A Novel and Eco-friendly Method for Recycling Waste Formwork into Cement-bonded Particleboard

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Abstract

Used timber formwork is one of the major construction wastes and presents significant burden to landfill disposal in Hong Kong. This study developed a novel way of recycling waste formwork and green materials into high-performance cement-bonded particleboards. The results showed that waste wood inhibited cement hydration and hindered strength development. The X-ray diffraction analyses confirmed that crystallization of calcium hydroxide was suppressed by high wood content. Nevertheless, with optimal amounts of Ordinary Portland Cement (OPC) and accelerator, cement-bonded particleboards could successfully comply with the criteria of mechanical strength and dimensional stability required by International Standard. These particleboards also presented favourable properties of thermal insulation and noise reduction, illustrating added value compared to commercial products on the market. On the other hand, replacing OPC by green cement composed of magnesia (MgO) not only fulfilled the standard requirements for cement-bonded particleboards, but showed better fire resistance as indicated by higher wood decomposition temperature in the thermogravimetric analyses. In addition, the use of 2-h CO_2 curing accelerated early-stage carbonation for strength development and sequestered 8.78% CO_2 (by weight) in the cement-bonded particleboards, which helped to mitigate carbon emission and global warming potential. Furthermore, a partial substitution of MgO cement by selected green materials (incinerator sewage sludge ash and mussel shell) demonstrated comparable performance of the particleboards, suggesting a viable option for cost reduction and waste recycling. A preliminary cost analysis indicated that the proposed approach would be commercially viable and competitive for available markets. This study presents an innovative and eco-friendly technology for recycling waste formwork into new construction materials in an economic and sustainable way.

Key words:

Waste formwork, Eco-friendly particleboard, Thermal/sound insulation, CO_2 capture, Green materials.

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Introduction

Significant Need for Recycling of Construction Timber Waste

Along with booming construction industry in Hong Kong, massive amounts of construction and demolition wastes are produced. As at 2013, approximately 3,591 tonnes of construction waste were disposed of daily, representing 25% of total solid waste received at landfills (HK EPD, 2015). Among the construction wastes, most inert wastes are diverted to public fill reception facilities, while non-inert wastes such as used timber formwork have to be discarded at landfills. The current practice of timber waste disposal is a non-sustainable solution that presents significant burdens on landfill depletion and greenhouse gas emissions (Tsang et al., 2007). In 2013, while there was a daily disposal of about 394 tonnes of wood waste at landfills, wood waste recycling was only 16.7 tonnes per day (6,100 tonnes throughout the year) with a recyclable value of $1,000 per tonne (HK EPD, 2015). To encourage construction waste sorting for recycling, it is essential to identify available and economically viable markets for recyclables and perceive the fundamental environmental benefits (Yuan et al., 2013). However, recycled timber formwork is usually contaminated by concrete and painting, which is considered unsuitable as wood flour/pellet for combustion (i.e., energy source) in view of significant air pollution (Helsen and Van den Bulck, 2005). Thus, recycling of construction timber waste presents a grand challenge in terms of technology innovation, environmental sustainability, and economic feasibility.

Innovative Timber Recycling into Cement-bonded Particleboard

Integrating recycled timber into cement-bonded particleboard has illuminated a prospective method in waste recycling (Alawar et al., 2009; Abdullah et al., 2011; Ashori et al., 2012; Fan et al., 2012; Soroushian and Hassan, 2012). The products are composed of cement, wood particles, water, and chemical additives. The use of concrete-contaminated timber formwork requires the least pre-treatment and minimises the secondary pollution as the concrete attached will not impair cement hydration. In view of low thermal conductivity and beneficial sound insulation property of timber, the final products could be utilised as thermal-insulating and sound-insulating materials. However, the soluble organic constituents of timber would retard the setting/hardening processes and reduce the mechanical strength of cement-bonded particleboards (Aggarwal et al, 2008). The adhesives, paints and preservatives in timber formwork would also complex with calcium and hinder the pH increase, resulting in undermined strength development via calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) generation by cement hydration (Weeks et al., 2008; Wang et al., 2015). Although the addition of accelerators ($CaCl_2$, $MgCl_2$, $FeCl_3$, $AlCl_3$ and $Al_2(SO_4)_3$) may enhance the early strength, it results in inadequate strength of the cementitious matrix in the long term (Almeida et al., 2002; Aggarwal et al., 2008; Huang and Shen, 2011; Makaratat et al., 2011), which compromises the application of cement-bonded particleboards. In order to address the above barriers, this study evaluates and optimises the mixture designs and process conditions for advancing the recycling of waste formwork into new marketable products for construction industry.

Ordinary Portland cement (OPC) is the most common binder that upon hydration produces C-S-H gel and monosulphate, filling in pores of the matrix and binding the interfaces for mechanical strength development (Shi et al., 2012). It calls for research and development of alternative cementitious binders to lower energy consumption (calcination of limestone at ~1450 °C) and carbon footprint (CO_2 emission ~0.85 t/t) associated with OPC production (Unluer and Al-Tabbaa, 2013). Magnesia cement (MgO) is a relatively new cementitious substitute for OPC, which is transformed from calcining magnesite ($MgCO_3$) at a markedly lower temperature (below 750 °C) than Portland cement clinker sintering required (up to 1450 °C) (Mo and Panesar, 2012; Al-Tabbaa, 2013; Habert, 2014). Besides, MgO cement demonstrates beneficial properties in utilisation, such as higher durability, lower sensitivity to impurities, stronger fire resistance, and aesthetically pleasant appearance (white in colour). However, high water absorption and relatively low availability of the raw materials (90% located in China) are the major limitations (Li and Chen, 2013; Unluer and Al-Tabbaa, 2013). Thus, this study assesses the use of MgO cement as a promising alternative material for OPC and introduces various types of water repellent materials to address the above problems.

Green and Environmentally Friendly Particleboard Production

In addition, MgO cement could produce a significant proportion of brucite ($Mg(OH)_2$) that may enable remarkable CO_2 sequestration during the particleboard production process. Accelerated carbonation using compressed carbon dioxide gas (i.e., CO_2 curing) could facilitate setting/hardening rate and reinforce the matrix strength via carbon dioxide dissolution, penetration, and early-stage formation of calcium and magnesium carbonates, such as calcite, aragonite, magnesium calcite, and magnesium carbonates (Borges et al., 2010; Al-Tabbaa, 2013; Zhan et al., 2013). The conversion of brucite into magnesium carbonates and/or hydrated magnesium carbonates in a short period of CO_2 curing contributes to changes in the microstructure. During accelerated carbonation, the pore size and total volume are reduced while the density and mechanical strength are enhanced accordingly (Al-Tabbaa, 2013; Zhan et al., 2013). Furthermore, in view of abundant amount of brucite available in MgO cement, the addition of incinerator sewage sludge ash (ISSA) and ground granulated blast slag (GGBS) may initiate pozzolanic reaction to further improve the strength and reduce water absorption (Donatello et al., 2010; Jin and Al-Tabbaa, 2014). The addition of selected food waste such as blue mussel shell (MS) containing nearly 95% $CaCO_3$ may provide excess nucleation sites to accelerate carbonate formation and strength establishment (Meldrum and Hyde, 2001; Unluer and Al-Tabbaa, 2013). Hence, this study further explores the viability of a simple approach to enhance mechanical properties and economic feasibility by blending the three different types of green materials as cement supplement.

Therefore, this study aims to: (i) determine the optimal binder formulation and process conditions to produce cement-bonded particleboard with high mechanical strength and dimensional stability; (ii) examine the properties of thermal insulation and noise reduction as a building material; (iii) compare the performance of OPC and MgO cement for recycling waste formwork; (iv) assess the potential use of CO_2 curing for strength enhancement; and (v) validate cost and augment the applicability of wood waste recycling through integration of green materials into the mixture. The acceptability for reuse is justified in terms of mechanical strength, dimensional stability, thermal conductivity and sound absorption capacity, while the microstructure and mineralogy of cement-bonded particleboards are characterised by spectroscopic and thermogravimetric analyses.

Materials and Methodology

Recycling Construction Timber Waste

Construction timber waste were recycled and used as aggregates in this study. Waste formwork was collected from Eco-park in Tuen Mun, Hong Kong, and then granulated and sieved to between 2.36 and 5 mm for further use (waste formwork surface adhered with mortar) (Fig. 1a&b). Two primary binders investigated in this study were ASTM Type I Ordinary Portland Cement (64.7% CaO, 21% SiO_2, 5.9% Al_2O_3) and magnesium oxide cement (90% MgO, 1.5% CaO, 4.5% SiO_2), with a specific mass of 3.16 g cm^{-3} and 3.58 g cm^{-3}, respectively. Incinerator sewage sludge ash (ISSA) were collected from Sludge Treatment Facilities in Tuen Mun, ground granulated blast slag (GGBS) from iron/steel-making industry in China, and Blue Mussel shell (MS) from kitchen waste of Hotel ICON in Hong Kong, respectively. These selected waste materials were oven-dried, ground to powder size, and examined as supplementary green binders in addition to MgO cement.

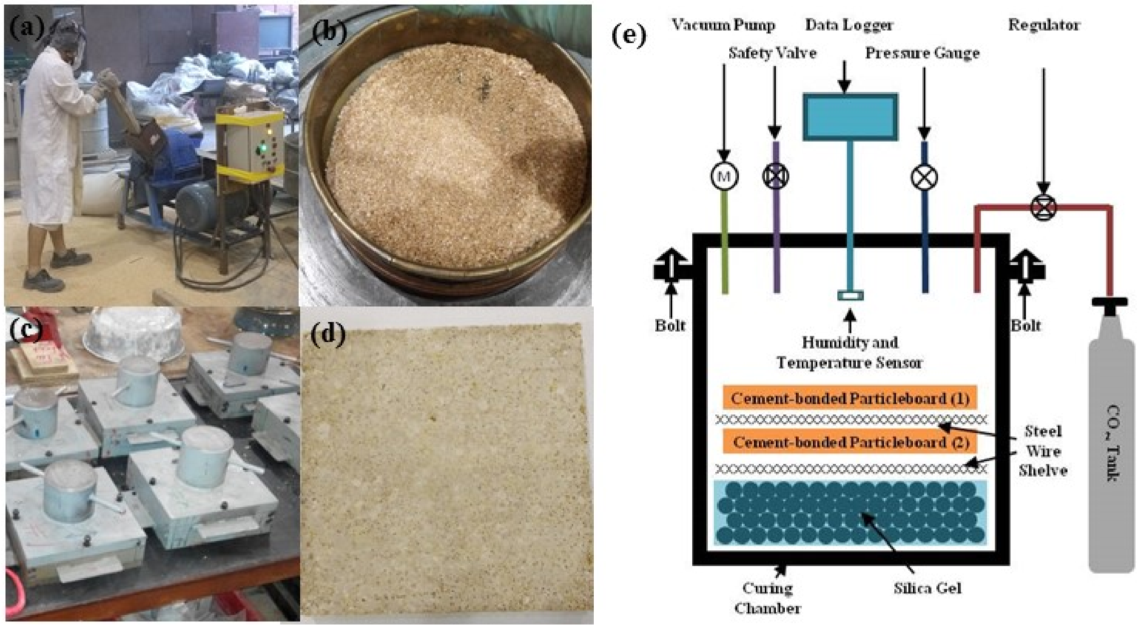

Figure 1. Experimental preparation and setup: (a) wood grinding; (b) wood sieving; (c) moulding/demoulding; (d) MgO cement-bonded particleboard; (e) CO_2 curing chamber.

Particleboard Production

Aggregates and binders were first mixed with a mechanical mixer homogeneously for 3 min, then transferred into steel moulds (160 × 160 × 15 mm), compressed with 4 MPa for 1 min. Each pair of mould and cap was fixed by four bolts. The prepared board were demoulded after 24 h and transferred to a curing chamber at 20°C and 95% humidity for 7- or 28-day curing before further analysis (Fig. 1c&d). To determine the optimal aggregate-to-cement ratio (A/C) of the particleboards, five A/C ratios (3:7, 4:6, 5:5, 6:4, and 7:3, by weight) were tested as shown in Table 1. Under a pressure of 4 MPa, the maximum mass loaded into the mould without overflow (160 × 160 × 15 mm) was recorded, and the porosity was regarded as 0. In the preliminary tests, porosity was kept at 15% (85% of maximum mass), and water-to-cement ratio (W/C) was 0.45, of which the results revealed inadequate mechanical strength for possible reuse. In order to meet the standard (ISO 8335, 1987), the parameters were revised to A/C at 3:7, 5% porosity and 0.3 W/C in the subsequent experiments.

Table 1. Mixture formulations for OPC and MgO cement-bonded particleboards

Mixture	OPC (%)	MgO (%)	Wood (%)	CaCl (%)
(1)OPC-Control	70.0	0	30	0
(2) OPC-7	66.5	0	30	3.5
(3) OPC-6	57.0	0	40	3.0
(4) OPC-5	47.5	0	50	2.5
(5) OPC-4	38.0	0	60	2.0
(6) OPC-3	28.5	0	70	1.5
(7) MgO-7	0	70	30	0
(8) MgO-6	0	60	40	0
(9) MgO-5	0	50	50	0
(10) MgO-4	0	40	60	0
(11) MgO-3	0	30	70	0

Remarks: % by weight

The potential use of CO_2 curing was investigated afterwards for promoting early-stage strength development and carbon sequestration. The demoulded particleboards were pre-dried at drying chamber (20 °C, 50% humidity) for different durations to obtain varying moisture contents before CO_2 curing. An accelerated carbonation was conducted at room temperature, where the samples were placed into a vacuum chamber at -0.5 bar with CO_2 purging under 0.1 bar pressure for 2 h (Fig. 1e). Anhydrous silica gel was used in the chamber to absorb evaporated water, and the kinetic change of the temperature and relative humidity inside were recorded during the carbonation process. The 2-h carbonated samples were divided into two identical portions for immediate assessment and additional 7-day air curing, respectively. The pH indicator test with 1% phenolphthalein was performed on the freshly split surface of the particleboards for the verification of carbonation front. Moreover, in order to reduce the economic costs and carbon emissions associated with MgO cement production, selected green materials (ISSA, GGBS, and MS) were incorporated to replace MgO cement at 10% and 20% dosage (Table 2). This would also help to boost up industrial by-product/waste recycling.

Table 2. Mixture formulations for MgO cement-bonded particleboards with green materials

Mixture	MgO (%)	ISSA (%)	GGBS (%)	MS (%)	Wood (%)
(1) 100% MgO	70	0	0	0	30
(2) 10% ISSA	63	7	0	0	30
(3) 20% ISSA	56	14	0	0	30
(4) 10% GGBS	63	0	7	0	30
(5) 20% GGBS	56	0	14	0	30
(6) 10% MS	63	0	0	7	30
(7) 20% MS	56	0	0	14	30

Remarks: % by weight

Mechanical Properties and Mineralogy Analyses

To validate the applicability of the particleboards, flexural strength (ASTM C1185) and tensile strength test (ASTM D1037) were performed by using a standard testing machine (Testometric CXM 500-50 KN) at a loading rate of 0.3 mm min^{-1}. Water absorption and thickness swelling (ASTM D1037) test were also conducted to examine the dimensional stability. In addition, its potential use for sound insulation was investigated in terms of sound reduction index by using an international standard (ASTM E336). Thermal conductivity was detected by Quick Thermal Conductivity Meter (QTM-500). Impact noise reduction was measured by using the tapping machine (ASTM E492). On the other hand, the crystalline-phase mineralogy of the crushed particleboards with different curing conditions was examined by a high resolution powdered X-ray diffractometer (XRD, Rigaku SmartLab). The scanning degrees ranged from 0° to 70° 2θ with 5° min^{-1} at 45 kV and 200 mA. The crystallization enthalpy from 100 to 1100 °C was assessed by performing thermogravimetric analysis (Netzch TGA/DSC) at 10 °C min^{-1} with dry argon stripping gas.

Results and Discussion

Recycling Waste Formwork into Cement-bonded Particleboards

As shown in Fig. 2a, the control OPC particleboards (i.e., without accelerator) showed a large discrepancy between the 7-day and 28-day flexural strength, which indicated that the nature of the wood imposed adverse effect on cement hydration. It is believed that the water-soluble extractives of wood (hemicelluloses, starch, sugar, tannins, phenols, and lignins) impede the normal setting and strength development during cement hydration. Compared to the control, the addition of $CaCl_2$ enabled higher early strength and lower long-term strength of the samples. This indicated that a proper amount of $CaCl_2$ was necessary for strength development of cement-bonded particleboards.

With an increasing wood content, the flexural strength gradually decreased (Fig. 2a) possibly due to insufficient formation of C-S-H gel. The slow cement hydration was reflected by a considerable difference (40%) between 7-day and 28-day flexural strength at an A/C ratio of 7:3. Fig. 2b reveals that the water absorption increased along with the increase of wood content, due to the high water absorption capacity of wood. Thus, this suggested that the wood volume should be confined to equal to or less than 50% (by weight) to fulfil the thickness swelling requirement (< 2%) of the particleboards (ISO 8335). However, the particleboards in Fig. 2a failed to meet the flexural strength standard of 9 MPa (ISO 8335). Hence, the density, water-to-cement (W/C) ratio, and dosage of accelerator ($CaCl_2$) were further adjusted to 1.49 g cm^{-3}, 0.3, and 2%, respectively, in the subsequent experiments. As a result, the flexural strength of the 28-day samples at an A/C ratio of 3:7 successfully attained 12.86 MPa. The products can thereby be adopted as lightweight cement-bonded particleboard, which has a density less than 1.84 g cm^{-3} and flexural strength greater than 9 MPa (ISO 8335).

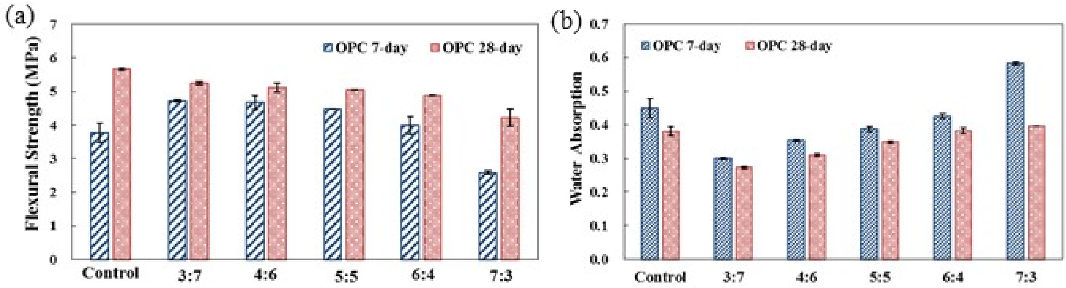

Figure 2. Flexural strength and water absorption of cement-bonded particleboards at varying A/C ratio with/without addition of $CaCl_2$: (a) flexural strength; (b) water absorption (A/C ratio of 3:7, 4:6, 5:5, 6:4, 7:3).

Thermal Insulation and Noise Reduction

The advantages of innovative cement-bonded particleboards produced at an A/C ratio of 3:7 were then quantified in terms of thermal insulation and noise reduction. Table 3 presents the thermal conductivity of different types of boards. The value of cement-bonded particleboard was only 26% of the ordinary concrete board at the same A/C ratio of 3:7 (with sand replacing timber as the aggregate). Besides, the density of cement-bonded particleboard was only 60% of the concrete board, representing lightweight building structure. As the thermal conductivity of waste formwork was distinctively low, the cement-bonded particleboards could outperform the ordinary ones as thermal-insulating materials while fulfilling the strength requirements.

Table 3. Thermal conductivity density of different boards

	Concrete board	Waste formwork	OPC particleboard
Thermal conductivity	1.74 W/m.K	0.06 W/m.K	0.46 W/m.K
Density	2.48 g cm^{-3}	0.58 g cm^{-3}	1.49 g cm^{-3}

Remarks: concrete board produced at a sand-to-cement ratio of 3:7 by weight.

In addition, Fig. 3 showed the impact noise reduction of three types of boards at low-to-medium noise frequency (i.e., 32 to 3150 Hz). The effectiveness of noise insulation of OPC particleboard was better than concrete board at nearly all noise frequency, although it was not as good as waste formwork at a high noise frequency. This result verified that the lightweight and resilient features of wood particleboard were effective for dissipating vibrational energy, as suggested by a recent study (Branco and Godinho, 2013). Interestingly, the OPC particleboard showed outstanding impact noise reduction at a low sound frequency (32-100 Hz). As this is major frequency range of structure-borne sound, cement-bonded particleboard of this study manifested an excellent acoustical insulation performance.

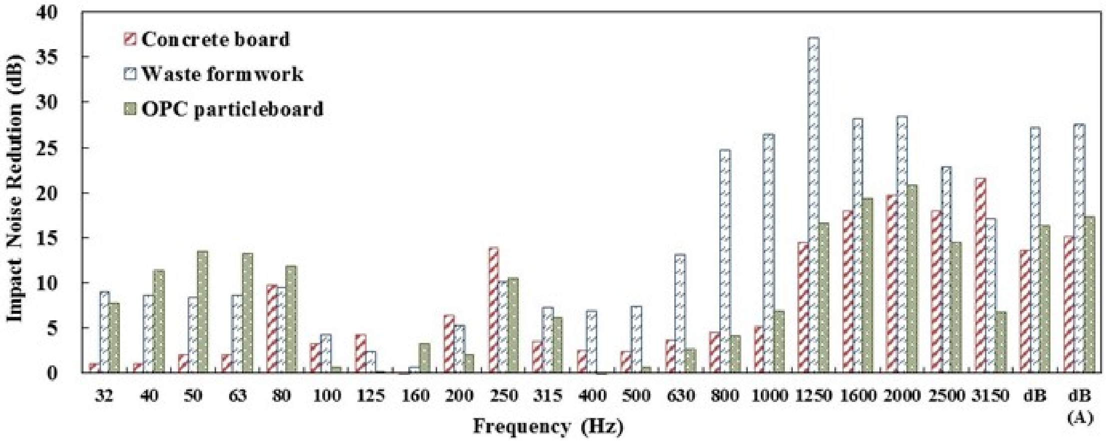

Figure 3. Impact sound pressure level reduction of different materials.

MgO Cement as a Green Substitute of OPC

As shown in Fig. 4a, the flexural strength of MgO cement-bonded particleboards was slightly weaker than that of OPC particleboards produced at the same A/C and W/C ratios. As MgO particleboards without accelerator showed only a slight difference of flexural strength between 7-day and 28-day conditions (A/C ratio of 3:7), the high early strength indicated a low sensitivity of MgO cement hydration to the wood aggregate. To obtain better cement hydration and stronger mechanical strength development, the particleboard density and W/C ratio were optimised to 1.38 g cm^{-3} and 0.3, respectively, in the subsequent experiments. Consequently, the flexural strength of the 28-day samples at an A/C ratio of 3:7 effectively reached 9.83 MPa. The products can thereby be adopted as lightweight cement-bonded particleboards according to International Standard ISO 8335.

However, the water absorption test (Fig. 4b) illustrated that MgO cement was prone to swelling and cracking, which was also revealed in a recent study (Li and Chen, 2013). Therefore, selected water repellents (i.e., calcium stearate and silane) were added to mitigate unfavourable water swelling. The silane showed better water resistant promotion in both OPC and MgO cement-bonded particleboards (Fig. 5). The water absorption rate of MgO cement-bonded particleboards was markedly reduced by 87%, and consequently the thickness swelling was negligible with the addition of 1% silane (by weight of cement). The improvement was attributed to the interfacial reactions with hydrated cement particles. Silane added into freshly made concrete during fabrication could disperse homogeneously and form hydrophobic lining on the pore walls (Dai et al., 2010), thereby reducing water capillarity and dissolution of detrimental substances (such as chlorides and organic acids) (Zhu et al., 2013). On the other hand, calcium stearate could generate hydrophobic layers on all possible surfaces to isolate unhydrated and partially hydrated cement grains from moisture absorption, but mechanical strength and rupture modulus might be compromised (Suryavanshi and Swamy, 2002). As a result, silane additive was the most suitable water repellent for particleboard production.

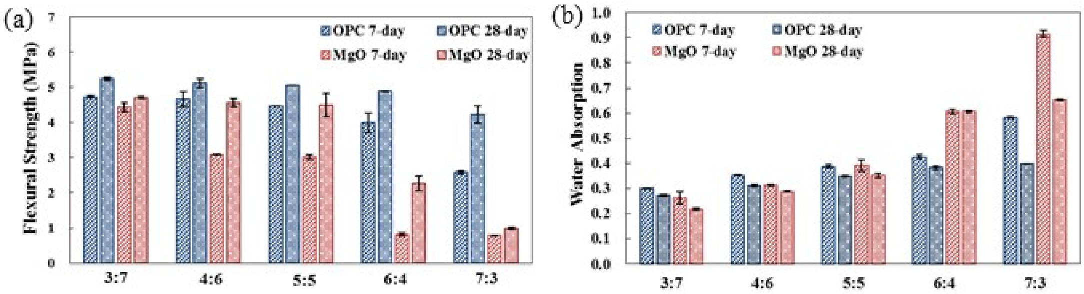

Figure 4. Flexural strength and water absorption of OPC and MgO cement-bonded particleboards at varying wood-to-cement ratio: (a) flexural strength; (b) water absorption.

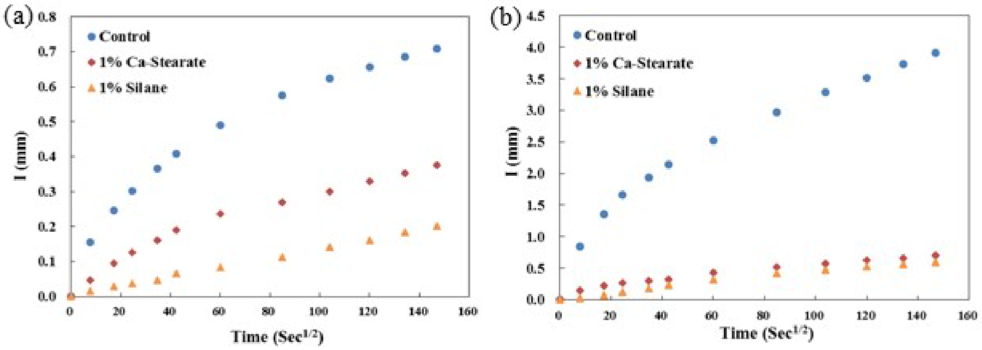

Figure 5. Water absorption rate of OPC and MgO cement-bonded particleboards mixied with varying 1% water repellents (by cement weight): (a) OPC; (b) MgO.

Mineralogical Analysis of OPC and MgO Cement-bonded Particleboards

The XRD spectra of OPC particleboards (Fig. 6a) reveal sharp peaks of CH at 18.2° and 34.2°, except for the samples at an A/C ratio of 7:3. Stronger CH signals were identified in the samples containing less wood content, which indicated a greater extent of cement hydration. This observation was consistent with the high flexural strength shown in Fig. 2a. Hence, XRD analysis provided spectroscopic evidence that a large volume of wood significantly hampered the CH formation in cement-bonded particleboards. The C-S-H formation was probably hindered but C-S-H was primarily non-crystalline and thus undetectable by XRD analysis. On the other hand, ettringite was identified at a high A/C ratio of 7:3, of which the acicular and relatively porous structures might be accountable for the strength deficiency of cement-bonded particleboards (Lee et al., 2005).

As shown in Fig. 6b, large primary peaks of brucite ($Mg(OH)_2$) were identified at 38.0° in the MgO cement-bonded particleboards at the A/C ratios of 3:7 and 5:5. The transformation of MgO (magnesia) into $Mg(OH)_2$ crystal (brucite) increased the solid volume in the matrix by densifying the microstructure. Crystalline-phase $Mg(OH)_2$ proved to make major contribution to strength development (Choi et al., 2014), however, its formation was interfered by the water-soluble extractives of wood at the high A/C ratio. These spectroscopic findings were in line with the flexural strengths shown in Fig. 4a. A large amount of unreacted MgO in the XRD spectra (main peak at 42.9 °) indicated a prolonged cement hydration and weaker strength development.

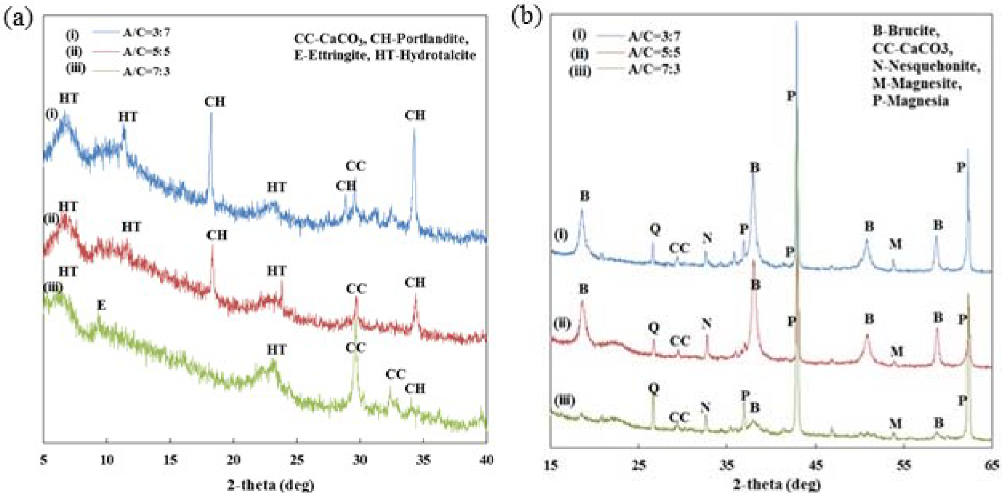

Figure 6. XRD spectra of OPC and MgO cement-bonded particleboards with different A/C ratio: (a) OPC; (b) MgO.

The TGA and DTG curves of OPC particleboards (Fig. 7a) revealed significant weight loss at 270-350 °C, in which the change was more substantial with increasing wood volume as a result of wood decomposition. It was noted that the temperature range was slightly higher than the general wood ignition point (190-260 °C) reported in the literature (Babrauskas, 2001). This was probably due to the C-S-H gel on wood particles, inferring certain extent of fire resistant property of OPC particleboards. Subsequent weight loss at 420-500 °C was ascribed to CH dehydration, which ascertained the XRD results (Fig. 6a). At a higher temperature between 700 and 800 °C, further weight loss was attributed to the decomposition of CC ($CaCO_3$). A distinct shoulder peak at nearly 800 °C was identified in the particleboards prepared at an A/C ratio of 3:7. This indicated the presence of well-crystalline calcite (Alhozaimy et al., 2012; Rostami et al., 2012; Lago and Prado, 2013), which could facilitate high strength performance of the cement-bonded particleboards.

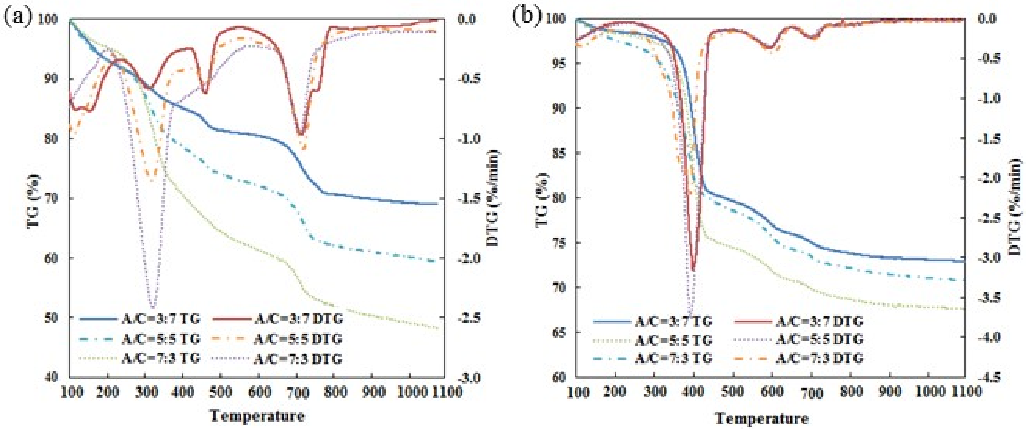

Figure 7. TGA and DTG spectra of OPC and MgO cement-bonded particleboards with different wood-to-cement ratios: (a) OPC; (b) MgO.

As for the MgO cement-bonded particleboards, the major endothermic peaks fell between 350-450 °C in the TGA and DTG curves (Fig. 7b). The decomposition temperature was notably higher than that of OPC particleboards, illustrating more desirable fire resistance capacity of MgO cement. In addition to wood decomposition, the sharp peaks were largely due to the removal of crystallisation water from hydrated magnesium carbonates as well as $Mg(OH)_2$ decomposition into MgO. The succeeding peaks at approximately 550 °C and 750 °C represented the loss of magnesite ($MgCO_3$) and well-crystallised $MgCO_3$ decarbonation, respectively (Mo and Panesar, 2012). These results corroborated with the XRD spectra (Fig. 6b), which showed subtle amount of $MgCO_3$ regardless of the wood content while most MgO cement remained unreacted. The large amount of MgO left behind could transform into additional $Mg(OH)_2$ under suitable moisture conditions. Although $Mg(OH)_2$ itself is poor in strength, it can react with CO_2 and proper amount of water at the appropriate curing conditions to form $MgCO_3$, which can result in higher mechanical strength (Unluer and Al-Tabbaa, 2013). Moreover, excess $Mg(OH)_2$ can foster pozzolanic reaction with selected green materials. Thus, accelerated carbonation by CO_2 curing and addition of green material were investigated in the subsequent experiments to facilitate strength development of MgO cement-bonded particleboards as well as reduce manufacturing costs and carbon emission.

Accelerated Carbonation and Carbon Sequestration by CO_2 Curing

The potential use of CO_2 curing was then investigated to accelerate carbonation and enhance early-stage strength development of MgO particleboards, as conceptually illustrated by Fig. 8a&b. The CO_2 curing process was a few thousand times faster than natural carbonation (Chun et al., 2007; Zhan et al., 2014). The role of moisture content was an essential reactant and crucial factor for effective CO_2 curing. At a low-moisture atmosphere, the carbonation reactions are retarded by limited amount of water, whereas a high-moisture environment may decrease CO_2 diffusion (Fig. 8c&d). Airborne CO_2 diffusion coefficient is up to 1390×10^{-8} m^2 s^{-1}, while the waterborne diffusion coefficient is smaller than the former by 10^4–10^5 times (Unluer and Al-Tabbaa, 2014).

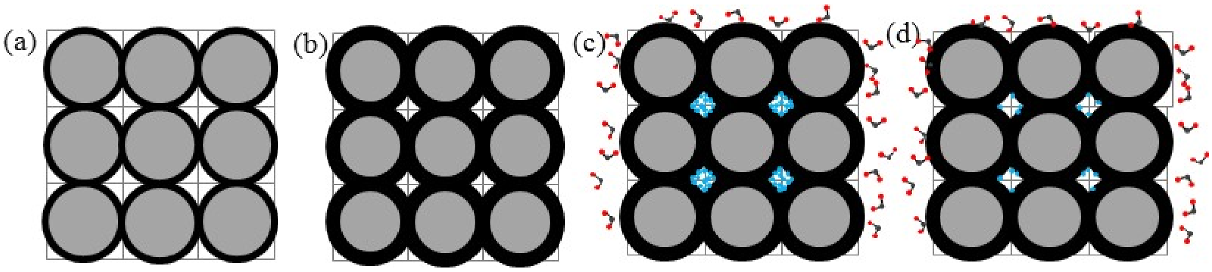

Figure 8. Conceptual illustration of microstructure in cement-bonded particleboards: (a) natural carbonation; (b) accelerated carbonation; (c) accelerated carbonation with high moisture content; (d) accelerated carbonation with low moisture content.

Rapid increases of temperature (23 to 32 °C) and relative humidity (48% to 90%) were detected inside the CO_2 curing chamber in the beginning 30 min, and initial conditions were resumed afterwards. As carbonation was an exothermic reaction, water evaporation and CO_2 absorption were positively correlated (Table 4). The water evaporation and CO_2 absorption were at most 4.71% and 8.78% (by weight), respectively. The MgO cement-bonded particleboards achieved higher flexural strength and absorbed less water (Fig. 9), when a larger amount of CO_2 was sequestered and stored in the particleboards (Table 4). The moisture content between 22.8% and 26.2% was considered suitable for CO_2 curing of MgO cement-bonded particleboards, in which 7.30-8.78% by weight of CO_2 could be captured from carbon emissions.

Table 4. CO_2 absorption and water loss of MgO particleboards with different moisture content

Moisture content (%)	**26.2**	**24.1**	**22.8**	**21.1**	**19.1**
CO_2 absorption (%)	7.30	8.78	7.47	6.95	6.17
Water loss (%)	4.47	4.71	4.05	3.70	3.20

Compared to 1-day air curing, MgO cement-bonded particleboards with 24.1% moisture content showed a significant increase in strength up to 4 times after 2-h CO_2 curing, although it was still below the required standard (ISO 8335). A 7-day air curing was subsequently conducted in addition to CO_2 curing for fostering long-term strength development after accelerated carbonation. Fig. 9a presented that the particleboards achieved a flexural strength as high as 11.8 MPa after 2-h CO_2 and 7-day curing, which successfully met the strength requirement (9 MPa) and far exceeded that of particleboards subject to 28-day air curing only. These results reinforced recent research that CO_2 curing could effectively enhance strength development by pore filling and porosity reduction (Harrison et al., 2013; Kashef-Haghighi and Ghoshal, 2013; Mo and Panesar, 2013; Wang et al., 2015).

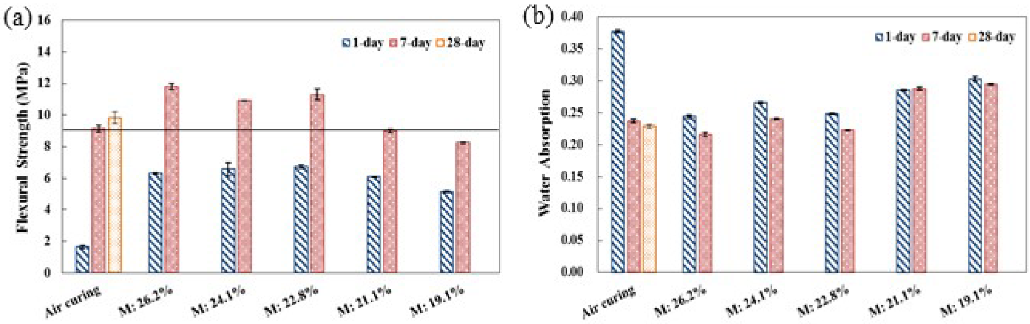

Figure 9. Flexural strength and water absorption of MgO cement-bonded particleboards after 2 h CO_2 curing and 7 day additional air curing: (a) flexural strength; (b) water absorption.

In addition, CO_2 curing contributes to conversion of brucite into magnesium carbonates and hydrated magnesium carbonates (including nesquehonite, hydromagnesite and dypingite). As illustrated in Fig. 10, the mineralogical changes in the microstructure depend on composition of MgO, moisture content, particle size distribution, matrix porosity, as well as CO_2 curing conditions (Harrison, 2003; Chun, et al., 2007; Chaka and Felmy, 2014). Hence, MgO cement-bonded particleboards subject to different curing approaches were further investigated by means of XRD analysis and pH indicator test.

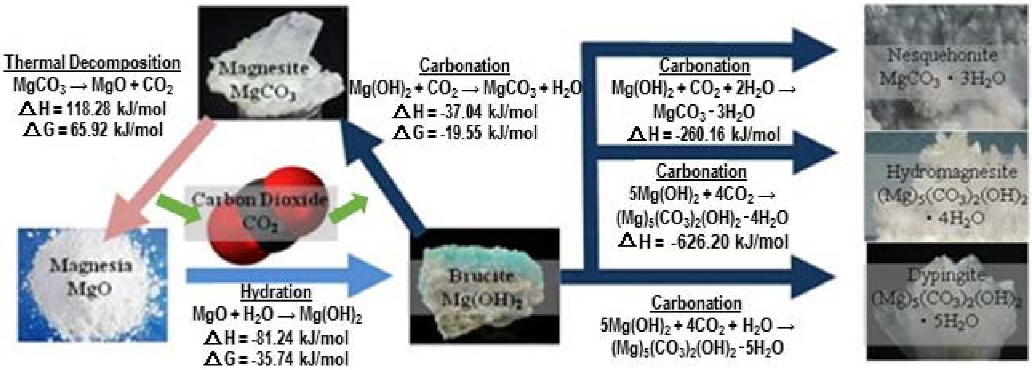

Figure 10. Thermodynamic reactions of the family of magnesium oxide.

The XRD spectra of 1-day air curing samples (Fig. 11a) show the main peak of brucite at 38.0°, which could provide basic but relatively weak strength. Followed by 2-h CO_2 curing, a decrease of brucite was noted while the peak of nesquehonite ($MgCO_3.3H_2O$) at 32.6° significantly intensified. The concomitant change at the early stage implied that the reaction of brucite with dissolved CO_2 formed nesquehonite in the porous structure. The mineralogy analysis provided additional lines of scientific evidence for the above findings that flexural strength was significantly improved by CO_2 curing (Fig. 9a). After an additional 7-day air curing, nesquehonite was continually converted into magnesite ($MgCO_3$) that was a more stable state with a higher strength. The high brucite content and low magnesite content of the 28-day air curing samples (Fig. 11a) may partially explicate their lower flexural strength when compared to the ones with 2-h CO_2 curing followed by 7-day air curing.

The dark pink colour throughout the surface after a pH indicator test (Fig. 11b) indicated a large amount of uncarbonated $Mg(OH)_2$ in the 1-day air curing MgO cement-bonded particleboard. Light pink was found in the centre of the surface after the 2-h CO_2 curing. The marked colour change implied that most $Mg(OH)_2$ had been converted to magnesium carbonates (nesquehonite) or hydrated magnesium carbonates, which resulted in a pH < 8.2 (Al-Tabbaa, 2013). In the following 7-day air curing, the colour changed slightly and reflected a small increase of carbonation. However, the colour was much lighter than that of 28-day curing, affirming that CO_2 curing could effectively accelerate carbonation in a short period of time. These results verify that accelerated carbonation is a feasible alternative to enhance mechanical strength of recycled products. This application also presents an appealing and novel approach to capture CO_2-flue gases from fossil fuel combustion power plants, which helps to negate the carbon footprint and greenhouse gas emission.

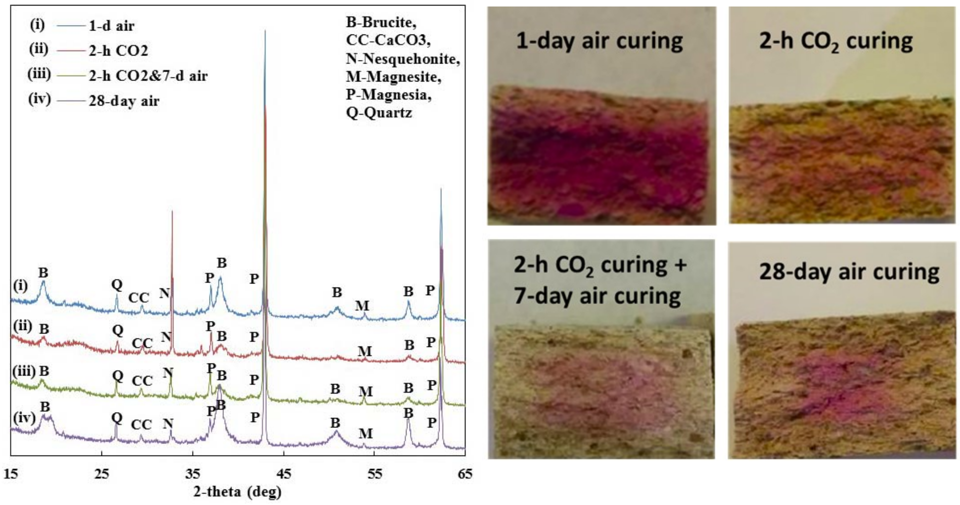

Figure 11. XRD spectra and phenolphthalein test of MgO cement-bonded particleboards subject to different curing approaches: (a) XRD spectra; (b) phenolphthalein test (pH indicator).

Beneficial Addition of Selected Green Materials

In this study, three selected green materials of different natures were incorporated to partially replace MgO cement. This novel adoption provides an opportunity to recycle industrial by-products as well as a viable option to reduce carbon footprint and production cost. The flexural strength in Fig. 12a shows an evident uplift with 10% ISSA substitution, and the XRD spectra (Fig. 12c) reveal a reduction of brucite (and probably magnesium silicate hydrates gel though undetectable by XRD) compared to the control samples (100% MgO cement). However, an addition of 20% ISSA resulted in a significant decrease in strength and an increase of water absorption. A large peak of gupeite identified in the XRD spectra might be the reason of the unexpected strength decrease. The findings implied that ISSA at a proper amount may promote pozzolanic reaction and form M-S-H gel to enhance strength, while it imposed an adverse effect at a higher substitution rate.

The application of 10% and 20% GGBS as substitute of MgO cement exhibited much lower compressive strength than the control samples. This might be because relatively large amount of CaO in GGBS could compete with MgO and form soluble metastable $CaCO_3$ (Stark and Ludwig, 1997), thus reducing the hydration rate of MgO cement. As a result, there was limited formation of $Mg(OH)_2$, which was confirmed by smaller brucite peaks in Fig. 12c. On the other hand, the lower solubility of $Mg(OH)_2$ than $Ca(OH)_2$ could hinder Mg^{2+} diffusion and consequently lead to slower carbonation (Panesar and Mo, 2013). Although the GGBS incorporation demonstrated an inferior performance in air curing condition, its high content of CaO may enhance capillary porosity and provide large capillary pores (>100 nm) for facile CO_2 diffusion and complete carbonation. Thus, CO_2 curing of mixture of GGBS and MgO cement suggests a direction for further technology development.

The replacement of MgO cement by MS at 10 and 20% in the particleboards satisfied the strength requirement (9 MPa) after 28-day air curing, which was comparable with 100% MgO cement. The XRD spectra of 20% MS substitution showed a major CC peak at 29.4^{o}, corresponding to the indigenous $CaCO_3$ of MS. Meanwhile, discernible peaks of magnesium calcite were identified at 39.4^{o}, 47.1^{o} and 47.5^{o}, respectively. Along with the XRD evidence, the interestingly good strength performance of MS samples could be attributed to accelerated formation of carbonates (magnesium calcite) (Meldrum and Hyde, 2001; Unluer and Al-Tabbaa, 2013). This was because MS addition provided more available nucleation sites as seed crystals for heterogeneous precipitation on the microstructure surface. These results suggest that the integration of green materials into MgO cement is competitive in terms of flexural strength and beneficial to waste recycling. In addition, the synergistic use of CO_2 curing and green materials warrants future investigation.

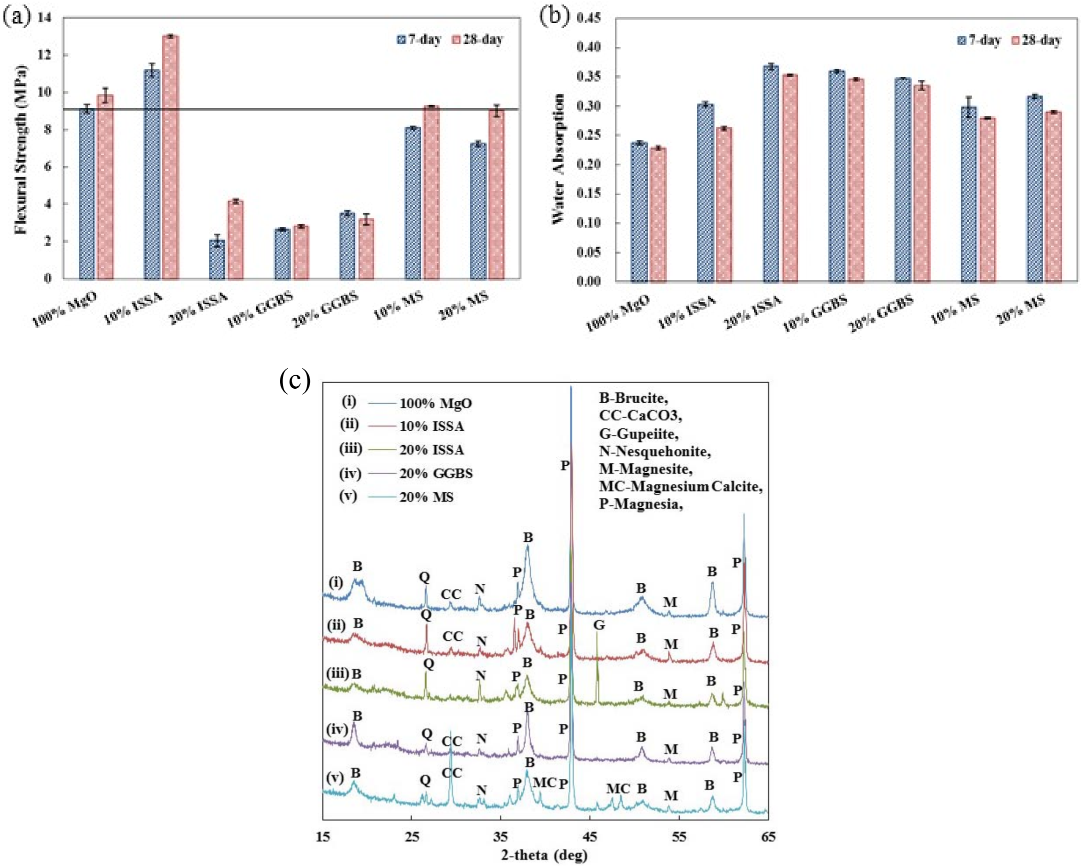

Figure 12. Mechanical performance and mineralogical properties of MgO cement-bonded particleboards with different replacement of green materials: (a) flexural strength; (b) water absorption; (c) XRD spectra.

Economic Viability of the Innovative Approach

A preliminary cost analysis has been conducted in this study to illustrate the commercial feasibility of producing cement-bonded particleboards with waste formwork. For the sake of simplifying variables, the costs for equipment, transportation, energy, labour, etc, are assumed available without extra costs in the industry. However, the environmental, economic and societal benefits provided by reducing landfill disposal, mitigating odour/dust nuisance, and avoiding secondary pollution are also not quantified in this case. Therefore, the primary costs include cement use and manufacturing processes, whereas the waste formwork, ISSA, GGBS, and MS are regarded as solid wastes for disposal otherwise. As quoted from the largest regional supplier (Alibaba, 2015), the prices of OPC, MgO and $CaCl_2 \cdot H_2O$ are approximately USD 52.8, USD 81.3, and USD 130.1 per tonne, respectively. For the OPC particleboards (assuming the density of 1.49 g cm^{-3}, A/C ratio of 3:7, W/C ratio of 0.3, and 2% $CaCl_2$ addition), the material cost is about USD 47.8 m^{-3}. Taking into account the energy consumed for crushing waste formwork and particleboard moulding under 4 MPa pressure for 1 min, the power costs on the bench scale are estimated to be about USD 2.4 m^{-3} (using USD 0.11 per kWh electricity consumption in Hong Kong). The total costs for OPC particleboards are about USD 50.2 m^{-3}.

Similarly, assuming the density of 1.38 g cm^{-3}, A/C ratio of 3:7, W/C ratio of 0.3, and the same manufacturing processes, the total costs for MgO particleboards are about USD 67.3 m^{-3}. With a 20% substitution of MgO cement by ISSA/MS (performance of GGBS is not yet acceptable), the total costs are reduced to USD 52.4 m^{-3}. However, if CO_2 curing is used instead of air curing, it accounts for USD

215.6 m^{-3} (66.1 m^3 of CO_2 sequestered per m^3, i.e., 8.78% by weight, where USD 48.5 for a 40-L CO_2 gas cylinder compressed at 150 bar). This presents an overwhelming cost factor, so it would be imperative to recover the exhaust CO_2 gas from power plants for CO_2 curing, which comes at negligible cost and helps to combat global warming. More importantly, the market prices are about USD 187 m^{-3} for cement-bonded particleboards (Alibaba, 2015), illustrating a high potential value of the recycled products for the building industry. Therefore, the novel and eco-friendly waste formwork recycling process developed in this study is likely to be commercially viable and competitive for available markets.

Conclusions

This study developed an innovative technological approach for recycling construction waste formwork into high-performance, eco-friendly, and low-cost cement-bonded particleboards. Although a high content of wood could impede the strength development, this study optimised the mixture design and treatment methods such that the particleboards could conform to the required criteria of strength and dimensional stability. The particleboards also presented favourable properties of thermal insulation and noise reduction for building use. In addition, MgO cement as a green substitute of OPC not only met the strength standard, but also outperformed OPC in terms of fire resistance. An innovative use of 2-h CO_2 curing accelerated the early-stage carbonation at the interior of the porous matrix for better strength development, while simultaneously enabling CO_2 sequestration and storage during waste formwork recycling. The addition of incinerator sewage sludge ash and mussel shell, which are abundant in Hong Kong, demonstrated comparable or superior mechanical strength compared to the single use of MgO cement. A preliminary cost analysis suggested the commercial viability of this novel recycling technology for available market in the building industry. This study showcased our leading edge in developing innovative technology and creating new ways to provide pragmatic and sustainable solution to waste recycling challenges in the local and regional context.

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