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Cement-bonded straw board subjected to accelerated processing

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Abstract

Agricultural residues offer great promise and new challenges as replacement for wood in engineered wood products. Wheat straw, for example, offers desirable geometric and mechanical attributes for replacement of wood in cement-bonded particleboard. The inhibitory effects of wheat straw on hydration of cement, however, represent the major obstacle against development of cement-bonded strawboard. Accelerated processing techniques involving carbonation reactions were successfully employed to produce cement-based board products incorporating wheat straw. Comprehensive mechanical, durability and physical tests confirmed the high potential of cement-bonded strawboard as a versatile building product capable of meeting the requirements in demanding applications.

Keywords: Cereal straw; Cement-bonded particleboard; Carbon dioxide; Accelerated curing

1. Introduction

Over the last decade, fiber cement products became well accepted and used in North American construction markets. The total US production of fiber cement was close to zero in early 1990's, and has approached 120 million square meter (1.2 billion square foot) in 2002 (based on 8 mm thickness). Fiber cement has found use primarily in three major application areas: siding, roofing, and tile backerboard; of these three applications, siding is the dominant one. Slurry-dewatering is now the dominant means of processing fiber cement boards in the United States [8]. The experience of other countries, however, indicates that different fiber cement board production techniques can find their own niche in building construction markets [7]. The project reported herein focused on the use of cereal straw in production of cement-bonded particleboard, using a processing scheme which employs a combination of pressure, heat and carbonation reactions to ensure rapid curing and high performance of end products.

Cement-bonded particleboard generally incorporates milled wood particles; our project investigated the use of cereal straw in lieu of wood. Cereal straw is generated at quantities which exceed those of edible grains (wheat, corn, rice, barley, rye and oats). The annual world production of cereal straw approaches 2 billion ton [3]. Different cereal straws offer different reinforcement qualities. Wheat and rye straws are noted for their higher reinforcement efficiency, while oat and barley straws contain higher proportions of leafy and extraneous materials and thus offer lower reinforcing effects.

Cereal straws and corn stalk have fiber lengths and diameters averaging about 1.5 mm and 15 μm, respectively, with a significant content of long fibers. In this respect they resemble bagasse. Cereal straws have a relatively low lignin content (typically 17–19% and as low as 12% for rice straw, compared to 40–50% for wood). The cellulose content of cereal straws ranges from 40 to 55% (compared to 50–60% for wood). All straws have a high hemicellulose content of 20–30% (compared to 7–25% for wood). Straw is also distinguished from wood by its high ash content of 5–20%

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(compared to <1% for wood) and its silica constituent [6]. One major concern with use of straw in cement-bonded boards result from the relatively high water- and alkali-solubility of straw when compared with wood [5], noting that increased water- and alkali-solubility adversely influences the physical properties of cement-bonded particleboard. The relatively loose crisscrossed chemical structure of cellulose and lignin in straw, which increases its water absorption, is another concern [9].

2. Relevant past investigations

Recent efforts to reinforced fiber cement boards with agricultural residues have focused on the adverse effects of the water soluble constituents of such residues on hydration and strength development of cement. Irle and Simpson [4] confirmed the inhibitory effects of cereal straws on hydration of cement. While hot water extraction proved effective in improving compatibility of inhibitory wood species with cement, this was not the case with cereal straws. Eusebio and Suzuki [1] investigated compatibility with cement of rice straw and coconut coir dust. Results revealed that cold and hot water extractives of rice straw were detrimental to strength development of cement in conventional curing processes; coconut coir dust extractives, on the other hand, did not adversely affect strength development of cement. This observation highlights distinct attributes of various agricultural residues.

Eusebio [2] recognized the retarding effects of a local fibrous agricultural residue, rattan shavings, and devised processing means of overcoming this deficiency. Rapid curing techniques involving carbonation reactions were employed to overcome this problem. The resulting boards exhibited satisfactory levels of strength and dimensional stability.

3. Materials and methods

Utilization of wheat in cement-bonded particleboard was the primary focus of this investigation. Straw was received from farms within three months after production. It was hammermilled on a 6-mm screen. Fig. 1 shows straw in as-received condition (left) and after size reduction (right). In order to mitigate any adverse effects of water- and alkali-soluble products in straw, after size reduction, straw was extracted through immersion in lime saturated water at room temperature for 48 h, followed by air drying to less than 10% moisture content.

Straw was then made into cement-bonded particleboard using an accelerated processing schemes involving injection of diluted CO_2 gas. Type I Portland cement with straw/cement weight ratio of 0.3 was used in the

Fig. 1. Wheat straw in as-received condition (left) and after size reduction (right).

process, targeting 10 mm thick boards with bulk specific gravity of 1.2. Sodium silicate was introduced at 2% by weight of cement to mitigate the retarding effects of straw extractives on hydration of cement, and lime was used at 10% by weight of cement to further accelerate reactions with carbon dioxide. The water/cement ratio of strawboard mixtures was 0.33.

The presence of carbon dioxide gas was used in our process to substantially accelerate the curing process of Portland cement. Hydration of cement primarily involves the reaction of calcium silicates C_3S and C_2S with water (H) to produce calcium silicate hydrate (CSH) and calcium hydroxide (CH) [10]:

$$C_3S + < 2.35H \rightarrow C_{1.65}SH_{<1.0} + 1.35CH$$

When carbon dioxide ($\overline{C}$) is introduced, it dissolves in water to form carbonic acid ($H\overline{C}$):

$$\overline{C} + H \rightarrow H\overline{C}$$

The resulting carbonic acid promotes a vigorous reaction of C_3S in the first few minutes:

$$C_3S + 1.2\overline{C}H \rightarrow C_{1.4}SH_{0.6} + 1.2C\overline{C} + 0.6H$$

The above reaction is analogous to that describing normal hydration of cement, except that calcite ($C\overline{C}$) is formed instead of CH and few minutes of CO_2 curing reacts as much calcium silicate as normal hydration of cement does in several hours. The CO_2 curing reaction presented above involves the evolution of considerable quantities of heat, which tends to evaporate some of the remaining free water. After few minutes, carbonation of the gel appears to be the major reaction:

$$C_XSH_Y + (X - X')\overline{C} \rightarrow C_{X'}SH_{Y'} + (X - X')C\overline{C} + (Y - Y')H$$

Leading to a progressive change in composition. This subsequent reaction maintains the rapid initial strain gain for up to few hours thereafter; prolonged carbonation continues to change the gel composition with little change in strength.

Water is an important ingredient in CO_2 curing because the dissolution of carbon dioxide to form carbonic acid is the first step in the CO_2 curing process; this step can be considered to concentrate the CO_2 at the surface of the reaction gains. Excess water, however, blocks the pore system and limits the diffusion of carbon dioxide throughout the cement-based system. Subsequent precipitation of calcium carbonate may make this blockage permanent. The relative humidity of the carbon dioxide gas also influences the rate of CO_2 curing. Low relative humidities coupled with the high heat of CO_2 curing cause water to be lost readily from the cement-based system and thus limit the rate of CO_2 curing. High relative humidities of the carbon dioxide gas suppress this loss.

The ingredients were mixed thoroughly for 10 min, spread uniformly within a mold (Fig. 2a), pressed (Fig. 2b) to reach a targeted thickness of 10 mm, and subjected to short-term carbon dioxide injection (CO_2 curing) discussed below.

Fig. 3 presents the press with CO_2 injection capabilities used to process cement-bonded boards with agricultural residues. Diluted CO_2 gas was produced by combining pure CO_2 with pressured air, at 30% CO_2 concentration controlled using flowmeters. The CO_2 curing process involved: (1) closing of the press to targeted thickness (density) over a period of 30 s; (2) application of vacuum on top face for 20 s; (3) application of CO_2 gas under pressure at 350 l/m flow rate on top

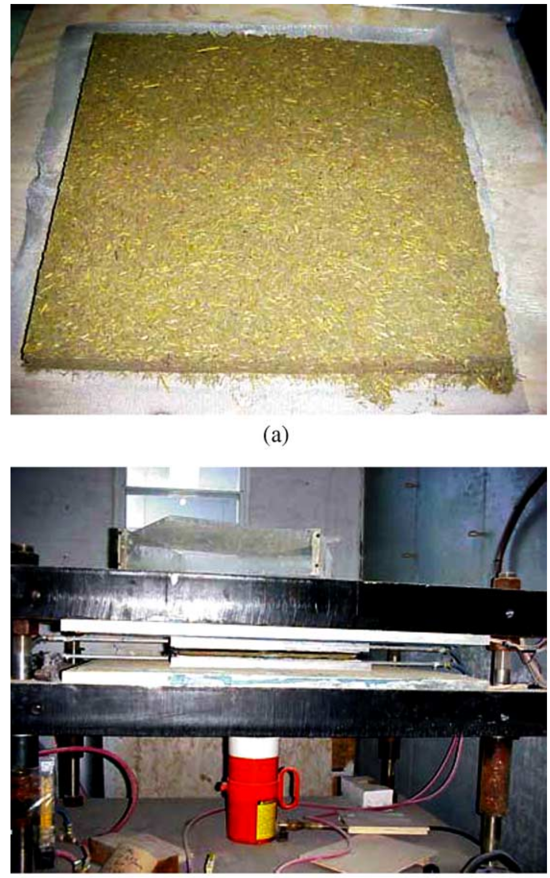
(a)
(b)

Fig. 2. Processing of cement-bonded boards: (a) uniformly spread mix; (b) press system.

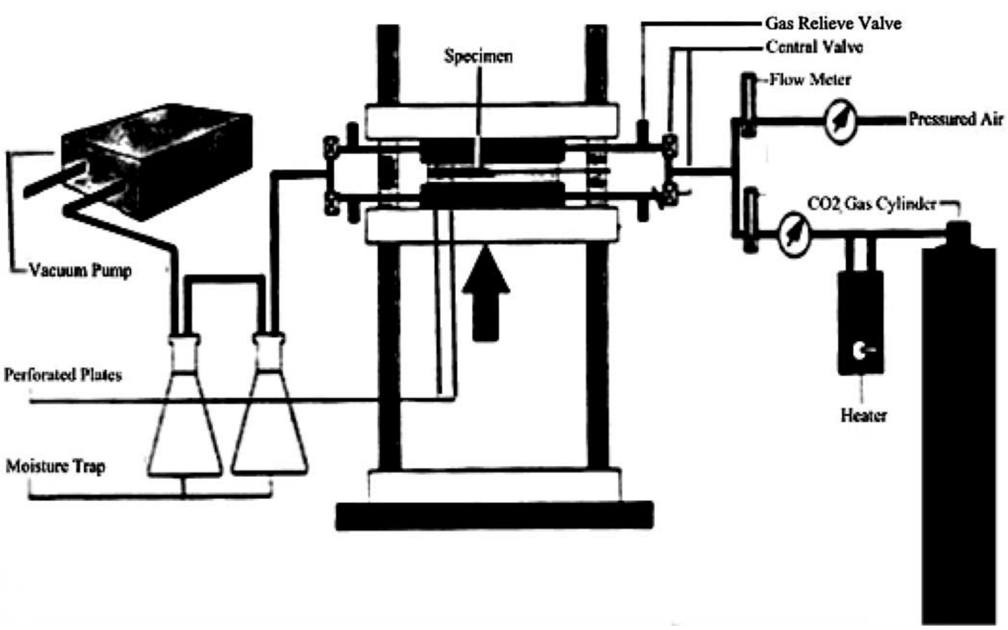

Fig. 3. Schematic presentation of the CO_2 curing process.

face and vacuum on bottom face for 40 s; (4) application of vacuum on bottom face for 20 s; (5) application of CO_2 gas under pressure at 350 l/m flow rate on bottom face and vacuum on top face for 40 s; (6) application of vacuum on both top and bottom faces for 30 s; (7) application of CO_2 gas under the same pressure as in steps 3 and 5 on both top and bottom faces for 60 s; (8) waiting for 30 s with all valves closed; (9) application of vacuum on both top and bottom faces for 30 s; and (10) opening of the press over a period of 30 s. The board was thus subjected to mechanical pressure for a total duration of 4.5 min, which implies that it reached sufficient rigidity and strength in less than five minutes to prevent spring-back (upon release of mechanical pressure) and allow immediate handling.

Cement-bonded boards (Fig. 4) were subjected to flexure tests (ASTM D 1037) immediately upon press release. The boards were then subjected to moist curing at 100 relative humidity and 22 °C for one week followed by one week of conditioning at 50% relative humidity and 22 °C.

They were then subjected to the following tests (ASTM D 1037):

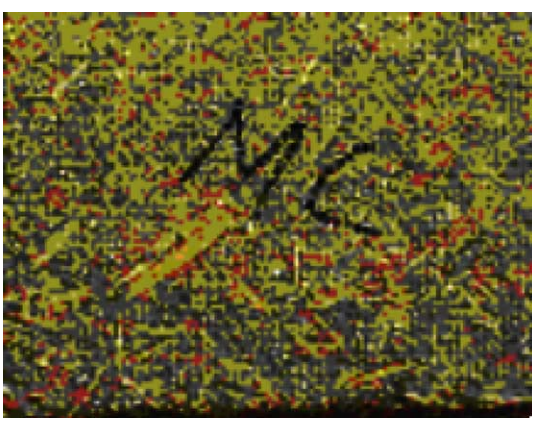

Fig. 4. Cement-bonded particleboards reinforced with wheat straw.

Fig. 5. Internal bond test set-up.

- Flexure, bulk specific gravity and water absorption capacity.
- Internal bond strength (Fig. 5).

Cement-bonded boards were also subjected to accelerated aging through exposure to either 50 cycles of wetting and drying (ASTM C 1185), 300 cycles of freezing and thawing (ASTM C 666) or 60 days of warm water immersion (ASTM C 1185), after which they were conditioned at 50% relative humidity and 22 °C for one week and subjected to flexure tests. The effects of wet–dry cycles on internal bond strength (Fig. 5) and bulk specific gravity of strawboard were also determined. Microscopic images of cement boards prior to and after exposure to wet–dry cycles were obtained in order to provide further insight into the aging and deterioration processes of strawboard.

All tests on boards with wheat straw were replicated 5 times in order to assess both central tendencies and variances of experimental data. Commercially available pulp fiber cement boards processed through slurry-dewatering were subjected to some parallel tests in order to provide a basis to judge performance characteristics of strawboard.

4. Test results and discussions

The flexural performance of cement-bonded strawboards was defined by two measures: (1) peak flexural stress (flexural strength); and (2) total area underneath the flexural load-deflection curve (flexural energy absorption). Immediately after removal from press, cement-bonded strawboard provided close to 4 MPa flexural strength and 500 N mm flexural energy absorption capacity, which was sufficient to handle strawboards immediately after opening of press. The long-term flexural characteristics of strawboards in unaged and aged conditions are summarized in Fig. 6 together with those of commercially available pulp fiber cement boards processed through slurry-dewatering. The flexural strength and energy absorption capacity of strawboard meet the requirements for major building applications; more importantly, they exhibit desirable durability characteristics under diverse accelerated aging effects. Desirable durability of strawboard is further confirmed in Fig. 7 which shows normal distributions based on the internal bond strength test data prior to and after exposure to wet–dry cycles.

Fig. 8a shows normal distributions based on the measured values of bulk specific gravity prior to and after exposure to wet–dry cycles. This figure confirms that the targeted bulk specific gravity of 1.2 has been reached, and that wet–dry cycles do not alter this attribute of strawboard. The effect of wet–dry cycles on

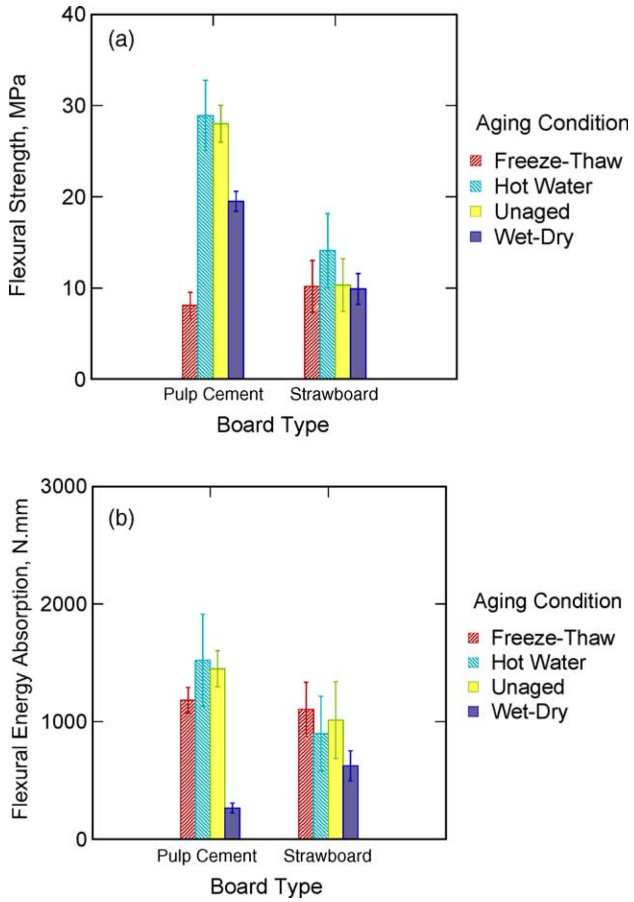

Fig. 6. Flexural performance characteristics in unaged and aged conditions (means and standard errors): (a) flexural strength; (b) flexural energy absorption.

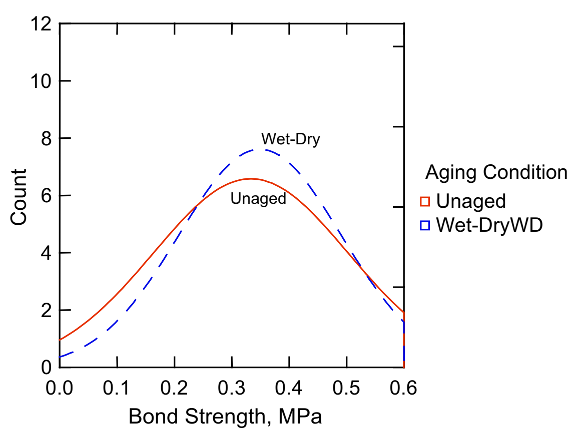

Fig. 7. Normal distribution of bond strength test data on strawboard in unaged condition and after exposure to wet–dry cycles.

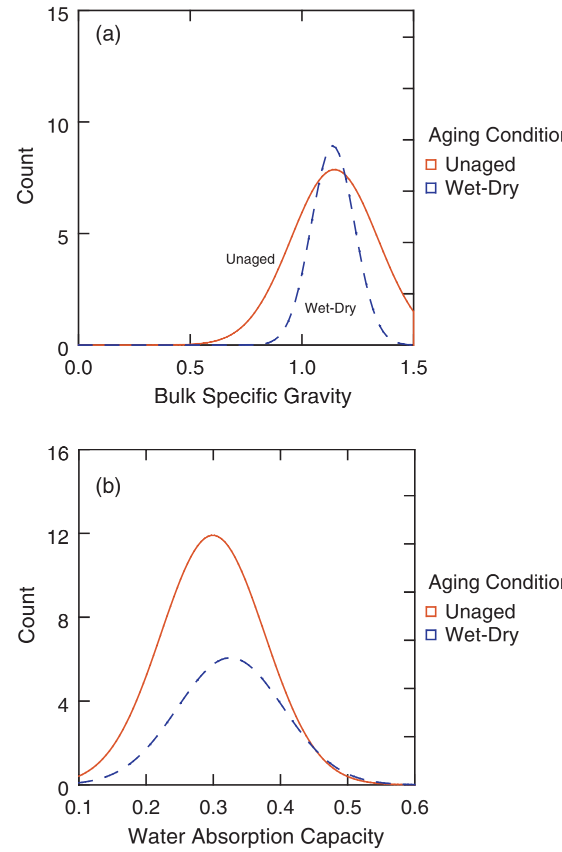

Fig. 8. Normal distributions based on the measured values of bulk specific gravity and water absorption capacity of strawboard prior to and after exposure to wet–dry cycles: (a) bulk specific gravity; (b) water absorption capacity.

water absorption capacity of strawboard is also relatively small (Fig. 8b).

Long-term weathering resistance of cement-bonded strawboard is a primary issue determining its commercial viability. The primary concern with long-term weathering effects on such products relates to differential moisture movements of the residues and the cement-based matrix. Upon wetting, lignocellulosic materials would swell more than the matrix, and would thus subject the matrix to internal pressure. This phenomenon would be repeated when the board is subjected to repeated wetting–drying cycles; the matrix could suffer permanent damage, in the form of microcracking and permanent deformations, when subjected to repeated application of internal pressure. One manifestation of this damage would be cracks formed at interfaces between straw inclusions and the cement-based matrix. We used microscopic observations at 75× magnification to test this hypothesis. Fig. 9a presents a typical micrograph of cement-bonded strawboard after CO_2 curing followed by 7 days of moist curing and 7 days of conditioning at 50% relative humidity, but prior to any accelerated aging effects. The interfaces between cement paste and wheat straw are observed in Fig. 9a to be largely intact, with limited interfacial microcracks caused by initial drying of the system. Fig. 9b presents a typical micrograph of strawboard after exposure to repeated wet–dry cycles. While somewhat more separation of the wheat straw from cement paste is observed in

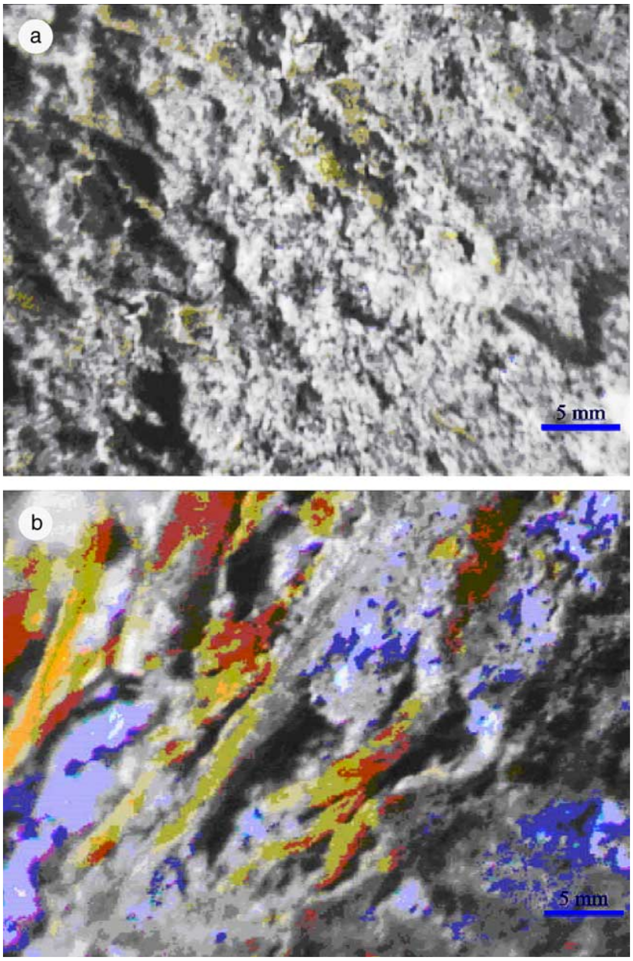

Fig. 9. Representative micrographs of cement-bonded strawboard prior to and after exposure to wet–dry cycles (75× magnification): (a) unaged specimen; (b) after wetting–drying cycles.

Fig. 9b, when compared with Fig. 9a, the product seems to have preserved its microstructural integrity after exposure to repeated wet–dry cycles.

5. Conclusions

Abundantly available agricultural residues, including wheat straw, can be valuable replacements for wood in cement-based building products. Carbonation reactions can be employed to overcome their inhibitory effects on hydration of cement in the context of accelerated means of processing cement-bonded particleboard with agricultural residues. Wheat straw, when employed in this process, yields cement-based boards with desirable mechanical attributes (flexural and internal bond strength) which are largely retained after exposure to various accelerated aging effects such as wet–dry and freeze–thaw cycles and extended immersion in warm water.

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