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Environmental and technical feasibility study of upcycling wood waste into cement-bonded particleboard

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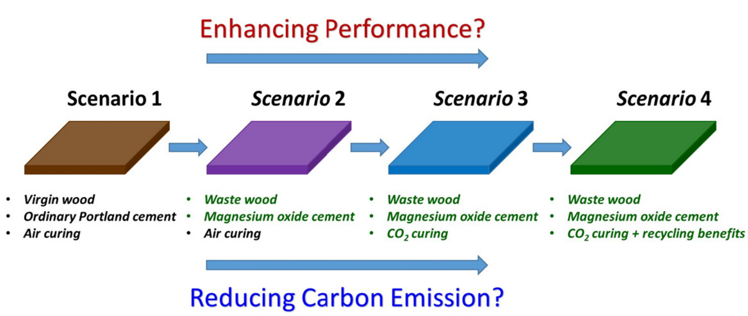
HIGHLIGHTS

- Wood waste can be valorized into secondary construction products.
- The developed products are technically viable and environmentally sustainable.
- Substantial GHGs emission can potentially be saved using the developed technology.
- This solution can minimize wood waste disposal and conserve virgin resources.

GRAPHICAL ABSTRACT



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ABSTRACT

The scarceness of virgin resources and sustainable management of waste materials in high-density city arouse heightened focus on new technology development for waste recycling and local utilization. Wood waste recovery from construction activities and upcycling into secondary products allow the substitution of virgin resources and minimize the environmental burdens within the frontier of industrial ecology. This study assessed the technical viability and environmental sustainability of cement-bonded particleboards (CBPs) produced with recycled wood aggregates and alternative binder; and compared the performance of its counterpart produced with virgin wood and ordinary binder using experimental analysis and life cycle assessment (LCA). The experimental results showed acceptable mechanical performance of the developed CBPs in compliance with the required standards. Adoption of carbon dioxide curing technology further enhanced the durability of the developed CBPs. Although similar greenhouse gases (GHGs) emission was observed for imported conventional CBPs and locally produced CBPs with alternative materials, the considerations of direct carbon sequestration and landfill avoidance contributed to a 9% reduction of the total GHGs compared to conventional CBPs. The LCA results also demonstrated that substantial amount of GHGs can be potentially saved depending on the recycling rates of wood waste in Hong Kong. Hence, technological innovation can effectively address problem of wood waste disposal and enhance material utilization and sustainability of the construction industry.

1. Introduction

Wood waste is generated in massive amount due to worldwide booming industrial activities. In Hong Kong, for example, hundreds of tonnes of wood waste are discarded at landfills daily, including timber formwork from construction industry and wooden pallet from shipping industry [1]. However, landfill disposal is non-sustainable in view of greenhouse gas emissions as well as competition with other land uses. Safety concern lies in possible leaching of contaminants from wood waste to the environment [2]. Such contamination may compromise the feasibility of thermal treatments as recycling options (e.g., incineration, gasification, and

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pyrolysis) because of air pollution and hazardous ash. As wood waste is considered as a recyclable and renewable resource [3], an emerging concept of circular economy emphasizes a closed-loop system for sustainable material use [4,5]. Therefore, it is necessary to devise an innovative and green technology to upcycle wood waste into value-added materials.

Using construction wood waste for synthesis of cement-bonded particleboards (CBPs) is a prospective upcycling option [6]. The CBPs can be versatile light-weight construction materials such as interior panels, noise barriers, partition walls, and ceilings [7]. While the traditional CBPs are made of ordinary Portland cement (OPC) and virgin wood, light-burned magnesium oxide cement (MOC) has been recently demonstrated as a viable substitute of OPC for transforming waste wood formwork into novel CBPs [6]. The MOC is an alternative candidate with a lower production temperature <750 °C compared to 1400 °C for OPC. The MOC hydration products formed during hardening process, namely brucite ($Mg(OH)_2$), can react with CO_2 to give carbonate compounds [6]. Curing in pressurized CO_2 has proven effective to expedite the mineral carbonate formation, which enhanced the physical properties of the final products and accelerated the hardening efficiency [8,9]. This signifies construction wood waste upcycling as an attractive strategy for carbon sequestration to abate global warming.

Nevertheless, environmental merits of the wood waste-derived MOC particleboards should be quantified for valid comparison to the traditional OPC particleboards. Life cycle assessment (LCA; ISO 14040–14044) [10] is a widely recognized tool to evaluate the environmental viability of construction materials in a holistic manner. A few recent studies assessed the potential of wood waste recycling and utilization in different scenarios including energy generation [11,12,13], papermaking [14], and resin-based particleboard [15,16]. In a previous LCA study on resin-based particleboard production, the transportation distance between raw materials and particleboard manufacturing site was one of the primary controlling factors of environmental impacts [17]. The use of green cements [18] and recycled materials [19] were demonstrated to be superior to their conventional and/or virgin counterparts in terms of the life cycle environmental benefits. A recent study on hempcrete block indicated that CO_2 uptake by the block during the use phase can alleviate the overall carbon footprint [20]. As for the CBPs production, there is a need to examine material transportation, source of materials, CO_2 utilization, etc., in the production phase, of which the significance may vary with construction materials and local context. So far, no LCA study has been found for CBPs produced with recycled wood waste. In addition to technical viability, it is thus important to assess the environmental sustainability for a holistic evaluation of innovative technology using comprehensive LCA.

This integrated experimental–modelling study aims to: (i) evaluate the technological performance of the MOC particleboards after CO_2 curing, in comparison to the OPC particleboards; and (ii) investigate the life cycle environmental benefits of the MOC particleboard production with recycled wood waste in the context of Hong Kong, which represents a typical high-density metropolis. By addressing both technological and environmental feasibility, the current study can assist the establishment of closed-loop material flow and sustainable management agenda for wooden construction waste materials.

2. Materials and methods

2.1. Materials

Waste wood formwork (Masson pine) was used as aggregates (in the form of flakes) in the CBPs, which was collected from a local recycling company at Hong Kong Eco-park. The collected wood was shredded into flakes by using a drum-knife flaking machine and screened before use. The particle sizes ranging from 2.36 to 5.00 mm (for both recycled and virgin wood) were selected as wood aggregates and mixed with binders to produce the CBPs. Two cements were investigated as the binders for CBPs production. One was the traditional OPC (64.7% CaO, 21% SiO_2, 5.9% Al_2O_3; ASTM Type I) with a specific density of 3.16 g cm^{-3} obtained from Green Island Cement Limited, Hong Kong. The other one was light-burned MOC (85% total MgO, 1.5% CaO, 4.5% SiO_2) with a specific density of 3.15 g cm^{-3} purchased from Liaoning province, China. For efficient strength development process, $CaCl_2$ in reagent grade (Tianjian Chemical Reagent Factory, China) was used as an accelerator in OPC particleboards with reference to our recent study [21]. For comparison, the same particle size range (as mentioned above) of wood aggregates was used in producing MOC and OPC particleboards.

2.2. Particleboard manufacture and property evaluation

For the production of MOC and OPC particleboards, wood waste, accelerator (only for OPC particleboards), and water were homogenously mixed with the respective cementitious binders (i.e., MOC or OPC) for 3 min using a mechanical mixer. The mixture was then transferred into steel moulds (160 × 160 × 15 mm). Each mould was compressed at 4 MPa for 1 min to reach specific dimensions before fixation with a cap and four bolts [22,23]. After 24-h hardening, the particleboards were demoulded and transferred to an air curing chamber at 20 °C and 95% humidity for 7- or 28-day curing before further analysis.

The MOC particleboards were subjected to CO_2 curing as follows. The 1-d demoulded particleboards were pre-dried in a drying chamber (20 °C, 50% humidity) for 1-h to achieve a moisture content of approximately 18%. The dried samples were placed in a vacuum chamber at −0.5 bar with CO_2 purging at 1.1 bar for 2 h (i.e., 0.1 bar higher than the atmospheric pressure). Anhydrous silica gel was placed in the chamber to absorb evaporated water. The 2-h carbonated samples were divided into two identical portions for immediate strength assessment and additional 7-d air curing following the above-mentioned protocol, respectively. All the experiments on CBPs production were triplicated for quality assurance and the average values with standard deviations were reported. Statistical analysis of the experimental results was performed by using one-way analysis of variance (ANOVA, Fisher's Least Significant Difference test, $p < 0.05$).

To evaluate the performance of CBPs, flexural strength tests [24] were performed 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 tests after 24-h water immersion [24] were conducted to examine the dimensional stability against moisture. The mix designs of the CBPs production in this study are summarized in Table 1.

2.3. Life cycle assessment of cement-bonded particleboard production

Comparative environmental impact of particleboard production was assessed by using the standard LCA techniques recommended by ISO 14040–14044 [10]. Two production processes including different mix designs and materials were considered in this study (Table 1). In consideration of different production processes and considerations, four scenarios of CBPs were developed and compared as follows:

- ***Scenario 1***: CBPs prepared from conventional materials (e.g., virgin wood and OPC). The production process involves normal air curing process.
- ***Scenario 2***: CBPs prepared from construction wood waste and alternative binder (e.g., MOC), using the conventional production process involving normal air curing process.
- ***Scenario 3***: Similar materials and mix designs as Scenario 2, but employs CO_2 curing in the production process.
- ***Scenario 4***: Same as Scenario 3, but also takes into account the environmental benefits of wood waste recycling (avoided impacts due to avoidance of landfill disposal).

Table 1
Mix-designs with density of cement-bonded particleboards.

Materials	Conventional CBP	CBP with alternative materials
OPC (%)	59	–
MOC (%)	–	57.9
Wooden aggregates (virgin, %)	23	–
Wooden aggregates (recycled, %)	–	24.7
Accelerator ($CaCl_2$) (%)	1	–
Water (%)	17	17.4
Density (kg/m^3)	*1.54*	*1.37*