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CO_2 curing and fibre reinforcement for green recycling of contaminated wood into high-performance cement-bonded particleboards

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ABSTRACT

To alleviate disposal burden of contaminated wood at landfills, construction wood waste can be recycled into cement-bonded particleboards, however, their qualities are often compromised by organic extractives and preservative chemicals in wood. In contrast to traditional approaches using phenol formaldehyde resin or chloride accelerator, this study proposed the use of eco-friendly CO_2 curing and fibre reinforcement to accelerate carbonation and enhance physical properties of the particleboards. Cement chemistry and microstructure characteristics were evaluated by using quantitative X-ray diffraction, mercury intrusion porosimetry, and scanning electron microscopy analyses. The 24-h CO_2 curing significantly facilitated cement hydration (i.e., more than 63 wt% amorphous cement hydrate) and accelerated $Ca(OH)_2$ transformation into $CaCO_3$, which contributed to strength development and carbon sequestration (as high as 9.2 wt%) in the particleboards. Consequently, the total pore area was reduced from 12.2 to 10.3 $m^2 g^{-1}$ and porosity from 34.8 to 29.7%. A subsequent 7-d air curing allowed cement rehydration and densified micropore structure, especially for capillary pores. As a result, mechanical strength, dimensional stability, and contaminants sequestration were enhanced to fulfil the requirement of International Standards. The results also illustrated the vital role of moisture content of particleboards in cement hydration and accelerated carbonation, for which the moisture content ranging from 16.7% to 17.9% was considered optimal. The addition of grid basalt fibre (0.5% by wood volume) enhanced the fracture energy of the particleboards by 6.5 times. This study presents a low-carbon and environmentally-friendly technology to upcycle construction wood waste into value-added materials in a sustainable way.

1. Introduction

Wood is a traditional and widely used construction material for formwork, trusses, beams, columns, wall, ceiling and scaffold because of its characteristics of lightweight, hard, and renewable. Yet its vulnerability to weathering, fire, and microbial degradation could significantly limit the lifespan of wood products. Wood is usually treated by preservative chemicals such as chromated copper arsenate (CCA), which impose toxic effects to ecological and human health [1–3]. Due to environmental concern of chemical leaching, large volumes of waste wood end up being disposed of at landfills rather than recycled. For instance, a lack of sound recycling approaches significantly hinder wood recycling in Hong Kong, which is merely 0.04%, although the estimated value for recycled timber is up to 130 USD per tonne [4,5]. Therefore, developing innovative and green approaches for timber waste recycling presents environmental benefits as well as economic incentives.

Incorporating timber waste into cement-bonded particleboards has been proposed as an appealing technology to solidify and stabilize contaminated materials, such as preservative chemicals, oil paints and adhesives. Meanwhile, it produces value-added products that capitalize the merits of both wood and cement, including light-weight, high toughness, long durability, dimensional stability, fire resistance, anti-microbe, good acoustic and thermal insulation properties [6]. In contrast to conventional particleboards made from wood and phenol-formaldehyde resin, cement-bonded particles are free of formaldehyde and thus more environmental-friendly to indoor environment and human health [7,8]. However, naturally present organic extractives and exogenous contaminants in woods, such as sugars and hemicelluloses as well as CCA, result in incompatibility of wood and cement. These inhibitory substances were found to complex with calcium, buffer

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pH increase, and form impermeable coating around non-hydrated cement particles, thereby compromising strength development via calcium silicate hydrate (C—S—H) and calcium hydroxide (CH) formation [9,10]. Inorganic accelerators (e.g., chloride and sulphate salts) were therefore employed to promote cement hydration, but they compromised the long-term strength and durability [11,12].

Accelerated carbonation by CO_2 curing potentially presents an eco-friendly approach to accelerate cement reaction and promote early strength development of cement-bonded particleboards, which could also sequestrate CO_2 in the matrix to combat global warming [13,14]. Previous studies have focused on cement and/or concrete, in which they showed that concentrated CO_2 gas reacted directly with cement (mainly tricalcium silicate) to generate C—S—H gel and $CaCO_3$, while hydrated CH was also converted to $CaCO_3$ by CO_2 diffusion, penetration, dissolution and reaction [15–17]. This process increased setting/hardening rate, densified the micro-structure, and enhanced mechanical strength as well as produced thermodynamically stable carbonate products for long-term stability [18]. The application of CO_2 curing could also improve the immobilization of heavy metals and mitigate the environmental impact [19,20]. However, accelerated carbonation is a diffusion-controlled reaction because continuous carbonation leads to formation of dense carbonated material surrounding interior non-carbonated material and hinders further penetration of CO_2 [21]. Pressurized CO_2 diffusion is probably a feasible approach for fast carbonation and strength development [22], yet water is necessary for the reactions of CO_2 curing while excessive water blocks the pores in the matrix [23]. Therefore, we propose that porous and humid wood particles in the particleboards would be highly beneficial and synergistic for novel application of CO_2 curing. This is because wood particles can provide air pores for facilitating CO_2 diffusion and accommodate sufficient amount of water for carbonation reactions, while CO_2 curing can mitigate interference of organic extractives and immobilize exogenous contaminants in wood waste in the meantime. A specific range of moisture content in CO_2 curing may be best for the particleboards production.

Besides, a simple but effective method for strength enhancement could be achieved by addition of fibre, such as steel, glass, carbon, basalt, polypropylene and polyethylene fibre [24,25]. Basalt fibre is a non-hazardous, inorganic fibre extruded from melted basalt rock, which was shown to demonstrate excellent strength and superior compatibility with cement products [26]. It could significantly enhance tensile strength and failure strain of matrix by fibre de-bonding, fibre sliding and crack bridging, as well as resistance against chemical (alkali) attack. Therefore, fibre incorporation may be deployed to enhance the performance of cement-bonded particleboards.

This study aimed to: (i) investigate the coupled effects of CO_2 curing and accelerator addition for boosting cement reaction in particleboards; (ii) elucidate the mechanisms of CO_2 curing for strength enhancement, contaminant immobilization, and CO_2 sequestration in cement-bonded particleboards via microscopic and spectroscopic analyses; (iii) characterize the roles of porous wood particles and their moisture content for CO_2 diffusion and accelerated carbonation; and (iv) evaluate functions of different basalt fibres in strength reinforcement and fracture energy enhancement.

2. Experimental methods

2.1. Turning waste wood into cement-bonded particleboard

Waste wood formworks were collected from construction sites through the assistance of a local recycling company in Hong Kong Eco Park. The wood samples were contaminated by preservative chemicals and adhered with cement mortar. The total metal concentrations in the wood samples were determined by using an inductively coupled plasma-atomic emission spectrometry (ICP-AES, PerkinElmer Optima 3300DV) after total acid digestion, which were 1460 mg kg^{-1} of Mn, 40.4 mg kg^{-1} of Zn, 39.2 mg kg^{-1} of Cr, 10.4 mg kg^{-1} of As, 4.4 mg kg^{-1} of Cu, and 4.0 mg kg^{-1} of Ni. These formworks were shredded by wood chipper after removal of nails, sieved to 0.3 to 2.36 mm, and recycled as aggregates in cement-bonded particleboards in this study.

The wood particles were moisturized with 55 wt% of tap water to achieve the saturated surface dry condition according to water absorption test. ASTM Type I Ordinary Portland cement (OPC) was used as the binder, which contained 63.2% CaO, 19.6% SiO_2, 7.3% Al_2O_3, 2.3% loss on ignition, with a density of 3.16 g cm^{-3}. Based on our previous findings, cement-bonded particleboard production was optimized with an aggregate-to-cement ratio at 3:7 by weight (i.e., 3:1 by volume), water-to-cement ratio at 0.3, and density of 1.54 g cm^{-3} in this study. The wood particles, OPC binder and water were mixed by a planetary stirrer for 3 min and the homogeneous mixture was transferred into a steel mould ($160 \times 160 \times 15$ mm) and subject to 4.0 MPa uniform compression for 1 min. A cap was fixed by four bolts on the mould and the hardened particleboards were demoulded after 24 h, and then received 7-d or 28-d air curing at 20 °C and 95% humidity in a curing chamber.

2.2. Significance of CO_2 curing and fibre reinforcement

Before CO_2 curing, the demoulded cement-bonded particleboards were pre-dried in a drying chamber (20 °C, 50% humidity) for varying duration (0–4 h) to achieve different moisture contents. These dried samples were subject to 24-h CO_2 curing in an air-tight chamber filled with 99.9% CO_2 at a pressure of 0.1 bar higher than atmospheric pressure at room temperature. To maintain constant humidity, silica gel was placed in the CO_2 chamber and the fluctuation of temperature and relative humidity was recorded during the course of CO_2 curing. The 24-h carbonated particleboards were cut into two equivalents for immediate tests and additional 7-d air curing, respectively. The carbonation front was assessed by spraying 1% phenolphthalein on the cross-section of samples as a pH indicator test. To reinforce the particleboard strength, two types of basalt fibre (namely short fibre and grid fibre) purchased from Guangdong province in China were applied at 0.3%, 0.5%, 2% by wood volume, respectively. Short fibre was evenly mixed with binder and wood during blending, while grid fibre was placed at the middle of two equant mixture before compression. The fresh products were cured in an air curing chamber (20 °C, 95% relative humidity) for 7 or 28 d.

2.3. Effects on physical properties and metal leachability

Mechanical strengths in terms of flexural strength and tensile strength of the particleboards were evaluated to validate their applicability for reuse by a standard testing machine (Testometric CXM 500-50 KN) at a loading rate of 0.3 mm min^{-1} [27]. Corresponding axial longitudinal displacements under stress were recorded by two internal linear variable differential transformers (LVDTs, 0.01 mm sensitivity). The fracture energy (G_F) of particleboards was then calculated from the flexural stress-deflection curve. The dimensional stability of the particleboards was examined in terms of thickness swelling and water absorption [27]. The metal leachability of contaminated wood and cement-bonded particleboard was assessed in terms of the toxicity characteristic leaching procedure (TCLP) [28], of which the metal concentrations were determined by ICP-AES. The TCLP leachability served as the acceptance criteria for on-site reuse [29].