Analyzing the influences of fabrication methods on the mechanical properties of Sumberejo kenaf/epoxy sandwich composites with polyurethane foam core

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Abstract. Natural fiber composite sandwich structures have developed significantly to create building materials that are strong and lightweight. The purpose of this study is to compare the cold press and vacuum assisted resin infusion (VARI) methods to investigate the mechanical properties of sandwich composites made of Sumberejo kenaf fiber (KF) reinforced epoxy (EP) as the skin and polyurethane (PU) foam as the core. The kenaf fibers were alkalized by NaOH solution. The results show that manufacturing KF/EP-PU foam sandwich composites using cold press has flatwise tensile strengths that are around (0.220 ± 0.031) MPa higher than VARI, which is only about (0.170 ± 0.057) MPa. This implies that cold press creates an enhanced composite structure. The core shear strength of cold press sample was 17% higher than VARI, with a value of (0.603 ± 0.052) MPa and (0.499 ± 0.016) MPa, respectively. Also, the skin bending stress of cold press sample was (6.106 ± 1.203) MPa while VARI sample had a value of (5.405 ± 0.687) MPa. However, the VARI method exhibited higher flatwise compressive strength with a value (0.393 ± 0.004) MPa and cold press method was (0.331 ± 0.032) MPa. In conclusion, the manufacturing method substantially impacts the mechanical properties of KF/EP-PU foam sandwich composites in this study. This study is a valuable reference for natural fiber sandwich composites as a building material.

Keywords. Kenaf fiber, polyurethane foam, flatwise tensile strength, flatwise compressive strength, core shear strength

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1 Introduction

Research on sustainable and environmentally friendly materials has increased recently, especially in the building and industrial sectors [1]. The example is natural fiber sandwich composite. It's surface enhances the structural integrity and appealing look and can be a great solution for ecologically conscious architectural and interior design projects [2, 3]. The advantage of natural fiber was that it was biodegradable, renewable, and lightweight, resulting in a sandwich composite with a strong structure, durability, eco-friendliness, and green components [4, 5]. Jute, hemp, kenaf, and flax are natural fibers suitable for construction materials. Foam and natural fiber reinforced polymer sandwich composite materials have good promise as alternative materials.

Foam materials were used as the core of the sandwich composite, which functioned as insulation and significantly lowered the overall weight of the panel. The interior insulation allows for the panel's lightweight design, simplifying assembly and transit. Because foam materials like polyurethane and polystyrene have better thermal insulation properties than other materials, sandwich composite or panels offer more energy-efficient solutions for building enclosures [6, 7]. The foam material substance lowers noice levels and vibrations, which enhances acoustic performance. Due to their lightweight and insulating qualities, natural fiber sandwich composites with foam cores are widely used in commercial and residential building applications [8, 9].

Numerous studies have been done on the mechanical characteristics of natural fiber sandwich composite with a polyurethane foam core. Increased fiber weight has improved mechanical qualities for bio-composites reinforced with natural fibers such as sisal, coconut/coir, jute, and sugarcane [10]. Kenaf fiber is a natural fiber commonly utilized in composites due to its high mechanical properties and low density [11]. Salman et al. [12] investigated the mechanical properties of composites comprised of kenaf fibers with various polymer matrix, such as epoxy, polyester, and vinyl ester. The findings showed that the strongest tensile and flexural strengths were found in kenaf fiber composites using epoxy as the matrix [12]. This study using the unidirectional kenaf fiber woven sheets refers to the investigation by Afkari et al. (2022) that a composite of kenaf fiber/epoxy with orientation (0°/0°/0°/0°) or unidirectional has good tensile strength and flexural strength than composites at the orientation (0°/90°/0°/90°) or bidirectional [13]. Using polyurethane foam as the core material in sandwich composites has shown to increase strength and have a high stiffness-to-weight ratio [14]. The mechanical qualities of sandwich structures, such as tensile strength, compression strength, and bending strength, have been found to increase with an increase in polyurethane foam density [15].

Conventional fabrication methods like VARI, hand lay-up, and compression molding can be used to create Natural Fiber Reinforced Polymer Composites (NFRP) [2]. The simplest method of processing a composite was hand lay up, however it has a lot of void forms. [16]. Vacuum Assisted Resin Infusion (VARI) uses the vacuum infusion and pressure technique, which enhances resin consistency, lowers void formation, and minimized material waste. The vacuum infusion process yields the best value for ultimate tensile strength in fiber reinforced polymer Composite samples. This is due to the resin injection flow equally and thoroughly wetting the entire fiber surface [17]. The fabrication of a natural fiber composite sandwich with a foam core using the VARI and cold press fabrication method has not been done before.

The literature states that the potential mechanical benefits and environmental friendliness of sandwich composites made of epoxy resin reinforced with natural fibers and a polyurethane foam core have generated great interest. This study aims to ascertain how the fabrication process affects the mechanical properties of sandwich composites made of a Sumberejo kenaf, epoxy, and polyurethane foam core. The results of this study can serve as

a guide for other researchers studying composite fabrication, particularly those looking for the best sandwich composite manufacturing processes.

2 Materials and methodology

2.1 Materials and fiber preparation

In this study, the skin layer of the sandwich composite was epoxy-reinforced kenaf fiber (KF). Sumberejo kenaf fiber obtained from Balittas, Malang, East Java, Indonesia, for thirty thousand rupiahs per kilogram. The epoxy resin used as a matrix is a mixture of epoxy EPR 174 and hardener EPH 555 (Justus Kimiaraya Ltd, Indonesia). Meanwhile, polyurethane (PU) foam used as the core of sandwich composite has a density of 40 kg/m^3.

Initially, kenaf fibers were cut into 40 cm lengths. Subsequently, kenaf fibers were soaked in 5% sodium hydroxide (NaOH) solution at room temperature for 24 hours. The ratio of NaOH flakes and aqua-bidestilation was 1:10. After soaking, a two-stage drying process was carried out, including drying kenaf fibers at room temperature (±23℃) for 48 hours and (±60℃) for 24 hours in an oven [13, 18]. Following the alkali treatment, kenaf fibers were woven into sheets by a 35 x 35 cm^2 dimension using weaving equipment at CV. Ridaka in Pekalongan, Central Java, Indonesia. Kenaf fiber woven sheets were using cotton 40 weight thread. Figure 1 shows the resulting of kenaf fiber woven sheets.

2.2 Composite fabrication

This study varies two fabrication methods: vacuum assisted resin infusion (VARI) and cold press. In the VARI fabrication, kenaf fiber woven sheets were stacked in four layers with unidirectional orientation. These four layers of kenaf fiber woven sheets formed the sandwich composite's upper and lower skin parts. Polyurethane (PU) foam placed between these two skin layers. Figure 2 shows the arrangement of kenaf fiber woven sheets and PU foam. The VARI fabrication process carried out by vacuuming some air and injecting epoxy resin into arrangement of kenaf fiber woven sheets and PU foam. Epoxy EPR 174 and hardener EPH 555 were mixed in a 2:1 ratio. The vacuum infusion process (as shown in Fig. 3) using a pressure of 60 cmHg at room temperature for 24 hours [19].

Meanwhile, the post-cured process was conducted for 30 minutes at 110℃. Sumberejo kenaf fiber/epoxy sandwich composite with polyurethane foam core fabricated by VARI or (KF/EP-PU foam VARI) were identified. Figure 4a shows the schematic's fabrication of VARI process.

Fig. 1. The kenaf fiber woven sheets

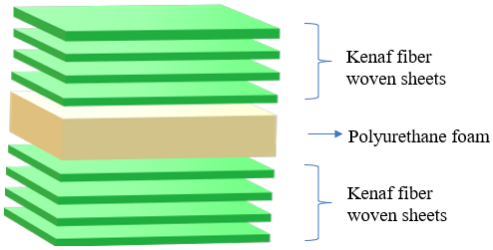


Fig. 2. The arrangements of kenaf fiber woven sheets and polyurethane foam.

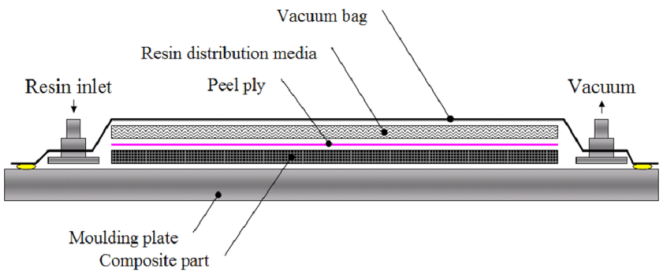


Fig. 3. Vacuum infusion process of composites. [19]

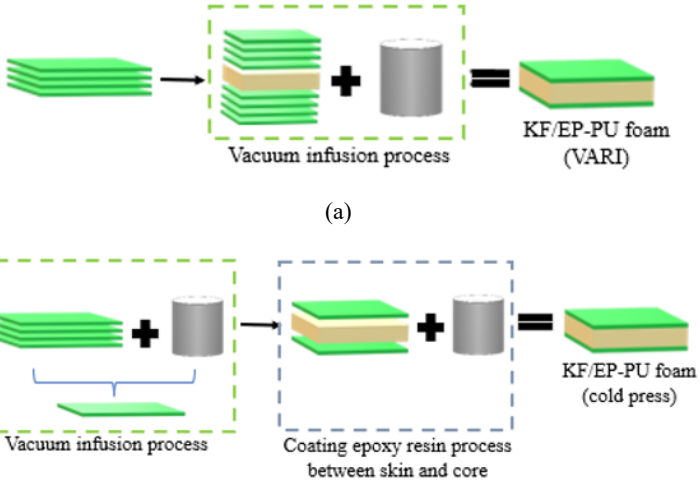


Fig. 4. The schematic's fabrication of KF/EP-PU foam (a) VARI process, (b) cold press process.

In cold press fabrication process, two skin parts (Sumberejo kenaf fiber-reinforced epoxy composites or KF/EP) were initially processed using vacuum infusion process as detailed earlier, as shown in Fig. 3 [19]. Kenaf fiber and epoxy resin ratio was 40 wt% and 60 wt%. Referring to the research results of [18] where the 40 wt% Sumberejo kenaf fiber was the optimal weight fraction for Sumberejo kenaf fiber-reinforced composite fabrication [18].

Hand lay-up techniques used for sandwiching polyurethane foam between two skin parts by coating the epoxy resin thoroughly. The coating process used a small brush. The kenaf fiber-epoxy composite and PU foam arrangement was pressed using 200 kg load at room temperature for 24 hours. Sumberejo kenaf fiber/epoxy sandwich composite with polyurethane foam core fabricated by cold press or (KF/EP-PU foam cold press) were identified. The schematic's fabrication of cold press process, as shown in Fig. 4b.

2.3 Sample testing and morphological analysis

Three types of mechanical tests carried out in this study were flatwise tensile test, flatwise compressive test, and flexural test. Flatwise tensile and compressive tests have been performed according to ASTM C297M-04 and ASTM C365-00, respectively [20, 21]. The square specimens with a 50 x 50 x 28 mm^3 dimension were cut for each test. The flatwise tensile test was conducted by joining or bonding the KF/EP skin of the sandwich composite or panel to both sides of thick steel plates using epoxy adhesives (Araldite). A tensile load was applied to the specimen by pulling the welded steel rod through the center of the thick steel plates. The flatwise compressive test was conducted by applying a load to the specimen through a cylinder loading block with a constant rate of movement of the cross-head of the testing machine. While the flexural test method used three-point bending test in this study. It was conducted based on ASTM C393M-11 with rectangular specimens of 250 x 45 x 28 mm^3 [22]. The loading fixture for three-point bending test used two support bars that span the specimen width below it, separated by a distance of 150 mm and one loading bar that spans the specimen width located on the top of the specimen. The head displacement rate for flatwise tensile and flatwise compressive tests was 1.0 mm/min, while the three-point bending test used 1.5 mm/min. Flatwise tensile, flatwise compressive, and three-point bending tests used a Universal Testing Machine (UTM).

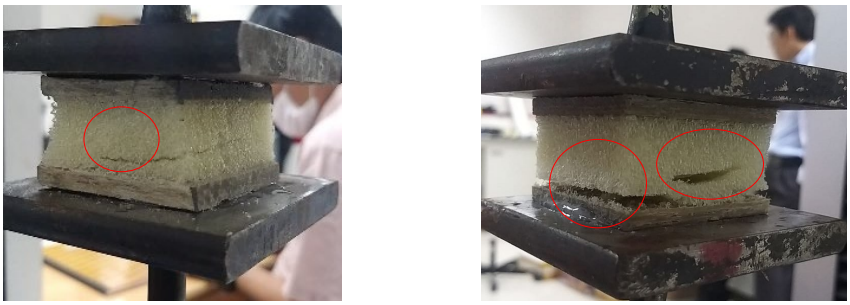
The surface morphology of the specimens before and after testing was observed using an Olympus SZX7 microscope. The value of magnification was 2.5 times. This morphological observation assessed the surface failures between kenaf fibers, epoxy resin, and PU foam after mechanical testing.

3 Results and discussion

3.1 Flatwise tensile behavior

During the test, failures were observed for both samples, as shown in Fig. 4. The first type of failure was skin-core debonding, followed by core cracking. Figure 5a shows the failure of cold press specimen. The tensile load did not affect the lamination between skin and core, resulting the core cracking in PU foam. A study by Sivalingan et al. (2021) investigated the tensile behavior of sandwich composites and showed the skins did not play a significant role in this test [23]. On the other hand, Fig. 5b depicts the occurrence of skin-core debonding and core cracking on the PU foam in VARI specimen. This indicates the strength of skin and core VARI specimen is lower compared to cold press specimen.

The results obtained from the flatwise tensile test clarified the description of failure modes in this study. A comparison of tensile strength between KF/EP-PU foam cold press and KF/EP-PU foam VARI is shown in Fig. 6.



(a) (b)

Fig. 5. Failures on KF/EP-PU foam after flatwise tensile test (a) cold press specimen, (b) VARI specimen.

The KF/EP-PU foam cold press has tensile strength value of (0.220 ± 0.031) MPa, which is 22% higher than KF/EP-PU foam VARI which has tensile strength value of (0.170 ± 0.056) MPa. It depended on how the coating of epoxy resin between skin and core. Cold press method strengthens the bonding between skin and core lamination, causing uniform impregnation of epoxy resin over the entire surface of kenaf fibers. Therefore, it causes an increase of adhesion between the polyurethane foam core and kenaf fiber/epoxy skin [17]. Hence, the cold press and VARI fabrication methods influence the flatwise tensile behavior of KF/EP-PU foam sandwich composite.

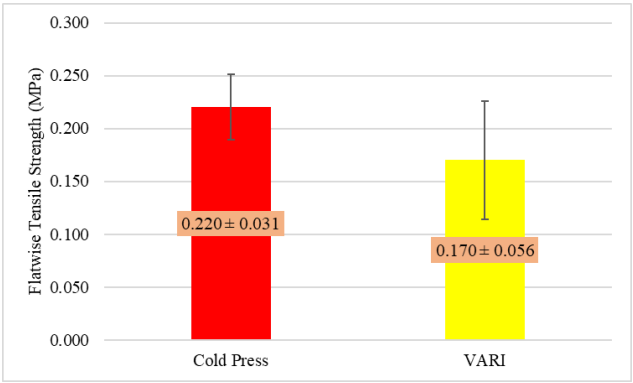


Fig. 6. Flatwise tensile strength of KF/EP-PU foam that were fabricated by cold press and VARI.

3.2 Flatwise compressive behavior

The compression test was carried out by applying a perpendicular load to skin layer. During compression testing, PU foam as the core plays a significant role in resisting the load received until the PU foam densified. After that, the skin plays a role in supporting the load received by a specimen. It shows the core layer has an important role in determining the flatwise compression strength than skin layer [23]. Figure 8 shows the flatwise compressive stress-strain behavior of these KF/EP-PU foam sandwich composites. For both of samples, the curve shows the same pattern of an elastic region initially up to strain approximately 4 % until maximum stress at strain 5%, and it experienced the failure due to core crushing. So, it was followed by a constant region between 6% and 50% strains and a subsequent sharp

increase in the stress. The skin assumed full loaded-bearing role when loaded beyond 50 % of the strain.

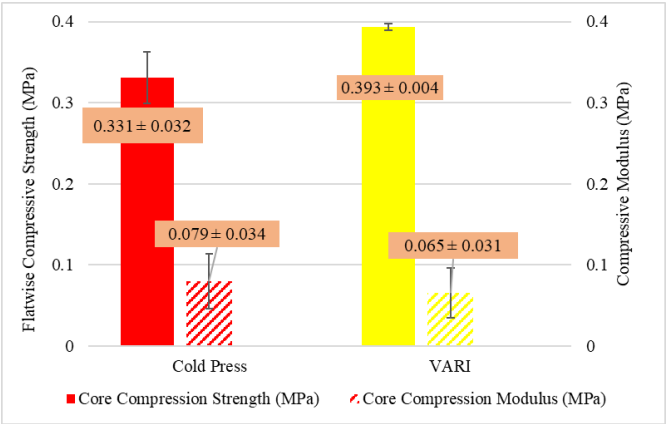
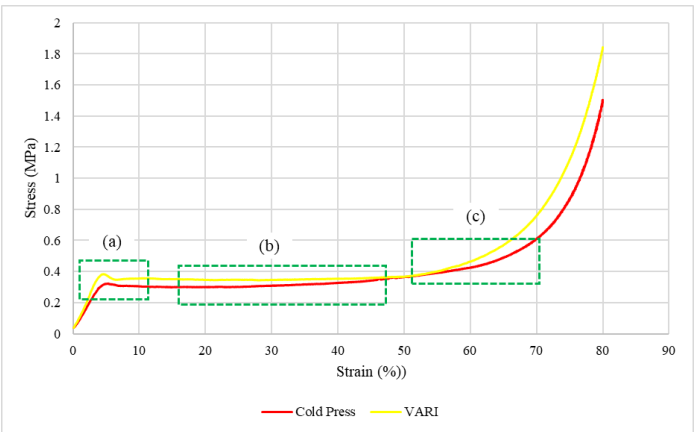
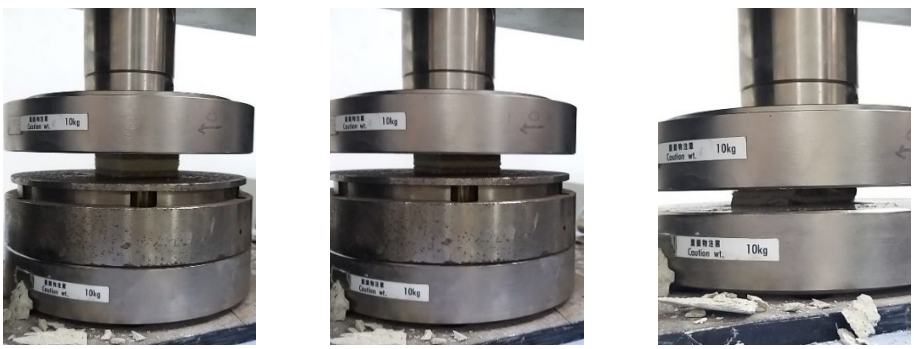


Fig. 7. Flatwise compressive strength and compressive modulus of KF/EP-PU foam were fabricated by cold press and VARI.

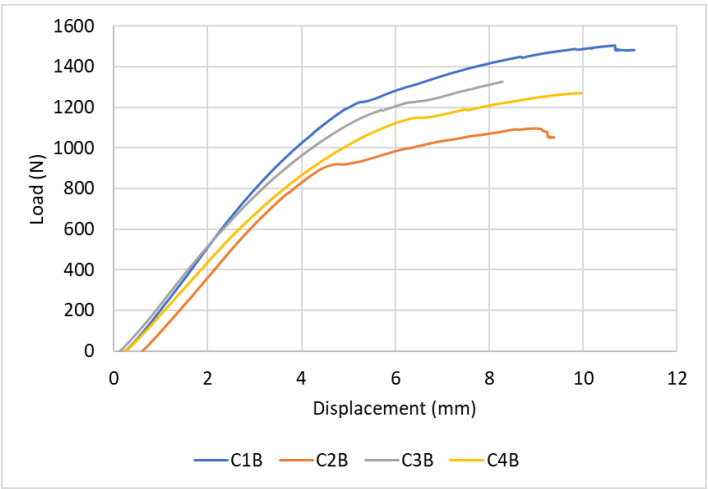




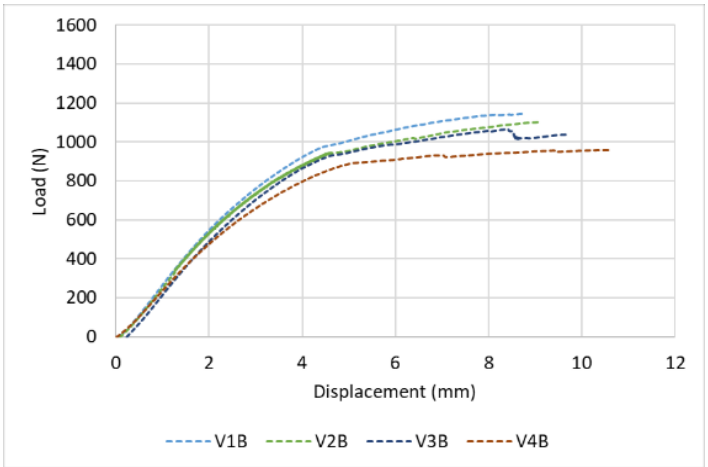
(a) (b) (c)

Fig. 8. The flatwise compressive stress-strain behavior of these KF/EP-PU foam sandwich composite. (a) Core Crushing, (b) Core Solidification, (c) Skin fully loaded.

Figure 7 shows the flatwise compressive strength and compressive modulus values obtained for each KF/EP-PU foam sandwich composite. The flatwise compressive strength values between cold press sample and VARI sample are slightly similar, with respective values of (0.331 ± 0.032) MPa and (0.393 ± 0.004) MPa. This is due to the exact characteristics of PU foam core used in both samples. The flatwise compressive strength of HDPE skin-integrated studs filled with PU foam with a density of 192 kg/m3 was examined by Sharafi et al. (2018) and has a value of 0.83 MPa [24]. The compressive modulus value between cold press sample and VARI sample has an insignificant difference, with values of (0.079 ± 0.034) MPa for cold press sample and (0.065 ± 0.031) MPa for VARI sample. Therefore, the flatwise compressive behavior of KF/EP-PU foam sandwich composite was not affected by the fabrication methods of cold press and VARI.



(a)

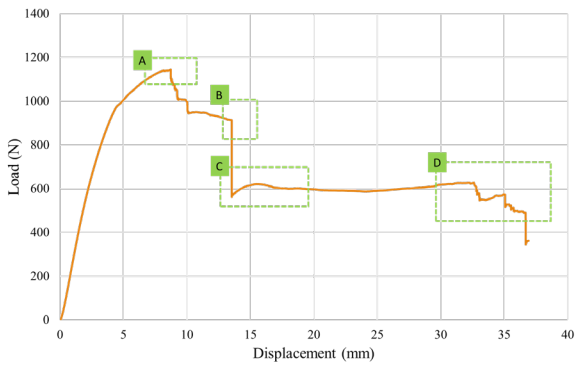


(b)

Fig. 9. The load versus displacement curve of three-point bending test on KF/EP-PU foam (a) cold press specimen, (b) VARI specimen.

3.3 Flexural behavior

Figure 9 shows the load versus displacement curve of three-point bending test. The bending failure loads for KF/EP-PU foam cold press specimens were 1504 N, 1096 N, 1325 N, and 1269 N (as shown in Fig. 9a). Also, the bending failure loads for KF/EP-PU foam VARI specimens were 1144 N, 1101 N, 1066 N, and 958 N, as shown in Fig. 9b. These specimens' maximum loads on load versus displacement curves indicated failure due to skin-core debonding and wrinkling at the top of the skin. The failure load of cold press sample was 17% higher than VARI sample, with values of 1298 N and 1067 N, respectively. Figure 10 shows the failure modes that occurred in one of the specimens during three-point bending test. The skin-core debonding and core fracture were initially failure on the specimen when it reached the maximum load (points a and b). The load experienced a drastic reduction at strain between 14% (point c) and showed indentation failure. The sample can still receive loads until a fracture occurs on the lower skin, as shown in (point d).



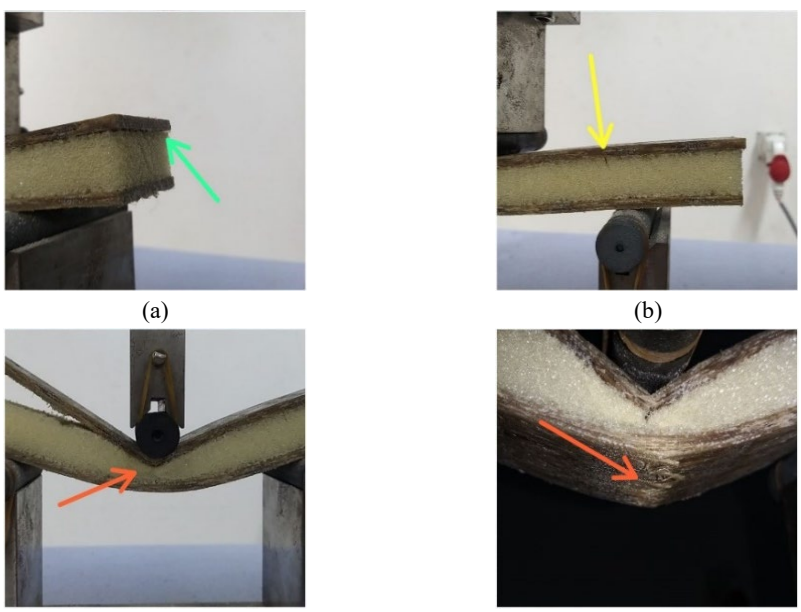
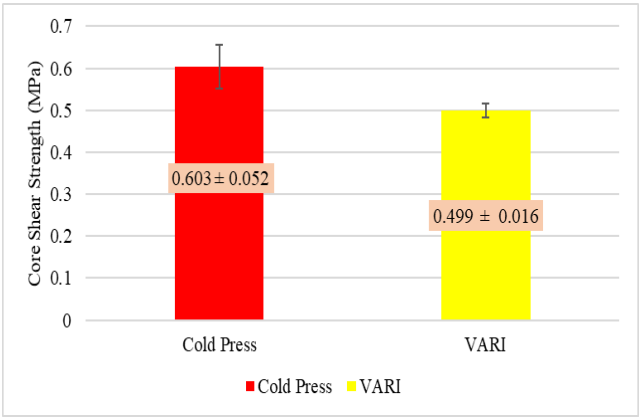
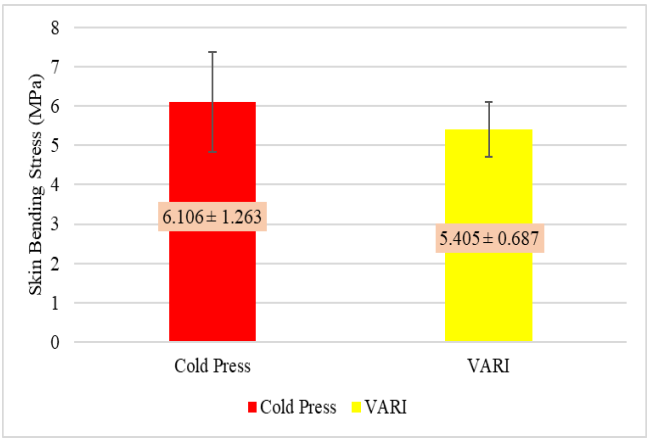


Fig. 10. The failure modes on KF/EP-PU foam sandwich composite during three-point bending test. (a) Skin core debonding, (b) Core facture, (c) Indentation failure, (d) Fracture at the bottom of skin.

From the three-point bending test, the core shear strength and skin bending stress were obtained (as shown in Fig. 11). Core shear strength of cold press sample was 17 % higher than VARI sample with values of (0.603 ± 0.052) MPa and (0.499 ± 0.016) MPa, respectively. Also, the skin bending stress of cold press sample was (6.106 ± 1.203) MPa, while VARI sample had a value of (5.405 ± 0.687) MPa. Then, cold press sample has 38 % higher value of skin bending stress than VARI sample. This shows that cold press fabrication produces stronger lamination between skin and core compared to samples produced by VARI fabrication. A study by Azmi et al. (2013) on a sandwich composite made of coconut coir and PU foam shows a core shear strength value of 0.191 MPa [25]. Additionally, woven roving polyester PU foam with a core thickness of 2 mm has been tested with a skin bending stress of 3.937 MPa [26]. Then, cold press and VARI fabrication methods affected the flexural behavior of KF/EP-PU foam sandwich composite.



(a)



(b)

Fig. 11. (a) The core shear strength of KF/EP-PU foam, (b) the skin bending stress of KF/EP-PU foam (were fabricated by cold press and VARI).

3.4 Morphological analysis

Figure 12 and Fig. 13 show the morphological analysis using microscope optics. The micrograph failure of top surface KF/EP-PU foam cold press and VARI after three-point

bending test was conducted in Fig. 12a and 12b, respectively. It shows on VARI specimen was complete fracture in all skin layers, different from the failure in cold press specimen where the fracture (fiber pull out) only occurred in some layers. The fracture fiber also occurred on sandwich composite in a study (Al-Azad et al., (2021)) [27]. Fractures on specimens can be seen clearly in Fig.12c and 12d, which show the fracture from the side surface. This explains that the skin bending stress value of KF/EP-PU foam cold press is more optimal than KF/EP-PU foam VARI.

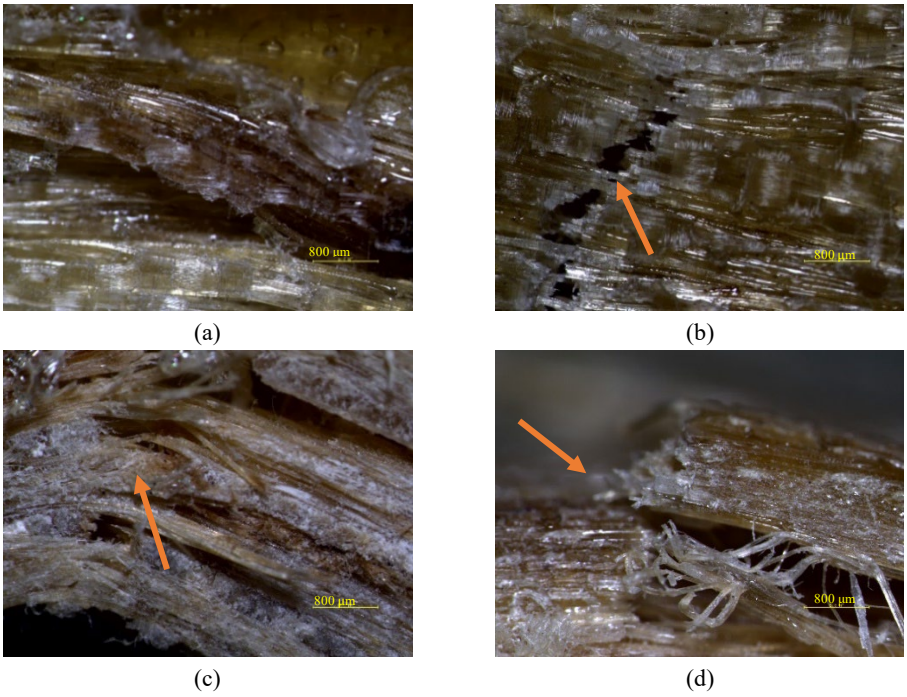
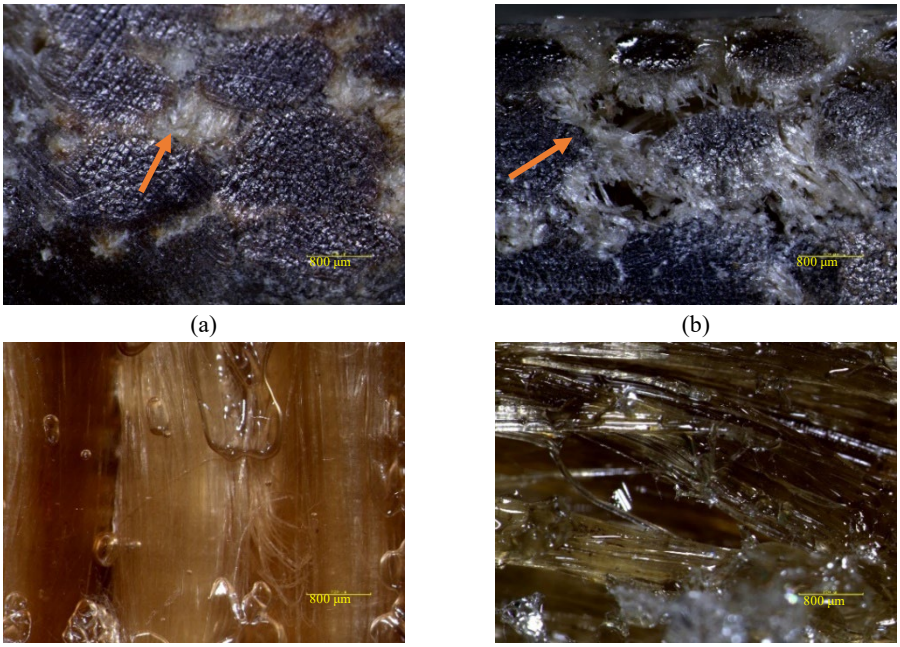


Fig. 12. The micrograph failure of Sumberejo kenaf fiber/epoxy sandwich composite with polyurethane foam core after three-point bending test (a) top surface of KF/EP-PU foam cold press, (b) top surface of KF/EP-PU foam VARI, (c) side surface of KF/EP-PU foam cold press, (d) side surface of KF/EP-PU foam VARI.

The micrograph failure of KF/EP-PU foam cold press and KF/EP-PU foam VARI after flatwise tensile test (as shown in Fig. 13a and Fig. 13b) presents the differences between these samples from the side surface. Figure 13a shows that kenaf fiber and epoxy on cold press sample have a better bonding condition than VARI sample after flatwise tensile test, which is shown in Fig. 13b. The kenaf fibers were debonding between the layer of woven sheets. It shows the sample has weak bonding between the layer of woven sheets for VARI fabrication process [13]. Furthermore, the skin-core lamination of cold press specimen looks smoother than VARI sample (as shown in Fig. 13c and Fig. 13d). It caused the epoxy resin coating on the surface of KF/EP skin and PU foam core by laying it up using a small brush for cold press fabrication. In contrast, VARI fabrication process used vacuum infusion method. After undergoing flatwise tensile test, the VARI sample looked to contain a small amount of epoxy resin, which is shown by the kenaf fibre's fibrous texture.



(a) (b)

(c) (d)

Fig. 13. The micrograph failure of Sumberejo kenaf fiber/epoxy sandwich composite with polyurethane foam core after flatwise tensile test (a) side surface of KF/EP-PU foam cold press, (b) side surface of KF/EP-PU foam VARI, (c) lamination surface of KF/EP-PU foam cold press, (d) lamination surface of KF/EP-PU foam VARI.

4 Conclusion

Sumberejo kenaf fiber/epoxy composites as skin and polyurethane foam as the core for sandwich composites (KF/EP-PU foam) were fabricated through two fabrication methods which were cold press and VARI. KF/EP-PU foam cold press has an optimal value of flatwise tensile strength compared to KF/EP-PU foam VARI with respective values of (0.220 ± 0.031) MPa and (0.170 ± 0.056) MPa. The core shear strength and skin bending stress of KF/EP-PU foam cold press increased up to 17% and 38% compared to KF/EP-PU foam VARI. The core shear strength for KF/EP-PU foam cold press and VARI was measured at (0.603 ± 0.052) MPa and (0.499 ± 0.016) MPa, respectively, while skin bending stress was measured at (6.106 ± 1.203) MPa and (5.405 ± 0.687) MPa, respectively. It was due to the epoxy resin wetting process for each fabrication method. In cold press sample, the epoxy resin effectively adheres to kenaf fibers, leaving them well-coated and bonded. KF/EP-PU foam cold press and VARI values for flatwise compressive strength were (0.331 ± 0.032) MPa and (0.393 ± 0.004) MPa, respectively.

The results of mechanical properties were supported by Optical Microscope (OM) observations of failures on the sandwich composites. Then, the manufacturing method used has a substantial impact on the mechanical properties of KF/EP-PU foam sandwich composites. Due to its efficiency in the epoxy resin impregnation process, the cold press method seems to be advantageous for certain qualities like flatwise tensile strength, core shear strength, and skin bending stress. However, when deciding on the best manufacturing technique for a building application, factors for additional parameters like flatwise compressive strength should be taken into account.

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