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Value-added recycling of construction waste wood into noise and thermal insulating cement-bonded particleboards

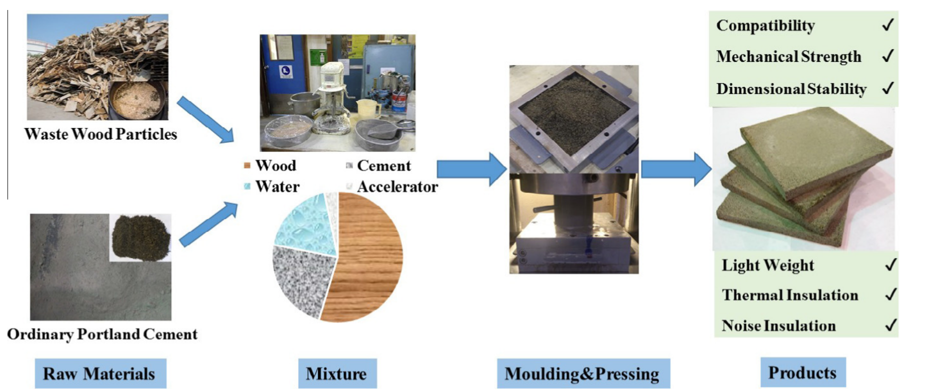
Lei Wang [a], Season S. Chen [a], Daniel C.W. Tsang [a,*], Chi Sun Poon [a], Kaimin Shih [b]

[a] Department of Civil and Environmental Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China
[b] Department of Civil Engineering, University of Hong Kong, Pokfulam, Hong Kong, China

HIGHLIGHTS

- Waste timber formwork can be recycled into value-added particleboards.
- Mineralogy and microstructure characteristics play important roles in recycling.
- Insoluble calcium hydrates enhance flexural strength and dimensional stability.
- Reduction of capillary pore volume contributes to high strength performance.
- Excellent structure-borne noise and thermal insulation enables broad application.

GRAPHICAL ABSTRACT



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ABSTRACT

Large amounts of waste wood formwork from construction sites end up with landfill disposal every day. This study aims to develop a practicable technology for recycling construction waste wood into formaldehyde-free cement-bonded particleboards that have value-added features of high strength, light weight, and thermal/noise insulation for reuse in building and construction applications. The mineralogy and microstructure of particleboards were characterized by X-ray diffraction, thermogravimetry, and mercury intrusion porosimetry analyses. Among the mineral admixtures, chloride accelerated precipitation of oxychlorides while sulphate produced calcium sulphoaluminate for promoting early strength development. The use of 2% $CaCl_2$ proved to be sufficient for improving the wood-cement compatibility. At wood-to-cement ratio of 3:7 by weight (i.e., 3:1 by volume), cement hydrates in the porous structure ensured acceptable dimensional stability (<2% swelling). By adjusting the water-to-cement ratio to 0.3 and density of the particleboards to 1.54 g cm^{-3}, the volume of capillary pores was effectively reduced from 0.16 mL g^{-1} to 0.02 mL g^{-1}. The more compact microstructure contributed to high fracture energy at 6.57 N mm^{-1} and flexural strength of 12.9 MPa. Using the above optimal production conditions, the particleboards complied with the International Standard (9 MPa) while enabling reuse as light-weight structure. The particleboards also manifested outstanding structure-borne noise reduction (at 32–100 Hz) and low thermal conductivity (0.29 W m^{-1} K^{-1}), suggesting potential application as acoustic and thermal insulating materials. Preliminary cost-benefit analysis illustrated economic viability of the proposed approach. Therefore, technological innovation is crucial for delivering an eco-friendly solution to waste wood recycling for the building and construction industry.

* Corresponding author.
E-mail address: dan.tsang@polyu.edu.hk (D.C.W. Tsang).

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1. Introduction

Construction waste disposal is closely associated with rapid economic growth in metropolitan cities and developing countries. The infrastructure establishment and building construction results in massive amounts of waste wood formwork that reaches its limited lifespan for reuse at construction sites. For instance, there are a few hundred tonnes of daily disposal of timber waste formwork at landfills in Hong Kong, although the majority of construction wastes are effectively recycled and inert materials are diverted to public fill use [1,2]. In view of its vulnerability to environmental and biological degradation, wood is usually treated by preservative chemicals such as chromated copper arsenate [3–5], which cause long-term ecological and human health risks due to environmental pollution by chemical leaching [6–8]. While landfill disposal is increasingly regarded as a non-sustainable management practice of waste wood formwork due to increased carbon footprint and limited landfill capacity [9–11], combustion of contaminated wood for energy recovery is limited by stringent requirements for waste pretreatment, air pollution control, and hazardous ash treatment [12]. Due to lack of robust recycling approach, only about 0.04% of wood waste is recycled in Hong Kong, even though recycled timber is estimated to value approximately 130 USD per tonne [2,13].

Recycling timber waste into cement-bonded particleboard has been proposed as an appealing technology. While waste wood are vulnerable to biological degradation and environmental weathering, complementary addition of cement significantly reinforces the strength performance and structure durability of wood particleboard [14,15]. As the waste wood particles act as granular skeleton, the recycled particleboard may present added values of light-weight and thermal-/noise-insulating materials for reuse. In contrast to traditional particleboard made from raw wood with phenol formaldehyde resin that compromises indoor air quality, cement-bonded particleboard is free from formaldehyde and thus eco-friendly to the environment and human health [16,17]. However, the existence of low-molecular-weight carbohydrates and chemical additives in waste wood were found to interfere with cement hydration and adversely influence the strength development [18,19]. Such incompatibility required inorganic accelerators such as chloride and sulphate salts to facilitate the formation of calcium silicate hydrate gel and calcium hydroxides [20–22]. Nevertheless, further studies are needed to elucidate the roles of moisture content and particleboard density in the development of mechanical strength and dimensional stability. This is related to the characteristics of microporous structure and hydration chemistry at the wood interface. Thus, this study aims to unravel the correlations between scientific mechanisms and particleboard properties for augmenting the development of a novel and sustainable wood recycling approach.

The performance and properties of the cement-bonded particleboards were characterized by: (i) determining the proper accelerator type and dosage to overcome low compatibility; (ii) optimizing the mixture formulation to accomplish acceptable mechanical strength and dimensional stability with respect to international standards for application; (iii) quantifying the advantages of low density, low thermal conductivity, and reduction of impact noise; (iv) elucidating the corresponding microstructure and mineralogy via microscopic and spectroscopic analyses; and (v) validating the cost and applicability of the proposed technical approach for waste wood recycling.

2. Experimental methods

2.1. Waste properties and particleboard production

Waste construction formwork (*Pinus massoniana*, softwood) was collected from a local recycling industry in EcoPark in Tuen Mun, Hong Kong, which received waste formwork that was treated with preservative chemicals against deterioration and contaminated with cement mortar at construction sites. The contents of heavy metals in the waste wood were determined using an inductively coupled plasma-atomic emission spectrometry (Perkin Elmer Optima 3300DV) after total acid digestion, which were 1460 mg kg^{-1} Mn, 39.2 mg kg^{-1} Cr, 10.4 mg kg^{-1} As, 4.4 mg kg^{-1} -Cu, and 4.0 mg kg^{-1} Ni. Besides, the water-soluble extractives were measured using high performance liquid chromatography after 6-h water washing at room temperature at a wood-to-water ratio of 1:10. The waste wood contained 8.7 mg kg^{-1} glucose and trace amounts of hemicelluloses and lignins. The waste formworks were granulated after manual removal of nails, and sieved to 0.3–2.36 mm and 2.36–5 mm particle sizes as fine aggregates and coarse aggregates, respectively.

The wood particles were supplemented with 60 wt% of tap water to meet the saturated surface dry condition according to preliminary tests. ASTM Type I Ordinary Portland Cement (OPC) was used as cementing material in this study, which had a density of 3.16 g cm^{-3}, 2.34% loss on ignition, and 63.2% CaO, 19.6% SiO_2, 7.32% Al_2O_3 based on X-ray fluorescence analysis. Five low-cost and effective accelerators of chlorides and sulphate salts ($CaCl_2$, $MgCl_2$, $FeCl_3$, $AlCl_3$, $Al_2(SO_4)_3$) were tested for enhancing the cement-wood interfacial compatibility.

The wood aggregates, OPC binder, and accelerators were homogeneously mixed for 3 min by a mechanical mixer, and compressed at 4 MPa for 1 min in the steel mould (160 × 160 × 15 mm), of which the cap was fixed by four bolts. The particleboards were demoulded after 24 h and subject to 7-d or 28-d air curing at 20 °C and 95% humidity in a curing chamber before further analyses. The five accelerators were applied at 1%, 2%, and 5% by weight of cement, respectively. The aggregate-to-cement ratio (A/C ratios at 3:7, 4:6, 5:5, 6:4, and 7:3, by weight), water-to-cement ratio (W/C ratios at 0.45, 0.40, 0.35, 0.30, 0.25, by weight), and the resulting densities were investigated (Table 1) for achieving the mechanical strength required by international standard for particleboards [23]. All experiments were conducted in duplicate and the average values were presented with the variations.

2.2. Mechanical strength, dimensional stability, thermal insulation, and noise reduction

The flexural strength [24] and tensile strength [25] of the particleboards were examined by a standard testing machine (Testometric CXM 500-50 KN) at a loading rate of 0.3 mm min^{-1}, which served to justify their applicability for reuse. The displacements under variable stress were recorded with the aid of internal linear variable differential transformer (LVDT, 0.01 mm sensitivity) by measuring the average axial longitudinal strain. The fracture energy (G_F) was then calculated from the flexural stress-deflection curve. The elastic modulus (E) of the particleboards were obtained from the secant slope of stress-strain curve (between 0 and 30 percent of the peak stress), which were compared to those of concrete boards. The compressive stress was examined by a universal testing machine with a maximum capacity of 3000 kN at a rate of 0.6 MPa s^{-1} and the corresponding strain was measured by strain gauges attached to the sample surface. The dimensional stability of the particleboards was evaluated in terms of water absorption and thickness swelling [25]. In addition to the standard

Table 1
Mixture formulations (wt%) for cement-bonded particleboards.

Binder	Aggregate[a]	Water to cement ratio	Density (g cm^{-3})
(a) Enhancing compatibility by accelerator addition			
49.5% cement + 0.5% $CaCl_2$/$MgCl_2$/$FeCl_3$/$AlCl_3$/$Al_2(SO_4)_3$	50% coarse wood	0.45	1.18
49.0% cement + 1.0% $CaCl_2$/$MgCl_2$/$FeCl_3$/$AlCl_3$/$Al_2(SO_4)_3$			
47.5% cement + 2.5% $CaCl_2$/$MgCl_2$/$FeCl_3$/$AlCl_3$/$Al_2(SO_4)_3$			
(b) Optimizing aggregate to cement ratio			
70% cement	30% coarse/fine wood	0.45	1.38
68.6% cement + 1.4% $CaCl_2$	30% coarse/fine wood		1.38
58.8% cement + 1.2% $CaCl_2$	40% coarse/fine wood		1.28
49.0% cement + 1.0% $CaCl_2$	50% coarse/fine wood		1.18
39.2% cement + 0.8% $CaCl_2$	60% coarse/fine wood		1.10
29.4% cement + 0.6% $CaCl_2$	70% coarse/fine wood		1.01
(c) Improving pore structure by adjusting water to cement ratio			
68.6% cement + 1.4% $CaCl_2$	30% coarse wood	0.45	1.38
		0.40	
		0.35	
		0.30	
		0.25	
(d) Enhancing compactness by adjusting density			
68.6% cement + 1.4% $CaCl_2$	30% coarse wood	0.30	1.38
			1.46
			1.54
			1.58
			1.62

[a] Fine wood: 0.3–2.36 mm; coarse wood: 2.36–5 mm.

requirements of particleboards [23], the additional merit of sound insulation was evaluated as sound reduction index [26] and impact noise reduction was measured by using tapping machine [27]. Quick Thermal Conductivity Meter (QTM-500) was adopted for thermal conductivity determination in this study, although the accurate value should be determined using standard sample dimension [28].

2.3. Microscopic and spectroscopic analyses

To elucidate the scientific mechanisms related to the particleboard performance, the mineralogy of the squashed particleboards produced under different conditions was revealed by using a high-resolution powdered X-ray diffractometer (XRD, Rigaku SmartLab). The scanning degrees ranged from 0° to 60° 2θ with 5° min^{-1} at 45 kV and 200 mA. The crystallization enthalpy (100–1100 °C) was evaluated by conducting thermogravimetric analysis of the particleboards (Netzch TGA/DSC) at 10 °C min^{-1} with dry argon stripping gas. Moreover, the microstructure of the matrix was assessed using a mercury intrusion porosimeter (MIP, Micromeritics Autopore IV), which determined the porosity and pore size distribution. The samples (3–5 mm) were immersed in acetone for 30 d and oven-dried at 60 °C for 7 d prior to MIP tests. Mercury was infused into the pretreated sample pores at 207 MPa following 6.6 Pa purging in vacuum.

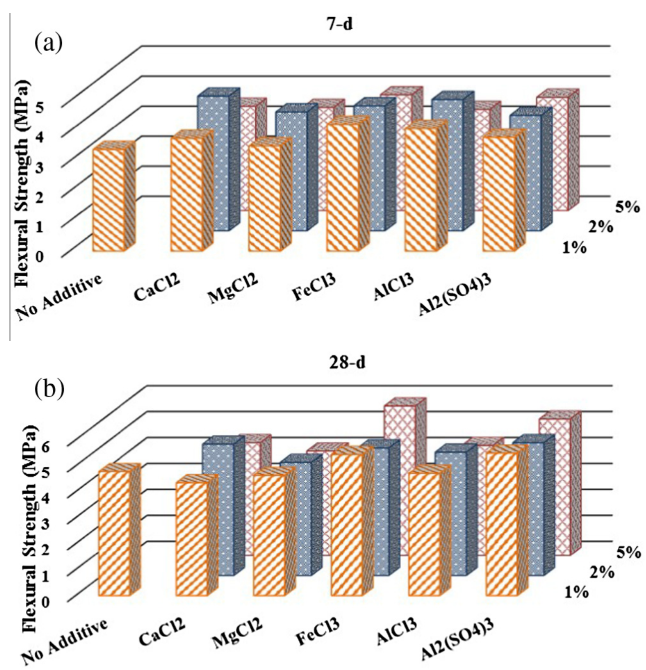

Fig. 1. Flexural strength of cement-bonded particleboards with various accelerators at different dosages: (a) 7-d curing; (b) 28-d curing.

3. Results and discussion

3.1. Mineralogical aspects of early strength development

Fig. 1 illustrates the integrated effects of accelerators on the flexural strength of cement-bonded particleboards at an A/C ratio of 5:5 by weight (i.e., 7:1 by volume) and W/C ratio of 0.45. Approximately 41% discrepancy of flexural strength was showed between the 7-d and 28-d particleboards without accelerator, which indicated the adverse effects of calcium complexation with water-soluble extractives of wood (hemicelluloses, starch, sugar, tannins, phenols, and lignins) that hindered early strength established by cement hydration. When the mineral admixtures were deployed as accelerators, flexural strength increased by 4–25% in 7-d cured particleboards with 1% accelerators (by weight of cement) (Fig. 1a). As the dosage increased to 2%, the flexural strength was further enhanced by 14–32%. However, 5% accelerator dosage did not strengthen the particleboards due to reduced amount of cement for producing hydration products. Thus, 2% dosage of accelerators was found appropriate for shortening the setting time and enhancing the early strength of particleboard production.

The XRD spectra (Fig. 2) demonstrated notably lower peaks of unreacted calcium silicates (29.3°, 32.1° and 34.0°) in 1-d cured particleboards with the addition of accelerators, signifying a higher

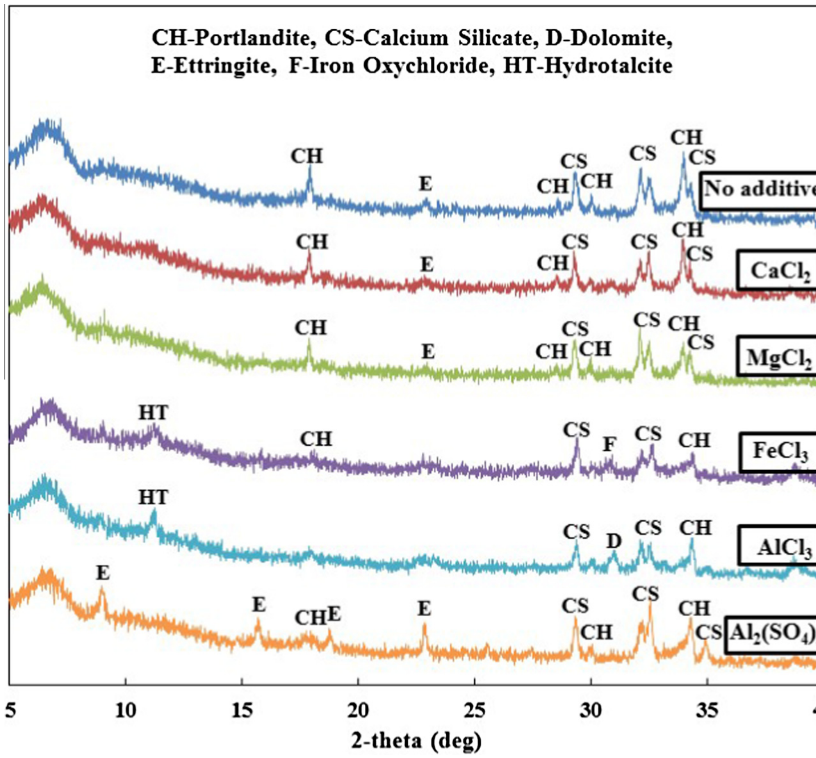

Fig. 2. XRD spectra of 1-d particleboards with various accelerators (5% by weight of cement).

degree of cement hydration. In the samples with $FeCl_3$, the peaks of calcium hydroxides (17.9° and 34.0°) were attenuated, while a new peak of iron oxychloride (FeClO) appeared at 30.9°. This might suggest that ferric chloride rapidly reacted with calcium hydroxides to form insoluble iron oxychloride. Chloride ions were also found to react with tricalcium aluminate and accelerate the precipitation of insoluble calcium chloroaluminate hydrates [21,29,30]. These exothermic chemical reactions might promote cement hydration and thereby reducing the peak intensity of calcium silicates and calcium hydroxides in the XRD spectra as observed. The precipitation of calcium chloroaluminate hydrates and iron oxychlorides probably accounted for the structure formation and early strength development. Similar reaction mechanisms were shown in other chloride accelerators as well.

On the other hand, aluminium sulphate ($Al_2(SO_4)_3$) possibly reacted with hydrated calcium aluminate to produce substantial amounts of crystalline calcium sulphoaluminate (a major ettringite) at 9.0°, 15.7° and 22.8° (Fig. 2). This transformation could promote crystallization and growth of coexisting hydrates and thus improving early strength [31–33]. Although 5% $FeCl_3$ and $Al_2(SO_4)_3$ might offer better long-term strength development, 2% $CaCl_2$ was selected for the subsequent experiments for its best compatibility improvement and highest 7-d strength improvement (Fig. 1). However, it should be noted that these salt-based accelerators may promote corrosion of metal nails, screws, or beams used for the particleboard installation, which should be taken into account upfront.

3.2. Microstructure characteristics with varying aggregate-to-cement ratio

As illustrated in Fig. 3a, wood particle size showed little effect on the flexural strength of particleboard, thus coarse wood particles were selected as aggregates for the sake of simpler grinding process and lower pretreatment cost. In contrast, the flexural strength (Fig. 3a) and tensile strength (Fig. S1a, Supplementary Materials) gradually decreased with an increasing aggregate-to-cement (A/C) ratio. The XRD analysis (Fig. 4c) showed a stronger peak of unreacted calcium silicates at 29.3° at an A/C ratio of 7:3

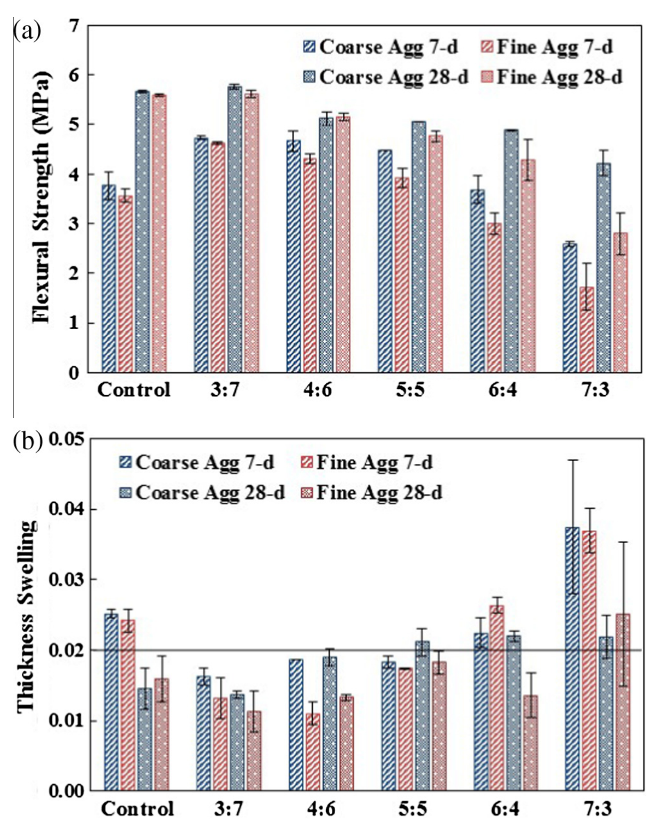

Fig. 3. Flexural strength (a) and thickness swelling (b) of particleboards at varying aggregate-to-cement (A/C) ratio (Agg: aggregate; Control: without accelerator at A/C ratio of 3:7; Others: with 2% $CaCl_2$ by weight of cement).

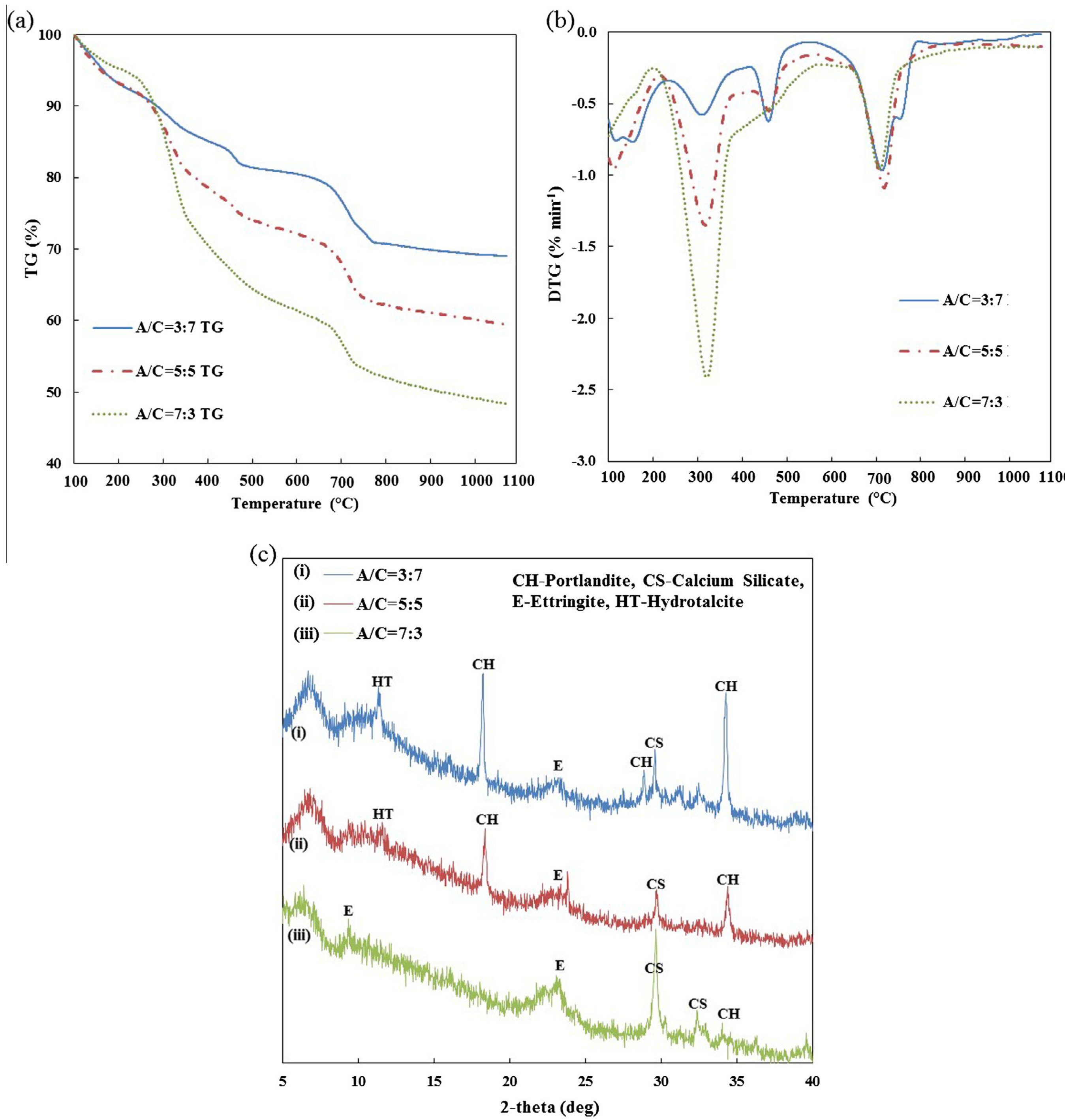

Fig. 4. TGA and XRD spectra of 28-d particleboards at varying aggregate-to-cement (A/C) ratio: (a) thermogravimetry (TG); (b) derivative thermogravimetry (DTG); (c) XRD spectra.

by weight (i.e., 16.4:1 by volume) but significantly lower peaks of calcium hydroxides at 18.2° and 34.2° as well as lower peak of calcium silicate hydrate at 6.5° with an A/C ratio of 3:7 by weight (i.e., 3:1 by volume) or 5:5 by weight (i.e., 7:1 by volume). These spectroscopic results evidenced that the weaker strength of particleboards with a high wood content resulted from insufficient formation of cement hydrates at the wood interface.

The thermogravimetric analysis of particleboards revealed a substantial weight loss at 270–350 °C (Fig. 4a&b), where the magnitude was positively correlated with wood content and indicative of wood decomposition. This temperature range was higher than the reported ignition point (190–260 °C) of wood on its own [34,35], implying that wood particles being enmeshed in the cement hydrates enhanced the fire resistance of particleboards to certain extent. In consideration of previous studies [36–38], subsequent weight loss at 420–500 °C was attributed to CH dehydration, which was more evident in the samples with lower wood volume. Further weight loss between 700 and 800 °C represented the breakdown of calcite ($CaCO_3$). This was also corroborated by the XRD analysis (Fig. 4c). A marked shoulder peak at approximately

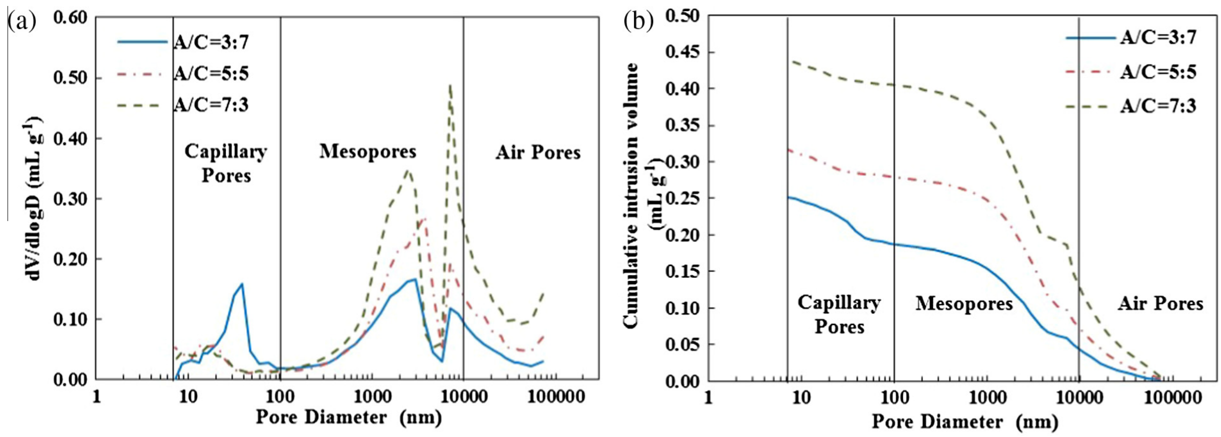

Fig. 5. Pore size distribution (MIP analysis) of 28-d particleboards at varying aggregate-to-cement (A/C) ratio: (a) differential distribution; (b) cumulative distribution (A/C: aggregate-to-cement ratio).

800 °C in the particleboards with an A/C ratio of 3:7 by weight suggested the presence of well-crystalline calcite that could contribute to high mechanical strength.

The porous structure of the particleboards was analyzed at varying A/C ratios. As shown by the MIP results (Fig. 5), the 28-d particleboards were characterized with a higher porosity of 42.5% at an A/C ratio of 7:3 by weight, while it was only 31.2% at an A/C ratio of 3:7 by weight. From the structural perspectives, peaks appeared between 5 nm and 100 nm in the pore size distribution were classified as capillary pores, while the other two peak ranges corresponding to mesopores and air pores were attributed to the wood particles [39,40]. The microstructure analysis revealed less amount of mesopores and air pores in the particleboards containing a lower wood content (A/C ratio of 3:7 by weight), verifying that mechanical strength was negatively related to total porosity and average pore diameter [41]. On the other hand, the thickness swelling increased along with increasing wood content (Fig. 3b), and the water absorption also demonstrated similar pattern (Fig. S1b). The dimensional stability of particleboards was correlated to the pore structure and the observed trends were attributed to the high water absorption and thickness swelling of wood particles. To maintain the thickness less than 2% as required by the international standard of particleboards [23], the wood content could not exceed 50% by weight. In view of the significant role of porosity in strength establishment as discussed above, subsequent experiments further adjusted the density of particleboards at an A/C ratio of 3:7 by weight in order to accomplish the required flexural strength standard of 9 MPa [23].

3.3. Strength improvement by tuning the porosity

Both flexural strength (Fig. 6a) and tensile strength (Fig. S2a) of the particleboards showed a gradual increase with decreasing water-to-cement (W/C) ratio until reaching 0.30. As expected, the thickness swelling (Fig. 6b) and water absorption (Fig. S2b) were similarly reduced by decreasing the W/C ratio and all the particleboards fulfilled the thickness swelling requirement [23]. Then, for the same density of particleboards at 1.38 g cm^{-1}, the total pore area of 4.4 $m^2\,g^{-1}$ and total porosity of 24.8% at a W/C ratio of 0.30 were much lower than those at a W/C ratio of 0.45 (12.3 $m^2\,g^{-1}$ and 31.2%) (Fig. 7). These MIP results reflected that a higher W/C ratio was companied by a larger porosity.

The volume of capillary pores (at approximately 30–40 nm pore diameter) were significantly reduced from 0.16 mL g^{-1} to 0.05 mL g^{-1} along with the decrease of W/C ratio from 0.45 to 0.30. This was probably attributed to a larger extent of intraparticle diffusion of calcium silicate hydrate gel due to slower hydration kinetics and nucleation/growth rates at a lower W/C ratio. Filling up the capillary pores could minimize the chance of structural failures, which are usually triggered by microcrack growth and propagation. However, at the W/C ratio of 0.25, there was insufficient water for cement hydration and strength development was consequently hampered. Thus, the W/C ratio of 0.30 was considered as optimal for producing a more compact particleboard.

Comparing the particleboards of a density of 1.38 g cm^{-3} and 1.54 g cm^{-3} with the same W/C ratio of 0.3 (Fig. 7), the increase of density resulted in a lower porosity and favourable pore struc-

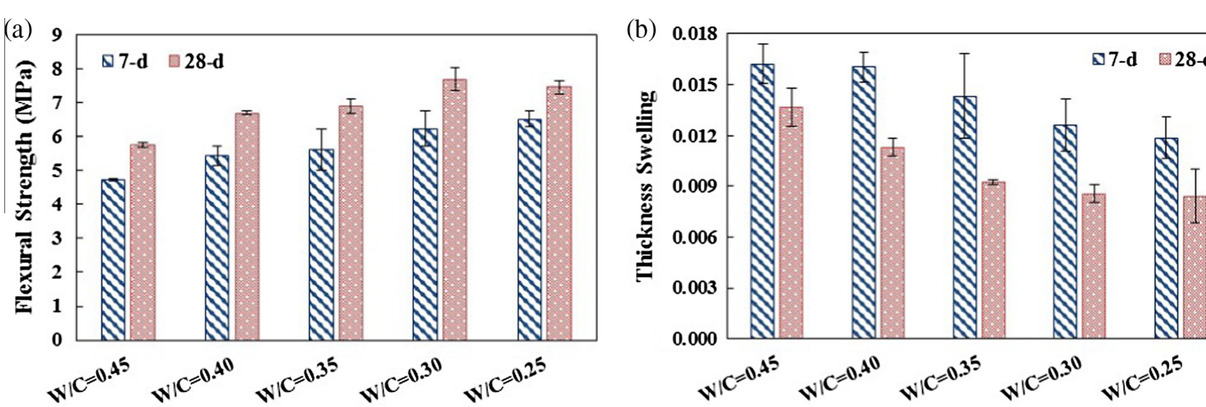

Fig. 6. Flexural strength (a) and thickness swelling (b) of particleboards at varying water-to-cement (W/C) ratio.

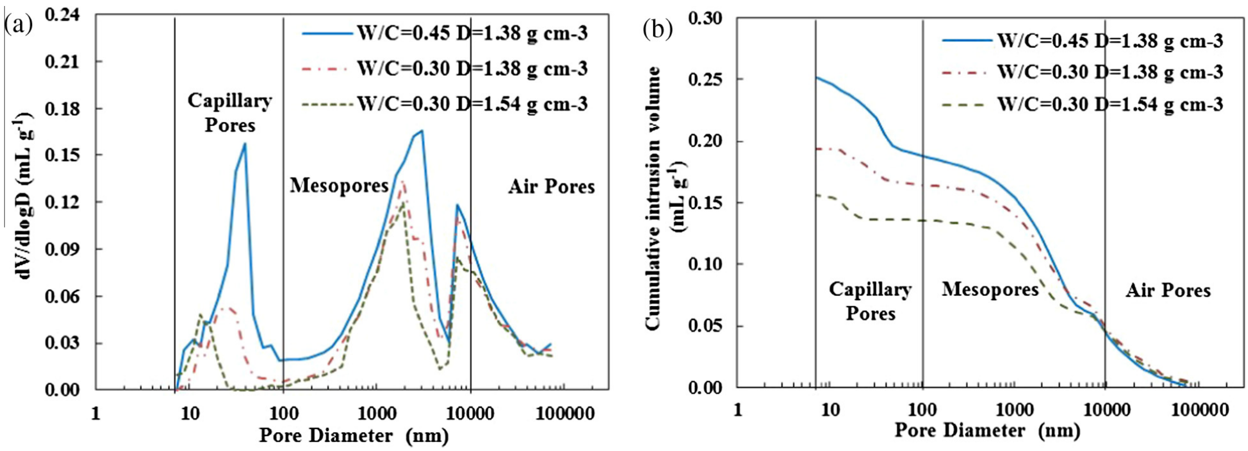

Fig. 7. Pore size distribution (MIP analysis) of 28-d particleboards at varying water-to-cement (W/C) ratio and varying density (D): (a) differential distribution; (b) cumulative distribution.

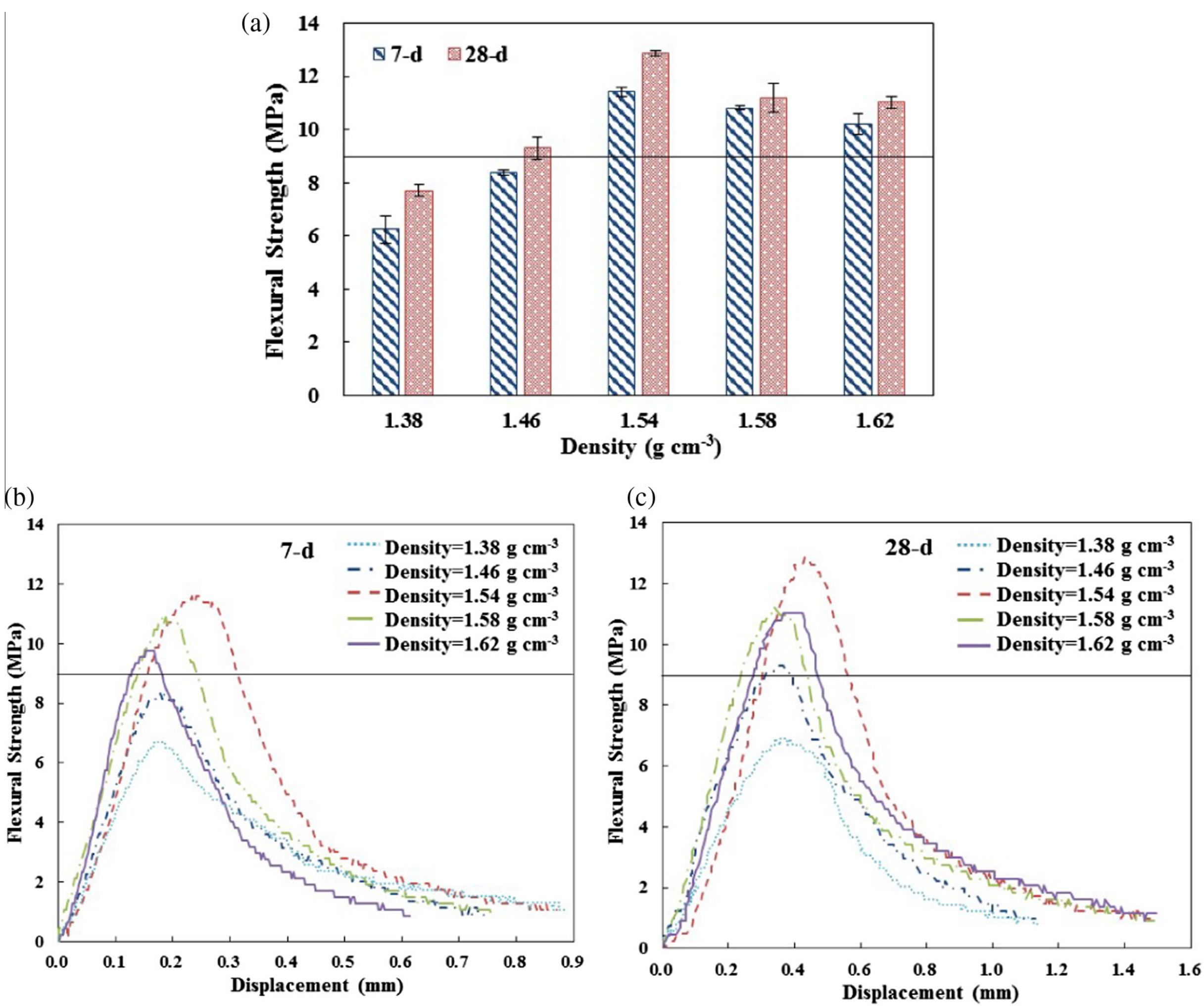

Fig. 8. Flexural strength and flexural stress-deflection curves of particleboards with varying density: (a) flexural strength; (b) 7-d flexural stress-deflection curves; (c) 28-d flexural stress–deflection curves.

ture for strength development. However, as shown in Fig. 8a, flexural strength of particleboards gradually increased with increasing density up to 1.54 g cm^{-3}, then decreased afterwards. This was because water overflow under the compression pressure of 4 MPa was observed at density beyond 1.54 g cm^{-3}, due to insufficient porosity for holding up the water content for necessary cement hydration in the matrix. The flexural stress-deflection curves of the particleboards with varying density (Fig. 8b&c) showed consistent results as above. The calculated fracture energy (G_F) increased from 2.61 N mm^{-1} (1.38 g cm^{-3}) to 3.89 N mm^{-1}

(1.54 g cm^{-3}) in the 7-d particleboards, whereas the G_F value progressively achieved 6.57 N mm^{-1} (1.54 g cm^{-3}) with continuous cement hydration in the 28-d particleboards. The optimal density was considered to be 1.54 g cm^{-3} as the 28-d flexural strength reached 12.9 MPa and far exceeded the standard requirement of 9 MPa [23]. In addition, the particleboard density (1.54 g cm^{-3}) was 32% lower than that of conventional concrete board (2.26 g cm^{-3}, using the same volume of sand replacing wood as aggregate, Table 2). Hence, the particleboards made up of waste wood can be regarded as light-weight building materials [42].

3.4. Added values of thermal insulation and noise reduction

Owing to the excellent property of wood for thermal insulation, the thermal conductivity of the particleboards produced at the above optimal conditions was 0.29 W m^{-1} K^{-1}. This value represented only 19% of that of concrete board (1.52 W m^{-1} K^{-1}) and it was nearly comparable to the value of solid wood panel (0.24 W m^{-1} K^{-1} at 1.0 g cm^{-3}) for thermal insulation uses in BS EN 13986 [43], despite being higher than that of waste wood (0.07 W m^{-1} K^{-1}).

Moreover, the impact noise reduction efficiencies were evaluated at low-to-medium noise frequency (i.e., 32–3150 Hz) (Fig. 9). The particleboards exhibited better noise insulation effectiveness than concrete boards at almost all frequency ranges. Although waste wood itself was most effective for noise reduction at higher noise frequency, the particleboards of this study showed outstanding noise insulation at a low sound frequency (32–100 Hz), in which the emission of structure-borne noise (i.e., 32–100 Hz) normally originates from vibrating room boundaries [44,45]. As the elastic modulus (E) of wood particleboard was only 18% of concrete board (Fig. S3), their low stiffness feature was favourable for dissipating vibrational energy and insulating impact sound. The moderate amount of air pores in the particleboards (Fig. 7) also contributed to the superior acoustic shielding properties, as suggested by recent studies [46,47]. Therefore, the particleboards of this study present embedded properties that enable wide building and construction applications for light-weight noise/thermal insulation uses, which help to promote wood recycling.

3.5. Assessing the economic viability

A preliminary cost analysis is performed in the present study to evaluate the economic feasibility of particleboard production from waste wood formwork. In order to simplify the scenario, a necessary assumption is made that fixed equipment assets, waste collection/transfer, labour, etc, are available at present or fully sponsored by recycling fund and producer responsibility scheme, such that these expenses are excluded from the calculation. On the other hand, intangible benefits associated with environmental, economic, and societal improvement such as landfill avoidance, odour/dust nuisance mitigation, and pollution prevention are also not included in this circumstance. Therefore, the major focus is on the variable (operating) costs for chemical use and production process.

The price quotation from the largest regional supplier shows that the cement cost is approximately 52.8 USD per tonne of OPC [48]. Based on the optimal parameters in this study (i.e., density of 1.54 g cm^{-3}, A/C ratio of 3:7 by weight, W/C ratio of 0.3, and 2% $CaCl_2$ accelerator in cement binder), the chemical costs are about 49.4 USD per m^3 of particleboard production. Considering the energy for waste wood grinding and particleboard compression under 4 MPa pressure for 1 min, the power consumption is estimated to be about 2.48 USD per m^3 for the bench-scale production (using 0.11 USD per kWh in Hong Kong for example). The total manufacturing costs are about 51.9 USD per m^3 of particleboard produced from waste wood.

It is interesting to note that the market prices for cement-bonded particleboards currently range from 132 to 475 USD per

Table 2
Thermal conductivity and density of different boards.

	Wood particleboard	Concrete board[a]	Waste wood
Density	1.54 g cm^{-3}	2.26 g cm^{-3}	0.45 g cm^{-3}
Thermal conductivity	0.29 ± 0.01 W m^{-1} K^{-1}	1.52 ± 0.03 W m^{-1} K^{-1}	0.07 ± 0.00 W m^{-1} K^{-1}

[a] Using the same volume of sand replacing wood as aggregate in the concrete board.

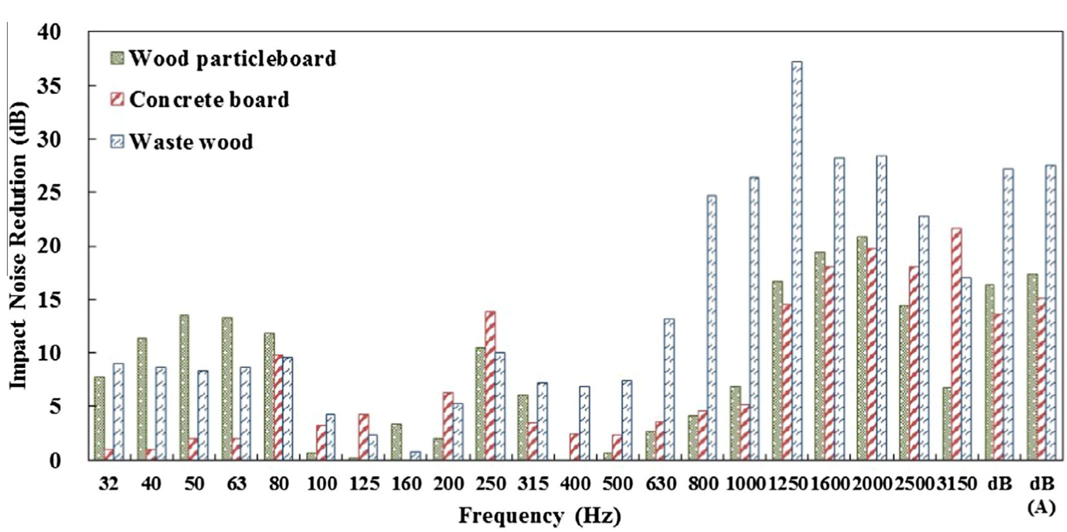

Fig. 9. Impact sound pressure level reduction of different materials (after 28-d curing).

m^3 depending on the functional properties [48] (Table S1), which demonstrate a compelling economic viability of the recycled products for the building industry. Therefore, the value-added and eco-friendly waste wood recycling technology presented in this study is promising in terms of commercial viability and market competitiveness, provided that fixed costs and capital expenditure in equipment can be covered or sponsored by waste management policy such as recycling fund and producer responsibility scheme.

4. Conclusions

This study proposed a value-added approach to facilitate waste wood recycling from construction sites by transforming end-of-life formwork into high-performance, eco-friendly, and low-cost cement-bonded particleboards. The mineralogical characterization revealed different mechanisms of accelerators in strength enhancement at the early stage, while the microstructure analysis demonstrated the importance of pore structure and chemical reactions at the wood interface. By optimizing the mixture formulation and binder-aggregate-water ratio, the density and porosity of the particleboards could be tailored to comply with international standard of mechanical strength and dimensional stability. The particleboards also presented additional environmental benefits of light weight, thermal insulation and noise reduction, which proved to be favourable for construction use. The preliminary cost-benefit analysis suggested the commercial viability of this novel recycling technology. Therefore, a widely adoptable and sustainable solution can be made possible through technological innovation to tackle waste recycling challenges.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.conbuildmat.2016.08.053.

References

[1] C.S. Poon, A.T.W. Yu, S.W. Wong, E. Cheung, Management of construction waste in public housing projects in Hong Kong, Constr. Manage. Econ. 22 (2004) 675–689.
[2] E.P.D. Hk, Monitoring of Solid Waste in Hong Kong: Waste Statistics for 2013, Environmental Protection Department, Hong Kong, 2015.
[3] S.N. Kartal, W.J. Hwang, Y. Imamur, Evaluation of effect of leaching medium on the release of copper, chromium, and arsenic from treated wood, Build. Environ. 42 (2007) 1188–1193.
[4] A. Bosmans, M.V. Auweele, J. Govaert, L. Helsen, Exergy analysis of the Chartherm process for energy valorization and material recuperation of chromated copper arsenate (CCA) treated wood waste, Waste Manage. 31 (2011) 705–713.
[5] D.C.W. Tsang, W.E. Olds, P.A. Weber, Residual leachability of CCA-contaminated soil after treatment with biodegradable chelating agents and lignite-derived humic substances, J. Soils Sediments 13 (2013) 895–905.
[6] A. Temiz, U.C. Yildiz, T. Nilsson, Comparison of copper emission rates from wood treated with different preservatives to the environment, Build. Environ. 41 (2006) 910–914.
[7] J.K. Saxe, E.J. Wannamaker, S.W. Conklin, T.F. Shupe, B.D. Beck, Evaluating landfill disposal of chromated copper arsenate (CCA) treated wood and potential effects on groundwater: evidence from Florida, Chemosphere 66 (2007) 496–504.
[8] D.C.W. Tsang, W.E. Olds, P.A. Weber, A.C.K. Yip, Soil stabilisation using AMD sludge, compost and lignite: TCLP leachability and continuous acid leaching, Chemosphere 93 (2013) 2839–2847.
[9] E.D. Gezer, U. Yildiz, S. Yildiz, E. Dizman, A. Temiz, Removal copper, chromium and arsenic from CCA-treated yellow pine by oleic acid, Build. Environ. 41 (2006) 380–385.
[10] M.H. Kim, H.B. Song, Analysis of the global warming potential for wood waste recycling systems, J. Clean. Prod. 69 (2014) 199–207.
[11] F. Ximenes, C. Björdal, A. Cowie, M. Barlaz, The decay of wood in landfills in contrasting climates in Australia, Waste Manage. 41 (2015) 101–110.
[12] A.J. Pedersen, L.M. Ottosen, Elemental analysis of ash residue from combustion of CCA treated wood waste before and after electrodialytic extraction, Chemosphere 65 (2006) 110–116.
[13] H. Yuan, W. Lu, J.J. Hao, The evolution of construction waste sorting on-site, Renewable Sustainable Energy Rev. 20 (2013) 483–490.
[14] Z. Naghizadeh, M. Faezipour, G. Ebrahimi, Y. Hamzeh, Manufacture of lignocellulosic fiber–cement boards containing foaming agent, Constr. Build. Mater. 35 (2012) 408–413.
[15] C. Faria, C. Chastre, V. Lúcio, Â. Nunes, Compression behaviour of short columns made from cement-bonded particle board, Constr. Build. Mater. 40 (2013) 60–69.
[16] S.Y. Wang, T.H. Yang, L.T. Lin, C.J. Lin, M.J. Tsai, Properties of low-formaldehyde-emission particleboard made from recycled wood-waste chips sprayed with PMDI/PF resin, Build. Environ. 42 (2007) 2472–2479.
[17] T.H. Yang, C.J. Lin, S.Y. Wang, M.J. Tsai, Characteristics of particleboard made from recycled wood-waste chips impregnated with phenol formaldehyde resin, Build. Environ. 42 (2007) 189–195.
[18] A. Ashori, T. Tabarsa, K. Azizi, R. Mirzabeygi, Wood–wool cement board using mixture of eucalypt and poplar, Ind. Crop. Prod. 34 (2011) 1146–1149.
[19] M.Z. Fan, M.K. Ndikontar, X.M. Zhou, J.N. Ngamveng, Cement-bonded composites made from tropical woods: compatibility of wood and cement, Cem. Concr. Compos. 36 (2012) 135–140.
[20] K. Riding, D.A. Silva, K. Scrivener, Early age strength enhancement of blended cement systems by $CaCl_2$ and diethanol-isopropanolamine, Cem. Concr. Res. 40 (2010) 935–946.
[21] N. Makaratat, C. Jaturapitakkul, C. Namarak, V. Sata, Effects of binder and $CaCl_2$ contents on the strength of calcium carbide residue-fly ash concrete, Cem. Concr. Compos. 33 (2011) 436–443.
[22] P. Torkittikul, A. Chaipanich, Optimization of calcium chloride content on bioactivity and mechanical properties of white Portland cement, Mater. Sci. Eng., C 32 (2011) 282–289.
[23] ISO, Cement-Bonded Particleboards – Boards of Portland or Equivalent Cement Reinforced With Fibrous Wood Particles, International Standard ISO 8335:1987(E), 1987.
[24] ASTM, Standard Test Methods for Sampling and Testing Non-Asbestos Fiber-Cement Flat Sheet, Roofing and Siding Shingles, and Clapboards, ASTM Standard C1185–08, 2008, http://dx.doi.org/10.1520/C1185-08R12.
[25] ASTM, Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials, ASTM Standard D1037–06a, 2012, http://dx.doi.org/10.1520/D1037-12.
[26] ASTM, Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings, ASTM Standard E336–10, 2011, http://dx.doi.org/10.1520/E0336-11.
[27] ASTM, Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine, ASTM Standard E492-90, 2009, http://dx.doi.org/10.1520/E0492-90R96E01.
[28] ASTM, Standard Test Method for Thermal Conductivity of Insulating Firebrick, ASTM Standard C182-88 (Reapproved 2013), 1988, http://dx.doi.org/10.1520/C0182-88R13.
[29] V.K. Peterson, M.C.G. Juenger, Time-resolved quasielastic neutron scattering study of the hydration of tricalcium silicate: effects of $CaCl_2$ and sucrose, Physica B 385–386 (2006) 222–224.
[30] J. Nasvik, Using calcium chloride for industrial floor construction, Concr. Constr. World Concr. 52 (2007) 55–58.
[31] X. Fu, C. Yang, Z. Liu, W. Tao, W. Hou, X. Wu, Studies on effects of activators on properties and mechanism of hydration of sulphoaluminate cement, Cem. Concr. Res. 33 (2003) 317–324.
[32] H.F. Xing, X.M. Yang, C. Xu, G.B. Ye, Strength characteristics and mechanisms of salt-rich soil–cement, Eng. Geol. 103 (2009) 33–38.
[33] N.C. Collier, X. Li, Y. Bai, N.B. Milestone, The effect of sulfate activation on the early age hydration of BFS: PC composite cement, J. Nucl. Mater. 464 (2015) 128–134.
[34] V. Babrauskas, Ignition of wood: A review of the state of the art, in: Interflam, Interscience Communications Ltd., London, 2001, pp. 71–88.
[35] T. Cafe, TC Forensic, Australia: Fire Cause and Origin, Forensic and Scientific Services, <http://www.tcforensic.com.au/docs/article10.html>, 2011 (last accessed on 10th November 2015).
[36] A. Alhozaimy, M.S. Jaafar, A. Al-Negheimish, A. Abdullah, Y.H. Taufiq-Yap, J. Noorzaei, O.A. Alawad, Properties of high strength concrete using white and dune sands under normal and autoclaved curing, Constr. Build. Mater. 27 (2012) 218–222.
[37] V. Rostami, Y. Shao, A.J. Boyd, Z. He, Microstructure of cement paste subject to early carbonation curing, Cem. Concr. Res. 42 (2012) 186–198.
[38] L. Wang, J.S.H. Kwok, D.C.W. Tsang, C.S. Poon, Mixture design and treatment methods for recycling contaminated sediment, J. Hazard. Mater. 283 (2015) 623–632.
[39] V. Penttala, Effects of microporosity on the compression strength and freezing durability of high-strength concretes, Mag. Concr. Res. 41 (1989) 171–181.
[40] M.J. Moura, P.J. Ferreira, M.M. Figueiredo, Mercury intrusion porosimetry in pulp and paper technology, Powder Technol. 160 (2005) 61–66.

[41] L. Wang, D.C.W. Tsang, C.S. Poon, Green remediation and recycling of contaminated sediment by waste-incorporated stabilization/solidification, Chemosphere 122 (2015) 257–264.
[42] P. Posi, S. Lertnimoolchai, V. Sata, P. Chindaprasirt, Pressed lightweight concrete containing calcined diatomite aggregate, Constr. Build. Mater. 47 (2013) 896–901.
[43] BSI, BS EN 13986, Wood-based Panels for Use in Construction – Characteristics, Evaluation of Conformity and Marking, 2004.
[44] Q. Li, Y.L. Xu, D.J. Wu, Concrete bridge-borne low-frequency noise simulation based on train–track–bridge dynamic interaction, J. Sound Vib. 331 (2012) 2457–2470.
[45] X. Zhang, X.Z. Li, Q.M. Liu, J.F. Wu, Y.D. Li, Theoretical and experimental investigation on bridge-borne noise under moving high-speed train, Sci. China Technol. Sci. 56 (2013) 917–924.
[46] F.G. Branco, L. Godinho, On the use of lightweight mortars for the minimization of impact sound transmission, Constr. Build. Mater. 45 (2013) 184–191.
[47] U. Berardi, G. Iannace, Acoustic characterization of natural fibers for sound absorption applications, Build. Environ. (2015), http://dx.doi.org/10.1016/j.buildenv.2015.05.029. in press.
[48] Alibaba.com China, <http://www.1688.com/> (last accessed 10th November 2015).