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Development of accelerated processing techniques for cement-bonded wood particleboard

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Abstract

The potential for substantial acceleration of the curing process of cement-bonded wood particleboard by injection of diluted carbon dioxide gas was investigated experimentally. Milled particles of softwood and hardwood were used as reinforcement in cement boards processed under pressure. Injection of pure as well as diluted carbon dioxide gas greatly reduced (by two orders of magnitude) the press time required to yield dimensionally stable products of sufficient strength for initial handling. Diluted carbon dioxide gas (about 25% CO_2 concentration in air) yielded immediate flexural attributes (upon press release) which were competitive against those obtained with pure carbon dioxide gas. It is hypothesized that dilution of CO_2 gas lowers the excess rate of reactions, thereby controlling the rise in temperature and allowing for more thorough penetration (and reaction) of CO_2 gas. These benefits seem to compensate for the reduced rate of reactions of diluted CO_2 gas. Competitive immediate performance characteristics are thus achieved with diluted CO_2 gas with in spite of the lower CO_2 gas consumption (and thus lower processing costs).

Keywords: Cement boards; Wood particles; Accelerated curing; Carbon dioxide gas; Carbonation reactions

1. Introduction

Manufacturing of cement-bonded wood particleboard involves long-term pressing of the fresh board at elevated temperatures [1]. This process intends to cure the board sufficiently to prevent spring-back (thickness increase) upon press release. The long curing time (about 8 h) under press reduces the productivity of plant and adds to the initial cost of the end product. The main thrust of this investigation is to accelerate the manufacturing process of cement-bonded wood particleboard through early exposure to CO_2. Accelerated curing in the presence of CO_2 could also enhance moisture resistance and stability of the system, and also improve compatibility of the cement-based matrix with wood particles. Accelerated CO_2 curing could also allow use of lower-value wood species which would otherwise, inhibit the slow hydration process of cement.

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2. Background

Cement-bonded wood particleboard can complement the moisture resistance, durability and dimensional stability of cement-based materials with the workability, impact resistance and low bulk density of wood [1]. Siding panels and roof shakes are some common applications of cement-bonded wood particleboard. The slow hydration process of cement and the inhibitory effects of some wood species on hydration of cement are some technological barriers against wider-spread use of cement-bonded particleboard [1]. In current practice, fresh cement-bonded boards are pressed and clamped for several hours at elevated temperatures before they harden and can be removed from the press without spring-back. Conventional pressing techniques in the manufacturing of cement-bonded wood particleboard require 8–24 h of clamp time. Efforts towards reducing this initial curing time by substantially increasing the setting and hardening rates of cement should still provide sufficient "open time" during which the wood–cement–water furnish stays plastic for mixing, forming and pressing efforts to take place. Developments in the area of rapid-setting boards have generally focus on altering the chemical composition of cement through the use of special cements and accelerating admixtures [1]. An alternative approach, CO_2 curing [2–9], promises to tremendously reduce the time required for hardening of cement-based binder, from few hours to few minutes, without disturbing the "open time" of the furnish.

The presence of CO_2 promotes the following chemical reactions in cement–water systems [2–9]:

$$3CaO \cdot SiO_2 + yH_2O + (3-x)CO_2 \rightarrow xCaO \cdot SiO_2 \cdot yH_2O + (3-x)CaCO_3$$

$$2CaO \cdot SiO_2 + yH_2O + (2-x)CO_2 \rightarrow xCaO \cdot SiO_2 \cdot yH_2O + (2-x)CaCO_3$$

Carbon dioxide lowers the pH value by forming carbonic acid [8,9]. It is neutralized by calcium silicate in cement, resulting in highly insoluble calcium carbonate. Calcium carbonate can appear as a mixture of veterite, calcite and aragonite. Calcium carbonate provides the initial strength necessary for early release of the board from press. While this process of calcium carbonate formation for strength development is very rapid and progresses substantially in a matter of minutes, conventional hydration of cement for development of sufficient strength is relatively slow and requires several hours for substantial progress. With CO_2 curing, about half the ultimate strength of cement-based systems can be developed in few minutes [8,9]. Past investigators have used gases with high CO_2 concentration to accelerate hardening of cement; the research reported herein focuses on dilution of CO_2 gas with air to yield more economical means to accelerate hardening of cement.

3. Experimental program

3.1. Experimental design

The effects of various processing and mix proportioning variables on the immediate flexural characteristics (upon press release) of CO_2-cured cement-bonded particleboard were investigated. The experimental program comprised sequential steps (Fig. 1) concerned with the effects of processing sequence, CO_2 concentration and mix proportions on immediate flexural strength. Three replicated test specimens were manufactured for each condition in order to derive reliable conclusions through statistical analysis of results.

The first step in our sequence of experiments compared the two process sequences of Fig. 2. Sequences I and II in Fig. 2 comprised total processing durations of 3.5 and 4.5 min, respectively. Sequence I involved application of: (1) 0.69 MPa (100 psi) CO_2 gas pressure on upper plate and 381 mm (15 in.) Hg of vacuum on bottom plate for 1 min; (2) 0.69 MPa (100 psi) CO_2 gas pressure on both top and bottom plates for 2 min; and (3) 381 mm (15 in.) Hg of vacuum on both top and bottom plates for 30 s. Sequence II involved the application of: (1) 0.69 MPa (100 psi) CO_2 gas pressure on the top plate and 381 mm (15 in.) Hg of vacuum on the bottom plate for 1 min; (2) 0.34 MPa (50 psi) CO_2 gas pressure on the bottom plate and 381 mm (15 in.) Hg of vacuum on the top plate for 1 min; (3) 0.69 MPa (100 psi) of CO_2 gas pressure on both top and bottom plates for 2 min; and (4) 381 mm (15 in.) Hg of vacuum on both top and bottom plate for 30 s. Softwood (southern pine) particles were used to evaluate these two process sequences. The preferred processing sequence selected here will be used to investigate the effect of CO_2 gas concentration in the second step of Fig. 1, following the experimental design of Table 1. The first two steps in experimental design were both implemented using constant wood/cement and water/cement weight ratios of

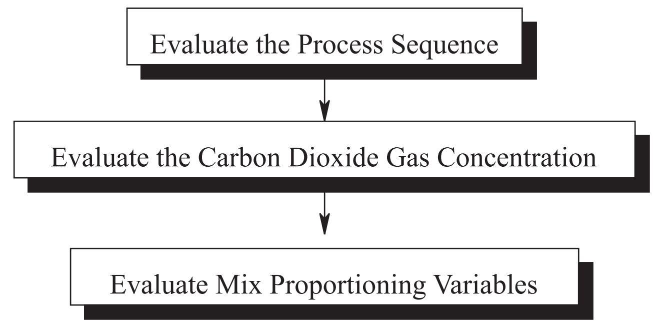

Fig. 1. The Sequence of experiments on cement-bonded wood particleboard.

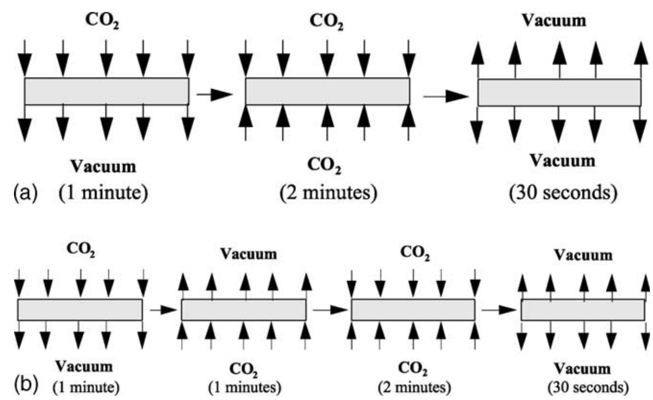

Fig. 2. Alternative processing sequences. (a) Sequence I and (b) Sequence II.

Table 1
Experimental program to evaluate various CO_2 concentrations

Wood species	CO_2 concentration			
	25%	50%	75%	100%
Softwood	*	*	*	*
Hardwood	*	*	*	*

Table 2
Experimental program for the evaluation of various mix compositions

Wood species	Wood–cement ratio (by weight)			
	0.28		0.35	
	CO_2 concentration (low)[a]	CO_2 concentration (100%)	CO_2 concentration (low)	CO_2 concentration (100%)[a]
Softwood	*	*	*	*
Hardwood	*	*	*	*

[a] Based on earlier steps.

0.28 and 0.25, respectively. The final (third step) in experimental program concerned the effects of wood/cement ratio (at a constant water/cement ratio of 0.25) as well as CO_2 concentration and wood species, using the preferred process sequence established in the first step, on immediate flexural strength. A $2 \times 2 \times 2$ factorial design of experiments (Table 2) was implemented to investigate the effects of these variables on immediate flexural performance of CO_2 cured cement-bonded wood particleboard upon press release.

3.2. Materials and manufacturing procedures

A softwood (southern pine) and a hardwood (aspen) were used in this investigation. Size reduction was accomplished in a hammermill, using a screen which yielded 0.65–3.35 mm particle size (passing through No. 6 sieve and staying on No. 20 sieve). The average moisture content of these particles was about 5% (oven-dried basis). Image analysis procedures were used to measure average particle dimensions. The average length, width, and thickness of wood particles are shown in Table 3.

Table 3
Wood particle dimensions

	Southern pine	Aspen
Length (mm): mean (st. dev.)	5.32 (1.73)	4.97 (1.66)
Width (mm): mean (st. dev.)	1.20 (0.67)	1.25 (0.47)
Thickness (mm): mean (st. dev.)	0.40 (0.15)	0.50 (0.22)

Table 4
Chemical composition of the Type I Portland cement used in this investigation

Chemical composition	Percent by weight
Tricalcium silicate (C_3S)	43.3
Dicalcium silicate (C_2S)	26.3
Tricalcium aluminate (C_3A)	11.0
Tetracalcium aluminoferrite (C_4AF)	8.6
Insoluble residue	0.12

Type I Portland cement with chemical composition of Table 4 was used in the mixtures of this investigation. Agricultural grade of calcium hydroxide ($Ca(OH)_2$) at 7.5% by weight of cement was also used when curing was accomplished using CO_2 gas. In this case, calcium hydroxide replaced an equivalent weight of cement. Different carbon dioxide (CO_2) gas concentrations in air (25%, 50%, 75%, 100%) were used. Different concentrations of CO_2 were achieved by controlling CO_2 gas and air flows during injection of gas.

Manufacturing of cement-bonded particleboard involved mixing of the constituents in a mortar mixer and placing the blend into a 305 mm (12 in.) square wooden box. The mix was spread in the box between two fine screens (with mild tampering). This assembly was then placed in a press, and the wooden box was removed. Fig. 3 shows the cement-bonded wood particleboard

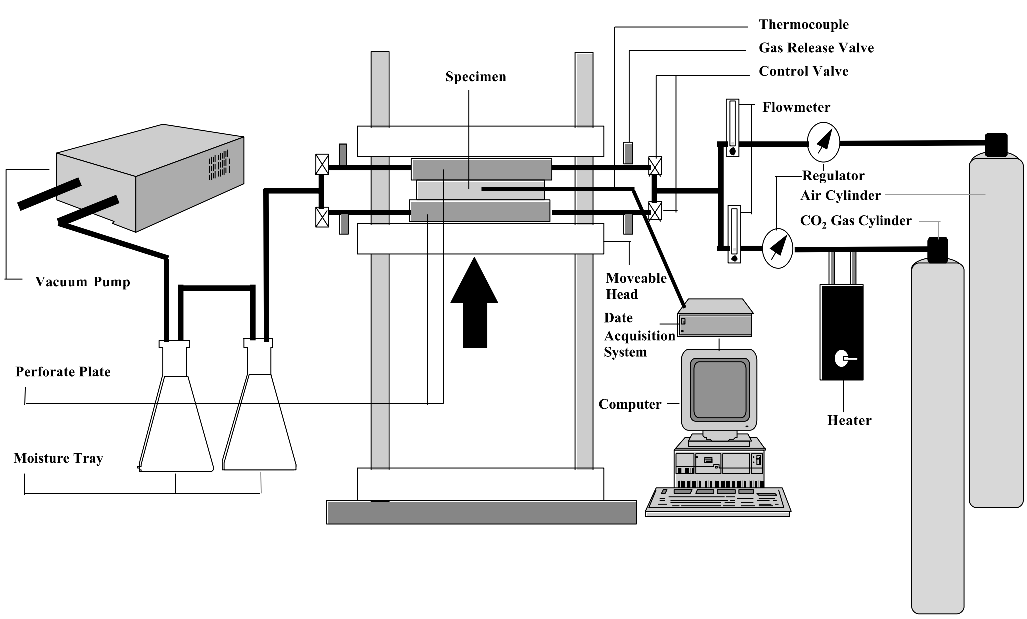

Fig. 3. Processing system incorporating CO_2 curing.

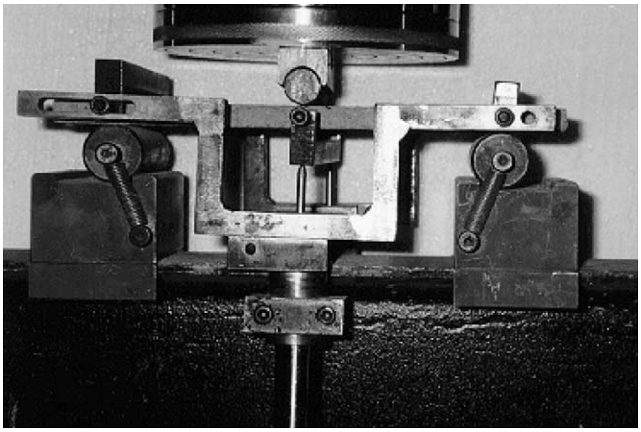

Fig. 4. The three-point flexure test set-up.

processing system for CO_2 curing. To produce various concentrations of CO_2 gas in air, as seen in Fig. 4, two gas cylinders (one CO_2 and the other air) were used. Each cylinder was connected to a flowmeter which controlled the gas flow level and thus CO_2 concentration. A CO_2 gas heating element was used in the CO_2 pressure supply line to prevent the gas from freezing. Pressure was applied on boards using a 50-ton capacity press. In the unsealed press, the platens were perforated with 2.38 mm (3/32 in.) diameter holes drilled in a 13×51 mm (0.5×2 in.) spacing pattern which covered an area of 305×305 mm (12×12 in.). The top and bottom perforated plate were connected to the CO_2, air and vacuum lines. The set-up is capable of applying any combination of CO_2, air and vacuum on either side of the board. A metal screen was used above the bottom plate. Moisture traps were used to prevent any potential damage to the vacuum pump by moisture.

3.3. Test procedures

Flexure tests were conducted following the guidelines recommended by ISO 8335 (International Standard) for cement-bonded wood particleboard [10]. The flexural test set-up was a slight modification of that in ISO; a "yoke" (Fig. 4) was used for accurate measurement of the mid-span deflection under three-point loading; this

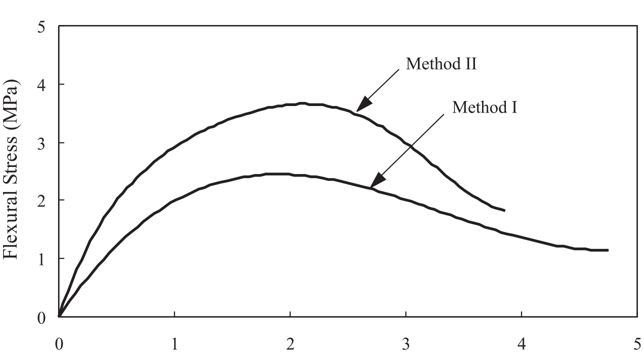

Fig. 5. Typical flexural load–deflection curves obtained with the two process sequence.

Table 5
Flexural performance of cement-bonded wood particleboards subjected to Methods I and II of CO_2-curing

Processing sequence	Flexural strength (MPa)	Flexural toughness (N mm)	Initial stiffness (N/mm)
Method I	2.04	279.180	72.986
	2.88	283.427	103.216
	2.62	293.882	141.029
Mean (st. dev.)	2.51 (0.43)	285.496 (7.566)	105.744 (34.092)
Method II	3.72	321.901	195.555
	3.67	358.995	249.643
	3.01	391.157	374.275
Mean (st. dev.)	3.47 (0.39)	357.351 (34.657)	273.158 (91.651)

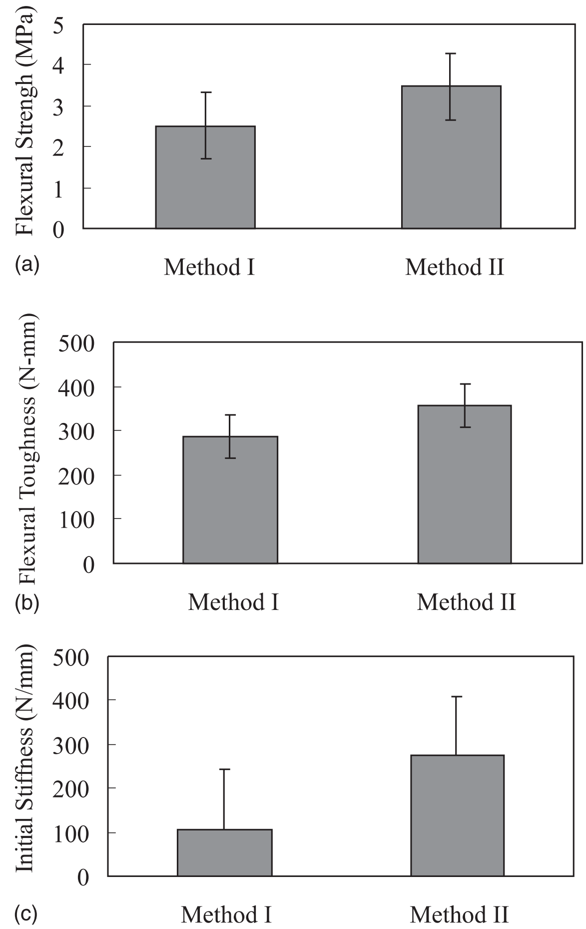

Fig. 6. Effects of the processing sequence on flexural performance: mean and 95% confidence interval. (a) Flexural strength, (b) flexural toughness and (c) initial stiffness.

set-up excluded extraneous deformations (e.g. due to penetrations into the specimen at supports and load points). The flexure test samples had a clear span of 20 cm (7.87 in.), a width of 10 cm (3.94 in.), and a thickness of 1.2 cm (0.47 in.). A displacement rate of 2.8 mm per min was used in flexure tests (which were conducted in a displacement-controlled mode). A computer-controlled data acquisition system was used to record the test data. The load–deflection curves were characterized by flexural strength, toughness (total area underneath the load–deflection curve), and initial stiffness (defined here as the stiffness obtained through linear regression analysis of the load–deflection points for loads below 15% of maximum load). The target density of CO_2-cured cement-bonded particleboard was 1.2 g/cm^3. All samples were tested immediately after processing through CO_2 injection.

4. Test results and discussion

Fig. 5 presents typical flexural load–deflection curves of cement-bonded particleboards subjected to the different CO_2-curing sequences (see Fig. 2). The flexural strength, toughness and stiffness test results are presented in Table 5 and Fig. 6. Analysis of variance of test results confirmed that, at 95% level of confidence, Sequence II of CO_2-curing yielded improved flexural performance. This sequence of CO_2-curing, when compared with conventional processing of cement-bonded wood particleboard, reduces the processing time of cement-bonded wood particleboard (under press) from several hours to 4.5 min.

Following the preferred sequence (II) of CO_2-curing, the effects of CO_2 concentration were evaluated. Fig. 7 presents typical flexural load–deflection curves obtained with different CO_2 concentrations. The flexural strength, toughness and stiffness test results are shown in Table 6 and Fig. 8. A lower concentration of CO_2 is observed to yield flexural performance characteristics which are comparable to those obtained with 100% CO_2 concentration. Block analysis of variance of the flexural test results indicated, at 95% level of confidence, that flexural strength, toughness and stiffness values were comparable at different CO_2 concentrations ranging from 25% to 100% (Table 7). Economic criteria encourage the use of low CO_2 concentrations. Softwood and hardwood particles yielded comparable results.

One may rationalize the competitive performance of low CO_2 concentrations by considering that excess acceleration of reactions could yield rapid hardening of the surface of board which would prevent thorough

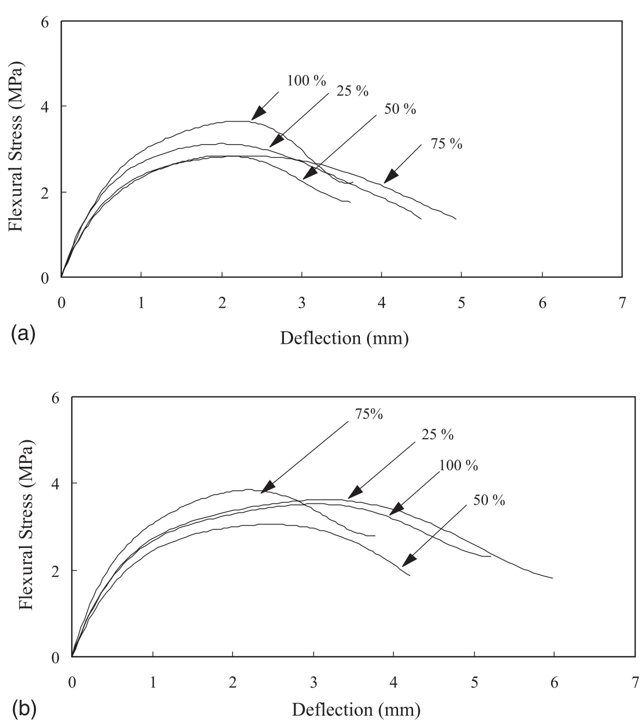

Fig. 7. Effects of CO_2 concentration of flexural load–deflection curves. (a) Softwood and (b) hardwood.

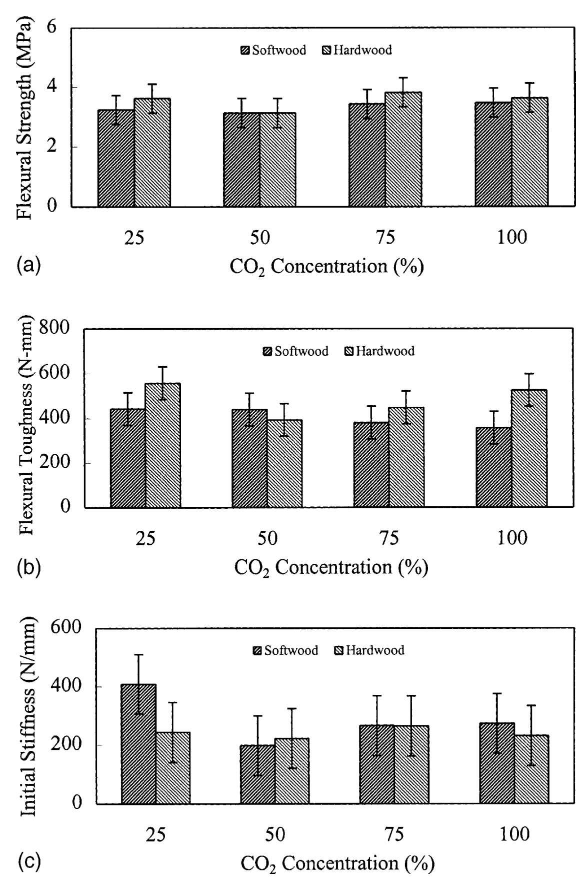

Fig. 8. Effects of various CO_2 concentrations on the flexural performance of cement-bonded wood particleboard: mean and 95% confidence interval. (a) Flexural strength, (b) flexural toughness and (c) initial stiffness.

penetration of the carbon dioxide gas. Excess heating of the fresh board due to excess acceleration of exothermic reactions could also generate thermal shrinkage micro-cracks within the system. These effects would compro-

Table 6
Effects of various CO_2 concentrations on the flexural performance of cement-bonded wood particleboard

Wood	CO_2 condition (%)	Flexural strength (MPa)	Mean (st. dev.)	Flexural toughness (N mm)	Mean (st. dev.)	Initial stiffness (N/mm)	Mean (st. dev.)
Softwood	100	3.72	3.47	321.901	357.351	195.555	273.158
		3.67	(0.39)	358.995	(34.657)	249.643	(91.651)
		3.01		391.157		374.275	
	75	3.47	3.43	471.230	380.754	269.821	265.818
		3.65	(0.24)	408.93	(107.373)	312.546	(48.852)
		3.18		262.103		215.088	
	50	3.06	3.13	442.948	439.942	189.677	198.056
		3.20	(0.09)	436.937	(4.250)	206.436	(11.843)
	25	3.24	3.24	476.143	442.417	410.047	408.616
		3.19	(0.05)	420.343	(29.668)	406.215	(2.092)
		3.30		430.767		409.586	
Hardwood	100	4.38	3.63	503.076	524.635	315.867	231.621
		3.52	(0.69)	521.453	(23.313)	221.524	(79.678)
		3.01		549.376		157.472	
	75	3.84	3.82	429.558	447.985	364.874	264.943
		3.82	(0.01)	436.215	(26.362)	253.246	(94.625)
		3.82		478.181		176.711	
	50	2.96	3.13	369.380	393.338	225.810	222.370
		3.06	(0.23)	384.436	(29.437)	219.542	(3.178)
		3.39		426.199		221.760	
	25	3.83	3.62	605.085	557.762	334.874	243.551
		3.47	(0.18)	523.413	(42.353)	240.326	(89.756)
		3.58		544.789		155.449	

Table 7
Flexure test results

	Wood–cement ratio							
	0.28				0.35			
	CO_2 concentration (25)		CO_2 concentration (100)		CO_2 concentration (25)		CO_2 concentration (100)	
	Softwood	Hardwood	Softwood	Hardwood	Softwood	Hardwood	Softwood	Hardwood
Flexural strength (MPa)	3.24	3.83	3.72	4.38	3.73	3.68	2.60	3.39
	3.19	3.47	3.67	3.52	2.25	3.15	2.25	2.08
	3.30	3.58	3.01	3.01	2.56	2.89	3.02	2.73
Mean (st. dev.)	3.24	3.62	3.47	3.63	2.85	3.24	2.62	2.73
	(0.05)	(0.18)	(0.39)	(0.69)	(0.78)	(0.40)	(0.38)	(0.65)
Flexural toughness (N mm)	476.143	605.085	321.901	503.076	661.279	670.329	330.915	549.339
	420.343	523.413	358.995	521.453	343.652	588.999	390.543	302.260
	430.767	544.789	391.157	549.376	437.263	321.624	501.891	360.276
Mean (st. dev.)	442.417	557.762	357.351	524.635	480.731	526.984	407.783	403.358
	(29.668)	(42.353)	(34.657)	(23.313)	(163.214)	(182.437)	(86.782)	(129.202)
Initial stiffness (N/mm)	410.047	334.874	195.555	315.867	294.624	351.066	117.124	59.266
	406.215	240.326	249.643	221.524	283.784	143.232	114.684	108.098
	409.586	155.449	374.275	157.472	272.656	204.627	96.532	98.496
Mean (st. dev.)	408.616	243.551	273.158	231.621	283.688	232.975	109.447	88.62
	(2.092)	(89.756)	(91.651)	(79.678)	(10.984)	(106.777)	(11.251)	(25.871)

mise any advantages associated with the greater extent of reactions at higher CO_2 concentrations.

5. Summary and conclusions

An experimental study was conducted to assess the effects of the CO_2 curing process variables on wood–cement composites made with milled softwood and hardwood particles. Alternative sequences of CO_2 and vacuum application on the two faces of board were investigated and the preferred sequence was selected. CO_2 curing reduced the required press time for product stability upon press release by two orders of magnitude.

CO_2 cured cement-bonded particleboards processed at different CO_2 concentrations were evaluated based on their flexural performance immediately upon press release. A lower CO_2 concentration (25%) yielded immediate flexural performance characteristics which were generally comparable to those obtained at 100% CO_2 concentration. In order to explain this observation, which has important economic implications, we have hypothesized that the excess rate of reactions and rapid heat generation associated with 100% CO_2 concentration, which could compromise any gains associated with the greater extent of reactions at higher CO_2 concentrations.

Acknowledgement

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References

[1] Dinwoodie JM. Wood–cement particleboards—a technical assessment. Building Research Establishment Information Paper, United Kingdom, April 1983.
[2] Simatupang MH, Habighorst C. The carbon dioxide process to enhance cement hydration in manufacturing of cement-bonded composites-comparison with common production method. In: Moslemi A, editor. Proceedings Inorganic Bonded Wood and Fiber Composite Materials Conference. Forest Products Research Society; 1993. p. 114–20.
[3] Simatupang MH, Geimer RC. Inorganic binder for wood composites: feasibility and limitations. In: Conners AH, editor. Wood adhesives. Forest Products Research Society; 1991. p. 167–76.
[4] Berger RC, Young JF, Leung U. Accelerated hydration of calcium silicate by carbon dioxide treatment. Nature Phys Sci 1972; 240(91):16–8.
[5] Lahtinen PK. Experiences with cement-bonded particleboard manufacturing when using a short-cycle press line. In: Moslemi A, editor. Proceedings Inorganic Bonded Wood and Fiber Composite Materials Conference. 1991. p. 32–4.
[6] Geimer RL, Suoza MR, Moslemi AA, Simatupang MH. Carbon dioxide application for rapid production of cement particleboard. In: Moslemi A, editor. Proceedings Inorganic-Bonded Wood and Fiber Composite Materials Conference. Forest Products Research Society; 1993. p. 31–41.
[7] Simatupang MH, Seddig N, Habighorst C, Geimer RL. Technologies for rapid production of mineral-bonded wood composite boards. In: Moslemi A, editor. Proceedings Inorganic Bonded Wood and Fiber Composite Materials Conference. Forest Product Research Society; 1991. p. 18–27.
[8] Goodbrake CJ, Young JF, Berger RL. Reaction of hydraulic calcium silicated with carbon dioxide and water. J Am Ceramic Soc 1979;62(9–10):488–91.
[9] Young JF, Berger RL, Breese J. Accelerated curing of compacted calcium silicate mortars on exposure to CO_2. J Am Ceramic Soc 1974;(September):394–7.
[10] International Standard ISO 8335. Cement-bonded particleboards. International Organization for Standardization, 1981.