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RECYCLING USED TIMBER FORMWORK INTO LIGHTWEIGHT, THERMAL-INSULATING CEMENT-BONDED PARTICLEBOARDS

RESEARCH SUMMARY

Construction Industry Council
Recycling Used Timber Formwork into Lightweight, Thermal-insulating Cement-bonded Particleboards
Research Summary

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FOREWORD

Massive amounts of construction waste were disposed into landfill in Hong Kong every year. To address the issue, the Construction Industry Council (CIC) funded a research team from the Hong Kong Polytechnic University to develop a technology for recycling waste wood formwork.

This report summarised how to recycle waste wood formwork into value-added cement-bonded particleboard. The optimal mixture formulation for the production of the cement-bonded particleboard was investigated. CO_2 curing was employed to improve the wood-cement compatibility, mechanical strength and dimensional stability. The incorporation of fibre could reinforce the mechanical properties of the particleboard. Moreover, the developed particleboard exhibited remarkable capability of thermal insulation and noise reduction.

Besides technical aspects, a cost analysis was performed to evaluate the economic feasibility of the developed technology and the economic viability was justified by the analysis, which was an excellent basis for its further commercialization.

I would like to congratulate and thank Dr TSANG and all those who have contribute to the research project, and look forward to the commercialization of the product. The CIC would like to work closely with the research team and industry stakeholders to promote the application of the innovative product in the industry.

Ir Albert CHENG
Executive Director of Construction Industry Council

PREFACE

Construction industry is a booming industry in Hong Kong, which generates massive amounts of construction and demolition wastes every year. The most valuable materials such as heavy metals are effectively recycled and the majority of inert wastes are diverted to public fill reception facilities for land reclamation purpose. However, the remaining non-inert wastes (approximately 20% of total volume) such as wood used in formwork require disposal at landfills afterwards. The waste wood formwork is usually contaminated with preservative chemicals. The landfill disposal of wood waste is internationally deemed to be a non-sustainable practice. Hence, the Construction Industry Council (CIC) engaged with the research team from the Hong Kong Polytechnic University (PolyU) to investigate the potential reuse of waste formworks.

This report introduces an innovative approach to recycle the waste formworks into value-added cement-bonded particleboards. In this research, accelerators were incorporated to improve the compatibility between wood and cement. CO_2 curing was employed to accelerate cement hydration and early strength development. The cement-bonded particleboards presented excellent properties, such as high strength, light weight, water resistant, acoustic and thermal insulation. Moreover, structured interviews and questionnaire were further performed to understand individuals' considerations in adopting the use of cement-bonded particleboards in construction projects. The project was successfully completed and the results achieved the anticipated goal. Here, we sincerely appreciate the support and assistance of CIC for our project. We wish to thank our laboratory technicians, Mr K. H. Wong and Mr W. S. Lam, for their responsive and efficient technical assistance, which greatly smoothed our experimental works. We would like to extend my thanks to former undergraduate students, David Tsang, Mandy Chiu, Kiwi Man and others, for helping carry out time-consuming laboratory works. We also extend special thanks to our interviewees from AECOM Asia Company Ltd., ATAL Engineering Ltd., Civil Engineering and Development Department, Construction Industry Council, Environmental Protection Department, Gammon Construction Ltd., Hong Kong Productivity Council, Hong Kong Waste Management Association, and Ove Arup & Partners Hong Kong Ltd.

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EXECUTIVE SUMMARY

Construction industry is a booming industry in Hong Kong, which generates massive amounts of construction and demolition wastes every year. The non-inert wastes (approximately 20% of total volume) such as wood used in formwork require disposal at landfills afterwards, which is the most dominant waste at public housing building sites in Hong Kong. In recent years, landfill disposal is increasingly regarded as a non-sustainable management practice of waste wood formwork due to limited landfill capacity, increased carbon footprint and potential leaching problem. Therefore, developing innovative approaches for timber waste recycling presents environmental benefits and economic incentives. This project upgrades technologies to effectively recycle waste wood formwork into high-performance particleboards.

The wood waste was collected from EcoPark in Tuen Mun, which received waste formwork from construction sites. The waste formworks were granulated after manual removal of nails, and sieved to 0.3 to 2.36 mm and 2.36 to 5 mm particle sizes as fine aggregates and coarse aggregates, respectively. Then, the wood particles were used to produce cement-bonded particleboards. In Phase 1, a series of experiments were conducted to explore the manufacturing process of cement-bonded particleboards and fabricate products with strong mechanical properties and high dimensional stability. The results showed that using coarse wood particles (2.36-5 mm), 2% $CaCl_2$ as additives, wood-to-cement ratio kept at 3:7, water-to-cement ratio at 0.3 and design porosity of 5%, the cement-bonded particleboards performed strong mechanical properties and high dimensional stability. The bending strength and thickness swelling of 28-day sample were 12.8 MPa and 0.76%, respectively, which could fulfill the international standard requirement for cement-bonded particleboards (9 MPa and 2%, respectively). Besides, 1% chopped basalt fiber addition dramatically enhanced the strength and deflection of the products.

In Phase 2, the manufacturing process and mixture design were improved to produce functional and tailored cement-bonded particleboards. The results showed that CO_2 curing significantly facilitated cement hydration 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. Besides, the particleboards presented excellent properties in terms of thermal insulation and noise reduction. The thermal conductivity of cement-bonded particleboard was only 26% of the ordinary concrete board, and the noise insulation effectiveness of OPC particleboard also was better than ordinary concrete board, especially at a low sound frequency (32-100 Hz).

In Phase 3, structured interviews and questionnaires were conducted to identify significant factors that affect decision-makers in government and private construction enterprises in using recycled products. Structured-interviews results showed that waste recycling intention is influenced by perceived benefits and costs, social and moral values and behaviour control beliefs. The regulatory compliance was the most determining category affecting individuals' decision-making in using recycled materials. Questionnaire results demonstrated that the industry concerned "high fire resistance" and "high mechanical strength" in recycled products, which was safety and quality concern. The deviation in consideration preferences of different stakeholders enable us to formulate effective recycled products market strategy and allow higher commercial acceptability and applicability of recycled products.

CONTENTS

1 INTRODUCTION

1.1 Background

Construction industry is a booming industry in metropolitan cities and rapidly developing municipalities, which generates massive amounts of construction and demolition wastes every year. For example, approximately 3,600 tonnes of construction waste were disposed daily in Hong Kong, accounting for a quarter of landfilling as of 2013 (HK EPD, 2015). The most valuable materials such as heavy metals are effectively recycled and the majority of inert wastes are diverted to public fill reception facilities for land reclamation purpose. However, the remaining non-inert wastes (approximately 20% of total volume) such as wood used in formwork require disposal at landfills afterwards, which is the most dominant waste at public housing building sites in Hong Kong. The wood formwork is reused on site but at the end of its service life is contaminated with residual cement. Moreover, timber boards are usually accompanied with preservative chemicals such as chromated copper arsenate (CCA) to protect wood from insects, fungi, and bacteria attacks, where CCA accounts for two-thirds volume of the preservative chemicals and poses a serious long-term risk of potential leaching and environmental contamination. In recent years, landfill disposal is increasingly regarded as a non-sustainable management practice of waste wood formwork due to limited landfill capacity, increased carbon footprint and potential leaching problem. Although waste combustion is a prevalent practice of energy recovery in Europe, contaminated wood is considered unsuitable for combustion in view of its complicated pretreatment as well as significant air pollution and ash treatment. Because of the stubbornly high production cost and technical limitation, the large-scale commercial production of biofuel (bioethanol) from wood waste has still not been implemented. Therefore, developing innovative approaches for timber waste recycling presents environmental benefits and economic incentives.

1.2 Research Aim, Objectives, and Deliverables

The overarching goal of this project is to recycle non-inert construction wastes, timber formwork in particular, into cement-bonded particleboards in Hong Kong, which diverts waste formwork from land, provides alternative materials for construction use, and sequesters carbon to abate global warming. According to the agreement, three measurable objectives were achieved as follows:

i. Determined the optimal mixture formulation and manufacturing process for the production of cement-bonded particleboards;

ii. Evaluated the physical qualities, mechanical properties, and chemical/structural characteristics of the cement-bonded particleboards; and

iii. Assessed the cost-effectiveness and environmental impacts of timber waste recycling, and identified the operational challenges and critical success factors.

1.3 Scope

The project includes the following scope of activities and works:

(a) Exploring the manufacturing process of cement-bonded particleboards and fabricating the products with strong mechanical properties and high dimensional stability.

(b) Improving the manufacturing process and mixture design to produce functional and tailoring cement-bonded particleboards (such as thermal-insulating, noise-insulating, anti-bacterial, fire-resistant boards).

(c) Analysing the technological and economic feasibility, environmental impacts, and societal implications of this technology. Providing recommendations for timber waste management in Hong Kong.

2 METHODOLOGY AND MATERIALS

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 to 2.36 mm and 2.36 to 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 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 subjected 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 for achieving the mechanical strength required by international standard for particleboards (ISO 8335, 1987). All experiments were conducted in duplicate and the average values were presented with the variations.

Abbreviations:
d = day(s) h = hour(s) min = minute(s)

2.2 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 to 4 h) to achieve different moisture contents. These dried samples were subjected 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 were recorded during 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 Physical Properties, Thermal Insulation, Noise Reduction, and Leachability

The flexural strength and tensile strength of the particleboards were examined by a standard testing machine 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, 0.01mm 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). 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. In addition to the standard requirements of particleboards, the additional merit of sound insulation was evaluated via sound reduction index and impact noise reduction was measured by using tapping machine. 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. The metal leachability of contaminated wood and cement-bonded particleboard was assessed in terms of the toxicity characteristic leaching procedure (TCLP), of which the metal concentrations were determined by ICP-AES. The TCLP leachability served as the acceptance criteria for on-site reuse.

2.4 Microscopic and Spectroscopic Analyses

The particleboard performance is highly dependent on its microstructure characteristics and interface chemistry. The crystalline-phase mineralogy of crushed particleboards under various conditions was revealed by Quantitative X-ray diffraction (QXRD) using a high-resolution powdered X-ray diffractometer (XRD, Rigaku SmartLab). A 20 wt% Al_2O_3 was added to the samples as internal standard to determine the content of amorphous phase, and the samples were scanned over a range of 5° to 50° 2θ with 2.5° min^{-1} at 45 kV and 200A. Rietveld refinement quantitative phase was carried out by whole powder pattern fitting (WPPF) method in Rigaku's integrated X-ray powder diffraction software (PDXL). The crystallization enthalpy (100 to 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. The surface morphology of the samples was investigated by scanning electron microscopy (SEM, JEOL Model JSM-6490). Gold was coated on the fractured cross-sections of samples and SEM was operated at an accelerating 20 kV voltage and 70–78 μA current.

2.5 Structured-Interview and Questionnaire

Structured interviews with experts serve as a streamline tool to identify significant categories that affect individuals' recycling intention and their subsequent behavior under the Theory of Planned Behavior (TPB). Recycling intention is affected by three constructs including attitudes, subjective norms and perceived behavioural control.

Eight questions were asked, including past behaviour of interviews, perceived costs, benefits and social pressure identified, factors determining the use of recycled materials, decision-makers for the use of recycled materials and product evaluation on innovative recycled particleboards. Ten structured face-to-face interviews were conducted; backgrounds of interviewees varied and were categorized into three groups, including government engineers, construction-related organizations and environmental consultants and contractors. The first group was government officials from Environmental Protection Department and Civil Engineering and Development Department, including Chief Engineer, Senior Engineer and Engineer. The second group was from Hong Kong Productivity Council, Construction Industry Council and Hong Kong Waste Management Association, including Principal Consultant, Assistant Director and Chairman. The last group was from ATAL Engineering Limited, AECOM, Ove Arup & Partners Hong Kong Ltd. and Gammon Construction Limited, including Directors, Engineer and Senior Site Administrator.

Thematic analysis was used to qualitatively analyze the content to formulate an overall impression of each interviewee in recyclables potential. It is flexible to highlight similarities and differences across scripts, and it can generate unanticipated insights for studying social behavior. A theme captures significant information in relation to the research question and represents patterned meaning of the data set. Initial codes were then generated, using open coding method. “Open coding” refers to breaking down, examining, comparing, conceptualizing and categorizing of data. Codes identify data feature and refer to “most basic segment or element of the original information that are assessed regarding to the research question”. Keywords from interviews were grouped according to their high repetition rate. Codes were then collated into potential themes, by gathering relevant information to each potential theme.

After developing the framework that investigated determinants in construction recyclables application potential, a step forward was taken to quantitatively identify determinants. Frequencies of keywords in the three interviewee categories were compared to understand the perceived thoughts of interviewee, including those from construction-related organizations, environmental consultants and contractors and government engineers. After that, determinants generated from thematic analysis of interview scripts were further surveyed to prioritize major categories from five respondent groups and identify perception differences among various respondents.

Questionnaire was further performed to understand individuals’ considerations in adopting the use of recycled products in construction projects, especially evaluating physical parameters of innovative recycled MgO-wood particleboard, and identifying perception differences among respondents. The questionnaire consisted of two sections: (1) product evaluation of innovative recycled particleboard and, (2) demographic characteristics of respondents, including age group, working experience in the construction industry and occupation. Six physical characteristics of recycled particleboard were compared with statutory values, including high flexural strength (9 MPa), low thickness swelling (2 %), low thermal conductivity (0.3 W m^{-1} K^{-1}), high noise reduction of structure-borne noise at 32Hz, low density (1840 g cm^{-3}) and high fire resistance. The questionnaire survey was conducted by a five-point Likert response scale to measure different components, with 5 indicating strong positive view, 3 indicating neutral view and 1 indicating strong negative view. Online questionnaires were distributed to individuals ranging from site managers, engineers from contractor firms, engineers from consultant firms, environmental consultants, academic experts, general public, government officials, and construction-related experts.

The first step of conducting statistical analysis on the results from questionnaire was to assess reliability, which is concerned with the internal consistency of statistical data, with the use of Cronbach's alpha (α). Cronbach's alpha (α) ranges from 0 to +1. A high value of α indicates a higher reliability of measured constructs, and vice versa. Cronbach's alpha is generally considered as high reliability with a value greater than 0.7. After checking the reliability of results, statistical analysis was performed in different horizon, comparing mean scores of categories. Finally, correlation analysis was performed to determine positive or negative relations among variables. Correlation between variables was determined by the Pearson's correlation coefficient. A positive correlation was indicated with a value close to +1 while negative correlation is indicated with a value close to -1. Coefficient greater than 0.8 was described as strong while the value less than 0.5 is described as weak. Cronbach's alpha of product evaluation was 0.81 that indicated good reliability.

3 RESULTS AND DISCUSSION

3.1 Mineralogical Aspects of Early Strength Development

Figure 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% to 25% in 7-d cured particleboards with 1% accelerators (by weight of cement) (Figure 1a). As the dosage increased to 2%, the flexural strength was further enhanced by 14% to 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 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 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. 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.

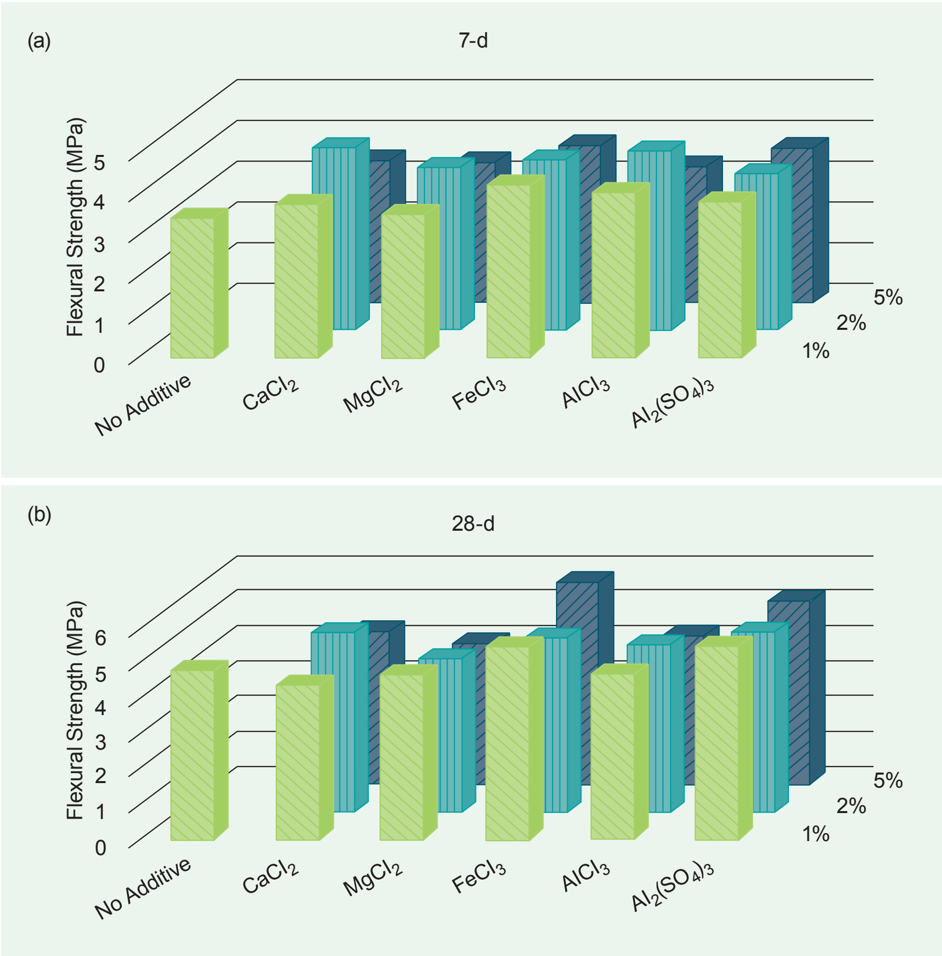


Figure 1. Flexural strength of cement-bonded particleboards with various accelerators at different dosages: (a) 7-d curing; (b) 28-d curing.

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°. This transformation could promote crystallization and growth of coexisting hydrates and thus improve early strength. 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 the highest 7-d strength improvement (Figure 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

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 and tensile strength gradually decreased with an increasing aggregate-to-cement (A/C) ratio. The XRD analysis showed a stronger peak of unreacted calcium silicates at 29.3° at an A/C ratio of 7:3 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). The 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, 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 (Babrauskas, 2001; Cafe, 2011), implying that wood particles being enmeshed in the cement hydrates enhanced the fire resistance of particleboards to a certain extent. In consideration of previous studies (Alhozaimy *et al.,* 2012; Rostami *et al.,* 2012; Wang *et al.,* 2015), 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. A marked shoulder peak at approximately 800 °C in the particleboards with an A/C ratio of 3:7 by weight suggested the presence of well-crystalline calcite that contributed to high mechanical strength.

The porous structure of the particleboards was analyzed at varying A/C ratios. As shown by the MIP results (Figure 2), 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.

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. On the other hand, the thickness swelling increased along with increasing wood content, and the water absorption also demonstrated similar pattern. 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, 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.

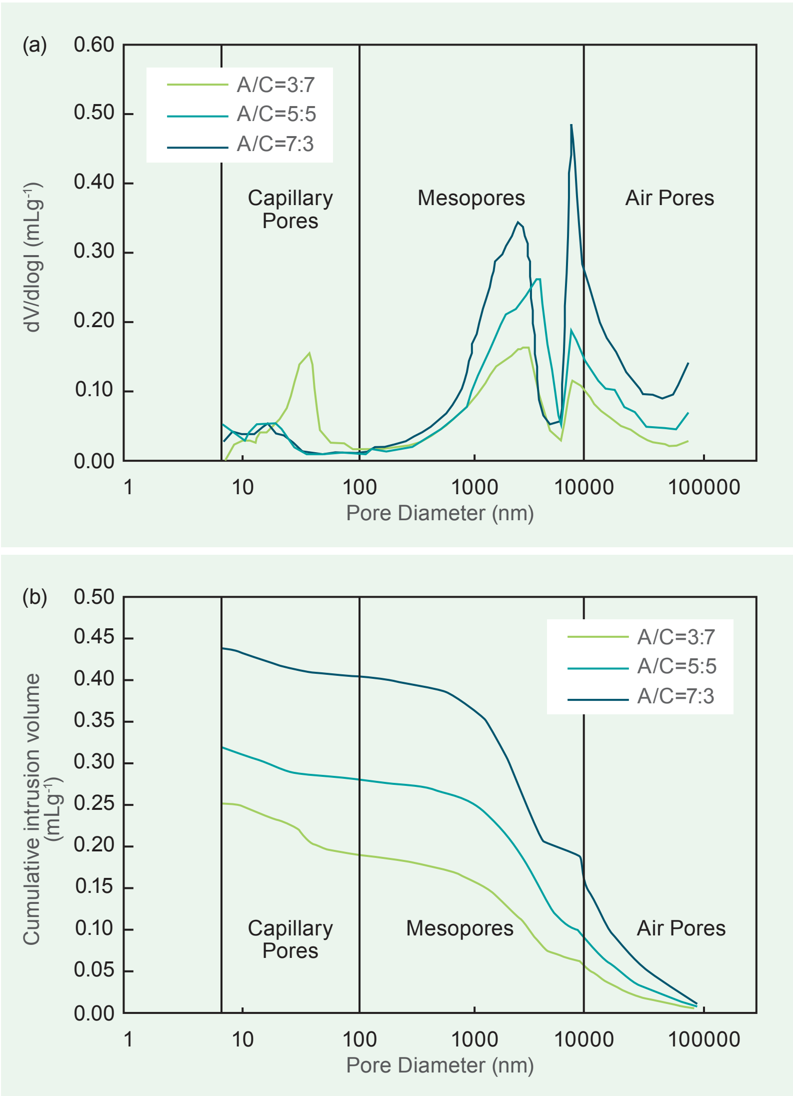


Figure 2. Pore size distribution (MIP analysis) of 28-d particleboards at varying aggregate-to-cement (A/C) ratio:(a) differential distribution; (b) cumulative distribution

3.3 Strength Improvement by Tuning the Porosity

Both flexural strength and tensile strength of the particleboards showed a gradual increase with decreasing water-to-cement (W/C) ratio until reaching 0.30. As expected, the thickness swelling and water absorption were similarly reduced by decreasing the W/C ratio and all the particleboards fulfilled the thickness swelling requirement.

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 intra-particle 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, the increase of density resulted in a lower porosity and favourable pore structure for strength development. However, 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 showed consistent results as above. 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. In addition, the particleboard density (1.54 g cm^{-3}) was 32% lower than that of conventional concrete board. Hence, the particleboards made up of waste wood can be regarded as light-weight building materials.

3.4 CO_2 Curing for Early Strength Development

In the absence of accelerator or CO_2 curing, the development of early strength was significantly retarded, showing approximately 31% discrepancy between 2-d and 9-d flexural strength. The 28-d air-cured samples fulfilled the thickness swelling requirement of 2%, but they were not strong enough to meet the strength requirement of 9 MPa. This could be attributed to the adverse effects of calcium complexation with water-soluble extractives of wood that hindered early strength established by cement hydration. Chloride ions could facilitate early strength development by accelerating precipitation of insoluble calcium chloroaluminate hydrate and generation of insoluble oxychloride from tricalcium aluminate and hydrated calcium hydroxides, respectively.

The applicability of CO_2 curing was assessed as an alternative approach to improve compatibility and early strength. The 1-d CO_2 curing enhanced early flexural strength of particleboards by 24% compared to that of air curing, which also distinctively improved dimensional stability. The XRD spectra demonstrated notably lower peaks of unreacted tricalcium silicate (C_3S, at 32.2°) and dicalcium silicate (C_2S, at 34.3°), particularly for C_3S, after 1-d CO_2 curing. A distinctive overlap peak of C_3S, C_2S and $CaCO_3$ (CC) appeared at 29.4°, indicating an effective carbonation of unhydrated cement. The QXRD result illustrated that CO_2 curing facilitated formation of amorphous cement hydrate (mainly C-S-H gel) to 63 wt% of cementitious matrix in the particleboards (i.e., except wood), which probably resulted from hydration of C_3S at the early stage, because C_3S presented higher solubility and lower activation energy compared to C_2S. Meanwhile, $Ca(OH)_2$ was transformed into $CaCO_3$ (approximately 3.8%), which increased the Mohs scale hardness from 2 to 3 and resulted in volume expansion by 1.12 times.

The MIP results illustrated that, in terms of total pore area and porosity, CO_2 curing produced much denser particleboards (12.2 m^2 g^{-1} and 34.8%) than 2-d air curing (10.3 m^2 g^{-1} and 29.7%). Figure 3 shows the pore size distribution of particleboards, which can be operationally categorized into capillary pores, mesopores, and air pores. The CO_2 curing reduced the porosity in all three major peaks of pore size distribution, particularly for capillary pores that decreased from 0.13 mL g^{-1} to 0.09 mL g^{-1} at the pore size between 31 and 48 nm (Figure 3a). As mechanical strength of cementitious products was found to inversely correlate to porosity, total pore area and average pore diameter, CO_2 curing significantly enhanced mechanical strength of cement-bonded particleboards in this study by facilitating cement hydration and densifying the microstructure.

Additional 7-d air curing after CO_2 curing further increased flexural strength, which was stronger than 28-d air cured sample and successfully fulfilled the standard requirement (ISO 8335, 1989). Compared to the samples with 1-d CO_2 curing only, QXRD results indicated that calcium silicates were further hydrated into amorphous C-S-H gel and portlandite after additional 7-d air curing, while the content of $CaCO_3$ remained relatively stable. The porosity consequently decreased from 29.7% to 26.5%, especially in capillary pores (Figure 3). These spectroscopic and microscopic results suggested that short-term CO_2 curing followed by air curing be a feasible and effective approach to enhance the mechanical strength and dimensional stability of cement-bonded particleboards.

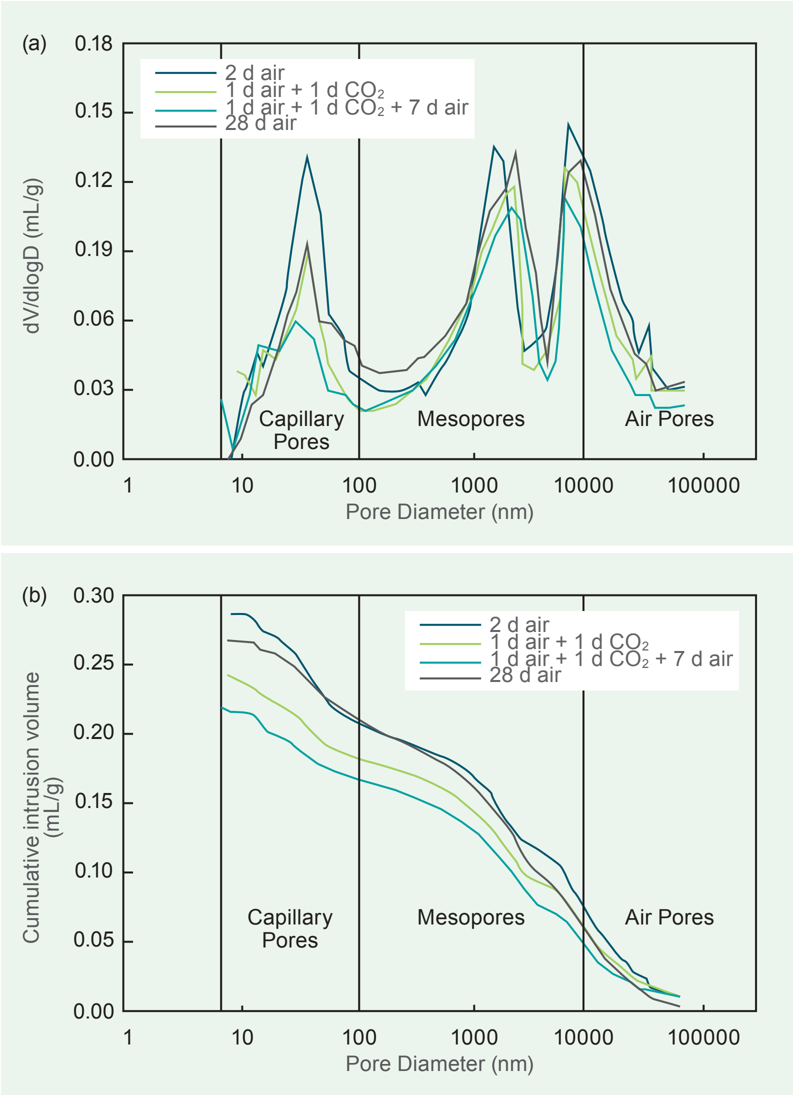


Figure 3. Pore size distribution (MIP) of cement-bonded particleboards produced by different curing methods: (a) differential distribution; (b) cumulative distribution

However, CO_2 curing was not effective for samples with 2% $CaCl_2$ addition. There was no obvious change in flexural strength between air cured and CO_2 cured samples. Although QXRD showed approximately 12% of $Ca(OH)_2$ in fresh samples, the carbonation degree was negligible after 1-d CO_2 curing. This may be a result of strong acidity of HCl compared to H_2CO_3, which prevented CO_2 from reacting with calcium chloride or oxychloride. Therefore, chloride accelerators should be excluded to ensure effective CO_2 curing.

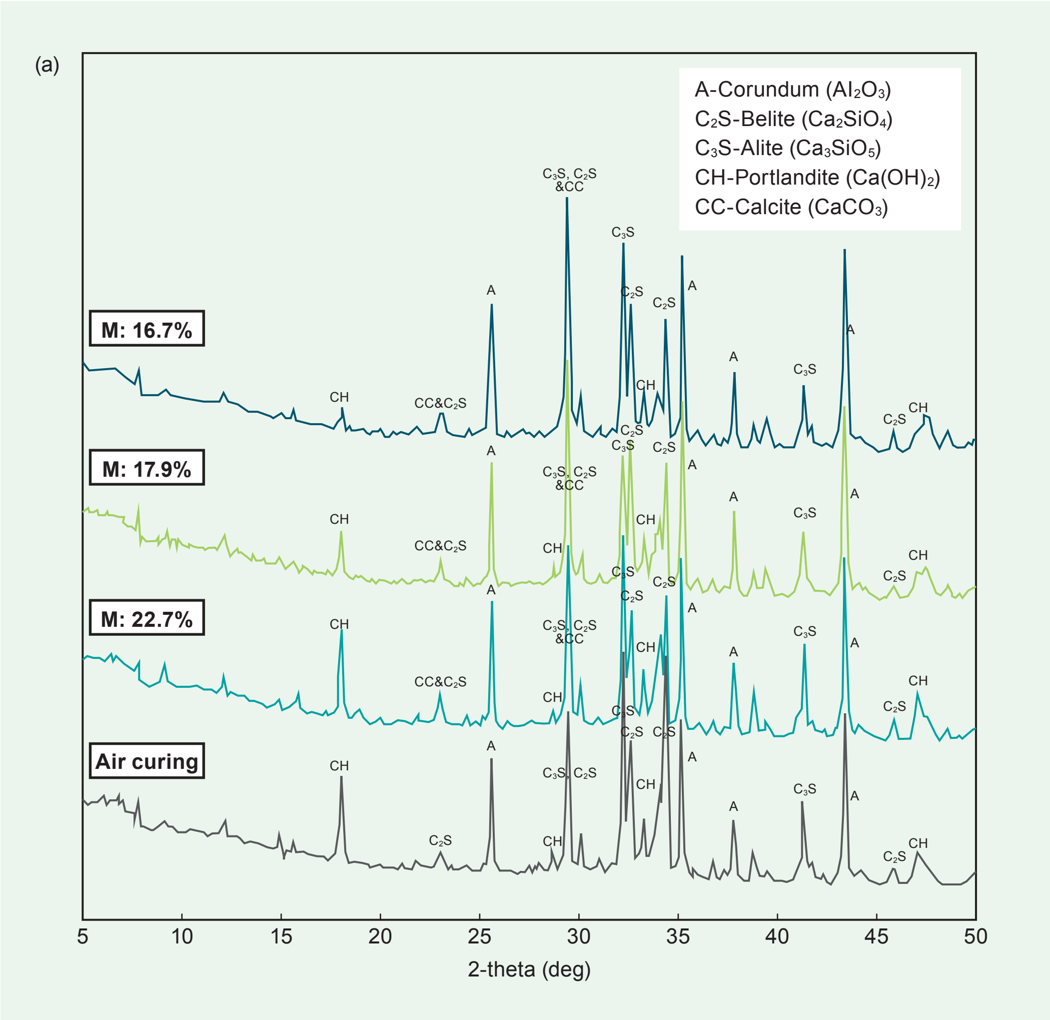
3.5 Significance of Moisture Content in CO_2 Curing

Moisture content is known to be essential for CO_2 dissolution and carbonic acid formation for further reaction with calcium silicates and calcium hydroxide. However, too much moisture in the particleboards would hinder CO_2 diffusion and overall carbonation rate, as CO_2 diffusion coefficient in water is 4 to 5 order-of-magnitude slower than that in air (about 1390×10^{-8} m^2 s^{-1}). Research finds that particleboards with lower moisture content between 14.9% and 17.9% presented much higher flexural strength and tensile strength than the samples with 22.7% moisture content. They also demonstrated less thickness swelling and water absorption. For samples with 17.9% moisture content, 1-d CO_2 curing was more effective than 28-d air curing in terms of flexural strength (9 MPa in standard requirement). Additional 7-d curing significantly enhanced flexural strength to 14.9 MPa, which outcompeted the samples with $CaCl_2$ accelerator (12.9 MPa).

Phenolphthalein pH indicator test corroborated the occurrence of deepest carbonation front. The colour of CO_2 cured samples turned into light red and periphery of the cross-section showed in colourless, indicating the decrease of pH, while dark red colour was observed throughout the cross-section surface of 2-d air cured samples. The change was more evident for samples at lower moisture content. However, all of the samples were not completely carbonated after 1-d CO_2 curing. This was probably due to the saturated humidity in the curing chamber without gas flow, where excessive external water vapour would form a dense membrane to hamper CO_2 diffusion into the matrix for complete reaction. Therefore, adjustment of humidity and provision of continuous gas flow require further studies for CO_2 curing.

There was an unexpected phenomenon that samples at 16.7% moisture content showed the highest CO_2 absorption, but its strength was not as high as samples at 17.9% moisture content. As shown in Figure 4a, the lowest peaks of $Ca(OH)_2$ at 18.0° and 34.1° were observed in samples at a moisture content of 16.7%, which revealed the largest extent of carbonation. The QXRD results (Figure 4b) further quantified that approximately 12.5 wt% $CaCO_3$ was generated in the 16.7% moisture samples, while there was only 8.6 wt% in the 17.9% moisture samples. This was consistent with the inverse correlation between CO_2 absorption and moisture content in the particleboards.

However, as shown in Figure 4b, the 16.7% moisture samples presented a larger amount of unreacted calcium silicate (i.e., C_3S and C_2S) and less formation of amorphous C-S-H gel than 17.9% moisture samples, implying that lower moisture content may hamper normal cement hydration. In view of the carbonation efficiency and flexural strength, the moisture content between 16.7% and 17.9% was considered as the optimal range to maintain sufficient cement hydration while facilitating CO_2 curing.



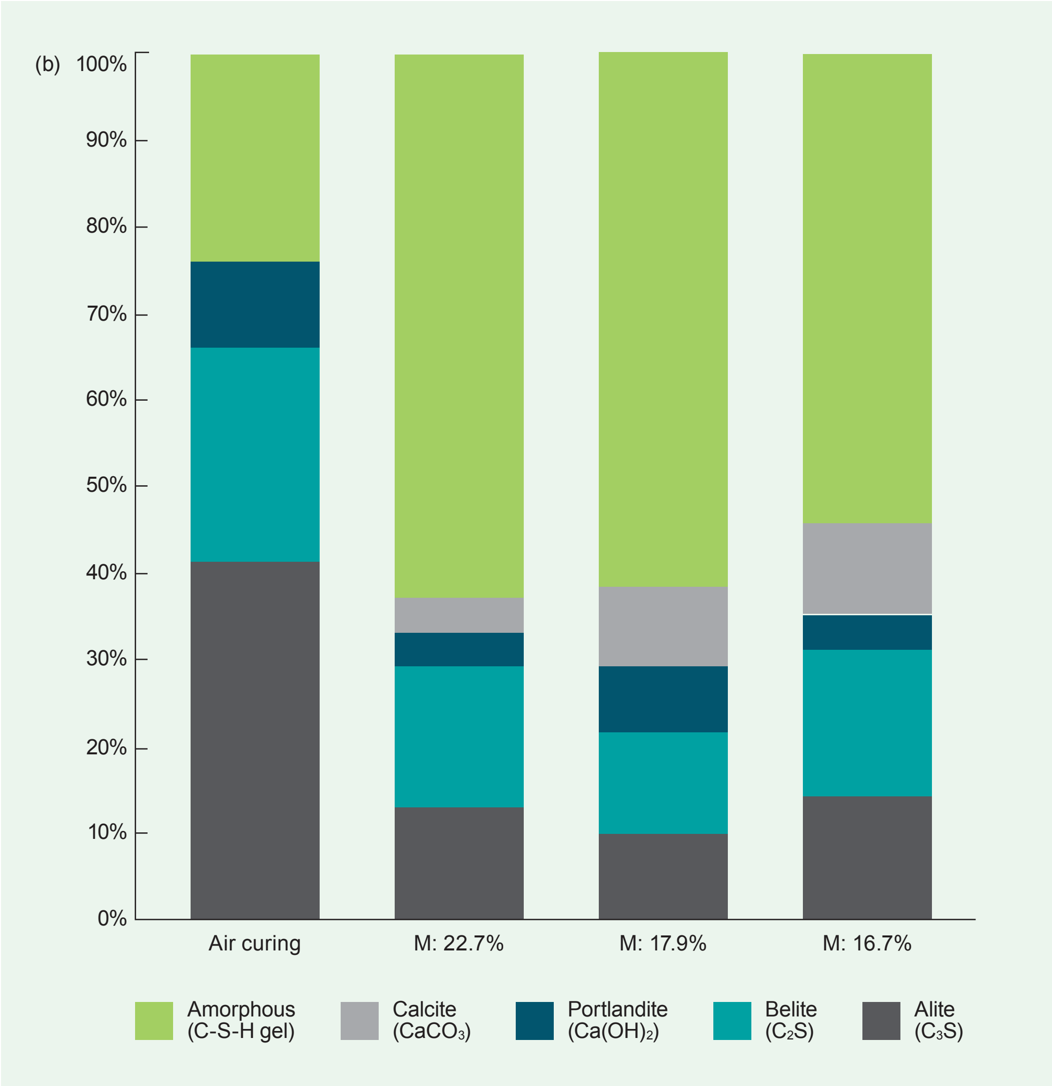


Figure 4. XRD spectra (a) and QXRD analysis (b) of cement-bonded particleboards produced by different curing approaches (M: moisture content).

3.6 Basalt Fibre Reinforced Cement-bonded Particleboard

With increasing incorporation of short basalt fibre, it was found flexural and tensile strength of particleboards gradually increased. The addition of 2% short basalt fibre (by wood volume) significantly enhanced the flexural strength to 16.8 MPa. The addition of grid fibre differed little from the same volume of short fibre in terms of strength reinforcement, but their effects on fracture energy (G_F) varied significantly. Based on the flexural stress-deflection curves, the calculated G_F in the 28-d air cured particleboards with 0.5% grid fibre achieved 23.51 N mm^{-1} compared to 3.64 N mm^{-1} in the absence of fibre, which was 3.5 and 1.6 times higher than those with 0.5% and 2% of short fibre, respectively.

In the fractured particleboards with short basalt fibre, smooth and clean surfaces could be observed in the cross-section with few mortar particles on the surface of cell-fibres, indicating insufficient adhesion between fibres and mortar. Some traces of cell-fibres and remaining cell-fibres were observed after flexural strength test, suggesting that fibre de-bonding, fibre sliding, and crack bridging contributed to strength enhancement. As for grid basalt fibre, it was progressively ruptured under a larger load rather than pulled out due to its interlocking nature, such that tensile load could be transferred to the fibre chords prior to the failure of particleboards. As a result, the incorporation of grid fibre enabled a significant enhancement of fracture energy and presented a simple but effective measure to improve the mechanical properties of cement-bonded particleboards.

3.7 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 (2004), 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 to 3150 Hz). 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. As the elastic modulus (E) of wood particleboard was only 18% of concrete board, their low stiffness feature was favourable for dissipating vibrational energy and insulating impact sound. The moderate amount of air pores in the particleboards also contributed to the superior acoustic shielding properties. 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.

3.8 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. 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 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 cubic metre 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 m^{-3} depending on the functional properties, 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.

3.9 Structured-interviews

Four key categories including Regulatory framework, Economic incentives, Logistics and management arrangement and Recognized accreditation scheme were identified from structured-interviews and classified as major determinants that affect the use of recycled products in Hong Kong. Regulation framework was the key category with the highest repetition rate of 291 counts, followed by Economic incentives (284 counts) and Logistics and management arrangement (128 counts) and Recognized accreditation scheme (83 counts).

Frequency distribution of four categories were compared among three interviewee sectors. Overall, both representatives from construction-related organizations and government engineers had the highest concern on Regulatory compliance. Under this category, representatives from construction-related organizations had the highest concern and with 44.4% of total count of keywords, followed by government engineers and environmental consultants and contractors, with 35.8% and 33.5% respectively. Such findings were in contrast to Lockrey's study about government's perspective on Construction and Demolition (C&D) waste in Vietnam, which considered logistics and economic incentives more than effective regulation.

On the other hand, environmental consultants and contractors had the highest concern on economic incentives that with 36.4% of total count of keywords. The most important behaviour determinant of contractors in Shenzhen and Switzerland on C&D waste management was economic viability, respectively. However, our study focused not only on corporates, but incorporating opinions from social and political stakeholders.

Prior studies suggested that contractor size, logistics and management support, incentives and employee involvement were attitudinal forces affecting C&D waste management, which ignored consideration on accreditation scheme that are commonly exist in many countries. In our study, the category with a general lowest concern of all three groups was accreditation scheme of recycled products. Among all groups, construction-related representatives had the lowest concern, with only 4% of total count of keywords, followed by government engineers and environmental consultants and contractors (i.e., 9.5% and 14.5% respectively).

3.10 Questionnaire

There were 191 responses. Respondents in the age groups of “18-25” and “26-35” were the majority that were 63% of the total. Aged group “18-25” was the largest that consisted of over one-third of total respondents. Most of the respondents had worked in the construction industry for “1-5 years”, “6-15 years”, “16-30 years”, which accounted for 44.5%, 18.9% and 18.9 % respectively. Respondents engaging in engineering from contractor and consultant firms, and general public were the three main components that were over 60% of the total respondents. In particular, categories of consultant and contractor firms were top two respondent groups.

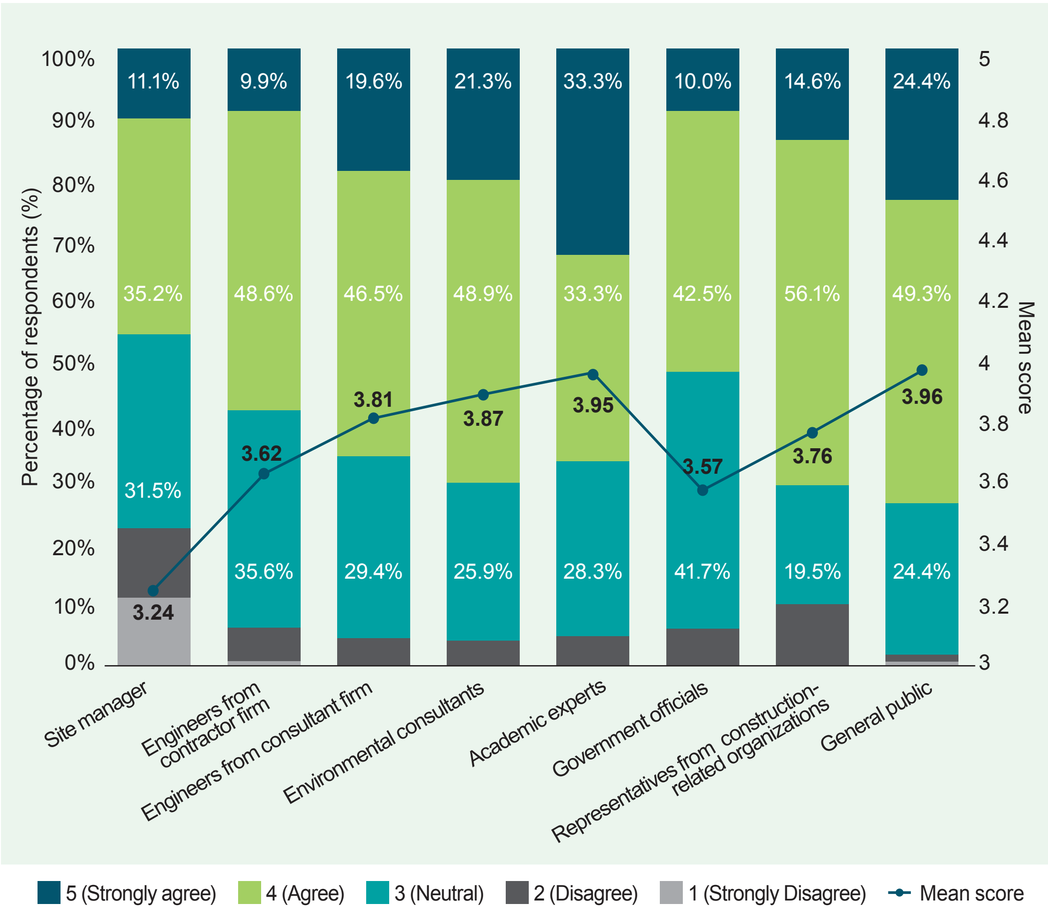


Figure 5. Comparison of percentage of respondents in score and mean score in product evaluation of innovative recycled particleboard.

Comparison among eight respondent groups were conducted, including site managers, engineers from contractor firms, engineers from consultant firms, environmental consultants, academic experts, government officials, representatives from construction-related organizations and general public. Mean score and various score distribution in each respondent group were compared. Generally, all groups had a mean score over 3.0, which showed a positive attitude towards the application potential of recycled products during construction projects. Academic experts (i.e., 3.95) and general public (i.e., 3.96) had the highest mean score in all respondent groups, while site managers had the lowest mean score (i.e., 3.24) (Figure 5). This demonstrated perception differences of different stakeholders within the construction industry. To further understand score distribution and respective level of agreement or disagreement in each respondent group, percentage of their various score allocation was compared. Overall, representatives from construction-related organization had the highest portion of 4.0 score (i.e. 56.1%). On the one hand, the highest percentage of site managers showed strong disagreement. On the other hand, highest percentage of academic experts showed strong agreement, which consisted about 33% of total academic experts (Figure 5).

Apart from understanding preferences of each respondent group upon the use of recycled products, their overall consideration on six physical characteristics of the innovative MgO-wood particleboard was discussed. Under all physical characteristics, respondents had the highest concern on its high fire resistance (i.e., 4.04), followed by high mechanical strength (i.e., 4.01), while they had the lowest concern on its low density (i.e., 3.50) and low thermal conductivity (i.e., 3.52) (Figure 6). It indicated that respondents had specific attention on the safety issue and functional quality of the innovative recycled particleboard. Such results could also be applicable for other similar types of recycled product in the market for construction industry.

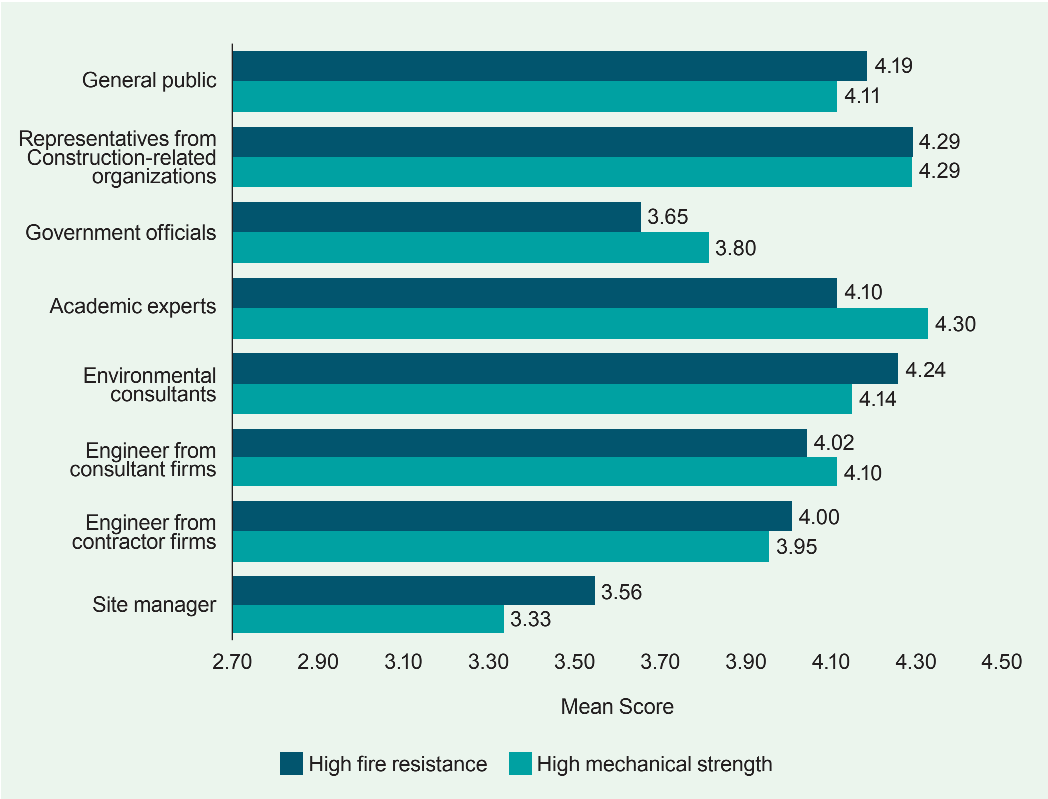


Figure 6. Comparison of mean score in 8 respondent groups under "high fire resistance" and "high mechanical strength" characteristics

To further identify differences in safety and quality concern of various respondent groups, mean score distribution under "high fire resistance" and "high mechanical strength" in all respondent groups were compared. Generally, site managers showed the lowest concern on both "high fire resistance" and "high mechanical strength", which were 3.56 and 3.33 respectively. Besides, government officials also demonstrated low awareness on fire resistance and mechanical strength of recycled products (i.e., 3.65 vs 3.80), when compared to other groups. Academic experts (i.e., 4.30) had the highest concern in the aspect of "high mechanical strength", which indicated a strong preference on quality concern of recycled products. On the other hand, representatives from construction-related organizations (i.e. 4.29) showed equally strong agreement on the importance of both "high fire resistance" and "high mechanical strength" among all respondents.

4 CONCLUSIONS AND THE WAY FORWARD

4.1 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.

Besides, accelerated carbonation by CO_2 curing effectively improved the wood-cement compatibility, mechanical strength, dimensional stability, and contaminants sequestration by promoting the formation of cement hydrates and carbonates in the porous matrix. Moisture content of the particleboards played an important role in CO_2 curing, which should be precisely controlled to strike an optimum balance between cement hydration and accelerated carbonation. An incorporation of fibre, especially grid basalt fibre, notably reinforced the mechanical properties of the particleboards. 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.

Structured-interviews results showed that C&D waste recycling intention is influenced by perceived benefits and costs, social and moral values and behaviour control beliefs. It further extended the TPB model by suggesting four major categories that affect individuals' decision-making in using recycled materials, which were "Regulatory compliance", "Economic incentives", "Logistics and management incentives" and "accreditation scheme". Of which, Regulatory compliance was the most determining category. This study also demonstrated perception difference of various groups of operative levels, and their considerations. Representatives from construction-related organizations and government official shared similar consideration on Regulatory compliance over other categories in both structured-interviews and questionnaire. At the same time, general public put Economic incentives as the major drive for using recycled materials. Overall, a comprehensive regulatory framework is the most determining category in promoting C&D waste recycling and enhance the use the recycled materials.

Questionnaire results demonstrated that the industry concerned "high fire resistance" and "high mechanical strength" in recycled products, which was safety and quality concern. Overall, site managers showed the least concern on both aspects while representatives from construction-related organizations showed the highest concern on such areas. Such deviation in consideration preferences of different stakeholders enable us to formulate effective C&D recycled products market strategy and allow higher commercial acceptability and applicability of recycled products.

4.2 Recommendation

Based on this study, the cement-bonded particleboards technology could be further improved. In this stage, the mixture was compressed at 4 MPa for 1 min in the steel mould, of which the cap was fixed by four bolts for 24 h before demoulding. In real application, the production efficiency should be further enhanced. In order to enhance the production efficiency, two schemes can be proposed. The first approach aims to shorten the pressing duration by introducing fast setting cement (magnesium phosphate cement) at the wood-to-cement ratios of 0.1-0.3 by weight (i.e., 0.7-2.1 by volume). The second approach aims to use rolling press method by using high-liquid cement (magnesium oxychloride cement and ultra-high performance cement) at the wood-to- cement ratios of 0.1-0.4 by weight (i.e., 0.7-2.8 by volume). Moreover, for the sake of utilizing industrial exhaust CO_2 gas from power plant, flue CO_2 gas should be used in future study. The effects of CO_2 curing parameters should be evaluated, such as CO_2 concentration (5-100%), CO_2 pressure (0-5 bar), relative humidity (50%-100%), gas impurities (SO_2, NO_2), etc.

Considering the superior properties of cement-bonded particleboards, interior decorative wall panels and noise barriers are two major potential applications. Thereby, the special technique parameters should be assessed in detail. For interior decorative wall panels, fire and thermal insulation should be evaluated, for instance, fire rating, flame spread, toxicant emission, thermal conductivity etc. It aims to improve the fire resistance of particleboards by using some fire retardants and protective coating. On the other hand, for noise barriers, the various acoustic properties should be evaluated, and the acoustic properties could be improved by varying pore structure and surface treatment.

Furthermore, based on the bench-scale results, the optimum mixture design and manufacturing parameters should be further evaluated in the pilot-scale validation. To ensure the applicability to different waste formworks, a demonstrative production line should be set up in construction site. Hopefully, the value-added particleboards from the on-site production line could be directly used as decorative wall panels in buildings. According to pilot-scale results, technology upgrading will be conducted to simplify process, reduce production cost, enhance production efficiency and improve the quality of products.

Economic feasibility determines the application of cement-bonded particleboards. The cost-benefit analysis will take into account disposal costs, chemical consumption, energy expenditure, quantity of value-added products and the corresponding unit prices, etc. which will be calculated in present values for comparison with potential use of alternative binders such as fly ash and silica fume. These evaluations will provide quantitative evidence for: (i) justifying economic cost savings of the proposed recycling technology with reference to the current disposal practices; and (ii) recommending the critical success factors for creating new recycling market for waste formwork. On the other hand, environmental impacts are of critical consideration in the decision making process. The proposed technology will be evaluated by life cycle assessment, which accounts for the holistic process flow starting from waste wood collection and transfer, through proposed manufacturing processes, versatile product application, and end-of-life disposal. Waste wood disposal at landfill will serve as the baseline scenario for comparison. Sensitivity test will be conducted with different operational settings, semi-quantitative weightings, and variability of the collected/assumed data to justify the environmental significance of operational practices, assumptions as well as data deviation. The results will provide important justification for future scale-up consideration.

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