Accelerated Ageing of Cement-Bonded Particleboard

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Abstract
Cement-bonded wood particleboards are believed to lose strength after ageing because wood is thought to be susceptible to degradation in high alkaline environment. The purpose of this study was to determine the stiffness and strength loss of cement-bonded particleboards when exposed to cyclic accelerated ageing. Aspen and larch cement-bonded particleboards were made in four different ways: conventional pressing, with and without laboratory-grade silica fume, and pressing in a carbon dioxide injection press, with and without silica fume. The boards were then exposed to 0, 7, 14, and 21 cycles of a 3-day, wet/freeze/thaw/dry exposure. The effect of freezing was tested in a set of samples using a simplified ageing cycle, without the freeze/thaw part of the cycle. The analysis indicated that the boards injected with carbon dioxide had better physical and mechanical properties initially and also retained higher properties after accelerated ageing. Aspen out performed larch in all mechanical properties both before and after ageing. Laboratory-grade silica fume reduced most board properties and did not improve board durability. About 40 percent of board strength was lost in the first seven cycles of ageing for both aspen and larch boards. The strength losses after the first seven cycles were not substantial. No significant difference was found in properties of boards tested after ageing, with and without freezing. Samples of exterior-grade aspen plywood, southern pine oriented strandboard (OSB), and a medium density phenol-formaldehyde aspen particleboard were exposed along with the cement boards. The particleboard delaminated after three cycles and the OSB after seven cycles of exposure. Plywood retained high strength values after 21 cycles of ageing. However, the plywood samples were severely twisted and warped.

Introduction
Cement-bonded wood particleboard is a composite somewhat similar to cement-asbestos board. It has been used in building construction mainly in wall and roof sheathing, floor, roof tiles, and fences. This composite has some unique characteristics such as fire and decay resistance, good dimensional stability, and good sound and heat insulation properties (7). Wood particles improve the ductility, flexural and tensile strengths, fracture toughness, and crack-inhibiting properties of the cement matrix. The improvement depends upon a number of factors such as wood species, particle type, form, volume, aspect ratio, mix composition, pressing technique, and curing method (1). Wood-cement composite is generally considered a durable material in severe conditions of exposure (15), but wood as a lignocellulosic material, is believed susceptible to degradation in high alkaline environments, such as occurs in cement paste. To be used as a construction material, wood-cement particleboard needs to be tested for durability.

The purpose of this study was to compare the durability of high-density cement-bonded particleboard, made with and without CO₂ gas injection, when exposed to a cyclic accelerated ageing process environment.

Background
The American Society for Testing and Materials (ASTM) defines durability as the capability of a building, assembly, component, product, or construction to remain serviceable over at least a specified time (4). Frohnsdorff notes that durability, an important attribute of most construction materials, is a relative quality. Materials that are durable in one place may not be in another (9). According to Garden, it is the interaction with the environment that determines the durability of materials (10). He also pointed out that the design has a great influence on durability of construction materials. Durability is defined herein as the loss (or retention) of mechanical or physical properties after exposure to the ageing process.

Accelerated ageing tests that expose samples to severe wet/dry and/or freezing cycles are faster alternatives to natural exposure to determine durability. However, literature citing the long-term durability of wood-cement composites in natural exposure is limited. It is recognized that accelerated ageing tests are usually not fully adequate for reliable prediction of long-term performance of composite materials. Previous durability studies, based on standard accelerated ageing tests or a few years of natural exposure, indicated a wide range of strength retention. Several papers have indicated that wood-cement boards are durable and that strength sometimes increases with exposure. Other researchers have shown that strength decreases with accelerated ageing. Nothing has been published about durability of cement-bonded particleboard made with carbon dio-
ide gas (CO₂) injection. Begström and Gram (6) concluded that the composite strength of a sisal fiber-cement is severely reduced after a few cycles of drying and soaking and that an ageing test based on soaking was not appropriate for this composite. Bentur and Mindess (2) working with cellulose fibers and cement, reached the same conclusions. Gram suggests (11) that a treatment with silica fume may be used to control embrittlement and enhance durability. Lempfer and Sattler (14) working with cellulose fiber and wood particles, observed reduction in strength after a soaking/drying cycle test and after natural exposure. They suggest coating or particle treatment to increase durability. The CO₂ gas injection was presented for the first time by Lahtinen (13). In this system, the press time could be reduced from hours to a few minutes. Also the board properties and the compatibility between wood and cement are enhanced according to Souza (17). Bentur and Akers (5) observed that fibers in wood fiber-cement composites that was cured in a rich CO₂ environment became filled with calcium carbonate (petrification), reducing the toughness of the composites. With natural weathering, the authors did not observe petrification. Akers and Studinka (2) observed a 30 percent reduction in degree of polymerization in cellulose fibers after 3 months of accelerated ageing in a rich CO₂ environment and 20 percent in 4 years of natural ageing exposure. They observed that although the fibers became embrittled, the final flexural and tensile strength were increased.

**Objectives**

The general objective of this study was to determine the effect of wet/freeze/thaw/dry cycles on the strength of high-density cement-bonded wood particleboards. The specific objective was to determine the durability of high-density boards fabricated with a combination of two press systems (conventional and CO₂ injection), two wood species (aspen and larch), and one additive (laboratory-grade silica fume). It was also an objective of this study to determine the effect of freezing on durability.

**Experimental Methods**

**Wood Preparation**

Aspen (*Populus sp.*) and larch (*Larix laricina*), harvested in northern Michigan were cut into logs, debarked, and shipped to the USDA Forest Service, Forest Products Laboratory (FPL), in Madison, WI. Chips (19 mm long) made from the logs were dried, stored for 2 weeks, and hammermilled into particles. The particles, ranging from +6 to -16 mesh, were soaked in water for 24 h and dried to reduce the amount of hydrolyzable sugars and tannin. The criteria used to select aspen and larch was compatibility between wood and cement species for cement composites, but larch is perhaps less compatible (13).

**Board Fabrication**

Boards measuring 660 mm by 600 mm by 13 mm thick were fabricated from aspen and larch particles, to a target specific gravity (SG) of 1.2 based on oven-dried hydrated weight. Type I Portland cement was used as a binder (matrix). Table 1 presents a summary of the experimental design. The boards were consolidated using a conventional press and a CO₂ gas injection press. The conventionally pressed boards were fabricated to a target wood/cement ratio of 0.25 and a water/cement ratio of 0.40. They were cold pressed to thickness and restrained by clamps for 24 h. The CO₂-injected boards were made with the same wood/cement ratio but water/cement ratio of only 0.25. They were cold pressed in a gas injection press with a sealed system using a gas pressure of either 600 or 1200 kPa. Gassing time was 220 s and total pressing time 400 s. A vacuum was not used. Board temperature, press and gas pressure, and gas flow were measured during pressing for all CO₂-injected boards.

**Testing**

Thickness in five points and weight were measured after pressing all boards. Modulus of elasticity of the whole board was determined immediately after removal from the press. Board modulus of elasticity was again determined after curing at 27°C and 80 percent relative humidity for 28 days. Five sets of samples were cut from each board. Four of these sets were exposed to 0, 7, 14, and 21 cycles of accelerated ageing. Each cycle consisted of the following:

1. immersion in water at 20°C for 24 h,
2. freezing at -17°C for 24 h,
3. thawing for 2 hours at 50°C and,
4. oven drying at 100°C for 22 h.

This accelerated ageing regime was developed based on work published by Gram (12) and adapted after exploratory work. The fifth set of samples was submitted to seven cycles of an alternative regime, without the freezing/thawing steps, to investigate the effect of freezing on durability.

After ageing, the specimens were conditioned and tested for static bending, dimensional stability (linear ex-

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**Table 1. Experimental design used for testing high-density cement-bonded particleboards.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Wood Species</th>
<th>Water/ Cement</th>
<th>Wood Cement</th>
<th>Gas Pressure (kPa)</th>
<th>Rep</th>
<th>Additives (%) of cement weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv.</td>
<td>aspen</td>
<td>0.4</td>
<td>.25</td>
<td>conventional</td>
<td>4</td>
<td>5(%)CaCl₂</td>
</tr>
<tr>
<td>Conv. + silica</td>
<td>aspen</td>
<td>0.4</td>
<td>.25</td>
<td>conventional</td>
<td>4</td>
<td>10(%) silica fume</td>
</tr>
<tr>
<td>CO₂</td>
<td>aspen</td>
<td>0.25</td>
<td>.25</td>
<td>600</td>
<td>4</td>
<td>5(%) Ca(OH)₂</td>
</tr>
<tr>
<td>CO₂ + silica</td>
<td>aspen</td>
<td>0.25</td>
<td>.25</td>
<td>1200</td>
<td>4</td>
<td>5(%) Ca(OH)₂ + 10(%) silica</td>
</tr>
<tr>
<td>Conv.</td>
<td>larch</td>
<td>0.4</td>
<td>.25</td>
<td>conventional</td>
<td>4</td>
<td>5(%) CaCl₂</td>
</tr>
<tr>
<td>Conv. + silica</td>
<td>larch</td>
<td>0.4</td>
<td>.25</td>
<td>conventional</td>
<td>4</td>
<td>10(%) silica fume</td>
</tr>
<tr>
<td>CO₂</td>
<td>larch</td>
<td>0.25</td>
<td>.25</td>
<td>600</td>
<td>4</td>
<td>5(%) Ca(OH)₂</td>
</tr>
<tr>
<td>CO₂ + silica</td>
<td>larch</td>
<td>0.25</td>
<td>.25</td>
<td>1200</td>
<td>4</td>
<td>5(%) Ca(OH)₂ + 10(%) silica</td>
</tr>
</tbody>
</table>
pansion, thickness swelling, and water soaking), and compression-shear (also called Minnesota-shear), according to ASTM D-1037/89 (3).

**Statistical Analysis**

The experimental design was completely randomized with a factorial arrangement of four treatments and two wood species. Each treatment combination was replicated four times. The effect of ageing and freezing were studied in separated one-way analysis of variance. In addition, the Ryan-Einot-Gabriel-Welsh multiple F test (REGWF) was used to detect significant differences between treatments and ageing regimes.

**Results and Discussion**

**Initial Board Properties**

Bending stiffness of conventionally pressed boards after 24 h of pressing was between 50 and 60 percent of their final stiffness measured after 28 days of cure. Similar out-of-press/28 day stiffness ratios were measured for the CO₂-injected boards after 400 s of pressing. Weight gain during pressing averaged 9 percent for all the CO₂-injected boards. This value (based on cement weight) is an indication of CO₂ reaction. Accuracy of the weight gain value is affected by loss of moisture during pressing or evaporation after pressing and before weighting. CO₂ efficiency (weight gain/measured gas consumption) was 41±14 percent for the boards made without silica fume. This efficiency means that, for each 100 g of gas used, 41 g were incorporated into the board. The remaining gas was used to fill the system or lost through leakages. Addition of silica fume reduced board permeability. Consequently more pressure was required to treat these boards and more gas was lost or left in the system.

**Table 2.** Physical and mechanical properties of aspen boards after 28 days of curing and after 7 cycles of ageing.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>MOE</th>
<th>MOR</th>
<th>Shear</th>
<th>Toughness</th>
<th>Thickness swell</th>
<th>Water abs.</th>
<th>Linear exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(GPa)</td>
<td>(MPa)</td>
<td>(kPa)</td>
<td>(N.mm)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Before ageing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conv.</td>
<td>3.4a</td>
<td>5.96ab</td>
<td>2269c</td>
<td>324a</td>
<td>2.0a</td>
<td>38b</td>
<td>.15a</td>
</tr>
<tr>
<td>Conv. + silica</td>
<td>2.2b</td>
<td>4.18b</td>
<td>3307bc</td>
<td>339a</td>
<td>1.8a</td>
<td>58a</td>
<td>.14a</td>
</tr>
<tr>
<td>CO₂</td>
<td>4.2a</td>
<td>7.60a</td>
<td>5522a</td>
<td>382a</td>
<td>1.5a</td>
<td>29c</td>
<td>.09b</td>
</tr>
<tr>
<td>CO₂ + silica</td>
<td>3.1ab</td>
<td>7.64a</td>
<td>4311ab</td>
<td>534a</td>
<td>3.2a</td>
<td>39b</td>
<td>.10ab</td>
</tr>
<tr>
<td>After 7 cycles of ageing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conv.</td>
<td>2.5a</td>
<td>3.69a</td>
<td>1651b</td>
<td>116a</td>
<td>.9a</td>
<td>44a</td>
<td></td>
</tr>
<tr>
<td>Conv. + silica</td>
<td>1.3a</td>
<td>3.02a</td>
<td>1895b</td>
<td>203a</td>
<td>.6a</td>
<td>49a</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>2.6a</td>
<td>4.74a</td>
<td>3369a</td>
<td>213a</td>
<td>.4a</td>
<td>32a</td>
<td></td>
</tr>
<tr>
<td>CO₂ + silica</td>
<td>2.2a</td>
<td>4.84a</td>
<td>3565a</td>
<td>309a</td>
<td>1.6a</td>
<td>37a</td>
<td></td>
</tr>
</tbody>
</table>

Note: means with the same letter, in the same group, are not significantly different at 5 percent level, using the REGWF F test. The average specific gravity was 1.1 for the conventional boards, and 1.2 for the CO₂ boards.

**Table 3.** Physical and mechanical properties of larch boards after 28 days of curing and after 7 cycles of ageing.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>MOE</th>
<th>MOR</th>
<th>Shear</th>
<th>Toughness</th>
<th>Thickness swell</th>
<th>Water abs.</th>
<th>Linear exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(GPa)</td>
<td>(MPa)</td>
<td>(kPa)</td>
<td>(N.mm)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Before ageing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conv.</td>
<td>2.8a</td>
<td>3.65a</td>
<td>2346b</td>
<td>157a</td>
<td>3.0a</td>
<td>36b</td>
<td>.18a</td>
</tr>
<tr>
<td>Conv. + silica</td>
<td>1.3a</td>
<td>1.80a</td>
<td>2233b</td>
<td>104a</td>
<td>4.7a</td>
<td>57a</td>
<td>.17ab</td>
</tr>
<tr>
<td>CO₂</td>
<td>2.0a</td>
<td>3.71a</td>
<td>4322a</td>
<td>235a</td>
<td>3.2a</td>
<td>37bc</td>
<td>.07b</td>
</tr>
<tr>
<td>CO₂ + silica</td>
<td>2.1a</td>
<td>3.18a</td>
<td>4148a</td>
<td>177a</td>
<td>2.7a</td>
<td>43c</td>
<td>.10ab</td>
</tr>
<tr>
<td>After 7 cycles of ageing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conv.</td>
<td>.67a</td>
<td>1.41a</td>
<td>1278b</td>
<td>72a</td>
<td>.8a</td>
<td>39a</td>
<td></td>
</tr>
<tr>
<td>Conv. + silica</td>
<td>.5a</td>
<td>1.18a</td>
<td>1449b</td>
<td>92a</td>
<td>1.1a</td>
<td>49a</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>.83a</td>
<td>1.55a</td>
<td>3249a</td>
<td>80a</td>
<td>2.1a</td>
<td>36a</td>
<td></td>
</tr>
<tr>
<td>CO₂ + silica</td>
<td>.42a</td>
<td>1.22a</td>
<td>3148a</td>
<td>132a</td>
<td>1.2a</td>
<td>44a</td>
<td></td>
</tr>
</tbody>
</table>

Note: means with the same letter, in the same group, are not significantly different at 5 percent level, using the REGWF F test. The average specific gravity was 1.1 for the conventional boards, and 1.2 for the CO₂ boards.
CO₂ efficiency for the boards with silica fume was only 26±7 percent.

**Board Properties Before Ageing**

Physical and mechanical properties and statistical comparisons for aspen and larch boards, obtained before ageing, are summarized in the first half of Tables 2 and 3 respectively. The mechanical properties of CO₂-injected boards were statistically higher than the boards made in the conventional manner. The differences would have been greater if the furnish had not been soaked prior to making the boards. The physical and mechanical properties of aspen boards were statistically better than those of the larch boards. Addition of laboratory-grade silica fume resulted in the reduction of strength of all conventionally pressed boards and most CO₂-injected boards. This is contrary to published results about use of silica fume as cement replacement (10). Specifications of the laboratory-grade silica fume showed a high silicon dioxide content (99 percent by weight) and a high surface area (198 m²/g). Toughness, which was determined by calculating the area under the load-deflection curve at maximum load, was the only property improved in some cases by silica fume.

After 24 h of soaking, thickness swelling was not significantly different among all treatment combinations; water absorption was not significantly different between the two wood species but was different for the four type of boards. CO₂ injection improved this board property whereas silica fume had a detrimental effect. Linear expansion was significantly reduced by CO₂ injection, which produced the most stable boards between the range of 50-90 percent relative humidity.

**Board Properties After Ageing**

Physical and mechanical properties and statistical comparisons for aspen and larch boards; obtained after ageing, are summarized in the second half of Tables 2 and 3, respectively. The boards did not show any sign of warping, delamination, or twisting after ageing. Conventionally made boards showed strong efflorescence; gas-injected boards did not show any efflorescence. Sample dimensions, weight, and consequently specific gravity were not significantly changed after ageing and conditioning. After 24 of soaking, thickness swelling of aged samples was substantially less than that of unaged samples; water absorption was not affected by ageing.

All mechanical properties were significantly reduced after 7 cycles of ageing, but no statistical difference was found between samples tested after 7, 14, and 21 cycles of ageing. However, the large coefficient of variation presented in this test (26, 29, 37, and 25 percent for MOE, MOR, toughness, and shear, respectively) needs to be considered before drawing final conclusions. The loss in mechanical properties from the exposure is presented in Figures 1 through 8. In most cases, the magnitude of strength reduction was substantially during the first seven cycles, averaging approximately 40 percent for all boards. The uniformity in initial strength loss indicates that mechanism of ageing was probably the same for all boards. Aspen had higher strength retention than did larch in all treatments. The performance of larch boards was poor which indicates that this may not a suitable wood species for cement boards without additional treatments. Boards fabricated with CO₂ injection performed better than the conventionally pressed boards (higher strength retention). Both MOE and MOR showed reduction after ageing, independent of wood species. This suggests that the matrix and either the wood or the bond between them were affected by ageing.

The statistical analysis indicated that freezing did not have any negative effect on mechanical properties after seven cycles, when the higher strength loss ratio occurred.

**Comparison of Tested Boards With Other Materials**

To determine the relative severity of the ageing test, samples of exterior-grade aspen plywood, southern pine oriented strandboard (OSB), and a medium-density phenol-formaldehyde aspen particleboard were exposed along with the cement boards. Plywood and OSB samples came from commercial sources and particleboard made at the Forest Products Laboratory. The particleboard delaminated.
Figure 3. The effect of accelerated ageing on toughness of aspen cement particleboard.

Figure 4. The effect of accelerated ageing on Minnesota shear strength of aspen cement particleboard.

Figure 5. The effect of accelerated ageing on modulus of elasticity of larch cement particleboard.

Figure 6. The effect of accelerated ageing on modulus of rupture of larch cement particleboard.

Figure 7. The effect of accelerated ageing on toughness of larch cement particleboard.

Figure 8. The effect of accelerated ageing on Minnesota shear strength of larch cement particleboard.
after three cycles and the OSB after seven cycles of exposure. Plywood retained high strength values after 21 cycles of ageing (75, 86, and 76 percent for MOE, MOR, and shear, respectively). However, the plywood samples were severely twisted and warped.

**Conclusions**

Four hundred seconds of consolidation time for CO$_2$-injected cement-bonded particleboards were enough to allow easy board handling. Initial MOE measured after pressing ranged between 50 and 60 percent of the final MOE measured after 28 days of cure. CO$_2$-injected boards had higher flexural and shear strength than the conventionally pressed board, after 28 days of curing. This was true for both aspen and larch boards. Aspen boards were stronger than the larch boards and also had better performance during ageing. Addition of laboratory-grade silica fume did not affect linear expansion and thickness swelling properties of the boards but increased the amount of water soaked. The silica fume also reduced most board strength properties.

The ageing exposure reduced board strength, mainly in the first seven cycles. However, the dimensional stability of all boards was not greatly affected by ageing. The CO$_2$ injection produced more stable boards. No significant difference was found in sample properties tested after ageing with and without freezing. This indicates that the seven cycles of wet/dry condition may be adequate for accelerated ageing for this composite.

The results showed that laboratory-grade silica fume does not improve ageing performance of the boards.

**Literature Cited**

INORGANIC-BONDED WOOD AND FIBER COMPOSITE MATERIALS

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