Bending Performance of Sandwich Flooring with Wood Exterior and Two-layer Cork Interior Reinforced Separately with Metal, Glass Fiber, or Carbon Fiber

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To expand the potential of cork composite wood flooring as an interior material, this study investigated the bending performance of sandwich-structured cork composite wood flooring. The cork composite wood flooring was composed of temperate and tropical wood species as face layer and a cork board reinforced with metal, glass fiber, or carbon fiber placed between two cork boards as the core layer. The MOE value of wood flooring with merbau (M) had the highest value (6.71 GPa) and that of larch (La) had the lowest value (5.40 GPa). Overall, the MOE value of wood flooring with tropical wood species had higher value than those with temperate wood species, which had lower densities. According to the core reinforcements, the CM (cork board-metal) type showed a higher MOE value than the CG (cork board-glass fiber) and CC (cork board-carbon fiber) types. However, within the specific MOE, the order was CG > CC > CM. The ratio measured to calculated MOE ranged from 1.0 to 1.1, it showed a similar or slightly higher value than the measured MOE. The MOR of wood flooring had the highest value (51.0 MPa) in that with teak (T) and had the lowest value (34.9 MPa) in that with larch (La). The specific MOR of the wood floorings with cork board reinforced with glass fiber and carbon fiber was 20 to 40% higher than those reinforced with metal. Stable fracture behavior was observed for the cork composite wood flooring reinforced with metal, glass fiber, or carbon fiber.

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Keywords: Wood floorings; Cork composite board; Metal; Glass fiber; Carbon fiber; Bending performance

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INTRODUCTION

The demand for sustainable and high-performance building materials is increasing due to environmental problems and developments in materials science. The construction industry must respond to climate change by reducing energy loss, using environmentally friendly building materials, and achieving eco-friendly certification (Ding 2008; Novais *et al.* 2019; Yadav and Singhal 2024).

Exterior and interior materials are selected considering resource renewability, energy efficiency, and environmental impact. To increase the energy efficiency of buildings and use sustainable materials, materials with lightweight properties and low thermal conductivity are being developed (Novais *et al.* 2019).

Materials with cellular structures have important uses in the construction industry due to their energy absorption capacity, damping, insulation, rigidity, and fire resistance (Gameiro *et al.* 2007). Materials with natural cellular structures, such as cork and wood, are lightweight, capable of withstanding relatively high strains, and commonly used as core materials in structural sandwich panels (Gibson 2003). Sandwich-structured composite materials can maximize the strength, lightness, and durability of each component lamina by laminating various materials. Therefore, as a material with high strength and light weight, it is expanding in the aerospace and marine industries, as well as interior and exterior building materials (Schubel *et al.* 2005).

Honeycomb-structured materials, foam, balsa wood, and polymer foam have been utilized as core materials. Recently, the applicability of eco-friendly cellular structure materials such as cork is expanding (Zenkert 1997; Anderson and Madenci 2000; Castro *et al.* 2010; Sargiani *et al.* 2012) The cork is extracted from the outer bark of the cork oak (*Quercus suber* L.). Such bark can be harvested on a nearly 10-year cycle, allowing for continuous utilization while protecting the tree (Mano 2007; Gil 2009; Sierra *et al.* 2016 Chen *et al.* 2020; Jia *et al.* 2024). Cork has a hexagonal honeycomb structure that gives it properties such as low density, low permeability for liquids and gases, high compressibility and dimensional stability, low thermal conductivity, and chemical and microbiological stability (Mano 2007; Pereira 2007; Anjos *et al.* 2008; Gil 2009; Anjos *et al.* 2014). Therefore, cork is used on floors, joints, *etc*., and is used in combination with a variety of adhesives (Gil 2009).

Despite its numerous advantages, including high elastic recovery and thermal insulation, cork exhibits comparatively poor mechanical performances in comparison to wood (Pereira 2007). Therefore, cork as a single material is limited in its application to low load-bearing environments. To overcome these limitations, many studies have been conducted to reinforce cork by combining it with wood or wood-based materials, or by composing dissimilar materials (Cha *et al.* 2022, 2023). The sandwich structure, which is a method of improving structural performance by laminating various materials, such as using a cork board with mechanical reinforcement of cork as a core, allows the properties of each laminated material to be optimized and utilized (Soares *et al.* 2011). Various studies have been conducted on the mechanical properties of sandwich-structured panels with cork agglomerates as the core. Sousa-Martins *et al*. (2013) analyzed the deflection characteristics of sandwich panels subjected to blast impact and reported on the axial dynamic compression behavior. Gameiro *et al*. (2007) reported quasi-static and dynamic behavior of cork under compressive loading. Lakreb *et al*. (2015) and Reis and Silva (2009) evaluated the mechanical properties of reinforced cork structures by performing compression and bending tests, respectively, while Castro *et al.* (2010) reported the properties for shear and impact absorption. Cha *et al.* (2022) also analyzed the bending behavior of cork composite boards reinforced with metal, glass fiber, and carbon fiber. These studies demonstrated the potential of cork-based composites in terms of elastic recovery and noise damping. However, further studies are needed to compare the performance of cork-based composites with various wood species and reinforcements.

To expand the potential of cork composite wood flooring as an interior material, especially in the field of flooring, this study manufactured a sandwich-structured cork composite wood flooring using four types of solid wood as face materials in combination with cork boards reinforced with metal, glass fiber, and carbon fiber as core materials. The effects of wood species of the face and cork composites reinforced with dissimilar materials in the core on the bending strength performance of wood flooring were investigated.

EXPERIMENTAL

Specimens

The materials used for face layer were four wood species that are widely used in the indoor flooring industry. Teak (*Tectona grandis*) and merbau (*Intsia bijuga*), tropical wood species with their high density, water resistance, and durability, were selected as face layer species commonly used in premium flooring materials (Miranda *et al.* 2011; Chuanshuang *et al.* 2012). In contrast, tulip tree (*Liriodendron tulipifera*) and larch (*Larix kaempferi*), temperate wood species widely used in domestic flooring and construction applications with relatively lower density but good machining properties and largely planted as plantation species, were selected (Shukla and Kamdem 2009; Byeon *et al.* 2018). Individual laminae were prepared from air-dried wood with a moisture content ranging from 12% to 15%. Their dimensions were 400 mm in the radial direction, 60 mm in the tangential direction, and 1,000 mm in the longitudinal direction. They were cut into sizes of 50 (W) × 4 (T) × 360 (L) mm. A total of 60 laminae were manufactured, with 15 for each tree species.

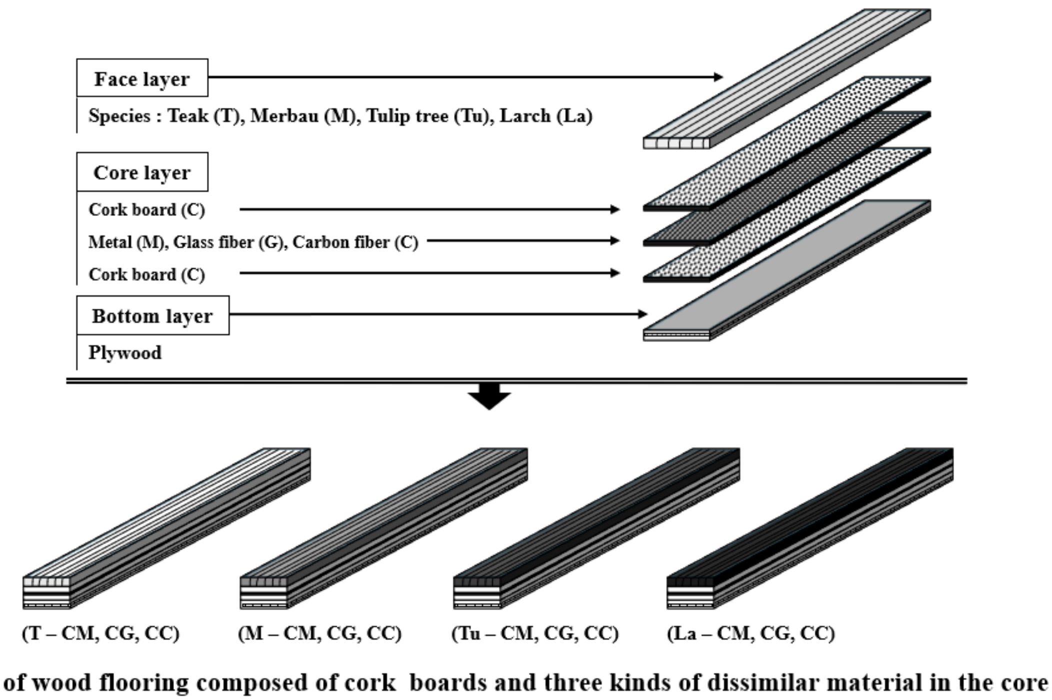

Fig. 1. Schematic diagram of cork composite wood flooring specimens according to face and core layer materials

As the core layer materials, cork composite boards reinforced with metal, glass fiber and carbon fiber were used. The strength properties of metal, glass fiber, and carbon fiber are shown in Table 1 (Cha *et al.* 2022; 2023). The cork board composed of 0.5 mm cork granule and bonded with pMDI (polymeric methylene diphenyl diisocyanate) was purchased in a roll measuring 1000 (W) × 2 (T) mm from Korea Cork Co., Ltd. and cut to a size of 50 (W) × 360 (L) mm. The metal, glass fiber, and carbon fiber reinforcements for the cork board were cut to 50 (W) × 360 (L) mm from 1000 (W) × 0.5 (T) mm. As the bottom layer materials, the five-ply plywood made from Lauan (*Pentacme contorta* Merr. & Rolfe) was selected with a thickness of 4 mm (T) and was cut to 50 (W) × 360 (L) mm.

Table 1. Mechanical Properties of the Materials to Reinforce the Cork Composite Boards

Type	ρ (kg/m^3)	E_T (GPa)	σ_T (MPa)	σ_B (MPa)
Metal (stainless steel)	8,200	210	1,040	650
Glass fiber	2,510	76	2,500	-
Carbon fiber	1,750	230	3,500	-
ρ, density; E_T, tensile modulus; σ_T, tensile strength; σ_B, bending strength.				

The adhesive used was a water-based polymer-isocyanate adhesive (MPU-500, Okong Co., Ltd, Korea). The adhesive was evenly spread on both sides of each solid wood, cork board, reinforcing material and plywood using a roller at a spread amount of 300 g/m^2. Enough pressure was applied to allow the excess adhesives to be discharged from between the layer materials and to form a uniform adhesive layer. The wood floorings were pressed at 0.6 MPa for 24 h at room temperature using a torque wrench and then cured for 7 days in a constant temperature and humidity room maintained at 20 °C and 65% RH. Figure 1 shows the arrangement of main composition materials of cork composite wood floorings, visualizing the laminated structures and reinforcements.

Test specimens were named according to the species as the face, with teak, merbau, tulip wood, and larch abbreviated as T, M, Tu, and La, respectively. For the core layer, cork board, metal, glass fiber, and carbon fiber were abbreviated as C, M, G, and C, respectively. Based on these combinations, a total of 12 types and 60 cork composite wood flooring specimens were manufactured: T-CM, T-CG, T-CC, M-CM, M-CG, M-CC, Tu-CM, Tu-CG, Tu-CC, La-CM, La-CG, and La-CC. Note that “C” in the next-to last position in the code means “cork,” but that “C” in the final position means “carbon”.

Static Bending Test

The static bending test of cork composite wood floorings was conducted by three-point loading using a universal testing machine (Instron 5969, Instron, Norwood, USA) according to KS F 3126 (2022). The span was 300 mm, and the crosshead speed was set at 10 mm/min. The modulus of elasticity (E) was calculated using Eq. 1, and the moduli of rupture (σ) was calculated using Eq. 2,

$$\boldsymbol{E} = \frac{\boldsymbol{Pl^3}}{\boldsymbol{4bh^3y}} \tag{1}$$

$$\boldsymbol{\sigma} = \frac{\boldsymbol{3P_{max}l}}{\boldsymbol{2bh^2}} \tag{2}$$

where P is the applied load (N), l is the span (mm), b is the width of specimens (mm), h is the thickness of specimens (mm), y is the deflection (mm), P_{max} is the maximum load (N), l is the span (mm), b is the width of specimens (mm), and h is the thickness of specimens (mm).

The calculated MOE was calculated for each specimen from the MOE of the individual laminae by the equivalent cross-section method and compared with measured MOE of cork composite wood flooring specimens.

Figure 2 shows the configuration of cross section for obtaining the MOE of a three-ply cork composite wood flooring from individual laminae. The MOE (E_β) of the 12 types of cork composite wood floorings were calculated using Eq. 3,

$$E_\beta = \frac{3\sum_{i=1}^{3} E_i I_i}{I} \tag{3}$$

where E_β is the calculated MOE from individual laminae, E_i is the MOE of ith laminae, I_i is the moment of inertia of individual laminae about the neutral axis (NN) of the cross-section, and I is the moment of inertia for the cross section.

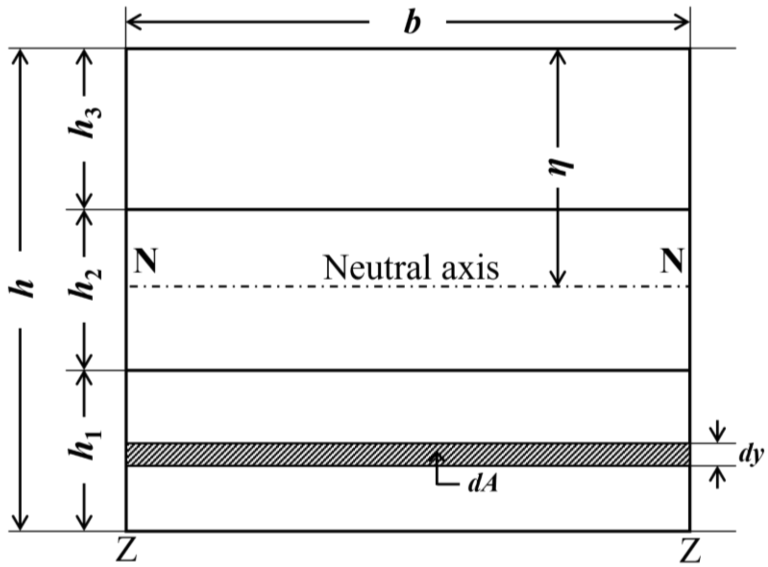

Fig. 2. Configuration of cross section of cork composite wood flooring. *NN,* neutral axis *η*, the distance from *ZZ* axis and neutral axis; *h*, height of three-ply laminated wood flooring; h_1, h_2 and h_3, heights of individual laminae of three-ply laminated wood flooring; *b*, width of three-ply laminated wood flooring; *A*, area (Park *et al.* 2003)

RESULTS AND DISCUSSION

Static Bending Modulus of Elasticity of Wood Floorings

The results of static bending test for 12 types of wood flooring are shown in Table 2, and the effect of wood species and cork composite boards on the static bending MOE is shown in Fig. 3.

Overall, merbau (M) had the highest average MOE (6.71 GPa), followed by teak (6.49 GPa), tulip tree (6.03 GPa), and larch (5.40 GPa). This showed that higher density species tended to have higher bending MOE. In comparison with MOE according to core reinforcements, the MOE of the CG (cork-glass fiber) core layer type with the merbau as the face had the highest value (7.18 GPa) and the CG core layer type with the larch (La) as the face had the lowest value (5.25 GPa). The MOE of temperate wood species as the face ranged from 5.25 to 6.31 GPa. And tropical wood species as the face ranged from 6.16 to 7.18 GPa. These values showed that the MOE of wood flooring composed of tropical wood as the face were approximately 1.1 to 1.2 times higher than that of temperate wood species as the face. In general, the MOE of the wood flooring tended to be highest in CM (cork board-metal), followed by CG (cork board-glass fiber) and CC (cork board-carbon fiber).

In contrast, the specific MOE (MOE/specific gravity) was highest value in the CC core layer type with tulip tree (Tu) as the face (13.5 GPa), which had the lowest density. Overall, both CG and CC core layer types showed approximately 1.1 to 1.3 times higher

MOE than that of the high-density CM type. Thus, as a core reinforcement in cork composite wood floorings, the use of glass fiber or carbon fiber is thought to be more effective and could improve stiffness-to-density and the reinforcement effect than metal.

Table 2. Results of the Bending Test of Wood Floorings Composited with Cork Boards and Three Kinds of Dissimilar Materials

Wood species	Types	ρ (kg/m^3)	E_α (GPa)	E_β (GPa)	σ (MPa)	*SE* (GPa)	$S\sigma$ (MPa)
Teak	CM	583	6.93	6.08	51.0	11.9	87.6
	CG	483	6.21	6.12	39.0	12.9	81.5
	CC	500	6.34	6.01	49.4	12.7	98.6
Merbau	CM	633	6.80	6.41	39.9	10.7	63.2
	CG	561	7.18	6.83	48.9	12.8	56.8
	CC	544	6.16	5.97	43.2	11.3	79.6
Tulip tree	CM	551	5.95	5.39	39.9	10.8	72.5
	CG	452	5.84	5.47	40.4	12.9	89.4
	CC	469	6.31	5.52	43.9	13.5	93.5
Larch	CM	551	5.56	5.07	41.6	10.1	75.5
	CG	475	5.25	5.27	34.9	11.1	73.4
	CC	480	5.39	5.30	36.2	11.2	75.3

Each value is the average of 10 measurements. ρ, density; E_α, measured value of MOE; E_β, true MOE calculated from individual laminae; σ, bending MOR; *SE*, specific bending MOE (MOE/specific gravity); $S\sigma$, specific bending MOR (MOR/specific gravity); CM, cork board-metal; CG, cork board-glass fiber; CC, cork board-carbon fiber.

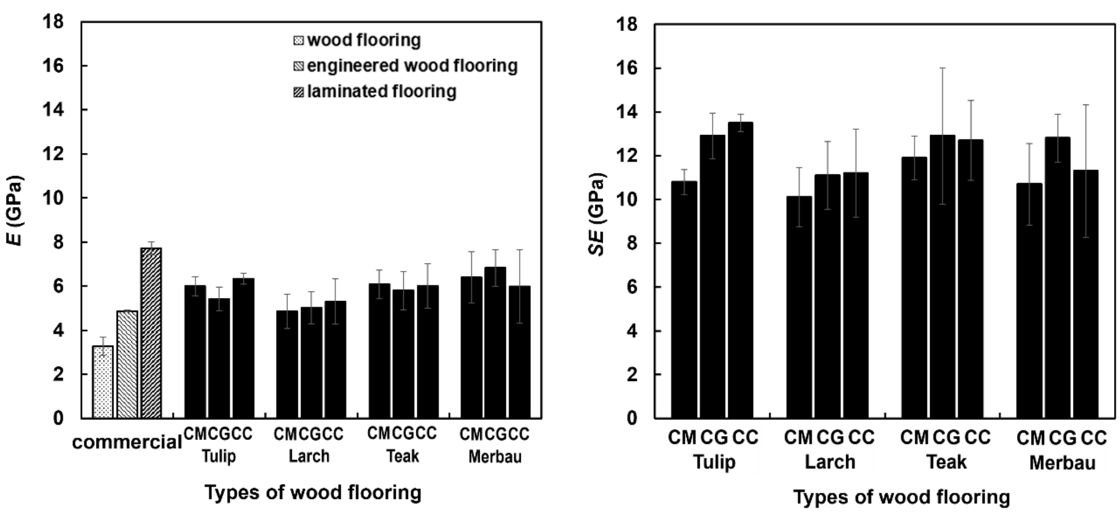

Fig. 3. Effect of wood species and dissimilar materials in the core on MOE of 12 types of solid wood flooring. *E*, static bending MOE; *SE*, specific MOE (MOE/specific gravity); CM, CG and CC; see Table 2.

Figure 4 shows the ratio (E_α/E_β) between the calculated MOE by the equivalent cross-section method and measured MOE of the wood flooring. The ratio between them ranged from 1.0 to 1.1, indicating that the measured MOE was the equal or slightly higher than the calculated MOE. This is thought to be due to the high span/height ratio, which decreases the influence of shear deformation, as well as the high stiffness of the dissimilar materials in the cork-composite core and the effect of the glue line.

The bending MOE values of the cork composite wood flooring (5.25 to 7.18 GPa) were 1.6 to 2.2 times higher than that of commercial solid wood flooring (3.27 GPa), 1.1 to 1.5 times higher than that of engineered wood flooring (4.87 GPa), and 1.1 to 1.5 times lower than that of laminate flooring (7.72 GPa). This is thought to be due to the difference in density, as laminate flooring is based on high density fiberboard (HDF) with a density of 850 kg/m³ or higher. It was also about 1.5 to 2.7 times lower than that of C40-grade LVL (14 GPa) and C24-grade structural materials (11 GPa) (Arriaga *et al.* 2023).

Therefore, the cork composite wood floorings in this study exhibited superior strength performance compared to commercial wood and engineered wood floorings and can be used as structural wood-based floor materials.

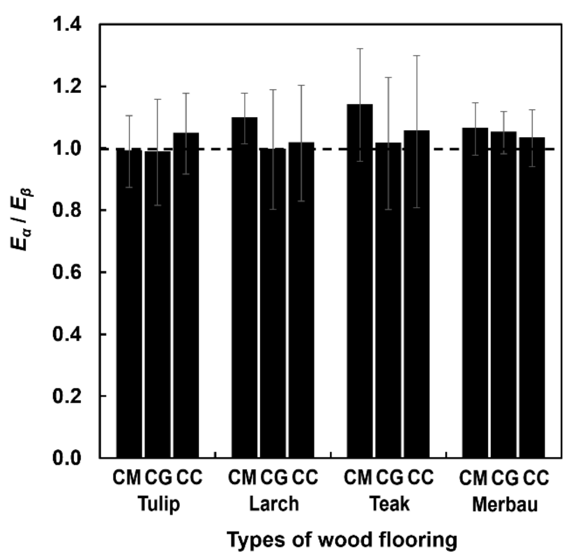

Fig. 4. Relation between measured MOE and calculated MOE of wood flooring specimens. E_α, measured MOE of wood flooring specimens; E_β, true MOE calculated from individual laminae; CM, CG and CC; see Table 2.

Static Bending Strength of Wood Floorings

The static bending moduli of rupture (MOR) for 12 types of wood floorings are shown in Table 2, and the effect of the core layer cork composite boards on the static bending MOR is shown in Fig. 5. In comparison with MOR according to wood species as the face, the MOR of the teak (T) had the highest average value (46.5 MPa), followed by merbau (44.0 MPa), tulip tree (41.4 MPa), and larch (37.6 MPa). Teak and merbau, which are relatively high-density wood species, had a higher MOR. It was thought that the density of the species directly affected the bending strength. In comparison with MOR according to core layer reinforcements, teak (T) face layer with CG (cork board-glass fiber) core type had the highest MOR value (51.0 MPa) and tulip tree (Tu) as the face with CG core type had the lowest MOR value (34.9 MPa). The MOR of wood flooring with temperate wood species as the face (34.9 to 43.9 MPa) was 1.1 to 1.5 times lower than that with tropical wood species as the face (39.0 to 51.0 MPa). The specific MOR (MOR/specific gravity) of wood flooring showed differences depending on the type of reinforcing material and wood species as the face. The wood flooring with teak (T) as the face and CC core type had the highest value (98.6 MPa) and merbau (M) as the face and CG core type had the lowest value (56.8 MPa).

The MOR value of wood flooring with CC core type was lower than the CM core type. However, specific MOR was 1.2 to 1.4 times higher. It was expected that it would be useful as a lightweight, high-strength composite material. The MOR of the wood flooring in this study (34.9 to 51.0 MPa) was 1.1 to 1.6 times higher than that of the commercial solid wood flooring (31.8 MPa), 1.0 to 1.5 times higher than the engineered wood flooring (33.7 MPa) and was a similar value to the laminate flooring. The MOR values of wood flooring were 1.0 to 1.5 times higher than MDF (31.9 MPa), 2.5 to 3.7 times higher than PB (13.7 MPa), and 1.4 to 2.1 times higher than OSB (24.1 MPa) (Park *et al.* 2009). These results suggest that cork composite wood flooring, due to their higher strength than common interior materials, are very suitable as cork-based lightweight floor materials.

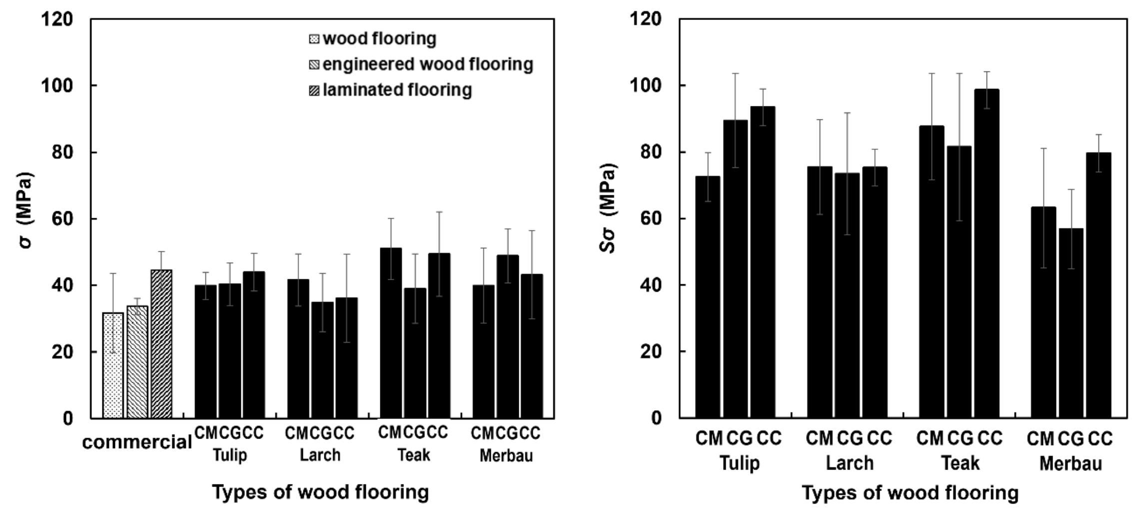

Fig. 5. Effect of wood species and dissimilar materials in the core on MOR of 12 types of solid wood flooring. σ, static bending MOR; *S*σ, specific MOR (MOR/specific gravity); CM, CG, CC; (Table 2)

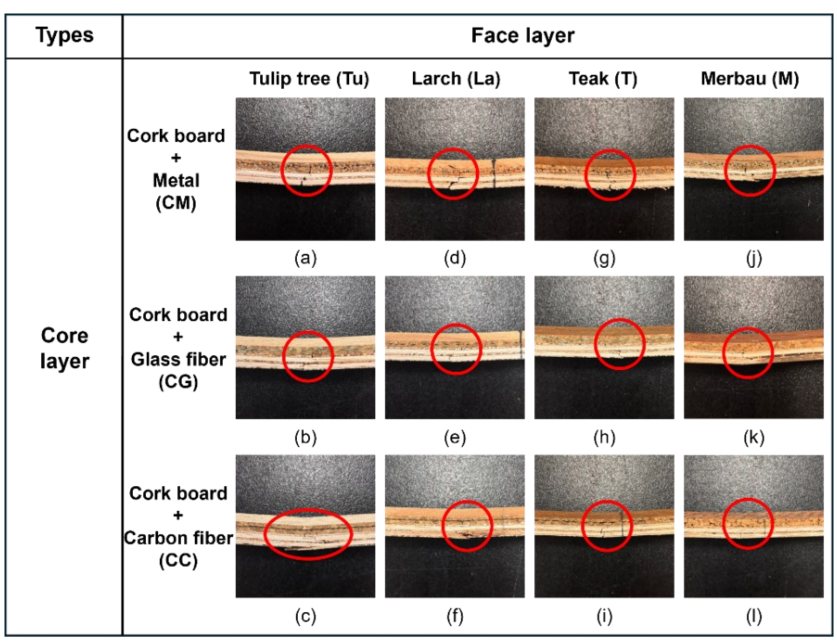

Fig. 6. Fracture behavior of the cork composite wood floorings: (a) Tu-CM, (b) Tu-CG, (c) Tu-CC, (d) La-CM, (e) La-CG, (f) La-CC, (g) T-CM, (h) T-CG, (i) T-CC, (j) M-CM, (k) M-CG, (l) M-CC

The fracture behavior of the cork composite wood floorings in this study differed from those reported for other cork-based sandwich panels. While typical shear fracture extending from the loading point along the core layer was observed in cork-based sandwich panels (Castro *et al.* 2010; Lakreb *et al.* 2015), in this study, the bending fracture behavior occurred only minor cracks in the cork board adjacent to bottom layer, and the upper cork board shows structural stability without fracture behavior (Fig. 6.). Such fracture behavior suggests that the cork composite board reinforced with metal, glass fiber or carbon fiber can provide greater damage tolerance and structural stability compared to cork agglomerates sandwich panels.

CONCLUSIONS

1. The bending modulus of elasticity (MOE) of cork composite wood flooring was in the order of teak > merbau > tulip > larch. Metal-reinforced wood flooring (CM) with a high density showed slightly higher values than those having the cork reinforced with glass fiber (CG) and carbon fiber (CC), but the specific MOE showed 10 to 30% higher values in CG and CC than in CM.
2. The difference between the calculated and measured values of bending MOE was small. It was possible to predict measured values from calculated values without a large error.
3. The modulus of rupture (MOR) of the cork composite wood flooring was in order of metal (CM) > glass fiber (CG) > carbon fiber (CC). This order was similar to that of the bending MOE, but the specific MOR showed 20 to 40% higher values in CG and CC than in CM.
4. The cork composite wood flooring reinforced with metal, glass fiber, or carbon fiber showed the typical fracture behavior that occurred on the tension side near the loading point, while little cracks occurred only in the lower cork board. The upper cork board showed structural stability without fracture behavior.
5. The cork composite wood floorings showed better bending performance than the commercial wood and engineered wood floorings. It is suitable for the application of an indoor flooring material and can contribute to the design and manufacture of composite floorboards with various reinforcements.

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