Mechanical Performance and Anti-Fungal and Anti-Algal Properties for Teakwood/Parawood/PVC Composites in UV-Weathering and Seawater Immersion Conditions

Sirichai Kanking,[a] Tawich Pulngern,[b] Vichai Rosarpitak,[c] and Narongrit Sombatsompop [a,*]

This work examined teakwood and parawood in wood/poly(vinyl chloride) composite (WPVC) materials under UV-weathering and seawater immersion. The mechanical properties as well as anti-fungal and anti-algal performance were considered. Teakwood and parawood (a rubberwood product) in WPVC materials at ratios of 0:100, 20:80, 40:60, 50:50, 60:40, 80:20, and 100:0 were investigated. UV-weathering ageing periods of 0 to 32 days and seawater immersion periods of 0 to 90 were studied. *Aspergillus niger* TISTR 3012 and *Chlorella vulgaris* TISTR 8580 were used as marine fungi and marine algae, respectively. Higher parawood content (in formulations of 0:100, 20:80 and 40:60) in WPVC composite materials enabled better mechanical properties than those of higher teakwood content (in formulations of 60:40, 80:20 and 100:0). Seawater immersion caused more deterioration of WPVC composite materials than UV-weathering ageing. Both anti-microbial agents and wood particles are potentially used in WPVC composite materials for anti-microbial properties, including the percentage reduction of fungal and algal growth. Increasing UV-weathering ageing and seawater immersion periods decreased the percentage reduction of fungal growth, but increased the percentage reduction of algal growth in WPVC composite materials. The results suggested higher parawood content (in a formulation of 20:80) for WPVC composite materials for coastal environment applications.

DOI: 10.15376/biores.18.3.5599-5622

Keywords: UV; Seawater; Mechanical properties; Anti-microbial properties; Teakwood; Parawood; Wood/poly(vinyl chloride) composite

Contact information: a: Polymer PROcessing and Flow (P-PROF) Research Group, Materials Technology Programme, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi (KMUTT), 126 Pracha-Uthit, Bangmod, Thungkru, Bangkok, 10140, Thailand; b: Department of Civil Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi (KMUTT), 126 Pracha-Uthit, Bangmod, Thungkru, Bangkok, 10140, Thailand; c: V.P. Wood Co., Ltd., 72/1 Moo. 4, Suksawat 41, Banphueng, Phra Pradaeng, Samut Prakan, 10130, Thailand;
** Corresponding author: narongrit.som@kmutt.ac.th*

INTRODUCTION

Coastal environments are located at the interface between the land and sea, which are comprised of coastal land and aquatic systems including islands, salt marshes, wetlands, beaches, rivers and estuaries, and transitional and intertidal areas (Crossland *et al.* 2005). Important parameters that influence the structure and appearance of sea-adjacent or marine accommodations include the wind, both land and sea breezes, UV light, seawater, transitional and intertidal behaviours, and micro-organisms.

An artificial wood used in modern houses and living constructions has become interesting in terms of being lightweight and having easy moulding and bending, easy installation and uninstallation, and a nature-like appearance. Wood/poly(vinyl chloride) composite (WPVC) has been considered for strengthening structural applications. It was found that the addition of wood flour in WPVC materials increased the flexural modulus and strength by up to 40 phr, while hardness was not affected (Jeamtrakull *et al.* 2012). Increasing the web thickness and decreasing the flange spacing of the log-wall panels resulted in an increment of ultimate load by 3.6 times and 2.3 times, respectively, but the ultimate load decreased by 4.8 times when increasing the slenderness ratio (Pulngern *et al.* 2017). Loading for the edge-wise direction in WPVC composite provided high flexural properties (Sombatsompop *et al.* 2010) and conversely showed fatigue failure for the flat-wise direction (Pulngern *et al.* 2010). Lateral impacts in both wind and seismic situations were used for the conceptual study of WPVC log-wall behaviour. The presence of metal fasteners for WPVC log-wall installation directly affected lateral loads, especially under cyclic loading, whereas the in-plane lateral load of full-scale WPVC log walls with through-bolts showed higher hysteretic parameters in terms of strength and energy dissipation, as well as better structural stability than log walls without through-bolts (Eakintumas *et al.* 2022a,b).

WPVC composite houses are used as modern accommodations for convenience and comfortable living. Kanking *et al.* (2021) found that WPVC materials show high potential use for better housing (in terms of an insulator and energy consumption) compared with fibre-cement material. However, WPVC composite material is a wood-incorporated material, which needs to consider the influence of UV and condensation ageing, as well as the fungi and algae attacks that occur in seawater environments. Pattamasattayasonthi *et al.* (2011) found that the tensile and flexural properties of WPVC composites decreases with increasing ageing period, especially condensation. The yellowness and hydrophilicity of WPVC composite increases with the UV ageing period. The colour fading of the wood polymer composite surface is affected by chromophoric groups in the lignin, which enhance the UV adsorption of the wood polymer composite. High lignin content increases the crack development and discolouration in wood polymer composite as a function of the UV-weathering ageing period (Chaochanchaikul *et al.* 2012, 2013). The presence of wood particles in WPVC composites enhances the absorption of UV radiation.

Considering the wood types, anti-microbial agents and micro-organisms in WPVC materials, the addition of a UV-weathering ageing period diminishes the flexural properties and dimensional stability of WPVC/parawood materials, but the properties of neat PVC are not affected. UV-aged WPVC/Parawood decreases the anti-fungal performance for 32 days using *Aspergillus niger* (*A. niger*). The deterioration of the mechanical properties for WPVC/Parawood materials during ageing is diminished slightly by the addition of IPBC fungicide. However, the addition of fungicide slowly deteriorates WPVC/Parawood materials. IPBC is recommended in WPVC at a dosage of 10,000 ppm (Kositchaiyong *et al.* 2014a, b). Propylene glycol-based HPQM as a biocide, combined with hardwood for WPVC materials during UV ageing, has a similar result (Srimalanon *et al.* 2016). The addition of ZnB as a fungicide inhibits fungal growth in wood polymer composites but does not affect the physical-mechanical properties of the neat polymer or wood polymer composites (Chan-Hom *et al.* 2017). Moreover, the mechanical properties of PVC and WPVC materials are affected by the addition of wood and wood types, but not affected by using terbutryn as an algaecide. The anti-algal performance using *Chlorella vulgaris* (*C. vulgaris*) is suggested by terbutryn with a recommended dosage of 1,000 ppm in WPVC composites (Kositchaiyong *et al.* 2013).

In this work, the proportional contents of teakwood and parawood were varied in wood/poly(vinyl chloride) composite (WPVC) materials, which were subjected to UV-weathering ageing periods of 0, 4, 8, 16, and 32 days and seawater immersion periods of 0, 7, 30, 60, and 90 days. The fungicide and algaecide in WPVC composite materials were fixed at 10,000 (Kositchaiyong *et al.* 2014b) and 1,000 ppm (Kositchaiyong *et al.* 2013), respectively. *Aspergillus niger* TISTR 3012 and *Chlorella vulgaris* TISTR 8580 were used as marine fungi and marine algae. The mechanical properties (tensile and flexural properties) as well as anti-fungal and anti-algal activities were investigated. This work makes it possible to recommend a suitable ratio of teakwood and parawood for WPVC composite materials for applying the appropriate UV-weathering ageing and seawater immersion period.

EXPERIMENTAL

Materials Formulation and Specimen Preparation

PVC and its additives, wood particles, and anti-microbial agents were employed as shown in Table 1 (Kositchaiyong *et al.* 2013, 2014b). WPVC composite materials were prepared from PVC compounds and wood particles at a weight ratio of 50:50. The ingredients were mixed using a hi-speed mixer and blended by a twin-screw extruder with counter-rotating screws (HAAKE^{TM} model Rheomex CTW100 QC, Thermo Electron (Karlsruhe) GmbH, Germany) using a processing temperature between 140 to 160 °C and a screw speed not over 40 rpm. A compression moulding machine (Labtech Engineering Co., Ltd., Bangkok, Thailand) using a holding pressure of 150 kgf/m^2 and heating temperature of 165 °C with pre-heating/heating/cooling step of 5/7/3 min was applied for moulding the PVC and WPVC specimens. The specimens are shown in Table 2.

Table 1. The Ingredients of Neat PVC and WPVC Composites

Ingredients	Function	Manufacturer/ Supplier	City, Country	Concentration (pph of suspension PVC)	
Suspension PVC grade SIAMVIC-258RB	Polymer matrix	V.P. Wood Co., Ltd.	Samut Prakan, Thailand	100.0	part
Emulsion PVC grade SIAMVIC-167GZ	PVC additive	V.P. Wood Co., Ltd.	Samut Prakan, Thailand	4.0	
Pb-Ba based organic polyfluorene *(PF 608A)*	Thermal stabiliser	V.P. Wood Co., Ltd.	Samut Prakan, Thailand	3.6	
Polyfluorene *(PF 601)*	Thermal stabiliser	V.P. Wood Co., Ltd.	Samut Prakan, Thailand	1.5	
High molecular weight complex compatible lubricant (*Finalux® G-741)*	External lubricant	V.P. Wood Co., Ltd.	Samut Prakan, Thailand	0.6	
Calcium stearate	Internal lubricant	V.P. Wood Co., Ltd.	Samut Prakan, Thailand	0.6	
Calcium carbonate *(Omyacarb-2T)*	Extender	V.P. Wood Co., Ltd.	Samut Prakan, Thailand	12.0	
Modified Chlorinated Polyethylene (CPE)	Impact modifier	V.P. Wood Co., Ltd.	Samut Prakan, Thailand	7.7	

Ingredients	Function	Manufacturer/ Supplier	City, Country	Concentration (pph of suspension PVC)
Acrylic Polymer *(PA-20)*	Processing aid	V.P. Wood Co., Ltd.	Samut Prakan, Thailand	6.0
Teakwood *(Average particle size of 100–250 µm))*	Filler	The Forest Industry Organization, Bangpho branch	Bangkok, Thailand	0, 20, 40, 50, 60, 80, and 100 pph of PVC compound
Parawood (*Hevea brasiliensis*) *(Average particle size of 100–250 µm)*	Filler	Pongsiri Timber Ltd. Part.	Ratchaburi, Thailand	100, 80, 60, 50, 40, 20, and 0 pph of PVC compound
N-(2-aminoethyl)-3-aminopropyl trimethoxysilane aminosilane *(KBM603)*	Silane coupling agent	Shin-Etsu Silicones (Thailand) Co., Ltd.	Thailand	1 wt% of total wood
3-iodo-2-propynyl-N-butylcarbamate (IPBC) *(Polyphase P100)*	Fungicide	Troy Siam Co., Ltd.	Prachinburi, Thailand	10,000 ppm of PVC compound
N2-tert-butyl-N4-ethyl-6-methylthio-1,3,5-triazine-2,4-diamine (Terbutryn) *(Fungitrol T80)*	Algaecide	Troy Siam Co., Ltd.	Prachinburi, Thailand	1,000 ppm of PVC compound

Table 2. The Formulations of Neat PVC and WPVC Composites

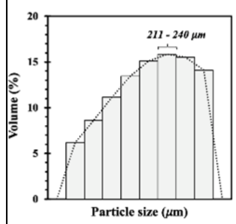
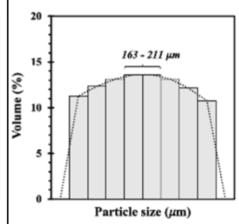
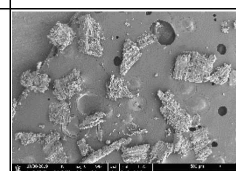
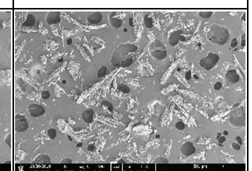
Wood	Weight Fraction Ratio of Teakwood : Parawood in PVC								
	0 : 0 (Neat PVC)	**0 : 0 (PVC)**	**0 : 100**	**20 : 80**	**40: 60**	**50 : 50**	**60 : 40**	**80 : 20**	**100 : 0**
	Anti-microbial agents								
Teakwood	0	0	0	20	40	50	60	80	100
Parawood	0	0	100	80	60	50	40	20	0

Wood Flour Characterisation

Wood flour characterisations consisted of a lignocellulosic constituent, specific surface area, particle size distribution, BET analysis, bulk density, SEM analysis, and aspect ratio, as shown in Table 3.

Table 3. The Characteristics of Wood Particles

Wood Flour Characterization	Analytical Technique / Standard	Teakwood	Parawood
Lignocellulosic Constituent (% w/w)			
Extractive free preparation	NREL/TP-510-42619	7.33 ± 0.18	4.89 ± 0.14
Total lignin	NREL/TP-510-42618	35.22 ± 0.26	28.33 ± 0.30
- Acid-soluble lignin		2.63 ± 0.03	4.54 ± 0.22
- Acid-insoluble lignin		32.59 ± 0.23	23.78 ± 0.21
Holocellulose	High performance liquid chromatography (HPLC) *(Column: VertiSep^{TM} LMP)*	42.25 ± 0.11	43.34 ± 0.46
- Cellulose		41.10 ± 0.13	42.09 ± 0.53
- Hemicellulose		1.14 ± 0.04	1.25 ± 0.07

Wood Flour Characterization	Analytical Technique / Standard	Teakwood	Parawood
Specific surface area (cm^2/g)	Laser diffraction particle size analyzer (Mastersizer 3000, Malvern Instruments Ltd., UK)	384.8 ± 7.8	251.9 ± 2.2
Particle size distribution (% vol)			
Bulk density (x 10^{-2}) (g/cm^3)	ASTM D6111-19a	1.87	2.59
BET surface area (x10^5) cm^2/g)	High performance adsorption analyzer with N_2 adsorption isotherm (3Flex, Micromeritics, USA) ASTM D1993-18	0.98 ± 0.06	1.33 ± 0.07
Pore volume (x 10^{-3}) (cm^3/g)		8.43	7.74
Pore size (A^0)		34.4	23.3
SEM photograph	Scanning electron microscopy (SEM) at 10-15kV (Nova NanoSEM 450, FEI, USA)		
Aspect ratio		3.16 ± 0.66	1.86 ± 0.85

Seawater Characterisation

As the testing medium for the seawater immersion conditions of WPVCs, this work used seawater obtained from a scuba diving zone around Koh Talu Island (Rayong, Thailand). The seawater was analysed using an ion chromatography analyser (Metrohm model 761 Compact IC, Switzerland) for characterisation of the ion composition of seawater before the test, as given in Table 4.

Table 4. The Ionic Compositions of Actual Seawater

Ion Salt Composition in Actual Seawater (Salinity)	Concentration	
	mg/L	ppt
Cl^-	21,614.73	21.61
Na^+	9,880.18	9.88
SO_4^{2-}	2,247.83	2.25
Mg^{2+}	1,381.72	1.38
Ca^{2+}	621.53	0.62
K^+	369.91	0.37
Total	**36,115.90**	**36.12**

Dimensional Stability

The cross-sectional areas of all specimens were measured after UV-weathering ageing and seawater immersion with any conditions before tensile and flexural tests, as the dimensional stability (Fig. 1). UV-weathering ageing and seawater immersion caused diffusion or penetration, which resulted in changes of cross-sectional areas in the specimens. Figure 1 shows the cross-sectional area of the specimens for tensile and flexural tests as a function of UV-weathering ageing and seawater immersion periods. Neat PVC had a smaller cross-sectional area than PVC with anti-microbial agents and WPVC composite materials. Particularly, WPVC composite materials had a larger cross-sectional area by approximately 5% for tensile (Fig. 1(a) and Fig. 1(c)) and 8% for flexural (Fig. 1(b), (d)) before UV-weathering ageing and seawater immersion, as compared with PVC with and without anti-microbial agents. PVC with anti-microbial agents showed a minor change with the addition of ageing periods. WPVC composite materials showed a larger cross-section by approximately 9% for tensile and flexural (Fig. 1(a) and Fig. 1(b)) during UV-weathering ageing periods, and approximately 14% for tensile and flexural (Fig. 1(c) and Fig. 1(d)) during seawater immersion periods because of water diffusion after ageing, compared with PVC with and without anti-microbial agents. Therefore, cross-sectional areas of all specimens have to be measured before testing the mechanical properties.

Seawater Micro-Organisms for Testing

Figure 2 shows the subculture procedures for seawater micro-organisms and cell counting before anti-microbial tests. *Aspergillus niger* TISTR 3012 and *Chlorella vulgaris* TISTR 8580 were representatively selected as a marine fungus and a marine alga, respectively, which were obtained from the Biodiversity Research Centre (BRC) and the Algal Excellent Centre (ALEC), Thailand Institute of Scientific and Technological Research (Pathum Thani, Thailand), respectively. A fungus was subcultured on Petri dishes of potato dextrose agar (PDA) using an incubator (Sanyo model MIR-153, United Kingdom) at a temperature of 30 °C for 7 days. The subcultured fungi having a diameter of 3 mm from a cork borer were continued in the flasks of potato dextrose broth (PDB) using a shaking incubator (JISICO model J-SIL, Korea) at 100 rpm with the same conditions before quantitative examination of fungal activity (Fig. 2(a)). Alga was subcultured on Petri dishes of BG-11 agar under a cool-white fluorescent lamp with an intensity of 2,000-3,000 lux at a temperature of 28 °C and a bright/dark cyclic period of 12/12 h for 14 days. One full scoop of an inoculation loop of the subcultured algae colonies was continued in the flasks of BG-11 broth under feeding O_2 with the same conditions before the quantitative examination of algal activity, as shown in Fig. 2(b). The subculture of two microbes was controlled by using an aseptic technique.

Ageing Conditions

UV-weathering ageing

The specimens were tested under both UV and condensation ageing following ASTM G154-16 cycle 1 with testing periods of 0, 4, 8, 16 and 32 days, as shown in Chinkamonthong *et al.* (2013).

Seawater immersion

The specimens were immersed in an acrylic chamber with 250 mL of actual seawater for testing periods of 0, 7, 30, 60 and 90 days following ASTM C1202-19. The actual seawater was filtrated by membrane filters with an approximate diameter of 0.45 μm and sterilised by an auto-steam steriliser (Vision Scientific model VS-1321-60, Korea) at 121 °C with a pressure of 15 Ib/in^2 for 15 min to eliminate the visible and invisible species, respectively. An acrylic chamber of actual seawater was shaken by a shaker (PNP Green SSeriker, Thailand) at 50 rpm during the test. The actual seawater in the acrylic chamber was changed for half of the testing periods, representing the seawater resistance behavior in the actual coastal applications.

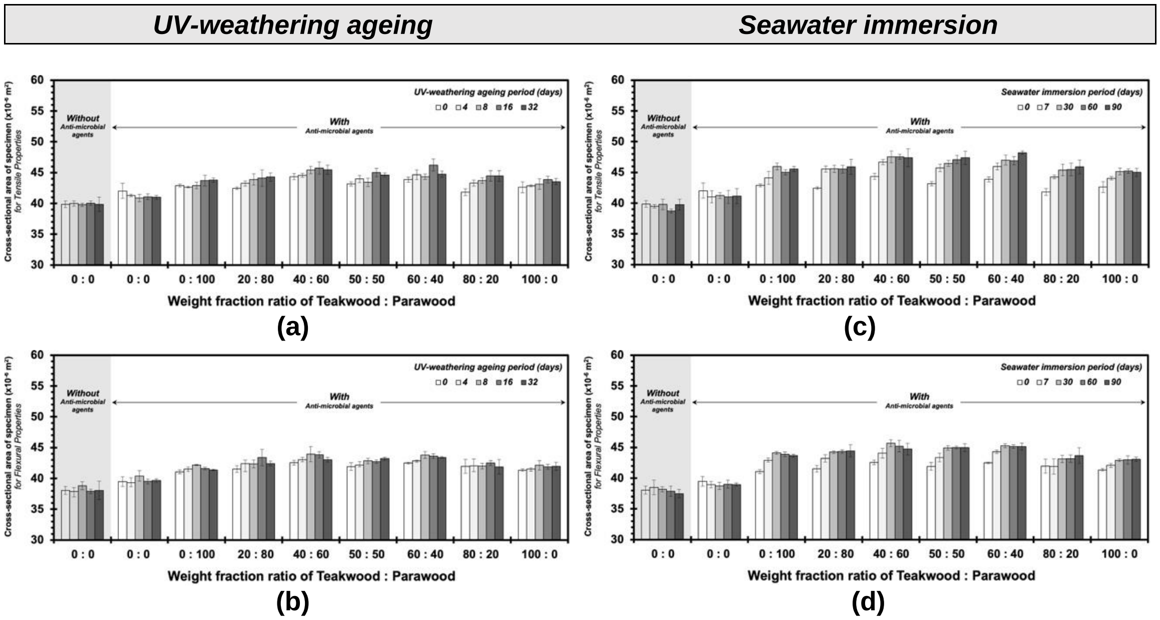


Fig. 1. The cross-sectional area of the specimens for (a), (c) tensile and (b), (d) flexural tests as a function of UV-weathering ageing and seawater immersion periods

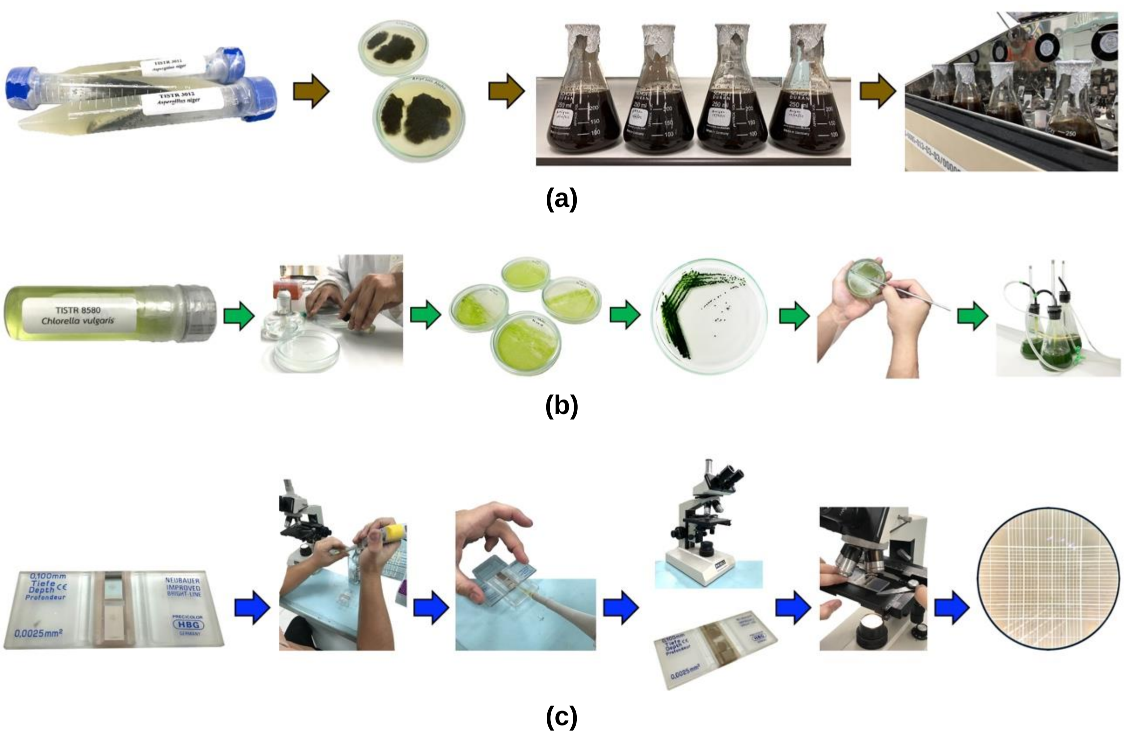


Fig. 2. The subculture procedures for seawater micro-organisms (a) fungi (b) algae and (c) cell counting, before anti-microbial tests

Mechanical Properties of PVC and WPVC Specimens

The tensile and flexural properties of the specimens after UV-weathering ageing and seawater immersion with any conditions were tested by following ASTM D638-14 with a testing speed of 5 mm/min and ASTM D790-17 with a testing speed of 1.36 mm/min using a universal testing machine (Shimadzu model Autograph AG-I, Tokyo, Japan).

Percentage Reduction of Fungal and Algal Growth

Quantitative examinations of *A. niger* and *C. vulgaris* activities for all specimens were modified slightly from ASTM D1413-07$^{\varepsilon 1}$ and ASTM D3731-20, respectively. The dried weight in mg/L for fungal growth and the chlorophyll-*a* content in μg/mL for algal growth were converted to the percentage reduction of species growths for all specimens.

Investigation of percentage reduction for fungal growth was initiated by preparing the subcultured *A. niger* cell suspension with an initial cell number of 1 x 10^4 cells/mL in flasks of PDB of 100 mL, whereas the subcultured *C. vulgaris* cell suspension with an initial cell number of 1 x 10^4 cells/mL in flasks of BG-11 broth of 100 mL was prepared for determining the percentage reduction of algal growth. An initial cell number of fungi and algae was counted by a haemocytometer (Precicolor HBG, Germany) and optical microscope (Meiji Techno Co., Ltd., Japan), and was also calculated by a dilution equation, as shown in Fig. 2(c). Square specimens (50 mm x 50 mm x 3 mm) were placed into 250 mL Erlenmeyer flasks containing PDB of 100 mL for the fungal test and placed into 250 mL Erlenmeyer flasks containing BG-11 broth of 100 mL for the algal test. Specimens for the fungal test were incubated and shaken by following Section of seawater micro-organisms for testing for 14 days, whereas the algal test was shaken by following Section of seawater micro-organisms for testing using a shaker (JEIO TECH model Lab companion SK-300, Korea) at a shaking speed of 150 rpm for 17 days.

The suctioning process of media for the specimens was applied after fungal incubation was done. The dried weight of fungi media in mg/L after using a hot-air oven of 80 °C for 3 days was calculated as the percentage reduction of fungal growth using the following Eq. 1, whereas the algal media of 1 mL of the specimens after algal incubation was done by being diluted with methanol 99.9% of 9 mL. The diluted algal media were placed in a dark room for 2 h to extract the chlorophyll-*a*. After the extraction process, the diluted algal media were centrifuged by a refrigerated centrifuge machine (Hettich Zentrifugen model Universal 32 R, Germany) at 5,000 rpm with a temperature of 4 °C for 5 min. The upper centrifuged algal media of 3 mL was examined by a UV/Visible scanning spectrophotometer (Mettler Toledo model UV5, Switzerland) to analyse the UV absorbance at wavelength numbers of 650 nm and 665 nm, as converted to the chlorophyll-*a* content. The chlorophyll-*a* content in μg/mL was also calculated as the percentage reduction of algal growth using Eq. 1,

$$\text{Percentage reduction of fungal growth and algal growth (\%)} = [(C-S)/C] \times 100 \quad (1)$$

where C and S are dried weight in mg/L for fungal growth and chlorophyll-*a* content in μg/mL for algal growth of control and all specimens, respectively.

RESULTS AND DISCUSSION

Mechanical Properties

UV-weathering ageing condition

Figure 3 shows the tensile properties of the specimens as a function of UV-weathering ageing periods. Figure 3(a) shows the tensile modulus of the specimens as a function of UV-weathering ageing periods. The addition of anti-microbial agents both IPBC and Terbutryn slightly increased the tensile modulus of PVC compared with neat PVC. It did not clearly show any changes in the tensile modulus because there were small amount of the anti-microbial agents being added. The presence of wood particles increased the tensile modulus of the WPVC composite materials when compared with PVC with and without anti-microbial agents. This was due to the rigidity of wood particles. Considering teakwood and parawood with any ratios in WPVC composite materials, the presence of higher parawood content in WPVC composite materials (in formulations of 0:100, 20:80 and 40:60) showed the higher tensile modulus compared with the presence of higher teakwood content in WPVC composite materials (in formulations of 60:40, 80:20 and 100:0). This was because the higher tensile modulus of the WPVC composite materials was dominated by parawood content with greater particle size distribution, higher bulk density and lower porosity, both pore volume and pore size while the lower tensile modulus of the WPVC composite materials was dominated by teakwood content with lower particle size distribution, lower bulk density and higher porosity, both pore volume and pore size (as given in Table 3) (Frigione and Marra 1976; Amin *et al.* 2019; Pereira *et al.* 2020; Zhang *et al.* 2020; Weaver *et al.* 2021; Amin *et al.* 2022). Moreover, parawood has greater particle size distribution, higher bulk density and lower porosity in both pore volume and pore size, which showed higher density in WPVC than the effect of air bubbles in WPVC, as resulted in WPVC composite material with higher parawood content gave higher tensile modulus than with higher teakwood content. The addition of UV-weathering ageing periods decreased the tensile modulus of the specimens, which clearly showed in WPVC composite materials because of the degradation of wood particles in WPVC composite materials. However, WPVC composite materials with higher parawood content (in formulations of 0:100, 20:80 and 40:60) still indicated higher tensile modulus than those with higher teakwood content (in formulations of 60:40, 80:20 and 100:0).

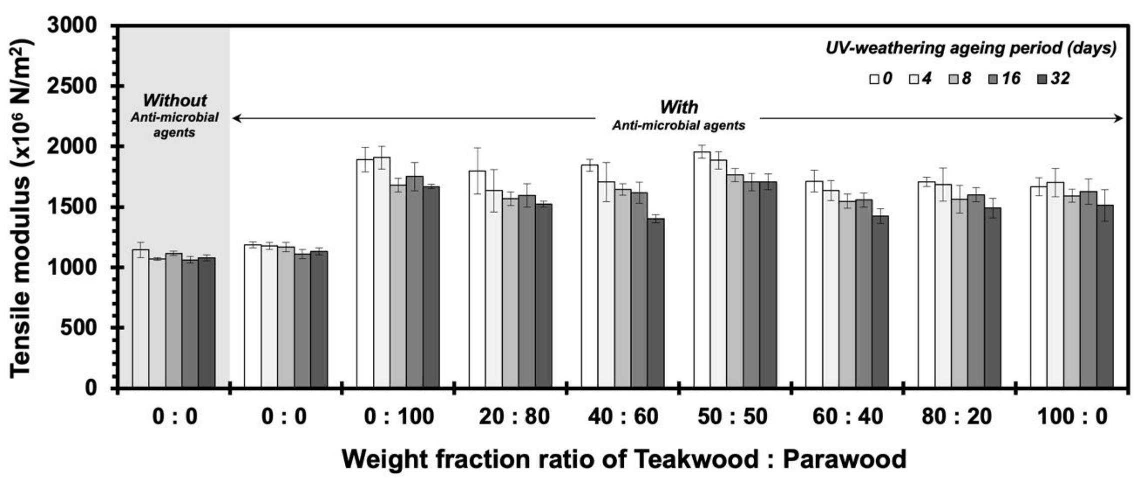
Figure 3(b) shows the tensile strength of the specimens as a function of UV-weathering ageing periods. The addition of anti-microbial agents both IPBC and Terbutryn slightly increased the tensile strength of PVC when compared with neat PVC. The tensile strength of PVC with and without anti-microbial agents was similar to the tensile modulus, but decreased in WPVC composite materials. This was because wood particles in WPVC composite materials acted as defects due to incompatibility between wood particles and PVC matrix, though a silane coupling agent was applied. Wood particles also produce air bubbles in WPVC composite materials. In addition, wood particles of both teakwood and parawood did not contribute to the reinforcement in the WPVC composite materials.

Figure 3(c) shows the elongation at break of the specimens as a function of UV-weathering ageing periods. The presence of anti-microbial agents, both IPBC and Terbutryn, did not significantly affect the elongation at break of PVC compared with neat PVC. The presence of wood particles in both teakwood and parawood decreased the elongation at break of WPVC composite materials compared to PVC with and without anti-microbial agents, which conformed to the discussion of tensile strength, while the addition of UV-weathering ageing periods had no effect on the elongation break of WPVC composite materials.

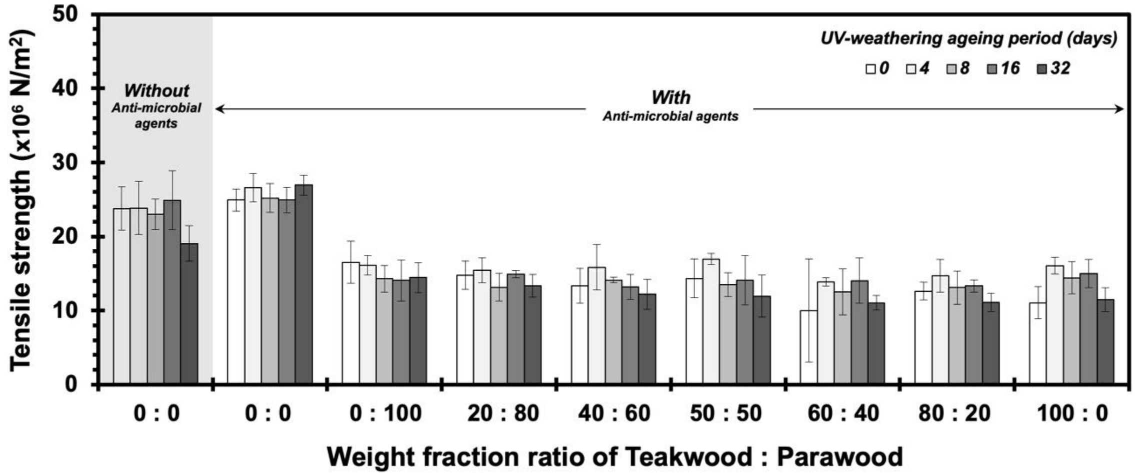
Figure 4 shows the flexural properties of the specimens as a function of UV-weathering ageing periods. The flexural properties of both flexural modulus (Fig. 4(a)) and flexural strength (Fig. 4(b)) were consistent with the discussion of tensile properties.

Considering the effect of UV-weathering ageing periods on the properties of the WPVC composite materials, the tensile and flexural properties of both tensile modulus and tensile strength, and flexural modulus and flexural strength of the WPVC composite materials decreased when increasing the UV-weathering ageing periods. However, decreases in the properties of WPVC composite materials by the addition of UV-weathering ageing periods were mainly affected by the degradation of wood particles in WPVC composite materials.

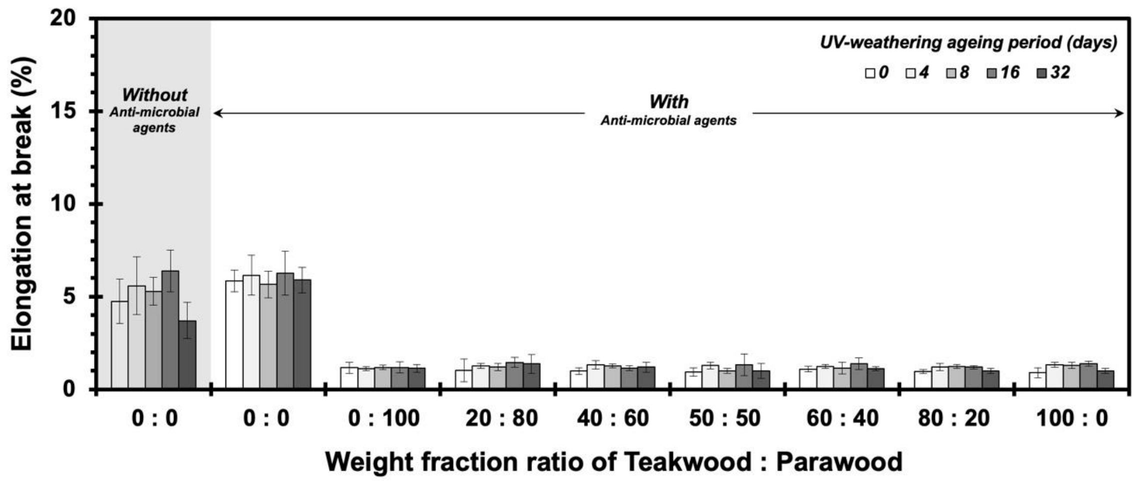
Moreover, the presence of higher parawood content in WPVC composite materials (in formulations of 0:100, 20:80 and 40:60) showed higher sensitivity with UV-weathering ageing than the presence of higher teakwood content (in formulations of 60:40, 80:20 and 100:0). This was due to WPVC composite materials being composed of higher parawood content, as mixtures with lower total lignin (as given in Table 3) were more easily damaged from UV degradation onto wood particle in WPVC composite materials than of higher teakwood content as higher total lignin (as given in Table 3). This was supported by Sadeghifar and Ragauskas (2020) and Tran *et al.* (2021). It can be said that the addition of lignin content in WPVC composite materials contributed to the higher UV protection of materials (Espinoza-Acosta *et al.* 2022).



(a)

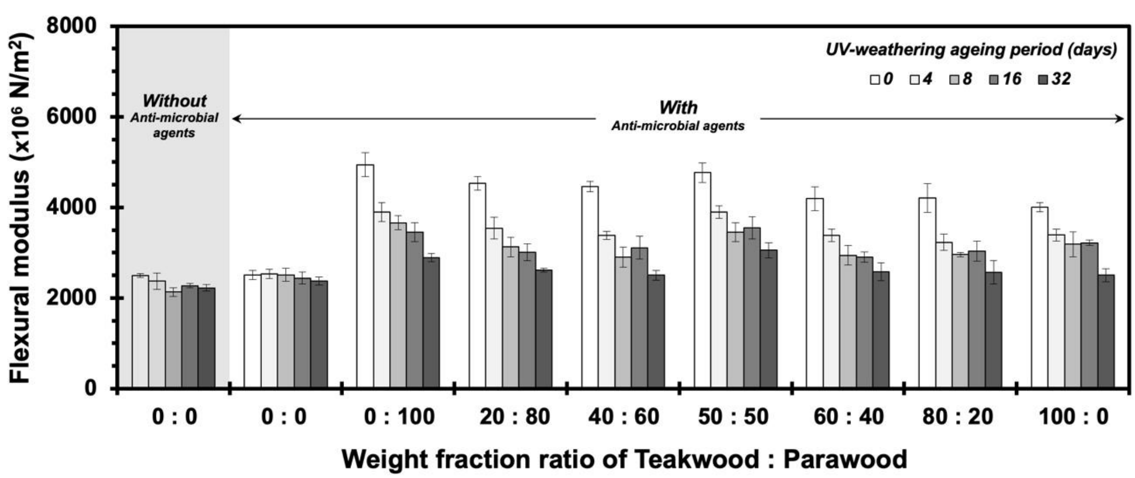


(b)

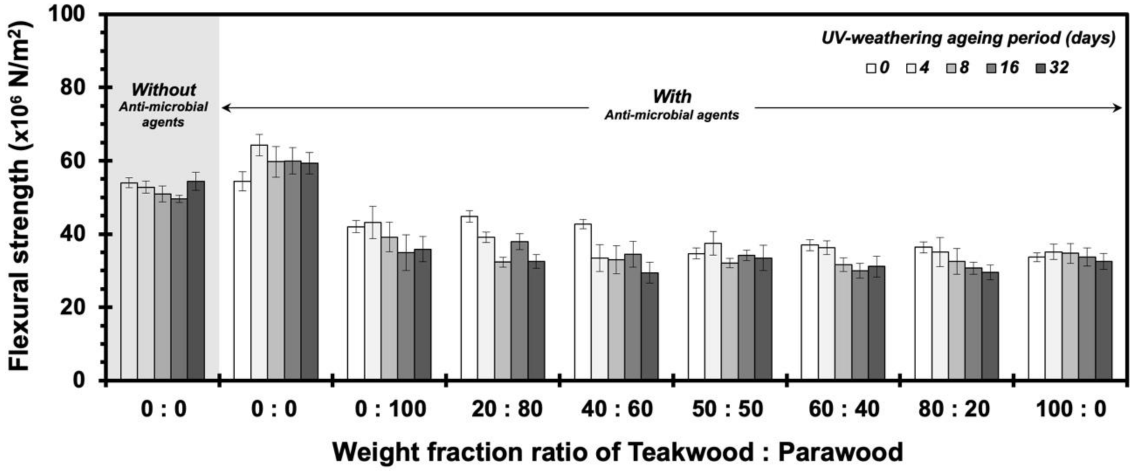


(c)

Fig. 3. (a) Tensile modulus, (b) strength, and (c) elongation at break as a function of UV-weathering ageing periods



(a)



(b)

Fig. 4. (a) Flexural modulus and (b) strength as a function of UV-weathering ageing periods

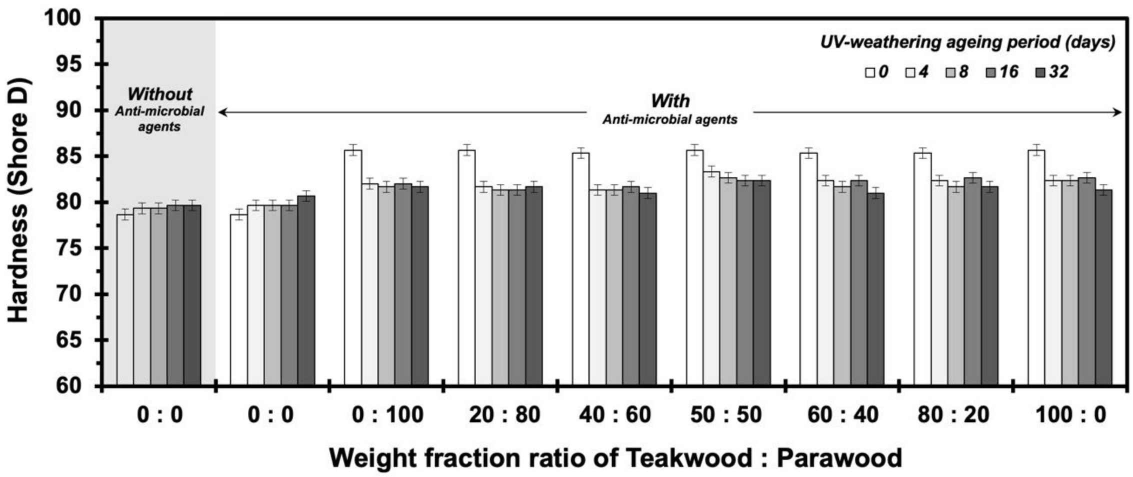
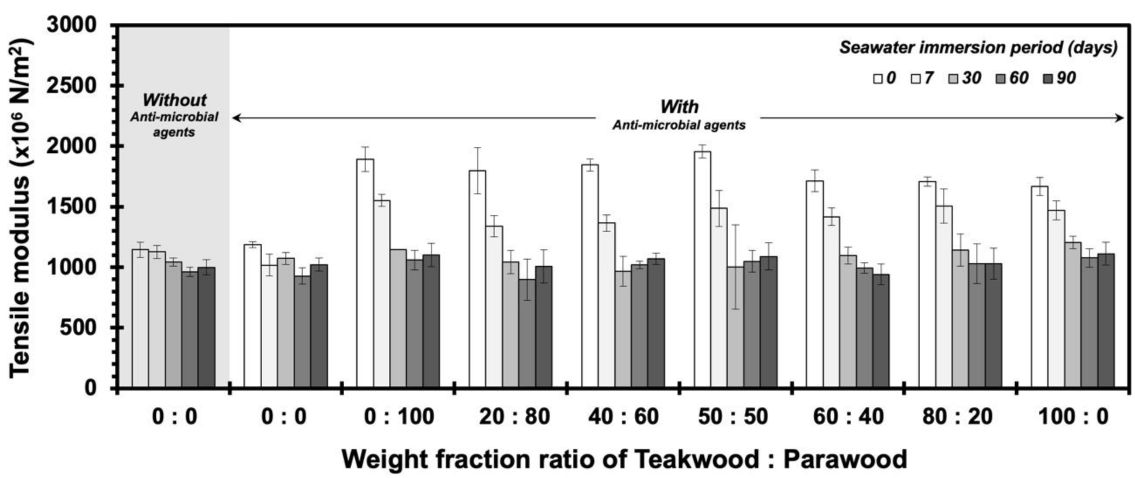


Fig. 5. The hardness of the specimens as a function of UV-weathering ageing periods

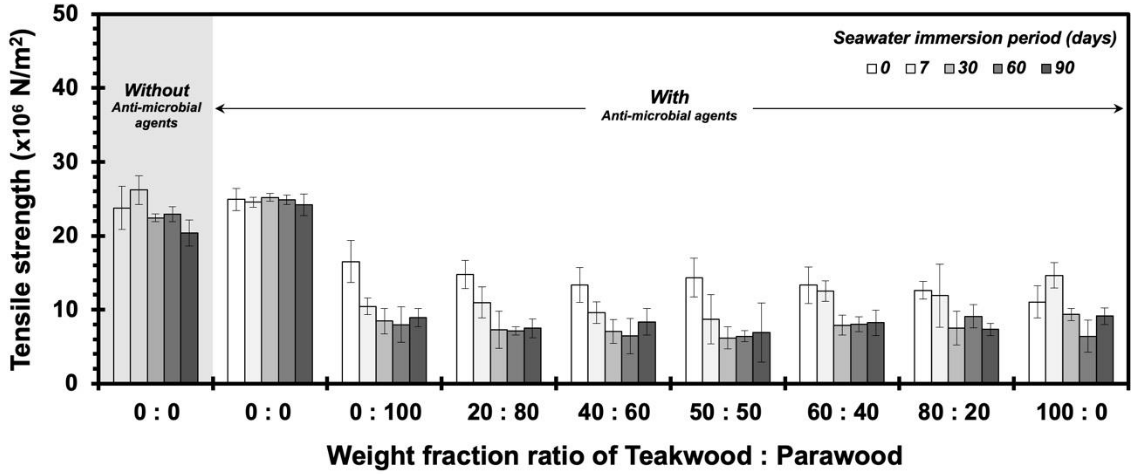
Figure 5 shows the hardness in shore D of the specimens as a function of UV-weathering ageing periods. The presence of anti-microbial agents both IPBC and Terbutryn did not significantly affect the hardness of PVC compared with neat PVC. The presence of wood particles in both teakwood and parawood increased the hardness of the WPVC composite materials compared with PVC with and without anti-microbial agents. This was due to the rigidity of wood particles. Considering the WPVC composite materials in teakwood and parawood, WPVC composite materials with higher teakwood content (in formulations of 60:40, 80:20 and 100:0) slightly increased the hardness compared to higher parawood content (in formulations of 0:100, 20:80 and 40:60). This was due to the higher total lignin of teakwood (as given in Table 3) increasing the surface hardness of WPVC composite materials. This was supported by Lang *et al*. (2018). The addition of UV-weathering ageing periods decreased the hardness of WPVC composite materials during UV-weathering ageing periods of 0 to 4 days. This was due to the water absorption of wood particles in WPVC composite materials under a condensation stage in UV-weathering ageing. The water absorption of wood particles in WPVC composite materials approached equilibrium during UV-weathering ageing periods of over 4 days.

Seawater immersion condition

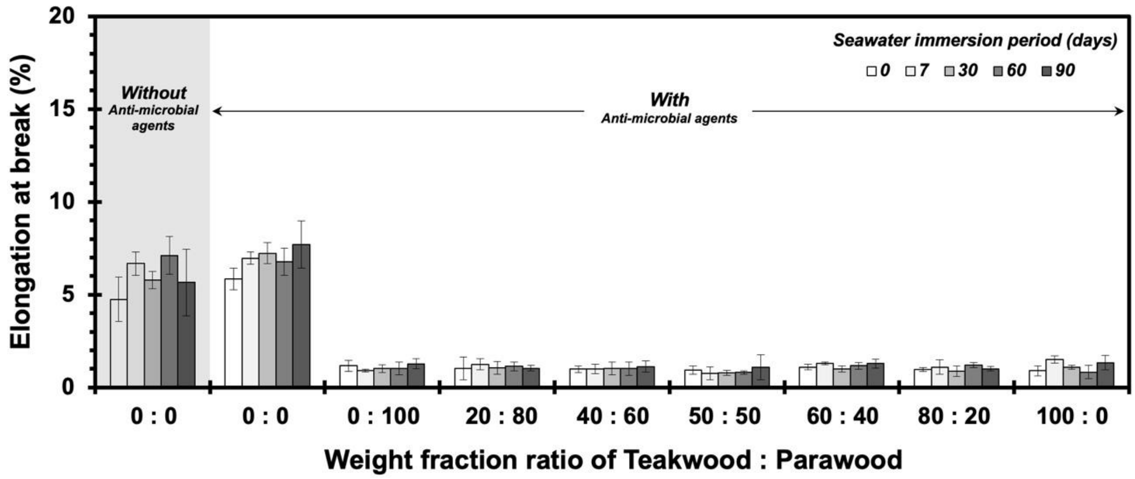
Figure 6 shows the tensile properties for PVC and WPVC as a function of seawater immersion period. The presence of anti-microbial agents, both IPBC and Terbutryn, did not significantly affect the tensile modulus of PVC when compared with neat PVC, which had a similar tensile modulus during UV-weathering ageing (Fig. 6a). The presence of wood particles increased the tensile modulus of WPVC composite materials during seawater immersion periods of 0 to 7 days when compared with PVC with and without anti-microbial agents. This was due to the rigidity of wood particles. The rigidity of wood particles was severely impacted by the water absorption and swelling of wood particles. Therefore, the tensile modulus of WPVC composite materials during seawater immersion periods of over 7 days (30 to 90 days) did not change compared with PVC with and without anti-microbial agents. Considering teakwood and parawood in WPVC composite materials, the presence of higher parawood content in WPVC composite materials (in formulations of 0:100, 20:80 and 40:60) showed higher tensile modulus when compared with the presence of higher teakwood content in WPVC composite materials (in formulations of 60:40, 80:20 and 100:0) during seawater immersion periods of 0 to 7 days. This was due to the higher bulk density and lower porosity of parawood (as given in Table 3). The influence of higher bulk density and lower porosity of parawood in WPVC composite materials was affected significantly by the water absorption and swelling of wood particles. Therefore, the tensile modulus of WPVC composite materials with higher parawood content did not significantly change compared with higher teakwood content during seawater immersion periods of over 7 days (30 to 90 days). The addition of seawater immersion periods decreased the tensile modulus of the specimens, but showed in WPVC composite materials, especially during seawater immersion periods of 0 to 30 days. This was because of water absorption and swelling of wood particles in WPVC composite materials. The water absorption of wood particles in WPVC composite materials was adequate during seawater immersion periods of over 30 days (60 to 90 days).



(a)



(b)

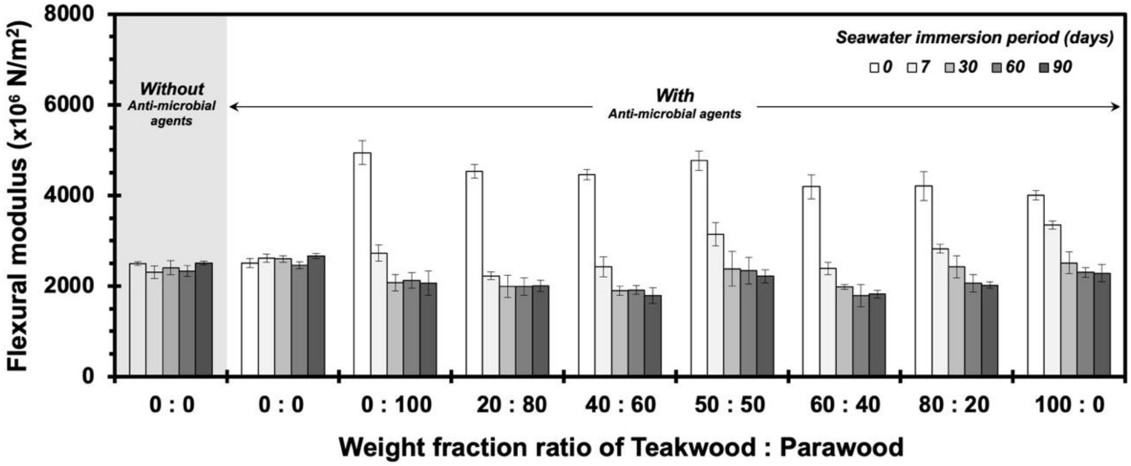


(c)

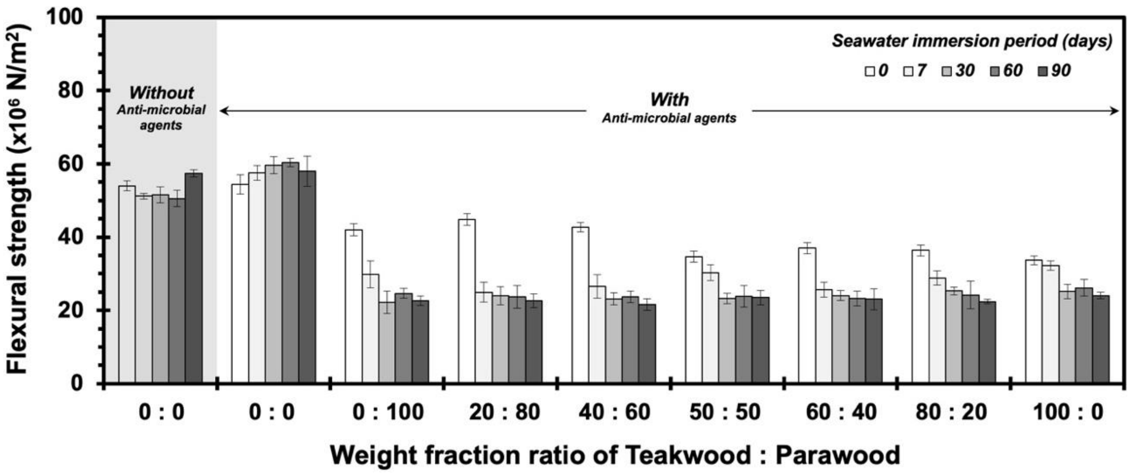
Fig. 6. (a) Tensile modulus, (b) strength, and (c) elongation at break as a function of seawater immersion periods

Figure 6(b) shows the tensile strength of the specimens as a function of seawater immersion periods. The addition of anti-microbial agents both IPBC and Terbutryn slightly increased the tensile strength of PVC compared with neat PVC. The tensile strength of PVC with and without anti-microbial agents had similar tensile modulus but decreased in WPVC composite materials. This was also discussed with tensile strength during UV-weathering ageing. Figure 6(c) shows the elongation at break of the specimens as a function of seawater immersion periods. The anti-microbial agents both IPBC and Terbutryn did not significantly affect the elongation at break of PVC compared with neat PVC. The presence of wood particles in both teakwood and parawood decreased the elongation at break of WPVC composite materials when compared with PVC with and without anti-microbial agents. It was also found in elongation at break during UV-weathering ageing.

Figure 7 shows the flexural properties of the specimens as a function of seawater immersion periods. The flexural properties of both flexural modulus (Fig. 7(a)) and flexural strength (Fig. 7(b)) were consistent with the discussion of tensile properties during seawater immersion periods. Considering the effect of seawater immersion periods on the properties of the WPVC composite materials, the tensile and flexural properties of both tensile modulus and tensile strength, and flexural modulus and flexural strength of the WPVC composite materials decreased with increasing seawater immersion periods. However, decreases in the properties of WPVC composite materials by the addition of seawater immersion periods were mainly affected by the water absorption and swelling of wood particles in WPVC composite materials.



(a)



(b)

Fig. 7. (a) Flexural modulus and (b) strength as a function of seawater immersion periods

WPVC composite materials with higher parawood content (in formulations of 0:100, 20:80 and 40:60) also showed higher sensitivity to seawater immersion periods than with higher teakwood content (in formulations of 60:40, 80:20 and 100:0), especially during seawater immersion periods of 0 to 30 days. This was because WPVC composite materials composed of higher parawood content with lower total lignin (as given in Table 3) underwent more swelling from the water absorption of wood particles in WPVC composite materials than of higher teakwood content with higher total lignin (as given in Table 3). This was due to plant-based lignin having a natural hydrophobic characteristic (Yeap 2020; Lisý *et al.* 2022), which made WPVC composite materials incorporated with higher teakwood content more hydrophobic than those with higher parawood content. WPVC composite materials with higher teakwood content enabled greater dimensional stability than those with higher parawood content, as mentioned in Fig. 1.

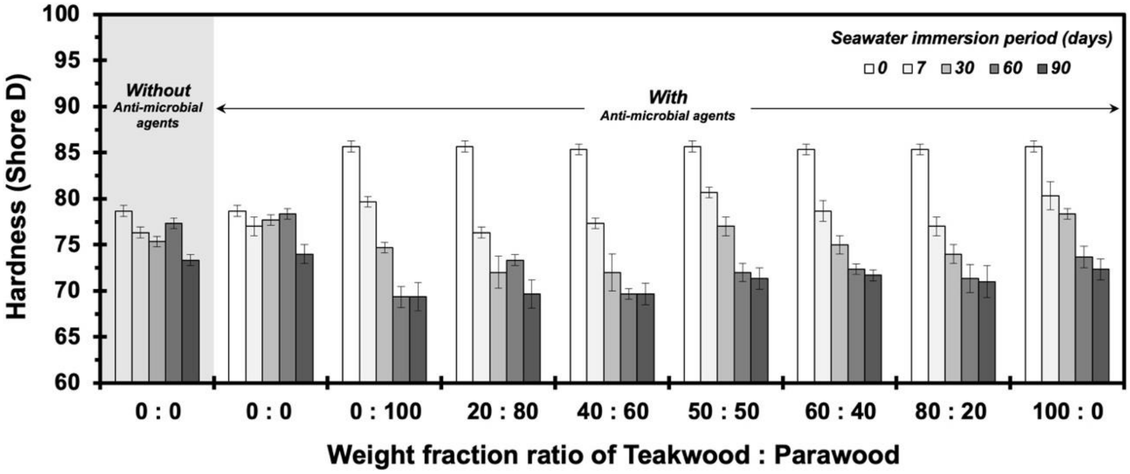


Fig. 8. The hardness of the specimens as a function of seawater immersion periods

Figure 8 shows the hardness in shore D of the specimens as a function of seawater immersion periods. The presence of anti-microbial agents both IPBC and Terbutryn did not significantly affect the hardness of PVC compared with neat PVC. The presence of wood particles in both teakwood and parawood increased the hardness of the WPVC composite materials before seawater immersion (day 0) compared to PVC with and without anti-microbial agents. This was attributed to the rigidity of wood particles. The hardness of WPVC composite materials was decreased by the addition of seawater immersion periods (7 to 90 days) due to the water absorption and swelling of wood particles in WPVC composite materials. WPVC composite materials were lower in hardness than PVC both with and without anti-microbial agents during seawater immersion periods of over 30 days (60 to 90 days). Considering teakwood and parawood in WPVC composite materials, WPVC composite materials with higher teakwood content (in formulations of 60:40, 80:20 and 100:0) increased the hardness compared with higher parawood content (in formulations of 0:100, 20:80 and 40:60). This was due to the higher total lignin of teakwood (as given in Table 3) increasing the surface hardness of WPVC composite materials. It was also found in hardness during UV-weathering ageing. The addition of seawater immersion periods decreased the hardness of WPVC composite materials during seawater immersion periods of 0 to 30 days. This was due to the water absorption and swelling of wood particles in WPVC composite materials. The water absorption and swelling of wood particles in WPVC composite materials reached near-equilibrium during seawater immersion periods of over 30 days (60 to 90 days).

The UV-weathering ageing and seawater immersion had an effect on the mechanical properties of WPVC composite materials, although the test concentrated on similar ageing periods for both UV-weathering ageing periods of 0 to 32 days and seawater immersion periods of 0 to 30 days. It was found that the overall mechanical properties of WPVC composite materials were more sensitive to seawater immersion than UV-weathering ageing. This is because seawater is an electrolyte having persistent ionisation and de-ionisation. Seawater, which is composed mainly of chloride ions at 21,610 mg/L (21.61 ppt), equivalent to 60% of ion composition in seawater (as given in Table 4) affected the high degree of seawater permeability onto WPVC composite materials from larger dipole-dipole interaction (known as polar-polar interaction) between WPVC surface and chloride ion in seawater, in addition to the water permeability and water absorption of wood particles in WPVC composite materials. The high degree of permeability, combined with the hydrophilicity of wood particles, increased the level of seawater diffusion and seawater transportation in WPVC composite materials (Gjørv and Vennesland 1979; Panigrahi *et al.* 2018; Villagrán Zaccardi *et al.* 2018; Mukaddas *et al.* 2019; Ariningsih *et al.* 2021). The water permeability, water diffusion, and water transportation of wood particles in WPVC composite materials during long-term seawater immersion were more influenced by the mechanical properties of WPVC composite materials than the degradation and water absorption of wood particles during UV-weathering ageing in both the UV ageing and condensation stages. Moreover, the wood particles in WPVC composite materials deteriorated by lower energy during UV-weathering ageing following the principle of ALARA. The mechanical properties of WPVC composite materials approached a saturation point during seawater immersion periods of over 30 days. This was supported by the cross-sectional area measurement of the specimens, as described in Fig. 1.

Anti-microbial Properties

Anti-fungal properties

Based on the mechanical properties described in Figs. 3 to 8, only selected conditions were selected to be used for anti-microbial properties. This includes WPVC composite materials with higher parawood content, in a formulation of 20:80, and WPVC composite materials with higher teakwood content, in a formulation of 80:20, compared with PVC both with and without anti-microbial agents. Figure 9 shows the percentage reduction of fungal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) as a function of UV-weathering ageing periods and seawater immersion periods compared to PVC with and without anti-microbial agents.

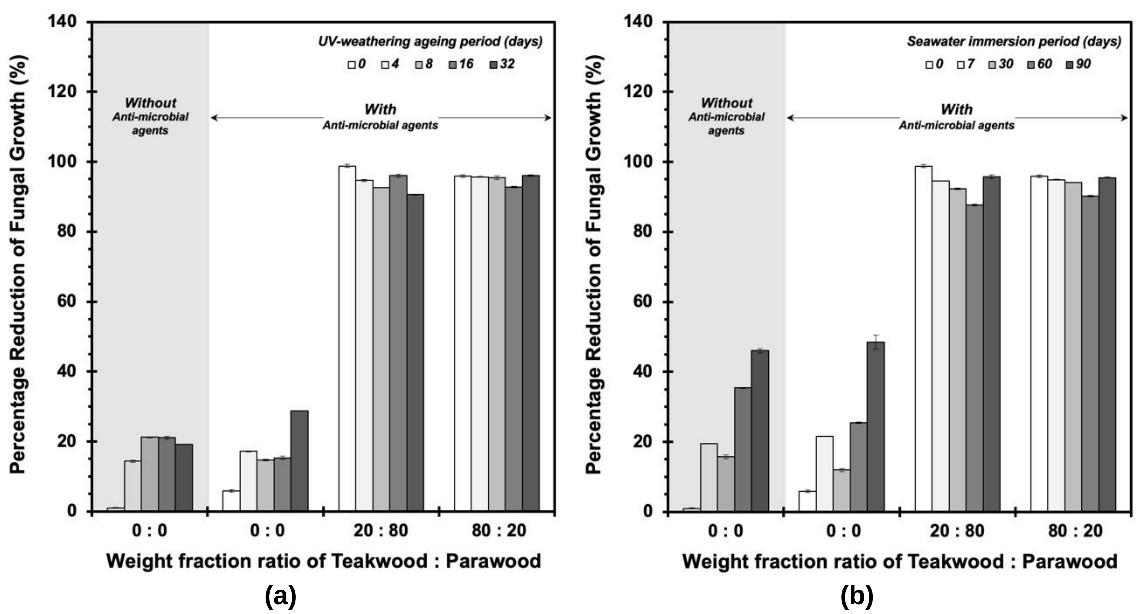


Fig. 9. The percentage reduction of fungal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) as a function of (a) UV-weathering ageing periods and (b) seawater immersion periods compared to PVC with and without anti-microbial agents

Figure 9(a) shows the percentage reduction of fungal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) as a function of UV-weathering ageing periods compared to PVC with and without anti-microbial agents. The presence of anti-microbial agents did not affect the percentage reduction of fungal growth for PVC compared with neat PVC due to IPBC as a fungicide, which cannot be released on the PVC matrix (Kositchaiyong *et al.* 2014b). The presence of wood particles in both teakwood and parawood increased the percentage reduction of fungal growth for WPVC composite materials compared to PVC with and without anti-microbial agents. This was because wood particles acted as good carriers to promote fungicides (Kositchaiyong *et al.* 2014b).

Considering higher teakwood content and higher parawood content, WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) showed similarly good percentages for the reduction of fungal growth. The addition of UV-weathering ageing periods similarly increased the percentage reduction of fungal growth of PVC with and without anti-microbial agents, which did not result in the presence of anti-microbial agents. This was because IPBC is a fungicide, which cannot be diffused without wood particles (Kositchaiyong *et al.* 2014b). The percentage reduction of fungal growth for WPVC composite materials both with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) decreased significantly with increasing UV-weathering ageing periods. This was due to (i) the addition of UV-weathering ageing periods, which leached the presence of anti-microbial agents in WPVC composite materials (Kositchaiyong *et al.* 2014a), and (ii) the degradation of IPBC by UV-thermal energy (Sørensen *et al.* 2010), which both followed a loss in tensile modulus and flexural modulus of WPVC composite materials, as described in Figs. 3(a) and 4(a). Moreover, the percentage reduction of fungal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) also showed higher sensitivity to UV-weathering ageing than with higher teakwood content (in a formulation of 80:20), according to mechanical properties for UV-weathering ageing condition. Figure 9(b) shows the percentage reduction of fungal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) as a function of seawater immersion periods compared to PVC with and without anti-microbial agents. The percentage reduction of fungal growth during seawater immersion was consistent with the percentage reduction of fungal growth during UV-weathering ageing. The addition of seawater immersion periods decreased the percentage reduction of fungal growth for WPVC composite materials, both with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20). This was because the anti-microbial agents in WPVC composite materials were leached during seawater immersion periods. Moreover, the percentage reduction of fungal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) also showed higher sensitivity to seawater immersion than with higher teakwood content (in a formulation of 80:20), according to mechanical properties for seawater immersion condition. However, the percentage reduction of fungal growth for WPVC composite materials during seawater immersion periods of 90 days conversely increased. This was because the excess seawater absorption increased the concentration of NaCl in WPVC composite materials, in which NaCl acted as a fungicide (Policar *et al.* 2011; Stockwell *et al.* 2012; Rodrigues *et al.* 2017).

Considering UV-weathering ageing and seawater immersion, the percentage reduction of fungal growth for PVC with and without anti-microbial agents was more sensitive to seawater immersion than to UV-weathering ageing. The percentage reduction of fungal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) was also more sensitive to seawater immersion than UV-weathering ageing. This was because anti-microbial agents were severely leached by the water permeability, water diffusion, and water transportation of wood particles in WPVC composite materials during seawater immersion periods.

Anti-algal properties

Figure 10 shows the percentage reduction of algal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) as a function of UV-weathering ageing periods and seawater immersion periods compared to PVC with and without anti-microbial agents. Figure 10(a) shows the percentage reduction of algal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) as a function of UV-weathering ageing periods compared to PVC with and without anti-microbial agents. The presence of anti-microbial agents increased the percentage reduction of algal growth for PVC compared to neat PVC. This was because Terbutryn is an algaecide, which gave low molecular interaction with PVC molecules. Therefore, Terbutryn showed a high ability to spread out and diffuse on the PVC matrix (Kositchaiyong *et al.* 2013). The presence of wood particles in both teakwood and parawood increased the percentage reduction of algal growth for WPVC composite materials compared to PVC with and without anti-microbial agents. Wood particles still acted as good carriers to promote algaecides, as well as fungicides in anti-fungal property results. Considering higher teakwood content and higher parawood content, WPVC composite materials with higher parawood content (in a formulation of 20:80) showed a greater percentage reduction of algal growth than those with higher teakwood content (in a formulation of 80:20). This was due to the lower specific surface area of parawood providing a lower interfacial area as well as the lower molecular interaction with Terbutryn. Therefore, Terbutryn in WPVC composite materials with higher parawood content (in a formulation of 20:80) will be freed to migrate and diffuse onto the specimens to kill the algae (Kositchaiyong *et al.* 2013). The addition of UV-weathering ageing periods increased the percentage reduction of algal growth for PVC with anti-microbial agents because the condensation stage in UV-weathering ageing enhanced the diffusivity of Terbutryn in PVC. The addition of UV-weathering ageing periods increased the percentage reduction of algal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20). This was due to the condensation stage in UV-weathering ageing and wood particles increasing the wettability of WPVC composite materials. The diffusion performance of anti-microbial agents varied directly with rigidity and wettability as well as the methods of incorporation used (Pongnop *et al.* 2011; Silapasorn *et al.* 2011; Gitchaiwat *et al.* 2012).

Figure 10(b) shows the percentage reduction of algal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) as a function of seawater immersion periods compared to PVC with and without anti-microbial agents. The percentage reduction of algal growth during seawater immersion periods tended to be similar to the percentage reduction of algal growth during UV-weathering periods. The addition of seawater immersion periods increased the percentage reduction of algal growth for PVC with anti-microbial agents as well as WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20). This was due to the percentage reduction of algal growth of PVC with anti-microbial agents and WPVC composite materials (in formulations of 20:80 and 80:20) being dominated by long-term wettability during seawater immersion.

Considering UV-weathering ageing and seawater immersion, PVC with and without anti-microbial agents, and WPVC composite materials (in formulations of 20:80 and 80:20) during seawater immersion showed a higher percentage reduction of algal growth than during UV-weathering ageing. This was because long-term wettability was more effective than the condensation stage. Moreover, the anti-microbial agents both IPBC and Terbutryn in PVC and WPVC composite materials can be performed without interfering with each other.

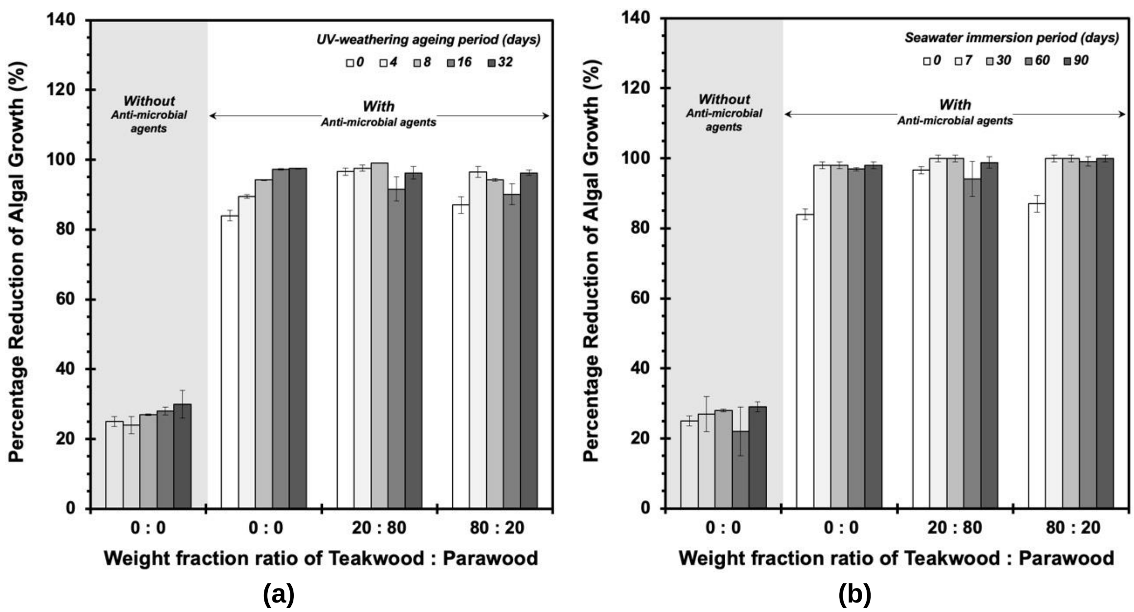


Fig. 10. The percentage reduction of algal growth for WPVC composite materials with higher parawood content (in a formulation of 20:80) and with higher teakwood content (in a formulation of 80:20) as a function of (a) UV-weathering ageing periods and (b) seawater immersion periods compared to PVC with and without anti-microbial agents

CONCLUSIONS

This work reported the mechanical performance and anti-fungal and anti-algal properties for polyvinyl chloride (PVC) and wood/PVC composites (WPVC) incorporated with teakwood and parawood particles during UV-weathering ageing and seawater immersion, which could be applied for coastal environment applications. The main findings of the work can be summarized as follows:

1. The presence of higher parawood contents (in formulations of 0:100, 20:80 and 40:60) in WPVC composite materials showed better mechanical properties than those of higher teakwood contents (in formulations of 60:40, 80:20 and 100:0).

2. Seawater immersion caused more deterioration of WPVC composite materials than UV-weathering ageing.
3. Both anti-microbial agents and wood particles in WPVC composite materials could be used as potentially good carriers to promote fungicides and algaecides for anti-microbial properties, including the percentage reduction of fungal and algal growth.
4. Increasing UV-weathering ageing and seawater immersion periods decreased the percentage reduction of fungal growth, but increased the percentage reduction of algal growth for WPVC composite materials.
5. With greater particle size distribution, higher bulk density and lower porosity of the parawood, as compared with the teakwood, high parawood content in a formulation of 20:80 in WPVC composite materials was recommended for coastal environment applications.

ACKNOWLEDGMENTS

The authors thank the Thailand Science Research and Innovation (TSRI), National Research Council of Thailand (NRCT) and V.P. Wood company limited under Research and Researchers for Industries (RRI) Ph.D. programme (PHD60I0064), Rubber research grant (RDG60T0127) and King Mongkut's University of Technology Thonburi (KMUTT) under Incubation of high caliber researcher project (65000168). The authors are grateful to the department of civil and environmental engineering technology, college of industrial technology, King Mongkut's University of Technology North Bangkok (KMUTNB) and department of materials engineering, faculty of engineering, Rajamangala University of Technology Rattanakosin (RMUTR) for supporting microbiology laboratories.

REFERENCES CITED

Amin, M. N., Murtaza, T., Shahzada, K., Khan, K., and Adil, M. (2019). "Pozzolanic potential and mechanical performance of wheat straw ash incorporated sustainable concrete," *Sustainability* 11(2), 1-20. DOI: 10.3390/su11020519

Amin, M. N., Siffat, M. A., Shahzada, K., and Khan, K. (2022). "Influence of fineness of wheat straw ash on autogenous shrinkage and mechanical properties of green concrete," *Crystals* 12(5). DOI: 10.3390/cryst12050588

Ariningsih, Y. S., Nuralinah, D., and Saputra, A. W. W. (2021). "Diffusion of chloride from seawater into the concrete analysis: A literature review on implemented approaches," *IOP Conference Series: Earth and Environmental Science* 930(1). DOI: 10.1088/1755-1315/930/1/012015

Chan-Hom, T., Yamsaengsung, W., Prapagdee, B., Markpin, T., and Sombatsompop, N. (2017). "Flame retardancy, antifungal efficacies, and physical-mechanical properties for wood/polymer composites containing zinc borate," *Fire and Materials* 41(6), 675-687. DOI: 10.1002/fam.2408

Chaochanchaikul, K., Jayaraman, K., Rosarpitak, V., and Sombatsompop, N. (2012). "Influence of lignin content on photodegradation in wood/HDPE composites under UV weathering," *BioResources* 7(1), 38-55.

Chaochanchaikul, K., Rosarpitak, V., and Sombatsompop, N. (2013). "Photodegradation profiles of PVC compound and wood/PVC composites under UV weathering," *Express Polymer Letters* 7(2), 146-160. DOI: 10.3144/expresspolymlett.2013.14

Chinkamonthong, R., Kositchaiyong, A., and Sombatsompop, N. (2013). "Effects of thermal and UV aging on antibacterial properties of linear low-density polyethylene and poly(vinyl chloride) films containing nano-silver colloid," *Journal of Plastic Film and Sheeting* 29(2), 144-162. DOI: 10.1177/8756087912464967

Crossland, C. J., Baird, D., Ducrotoy, J. P., Lindeboom, H., Buddemeier, R. W., Dennison, W. C., Maxwell, B. A., Smith, S. V., and Swaney, D. P. (2005). "The coastal zone - a domain of global interactions," in: *Coastal Fluxes in the Anthropocene. Global Change — The IGBP Series*, Springer, Berlin, pp. 1-37. DOI: 10.1007/3-540-27851-6_1

Eakintumas, W., Pulngern, T., Rosarpitak, V., and Sombatsompop, N. (2022a). "Experimental investigation of lateral resisting elements for the wood polyvinyl chloride composite log-house under in-plane lateral loads," *Journal of Vinyl and Additive Technology* 28(1), 153-171. DOI: 10.1002/vnl.21877

Eakintumas, W., Pulngern, T., Rosarpitak, V., and Sombatsompop, N. (2022b). "Finite element modeling and experimental investigation for wood/PVC composites log-walls under in-plane lateral load," *Polymers* 14(21). DOI: 10.3390/polym14214673

Espinoza-Acosta, J. L., Figueroa-Espinoza, E. G., and Rosa-Alcaraz, M. de los Á. D. la. (2022). "Recent progress in the production of lignin-based sunscreens: a review," *BioResources* 17(2), 3674-3701. DOI: 10.15376/biores.17.2.Espinoza

Frigione, G., and Marra, S. (1976). "Relationship between particle size distribution and compressive," *Cement and Concrete Research* 6, 113-128.

Gitchaiwat, A., Kositchaiyong, A., Sombatsompop, K., Prapagdee, B., Isarangkura, K., and Sombatsompop, N. (2012). "Assessment and characterization of antifungal and antialgal performances for biocide-enhanced linear low-density polyethylene," *Journal of Applied Polymer Science* 128(1), 371-379. DOI: 10.1002/app.37675

Gjørv, O. E., and Vennesland. (1979). "Diffusion of chloride ions from seawater into concrete," *Cement Concrete Res.* 9(2), 229-238. DOI:10.1016/0008-8846(79)90029-2

Jeamtrakull, S., Kositchaiyong, A., Markpin, T., Rosarpitak, V., and Sombatsompop, N. (2012). "Effects of wood constituents and content, and glass fiber reinforcement on wear behavior of wood/PVC composites," *Composites Part B: Engineering* 43(7), 2721-2729. DOI: 10.1016/j.compositesb.2012.04.031

Kanking, S., Pulngern, T., Rosarpitak, V., and Sombatsompop, N. (2021). "Temperature profiles and electric energy consumption for wood/poly(vinyl chloride) composite and fibre cement board houses," *Journal of Building Engineering* 42, 102784. DOI: 10.1016/j.jobe.2021.102784

Kositchaiyong, A., Rosarpitak, V., Hamada, H., and Sombatsompop, N. (2014a). "Anti-fungal performance and mechanical-morphological properties of PVC and wood/PVC composites under uv-weathering aging and soil-burial exposure," *International Biodeterioration and Biodegradation* 91, 128-137. DOI: 10.1016/j.ibiod.2014.01.022

Kositchaiyong, A., Rosarpitak, V., Prapagdee, B., and Sombatsompop, N. (2013). "Molecular characterizations, mechanical properties and anti-algal activities for PVC and wood/PVC composites containing urea- and triazine-based algaecides," *Composites Part B: Engineering* 53, 25-35. DOI: 10.1016/j.compositesb.2013.04.036

Kositchaiyong, A., Rosarpitak, V., and Sombatsompop, N. (2014b). "Antifungal properties and material characteristics of PVC and wood/PVC composites doped with carbamate-based fungicides," *Polymer Engineering & Science* 54(6), 1248-1259. DOI: 10.1002/pen.23672

Lang, J. M., Shrestha, U. M., and Dadmun, M. (2018). "The effect of plant source on the properties of lignin-based polyurethanes," *Frontiers in Energy Research* 6, 1-12. DOI: 10.3389/fenrg.2018.00004

Lisý, A., Ház, A., Nadányi, R., Jablonský, M., and Šurina, I. (2022). "About hydrophobicity of lignin: a review of selected chemical methods for lignin valorisation in biopolymer production," *Energies* 15(17). DOI: 10.3390/en15176213

Mukaddas, A.M., Abd Aziz, F.N.A., Mohd Nasir, N.A., and Mohamed Sutan, N. (2019). "Water permeability and chloride and sulphate resistance of rubberised fibre mortar," *Journal of Civil Engineering, Science and Technology* 10(2), 135-146. DOI: 10.33736/jcest.1741.2019

Panigrahi, S., Kumar, S., Panda, S., and Borkataki, S. (2018). "Effect of permeability on primary processing of wood," *Journal of Pharmacognosy and Phytochemistry* 7(4), 2593-2598.

Pattamasattayasonthi, N., Chaochanchaikul, K., Rosarpitak, V., and Sombatsompop, N. (2011). "Effects of UV weathering and a CeO_2-based coating layer on the mechanical and structural changes of wood/PVC composites," *Journal of Vinyl and Additive Technology* 17(1), 9-16. DOI: 10.1002/vnl.20246

Pereira, M. C., Soares, A., Flores-Colen, I., and Correia, J. R. (2020). "Influence of exposure to elevated temperatures on the physical and mechanical properties of cementitious thermal mortars," *Applied Sciences (Switzerland)* 10(6). DOI: 10.3390/app10062200

Policar, T., Smyth, J., Flanigan, M., Kouba, A., and Kozák, P. (2011). "Sodium chloride as effective antifungal treatment for artificial egg incubation in *Austropotamobius pallipes*," *Knowledge and Management of Aquatic Ecosystems* 401(13), 1-6. DOI: 10.1051/kmae/2011027

Pongnop, W., Sombatsompop, K., Kositchaiyong, A., and Sombatsompop, N. (2011). "Effects of incorporating technique and silver colloid content on antibacterial performance for thermoplastic films," *Journal of Applied Polymer Science* 122(5), 3456-3465. DOI: 10.1002/app.34448

Pulngern, T., Chucheepsakul, S., Padyenchean, C., Rosarpitak, V., Prapruit, W., Chaochanchaikul, K., and Sombatsompop, N. (2010). "Effects of cross-section design and loading direction on the creep and fatigue properties of wood/PVC composite beams," *J. Vinyl and Additive Technology* 16(1), 42-49. DOI: 10.1002/vnl.20227

Pulngern, T., Eakintumas, W., Rosarpitak, V., and Sombatsompop, N. (2017). "Compressive load, thermal and acoustic properties of wood/polyvinyl chloride composite log-wall panels," *Journal of Reinforced Plastics and Composites* 36(16), 1183-1193. DOI: 10.1177/0731684417699712

Rodrigues, A. I., Gudiña, E. J., Teixeira, J. A., and Rodrigues, L. R. (2017). "Sodium chloride effect on the aggregation behaviour of rhamnolipids and their antifungal activity," *Scientific Reports* 7(1), 12907. DOI: 10.1038/s41598-017-13424-x

Sadeghifar, H., and Ragauskas, A. (2020). "Lignin as a uv light blocker-a review," *Polymers* 12(5), 1-10. DOI: 10.3390/POLYM12051134

Silapasorn, K., Sombatsompop, K, Kositchaiyong, A., Wimolmala, E., Markpin, T., and Sombatsompop, N. (2011). "Effect of chemical structure of thermoplastics on antibacterial activity and physical diffusion of triclosan doped in vinyl thermoplastics and their composites with $CaCO_3$," *Journal of Applied Polymer Science* 121(1), 253-261. DOI: 10.1002/app.33555

Sombatsompop, N., Prapruit, W., Chaochanchaikul, K., Pulngern, T., and Rosarpitak, V. (2010). "Effects of cross section design and testing conditions on the flexural properties of wood/PVC composite beams," *Journal of Vinyl and Additive Technology* 16(1), 33-41. DOI: 10.1002/vnl.20202

Sørensen, G., Nielsen, A. L., Pedersen, M. M., Poulsen, S., Nissen, H., Poulsen, M., and Nygaard, S. D. (2010). "Controlled release of biocide from silica microparticles in wood paint," *Progress in Organic Coatings* 68(4), 299-306. DOI: 10.1016/j.porgcoat.2010.03.009

Srimalanon, P., Yamsaengsung, W., Kositchaiyong, A., Wimolmala, E., Isarangkura, K., and Sombatsompop, N. (2016). "Effects of UV-accelerated weathering and natural weathering conditions on anti-fungal efficacy of wood/PVC composites doped with propylene glycol-based HPQM," *Express Polymer Letters* 10(4), 289-301. DOI: 10.3144/expresspolymlett.2016.27

Stockwell, M. P., Clulow, J., and Mahony, M. J. (2012). "Sodium chloride inhibits the growth and infective capacity of the amphibian chytrid fungus and increases host survival rates," *PLoS ONE* 7(5), e36942. DOI: 10.1371/journal.pone.0036942

Villagrán Zaccardi, Y. A., Sosa, M. E., and Di Maio, Á. A. (2018). "Limitations of sorptivity and water permeability for the estimation of the chloride penetration rate in concrete regarding the accomplishment of prescriptive design for durability in the marine environment," *Revista ALCONPAT* 8(3), 301-316. DOI: 10.21041/ra.v8i3.302

Weaver, J. S., Whiting, J., Tondare, V., Beauchamp, C., Peltz, M., Tarr, J., Phan, T. Q., and Donmez, M. A. (2021). "The effects of particle size distribution on the rheological properties of the powder and the mechanical properties of additively manufactured 17-4 PH stainless steel," *Additive Manufacturing* 39, 101851. DOI: 10.1016/j.addma.2021.101851

Yeap, R. Y. (2020). *The Potential of Lignin to Increase the Hydrophobicity of Micro/nanofibrillated Cellulose (MNFC)*, Master of Applied Science Thesis, The University of British Columbia, Vancouver, Canada.

Zhang, S., Cao, K., Wang, C., Wang, X., Deng, G., and Wei, P. (2020). "Influence of the porosity and pore size on the compressive and splitting strengths of cellular concrete with millimeter-size pores," *Construction and Building Materials* 235, 117508. DOI: 10.1016/j.conbuildmat.2019.117508

Article submitted: May 8, 2023; Peer review completed: June 18, 2023; Revised version received: June 18, 2023; Accepted: June 28, 2023; Published: July 5, 2023.
DOI: 10.15376/biores.18.3.5599-5622