented the extreme range of densities evaluated with hammermilled fiber. Specimen A, red maple, was the most dense (292.8 kg/m^3, 18.3 lb/ft^3); specimen F, compacted juniper, in the middle density range (148.8 kg/m^3, 9.3 lb/ft^3); and specimen G, uncompacted juniper, the least dense (100.8 kg/m^3, 6.3 lb/ft^3).

Specimen F exceeded HIC performance criteria on drop 9. Specimen G exceeded maximum allowed deceleration in drops 5 through 10 and maximum allowed HIC in

Table 7—Results of scale-up phase impact tests for surfaced specimens

Specimen ID	Drop number	Peak deceleration (G)	HIC
J	1	50	248
	2	63	298
	3	72	347
K	1	47	209
	2	65	325
	3	69	406
L	1	67	304
	2	68	350
	3	63	357
M	1	73	308
	2	67	332
	3	62	315
N	1	46	171
	2	48	227
	3	60	319
O	1	55	239
	2	56	312
	3	60	324
P	1	45	166
	2	52	256
	3	60	289
Q	1	51	199
	2	55	236
	3	54	248
R	1	46	211
	2	53	213
	3	62	251
S	1	52	235
	2	52	244
	3	57	272
T	1	48	208
	2	62	268
	3	72	326
U	1	45	207
	2	56	242
	3	60	229

Table 8—Results of scale-up phase impact tests for unsurfaced specimens

Specimen ID	Drop number	Peak deceleration (G)	HIC
W	1	64	227
	2	89	389
	3	89	397
X	1	48	195
	2	68	274
	3	76	307
Y	1	39	60
	2	100	509
	3	119	652
Z	1	44	51
	2	83	334
	3	96	448
XX	1	51	235
	2	69	310
	3	75	322

drops 4 through 10. Successive impacts had the following general effects on cushioning:

- The mat was successively compressed and EWF was progressively forced from the impact area.
- Cushioning behavior continued to change significantly, especially after the third impact.
- Cushioning behavior began to stabilize after about 10 impacts.
- Initial drop impact parameters were rather insensitive to level of compaction and became more sensitive with succeeding drops.

Compaction of EWF is a major factor in impact testing. Our overall impression was that the initial impact drop was generally better by the uncompacted specimen and successive impacts reduced cushioning performance when compared to that of compacted specimens. However, all tested configurations passed the F1292 performance criteria on the second and third drops (Tables 5 to 8). Moisture content of EWF was found to have a mild effect on cushioning performance. Although we cannot establish the significance of moisture content because of the small number of specimens tested, specimens with high moisture content generally provided better cushioning than did specimens with lower moisture content.

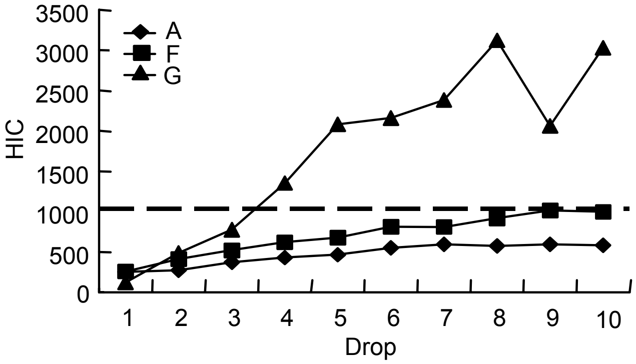

Figure 5—HIC values for three densities of EWF. Specimen A is red maple; specimen F, compacted juniper; and specimen G, uncompacted juniper.

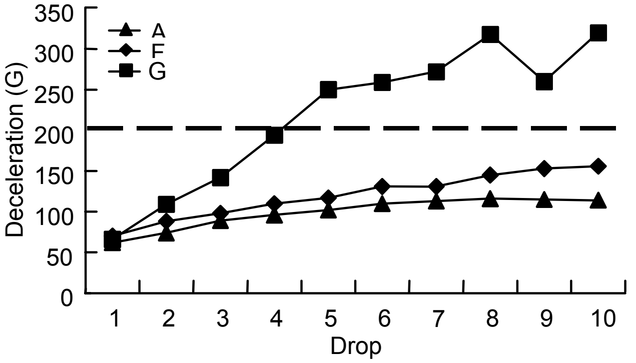

Figure 6—Maximum deceleration (G) values for three densities of EWF. Specimen A is red maple; specimen F, compacted juniper; and specimen, G uncompacted juniper.

Stiffness and Elasticity

We observed different impact behavior for full-depth specimens depending on the type of surfacing. Compared with unsurfaced EWF, silicone-stabilized surfaces "bounced" or rebounded after impact (Fig. 7). Latex produced similar results, but to a lesser degree. Polyurethane produced a brittle fractured surface like a fractured eggshell (Fig. 8). For unsurfaced specimens and more elastic silicone binders, the plot of deceleration as a function of time showed a smooth curvilinear rise to maximum in 15 to 20 μs (Figs. 9 and 10). For brittle binders, the plot showed two distinct peaks and the rise to maximum deceleration was 5 to 10 μs (Fig. 11).

Silicone and latex binders retained resilient and flexible behavior after curing, which produced the elastic rebound effect. These resilient surface layers began to deteriorate after several impacts. Because of weak interparticle bonding, the surface layer did not absorb significant energy upon failure. Conversely, the polyurethane binders absorbed energy by way of two mechanisms, fracture of the bonded surface and cushioning of the underlying EWF layer.

Figure 7—Typical silicone stabilized specimen after three impact events.

Figure 8—Polyurethane stabilized specimen after three impact events.

The bonded surface fractured progressively with each succeeding impact.

The importance of these two behaviors (surface fracture and underlayer cushioning) was also observed using the deceleration and HIC parameters. Specimens with an elastic binder initially provided better cushioning. However, as the surface deteriorated with subsequent drops, the behavior of these specimens was similar to that of baseline unsurfaced EWF. Initially, the brittle binders provided slightly poorer cushioning (that is, were harder); with subsequent impacts, their behavior was similar to that of unsurfaced EWF. In the section on accessibility, we will discuss the implications of reduced cushioning performance on accessibility evaluations of these brittle surfaces.

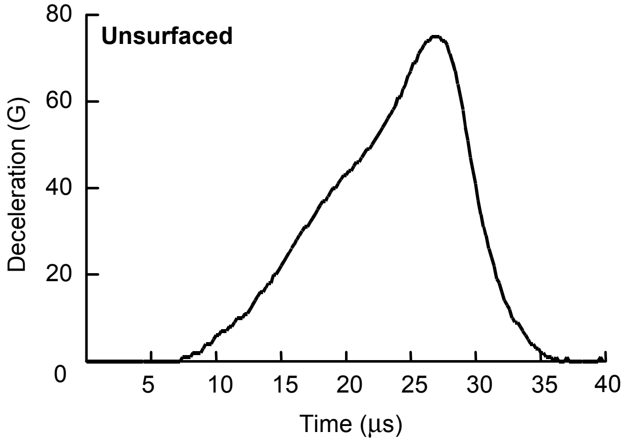

Figure 9—Deceleration as a function of time for unsurfaced EWF.

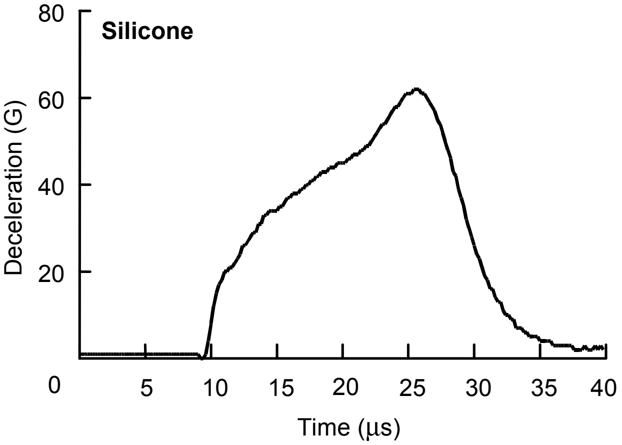

Figure 10—Cushioning behavior of silicone stabilized EWF specimen (R).

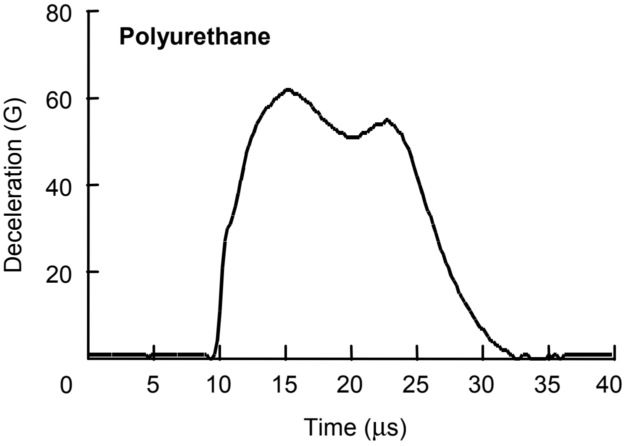

Figure 11—Cushioning behavior of polyurethane stabilized EWF specimen (M).

Table 9—Results of rotational penetrometer test on surfaced and unsurfaced specimens[a]

Specimen ID	Firmness (in.)	Firmness (%)	Stability (in.)	Stability (%)
		Surfaced specimens		
C3 carpet	0.32	(0.03)	0.37	(0.02)
C1 carpet	0.18	(0.01)	0.20	(0.01)
J	0.58	(0.06)	0.77	(0.11)
K	0.46	(0.06)	0.58	(0.06)
L	0.26	(0.02)	0.31	(0.01)
M	0.26	(0.03)	0.30	(0.03)
N	0.50	(0.05)	0.57	(0.07)
O	0.49	(0.03)	0.59	(0.04)
P	0.51	(0.01)	0.57	(0.05)
Q	0.44	(0.04)	0.47	(0.04)
R	0.44	(0.04)	0.59	(0.05)
S	0.42	(0.08)	0.51	(0.12)
T	0.55	(0.05)	0.84	(0.12)
U	0.51	(0.06)	0.59	(0.07)
		Unsurfaced specimens		
W (Control)	0.49	(0.02)	1.00	(0.07)
X	0.44	(0.03)	1.01	(0.12)
XX	0.69	(0.06)	1.23	(0.18)

[a] Present test criteria for stability and firmness are expressed in inches. 1 in. = 25.4 mm. Values in parentheses are standard deviation.

Effect of Interfacial Layer

In preliminary tests, the two interfacial enhancements (perforation and geotextile reinforcement) had little effect on cushioning performance of full-depth specimens. Nonetheless, the geotextile kept the surface layer contiguous during the impact tests and effectively reduced the loss (movement) of EWF from the impacted area. At the end of impact testing, significant adhesion remained between the geotextile and the bonded surface layer.

Accessibility

A rotational penetrometer was used to test carpet calibration samples, surface-stabilized EWF specimens, and unsurfaced EWF specimens (Table 9). Results from calibration samples indicated that average C3 values were comparable to previously reported C3 carpet readings. Average C3 carpet values were within 10% and average C1 values were approximately 20% lower than those reported by Axelson and Chesney (1999). We are unable to explain or correct the difference in measurements for these identical sets of carpet materials.

Unsurfaced Specimens

In accessibility tests, compacted EWF specimens were rated as moderately firm and moderately stable (Table 4). These results are generally parallel to the findings of Axelson and Chesney (1999). The uncompacted EWF specimens, Y and Z, could not be tested because their resistance to the rotational pentrometer did not approach the lower limit of the mechanical range of this device. Both of the noncompacted specimens would therefore be considered not firm and not stable.

Surface-Stabilized Specimens

Only specimens L and M were rated as firm. Specimens J, N, P, T, U, and XX were rated as not firm, and the remaining specimens were rated as moderately firm (Figs. 12 and 13).

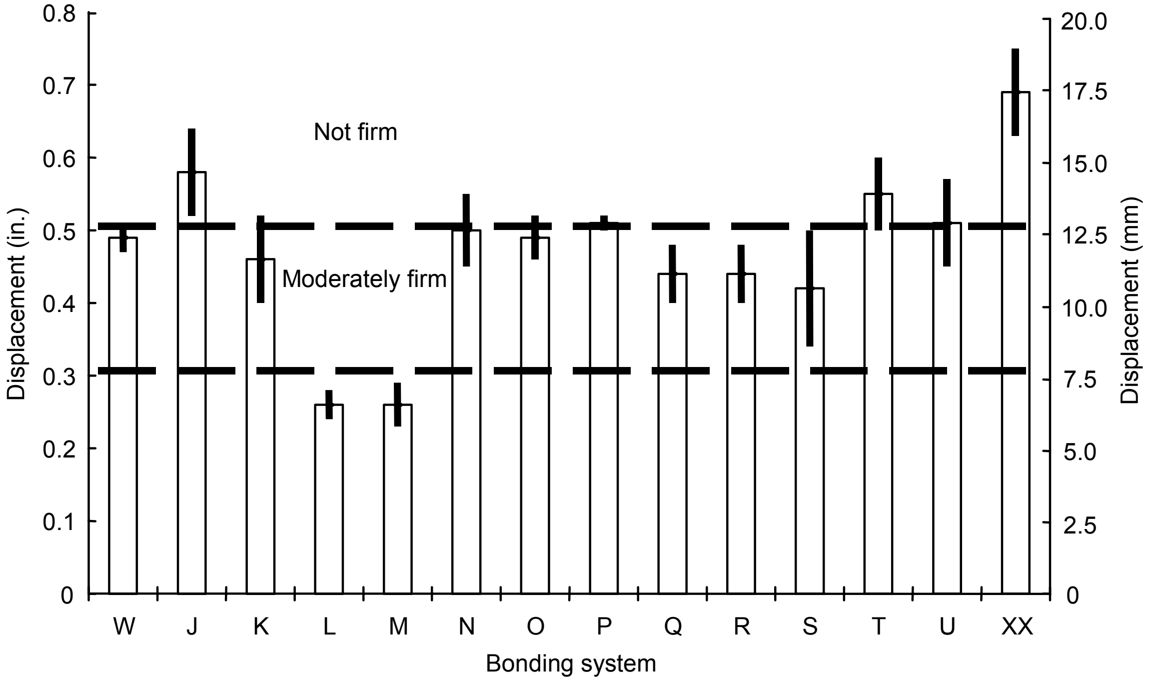

Figure 12—Rotational penetrometer firmness of various bonding systems. Vertical bars indicate standard deviation.

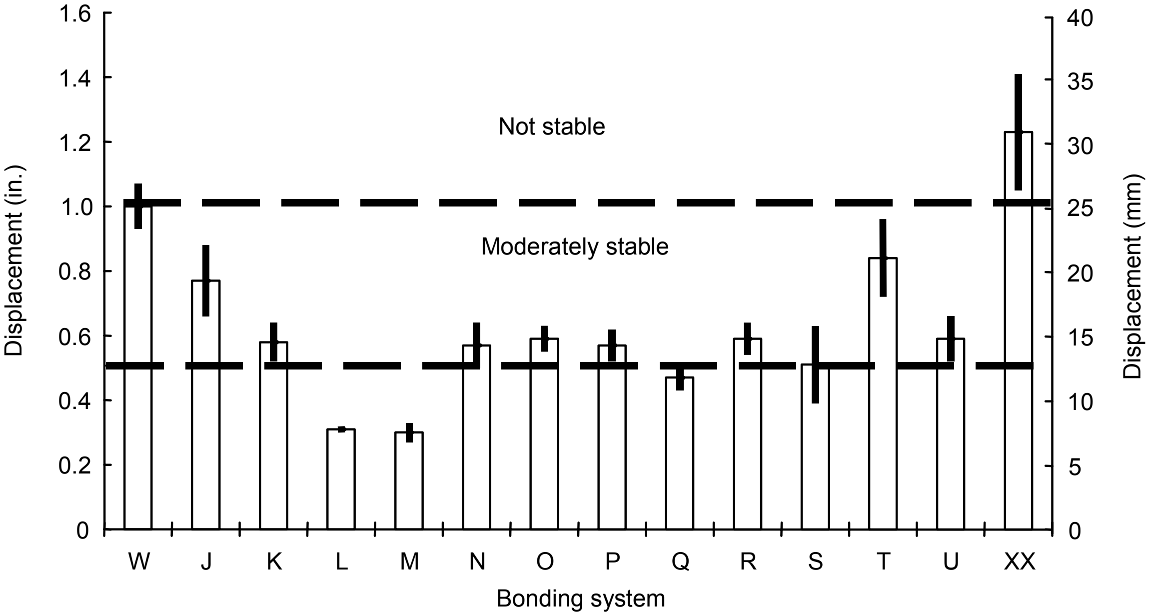

Figure 13—Rotational penetrometer stability of various bonding systems. Vertical bars indicate standard deviation.

Note that unsurfaced specimens W (EWF control) and X were also rated moderately firm. In stability measurements, specimens L, M, Q, and S were rated as stable, XX as not stable, and all others as moderately stable.

The stability of most stabilized EWF specimens was generally good. The only material that showed no improvement was the surface-coated latex Soil-Sement specimen (XX). The binder remained tacky and did not penetrate to bind the deeper EWF particles. Thus, when the rotational pentrometer was turned 360°, the caster created a shear plane, which caused a large section of the top layer to pull away from the underlying EWF.

The firmness and stability of the polyurethane-stabilized specimens (L and M) made with ReacTITE were significantly better than that of the other test materials. The ReacTITE binder typified the performance requirements sought for the two incongruous performance tests of impact cushioning and reduced work for accessibility. Impact cushioning requires a soft surface and the accessibility test a hard surface. Specimens L and M had a thin surface layer underlaid by soft EWF. Upon impact, the thin shell was broken and significant energy was absorbed in the process. After the impactor had broken through the hard shell, the behavior of the specimen reverted to that of a full-depth EWF specimen.

The optimal performance of a surface system requires a balance between stiffness and elasticity. The surface layer must have adequate stiffness to yield a “stiff plate on an elastic medium” response. The system must be stiff enough to resist flexural fracture as well as punch-through shear by a wheelchair caster or wheel. The “brittle eggshell” surface effect was not as readily apparent with the other polyurethane system (Vitriturf) used with specimens J and K. Vitriturf did not produce a surface as strong and stiff as that produced by ReacTITE. The fact that the particles were not as tightly bound for specimens J and K was also shown by the stability rating; particles became detached by the rotating caster.

Top coating with the latex binder (Soil-Sement) moderately improved the stability of specimens Q and S. The latex binder and the silicone systems (AllGuard and 3–5000) were not consistently distinguished by the two test procedures. Compared to unbonded EWF, silicone- and latex-stabilized surfaces were significantly more stable. However, their firmness ratings could not be consistently or confidently distinguished from that of unsurfaced EWF. If firmness is less critical than stability, then we believe that both the silicone and latex systems are promising.

Conclusions

Compaction of engineered wood fiber (EWF) is a major factor in impact testing. The initial drop was better cushioned in uncompacted specimens, and successive impacts decreased cushioning performance when compared to that of pre-compacted specimens. However, all configurations (surfaced and unsurfaced) passed the standard impact performance criteria on the second and third drops. The EWF moisture content was shown to have a mild effect on cushioning performance. Although we cannot establish the significance of moisture content because of the small number of specimens tested, the higher moisture content specimens provided better cushioning behavior.

Binders generally stabilized EWF specimens. The two polyurethane stabilized surface binders significantly improved firmness and stability. This binder seems capable of bridging the two performance tests, one of which requires impact cushioning and the other reduced work (as indicated by stability and firmness) for accessibility. The thin surface of polyurethane-stabilized specimen is capable of supporting a wheelchair caster but it breaks through upon impact, absorbing significant energy in the process. Both the latex binder and the silicone systems were significantly more stable than were unbonded EWF, but inferior, in our opinion, to the polyurethanes. The firmness of latex and silicone systems could not be distinguished from that of unsurfaced EWF.

Recommendations

We recommend further study of systems that utilize easy-to-process EWF/binder combinations. In our study, many combinations yielded promising test results for surface energy absorption and resiliency and appeared to improve accessibility significantly, with continued optimization of performance likely.

A logical next phase, now underway at the Forest Products Laboratory, is to develop larger scale and longer term prototype surfaces for outdoor testing using our preliminary results to select stabilizing binder systems.

We need to engage the EWF and adhesive resin industries for assistance in developing further information on the stabilized EWF concept. This information would include lower cost binder systems, with mid-range elasticity and good extensional behavior, for reducing biodeterioration.

We acknowledge the experimental nature of this investigation. The concept needs to be made more feasible and practical in terms of performance and costs. To ensure reliable surfacing systems we need to improve our understanding of the effects of EWF decay and durability on impact behavior, accessibility, maintenance, and cost.

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