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Effect of oil palm fiber on mechanical properties of sandwich-structured glass

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ABSTRACT

The aim of this study was to develop a sandwich-structured glass using a conventional stacking method. The sandwich-structured glass comprised two facesheets of silicate glass, and the interlayer part was made up of different core elements, which are epoxy and oil palm fiber, to yield impact resistance features on the glass structure. Scanning electron microscopic image showed a modification in surface morphology of spikelet and stalks fibers, with a formation of fibrils in helical spirals and an appearance of a rougher surface after chemical treatment during extraction process. Mechanical properties of the sandwich-structured glass increased from 280.60 MPa to 402.46 MPa after the incorporation of oil palm fiber and epoxy in the interlayer part. The interlayer part acted as a platform to distribute applied stresses and enhanced the compressive strength of the glass. The generation of cracks on the glass surface varied significantly, depending on the type of fibers used as fillers and the interfacial bonding in the interlayer part of the sandwich-structured glass. The current design of sandwich-structured glass showed the desired mechanical properties and moderate appearance of glass fractures, which can be used as an impact-resistant glass in the construction field.

Keywords: sandwich-structured glass; oil palm fiber; mechanical properties; cracks

1. INTRODUCTION

Composite materials have become an important innovation in the field of materials sciences. These materials are utilized in various applications such as packaging, fixtures, paneling, joining panels, railing, automobiles, kitchen appliances, civil construction, military uses, marine industries, and in space or aircraft production. Composites offer multipurpose functions based on their properties and can be acquired at a fair price (Ashby, 2011). An epoxy glue is a synthetic mixture of a resin or epoxy polymer. Today, organic fiber is being integrated into different types of materials to improve their properties. Moreover, organic fibers can be applied as a major component in the construction field (Khalil et al., 2008).

Epoxy glue, an adhesive material, is useful as a filler (Szewczak, 2021) and is a versatile polymer with favorable features of thermal stability, high adhesive strength, adequate dielectric properties, repeatability, acceptable environmental vulnerability such as humidity, and satisfactory thermomechanical stresses (Licari and Swanson, 2011). Composites have the advantage of being a combination of two or more elements that are not soluble in the other, at a macroscopic level, reciprocally. Composites display myriad features that are not often detected in conventional materials (Shankar et al., 2013). Nevertheless, obtaining a sandwich-structured composite with acceptable transparency, durability, and load-bearing capacity has been a challenging task (Gotzinger et al., 2021).

Materials consisting of reinforcing/filler and matrix/ continuous phases, which are divided by an interface phase, are known as composites. However, the composition of these phases affects the overall performance of the composite (Bichang'a et al., 2022). Empty fruit bunch (EFB) is the main overflowing scrap produced in the palm oil manufacturing sector. EFB is made up of a combination of 80% stalk and 20% spikelet; and consists of cellulose (22.2–65%), hemicellulose (19.5–38.8%), and lignin (10–34.37%). The spikelet and stalk have similar chemical composition and fiber properties, namely, high stiffness, low density, and reasonable price (Jacob et al., 2004). Oil palm EFB exhibits a coarse appearance, a spiky form, and is rich in carbon. In addition, oil palm EFB exists in large quantities in nature, especially in compact and multicellular solid fibers (Puasa et al., 2022). Natural fiber-reinforced composites have the advantages of having a low production cost, being lightweight, biodegradable, and renewable, as well as having certain outstanding mechanical properties. In addition, such composites are environmentally-friendly and carbon-neutral (Bichang'a et al., 2022). However, the use of a single element of fiber or matrix counteracts with the desirable features of composite materials (Wu et al., 2014). Therefore, the selection of components and production approaches are very particular, having to rely on balancing the economic convenience and mechanical properties (Rubino et al., 2020).

The fabrication of epoxy nanocomposites from oil palm nano filler was investigated by Saba et al. (2016). They found that the interfacial strength between filler and polymer affects the mechanical properties and is an important factor in the development of polymer nanocomposites. In recent years, the quality of being sandwich-structured has emerged as an immensely coherent category of structures that are typically utilized in planar elements for applications wherein a high stiffness-to-weight ratio is a prerequisite. Having this type of structure has been crucial for horizontal elements with a dead load that reacts perpendicular to the element and build on to the general load applied to the structure (Vitalis et al., 2018). Glass possesses high stiffness, resists erosion, and is a naturally transparent material. It is progressively utilized in architecture and construction and has been continuously innovated further for diverse applications (Gotzinger et al., 2021; Ghoshal et al., 2013). The sandwich structure is manifested as a core attached to two distinguishable stiff and strong facesheets, in which the core distributes the load from one facesheet to another. While the facesheets contribute to the turgidity and bending, the adhesive is used as a bonding agent to transfer the shear and axial loads to the core material (Alsubari et al., 2021). However, the mechanical properties of epoxy resin as a bonding agent in terms of strength, modulus, and toughness have not been applied to certain applications. This is due to its disadvantages, such as low-impact resistance, delamination, fracture toughness, and inherent brittleness. Therefore, the physical and mechanical properties of the bonding agent could be improved by the inclusion of additive materials in the range of 1%–10% (Saba et al., 2016). In the present study, a simple configuration of a sandwich-structured glass made up of different elements of epoxy (as an adhesive material) and fiber (as a filler) effectively distributed the energy from the applied stresses on the glass surface.

2. MATERIALS AND METHODS

2.1 Materials

The EFBes were obtained from Sungai Burung Palm Oil Mill Sdn. Bhd. (Tawau, Sabah, Malaysia). The silicate glass was obtained from a local manufacturer in Kota Kinabalu, Sabah, Malaysia. All of the chemicals for the extraction of organic fibers were purchased from distributors in Malaysia. Information about the manufacturing companies is given, as follows: sodium hydroxide (NaOH), potassium hydroxide (KOH), and boric acid (H_3BO_3) were produced by Merck KGaA (Darmstadt, Germany); and the pH paper (pH 0–14) was purchased from HmbG, Johor Bahru, Malaysia. For the design and characterization of the sandwich-structured glass, all of the materials were purchased from distributors in Malaysia. Information about the manufacturing companies, is given as follows: the epoxy was produced by the Gorilla Glue Company (Cincinnati, OH, USA). The ammonium hydroxide solution (Mallickrodt Chemical, 30% NH_4OH) was produced by ChemAR (Selangor, Malaysia).

2.2 Extraction of organic fibers

Manual segregation of the EFBes was done to obtain different parts of the bunches, namely, the spikelet and stalk. After that, a shredding process was done to obtain the spikelet and stalk fibers. The extraction of the organic fibers involved a few stages of chemical treatment. A pre-treatment process was conducted using 5% NaOH in boiling conditions for 2 h. Further treatment was performed using 10% NaOH at a temperature of 20 °C for 8 h. Moreover, a strong alkali treatment was done using 24% KOH and 2% H_3BO_3 at a temperature of 20 °C for 2 h. Upon the completion of the chemical treatment process, the fibers were subjected to a filtration and rinsing process using distilled water. The pH level of the distilled water required to clean the fibers was tested using pH paper. This process was repeated until the distilled water showed a natural pH level. Next, the fibers were subjected to a drying process using an oven (Carbolite, United Kingdom) at a temperature of 100 °C for 24 h. After the completion of the drying process, the fibers were subjected to a grinding process using a blender. This step was followed by a sieving process (Sieving set/RX-29 (Tyler USA)) to produce fibers with a size of 250 μm. The consideration to select only fibers with a size of 250 μm is due to their transparency on glass and their ability to be combined with epoxy to form the interlayer part of the sandwich-structured glass.

2.3 Design of sandwich-structured glass

The single-layer silicate glass was labeled as Si. To construct a sandwich-structured glass, two pieces of glass with sizes of 3.5 cm × 3.5 cm (length × width) were used as a facesheet. The interlayer of the sandwich-structured glass was produced using 0.01 g of oil palm fibers added to 0.3 mL of epoxy. The mixture was stirred until a homogeneous combination was attained. Then, the mixture was applied to the first glass surface. Subsequently, the second glass surface was kept in contact with the first glass surface consisting of epoxy and fibers. Then, a uniform pressure of 3.112 kPa was applied to the sandwich-structured glass for 10 min at room temperature. The uniform pressure applied was important to develop the sandwich-structured glass. In addition, the uniform pressure applied increased the degree of the compaction of the fiber preform, causing a substantial modification in the permeability of the reinforcement during the epoxy infusion and in the fiber volume fraction porosity (Tanoglu and Seyhan, 2003). Table 1 summarizes the glass code, elements in the interlayer part, and size of fibers that were applied in the design of the sandwich-structured glass.

Table 1. Code for the sandwich-structured glass, interlayer elements, and size of the fibers used as fillers

Glass code	Interlayer elements	Size of fibers (μm)
SiE	Epoxy	-
SiEF(spikelet)250	Epoxy and spikelet fibers	250
SiEF(stalk)250	Epoxy and stalk fibers	250

2.4 Characterization of glass

To determine the chemical durability of single-layer glass, the weight of the glass sample before the immersion process was determined using an analytical digital balance (Adam equipment ADA-210/LE balance, United Kingdom) with an error of ± 0.0001 g. Different aqueous solutions of distilled water and ammonium hydroxide solution were used as immersion solutions. The glass sample was immersed in a solution and sealed in a bottle for 3 d. Then, the glass sample was subjected to a drying process at room temperature. Upon the completion of the drying process, the glass sample was weighed using an analytical balance. The weight loss (W_L) of the single-layer glass was determined using the following equation (Guo et al., 2012; Dousti et al., 2014):

$$W_L = \frac{W_B - W_A}{W_A} \times 100 \quad (1)$$

where W_A and W_B represent the weights of glass after and before immersion in an aqueous solution, respectively.

The surface morphology of glass was determined using an SU 3500 Hitachi Bruker tabletop scanning electron microscope (SEM) fitted with an energy dispersive X-ray (EDX) analysis (SU 3500 Hitachi, Tokyo, Japan). The operating voltage was performed at 15 keV. The mechanical properties of the glass were characterized using Universal Mechanical Testing (Gotech/AI-7000L-10/Fritsch/Pulversette 14, Taiwan, China) with a maximum load of 10 tons. All measurements were performed at room temperature.

3. RESULTS AND DISCUSSION

3.1 Chemical durability of single-layer glass

Durability is one of the most important features of glass, and any dissolution on the glass surface may form a rough surface that, consequently, modifies the mechanical properties of glass (Popovici and Lupascu, 2012). The term 'chemical durability' has been used generally to indicate the resistance that could be provided by the glass against the attack coming from aqueous solutions and atmospheric agents (Paul, 1982). The quality of a glass surface is affected by corrosion, which is a common chemical phenomenon. This is because glass can deteriorate due to the constant exposure to corrosive conditions. If a glass surface is brought in contact with water or any aqueous solution, a chemical reaction might occur between the glass and this medium. In this situation, a chemical exchange might take place over the glass surface and induce some undesirable effects, such as alteration in the transmittance and mechanical strength of a material (Popovici and Lupascu, 2012). According to Paul (1982), alkali ions, which are extracted into the solution when the glass is placed in contact with an aqueous solution, induce the formation of silica and an alkali-deficient leached layer on the glass surface. There is the formation of a barrier that alkali ions must diffuse before they can enter the solution. Therefore, the alkali levels being extracted are lower due to the formation of this layer.

In the present study, the determination of the chemical durability of a single-layered silicate glass is vital to evaluate its ability to resist chemical attack and its suitability to be used as a facesheet for sandwich-structured glass. Figures 1 and 2 show the physical appearance of a single-layered silicate glass before and after immersion in different aqueous solutions. It could be observed that there were no significant changes on the glass surface after the immersion process. Furthermore, no layers were formed, and no elements were deposited on the glass surface. The weight loss value of the single-layered silicate glass was calculated to evaluate the ability of a single-layered silicate glass against corrosion. There were variations in the weight loss value of a single-layered silicate glass after being exposed to different aqueous solutions. In the current study, the total weight loss values of a single-layered silicate glass after the immersion process in distilled water and ammonium hydroxide solution were very low, at 1.24% and 3.33%, respectively. Another type of host glass, tellurite glass, was shown in a study to have a higher percentage of weight loss, with values of 35.0% and 37.5%, respectively, as a result of severe attacks from NaOH solution (Dousti et al., 2014; Mahraz et al., 2014). This showed that a single-layered silicate glass possessed acceptable features of resistance toward distilled water and ammonium hydroxide solutions. This implies that silicate glass is a suitable candidate that can be used to develop sandwich-structured glass.

(a) (b)

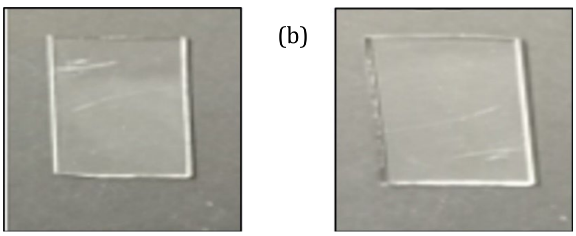

Figure 1. The physical appearance of a single-layered silicate glass (a) before the immersion process in distilled water and (b) after the immersion process in distilled water

(a) (b)

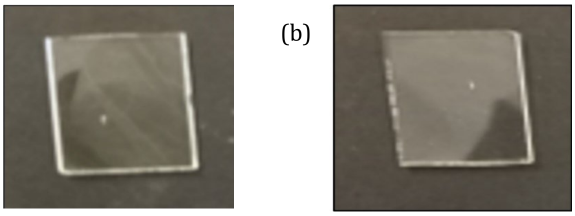

Figure 2. The physical appearance of a single-layered silicate glass (a) before the immersion process in ammonium hydroxide solution and (b) after the immersion process in ammonium hydroxide solution

3.2 Physical appearance of sandwich-structured glass

Figure 3a represents sandwich-structured glass with epoxy and without fibers in the interlayer part. Meanwhile, Figures 3b and 3c represent sandwich-structured glass with epoxy as adhesive material and spikelet and stalk fibers as fillers in the interlayer part. The sandwich-structured glass with epoxy and without fibers showed good transparency. However, a slight reduction in the transparency of the glass was evidenced by the addition of spikelet and stalk fibers as fillers. Another significant detail that could be observed was that the sandwich-structured glass appeared yellowish in color with the incorporation of epoxy in the interlayer part. According to Krauklis et al. (2018), this phenomenon is usually observed even if the epoxy is kept at room temperature, with or without exposure, and even at medium humidity levels. The yellowing phenomenon under light exposure was due to the photo-yellowing induced by the photo-oxidation mechanism.

(a) (b) (c)

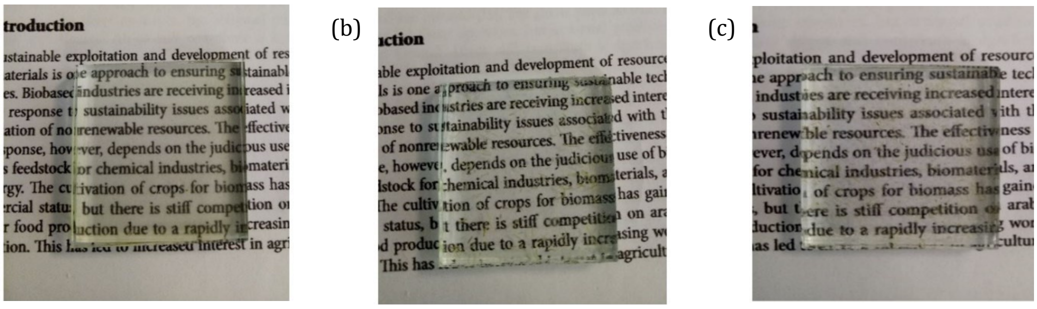

Figure 3. The physical appearance of a sandwich-structured glass (a) with epoxy and without fibers, (b) with epoxy and spikelet fibers, and (c) with epoxy and stalk fibers

3.3 Surface morphology of fibers

All natural fibers exhibit discrete surface morphologies and physical or mechanical properties. Climate and growing conditions contribute to the production of some natural fibers with complex surface morphologies and to the variations in the dimensions of natural fibers (Pai and Jagtap, 2015). Scanning electron microscopy can be used to investigate the surface morphology of fibers and the occurrence of fractures on the surface of fibers (Izani et al., 2013). It has been acknowledged that most natural fibers are lignocellulosic but also consist of other elements such as hemicelluloses, silicas, ashes, oils, waxes, pectins, and additional water-soluble elements. Cellulose is a semicrystalline polysaccharide, while hemicellulose is a particularly subdivided amorphous polymer (Pai and Jagtap, 2015). Nonetheless, fiber extraction may become complicated due to the nature of hemicelluloses, which are extremely heterogeneous groups of structural polysaccharides. This causes them to be closely connected with cellulose and lignin in the plant cell wall (Nafu et al., 2015). Therefore, a chemical treatment with NaOH can be performed to facilitate the removal of hydroxyl groups and a certain part of lignin, hemicellulose, wax, pectin, and oil that surrounds the fibers (Ibrahim et al., 2015).

Figure 4a shows the SEM image of the spikelet fibers, which displays the formation of fibrils in helical spirals due to the effect of the NaOH solution. In addition, the fiber extraction process causes the elimination of a great number of silica elements from the surface of the fiber (Law et al., 2007). In general, weak interfacial compatibility between a natural fiber and polymer matrix occurs due to the presence of hydroxyl groups on the fiber surface, which absorb water molecules and form hydrogen bonds. This feature subsequently disrupts intermolecular contact with a hydrophobic polymer matrix. Chemical treatment during the extraction process yields fibers with a fibrillary structure that enhances the contact area available for superior bonding with the polymer matrix, which in turn increases the interfacial wettability (Wang et al., 2019).

Figure 4b shows the SEM image of the stalk fibers, which illustrates the appearance of a rougher surface with fewer silica bodies as compared to that of spikelet fiber, due to the alkali treatment. The rough surface was observed due to the removal of a high portion of lignin and a lower portion of silica bodies. The removal of the silica bodies from the stalk fibers led to the generation of pores that were evident on the fiber surface. The higher concentration of NaOH causes the stalk fiber surface to become coarse and irregular, with the deposition of some substances due to residue from fiber degradation (Ibrahim et al., 2015). The determination of fiber surface conditions is crucial to enhance the interfacial bonding and reduce the direct linkage between fiber and matrix, which produces materials that are rigid and have a low impact resistance (Ehrburger and Donnet, 1980).

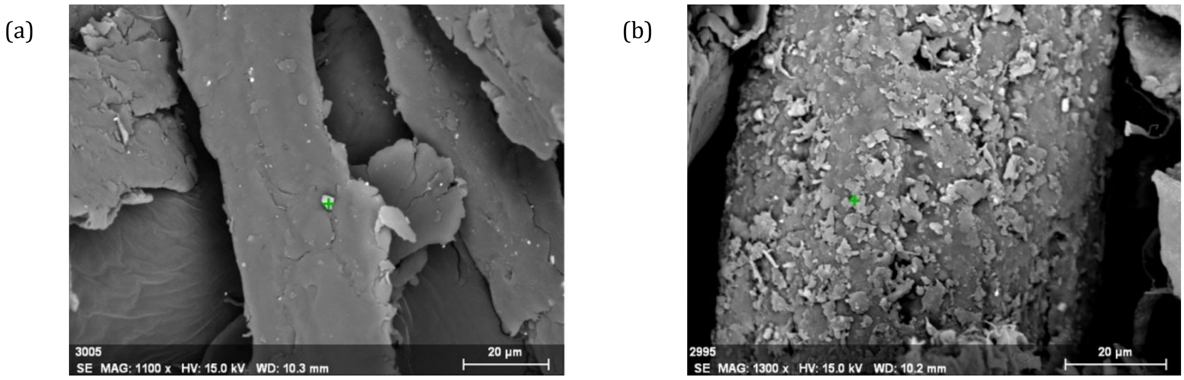

Figure 4. SEM image of the (a) spikelet fibers and (b) stalk fibers

EDX spectroscopy is governed by the principle of the photoelectric effect, in which photons with greater energy stimulate the ionization of electrons from the inner shell and produce electron vacancies in the inner shell, as illustrated by the K, L, and M shells. Most of the samples are electrically non-conducting. Therefore, a conducting surface layer is needed to create a medium for the incident electrons to flow to the ground (Craven et al., 2022). Variation in the chemical elements of oil palm is determined by the types and origins of oil palm trees (Chew and Bhatia, 2008). In addition, the features of the natural fibers are susceptible to the type, growing setting of plants, fiber production technique, fiber production segment of the tree, and growth of the plant (Tamanna et al., 2021). Figures 5a and 5b show the EDX spectra of the spikelet and stalk fibers. The EDX spectra disclose the appearance of C, O, Si, Au, and Mg. Nevertheless, the detection of the Au element is due to the coating material (Goldstein et al., 1981). Less Si elements were detected in the stalk (0.83 wt% and 0.52 at%) fibers as compared to those in the spikelet (18.93 wt% and 12.30 at%) due to the higher removal of the silica bodies from the stalk fibers. The identified elements for palm oil fibers are in good agreement with the previously reported elements of K, Si, Ca, Mg, and Al by Nafu et al. (2015). The quantitative elemental analysis of the spikelet and stalk fibers in terms of weight and atomic percentage is presented in Table 2.

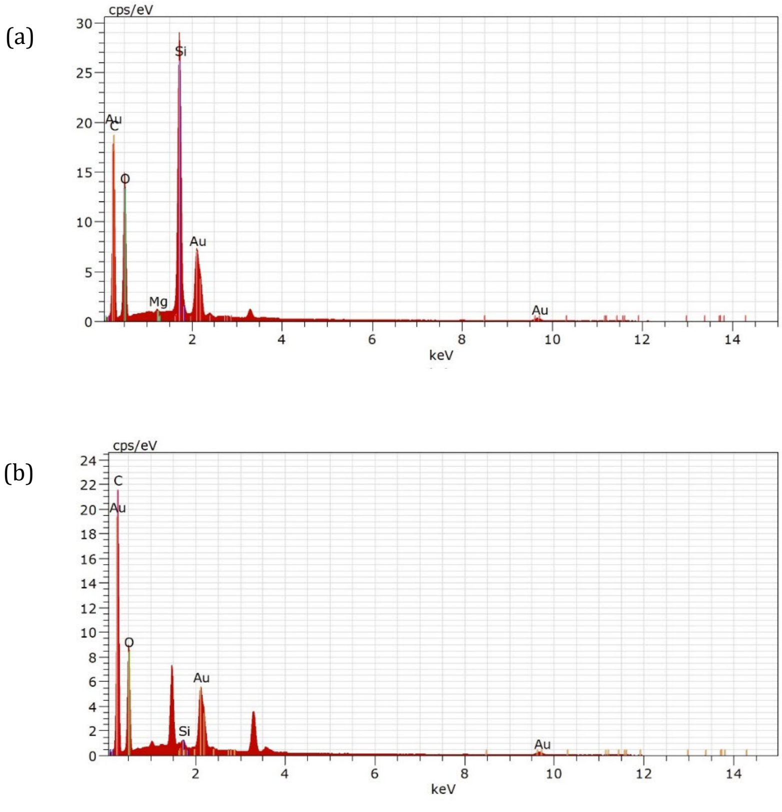

Figure 5. EDX spectra of the (a) spikelet fibers and (b) stalk fibers

Table 2. The elemental traces from the EDX spectra for the spikelet and stalk fibers

Element	Line	Spikelet		Stalk	
		Weight%	Atomic%	Weight%	Atomic%
Carbon (C)	K	37.25	56.61	46.32	68.32
Oxygen (O)	K	25.68	29.29	25.96	28.74
Silicon (Si)	K	18.93	12.30	0.83	0.52
Gold (Au)	M	17.96	1.66	26.90	2.42
Magnesium (Mg)	K	0.17	0.13	-	-

3.4 Mechanical properties

Various features and performances of glass can be attained depending on the type of glass, size of fibers, and chemistry (Rubino et al., 2020). Different types of matrices with optimum stiffness, tensile strength, flexural strength, and elongation at the break can be produced by the incorporation of fibers from oil palm EFB (Chaiwong et al., 2019). Each natural fiber possesses mechanical properties distinct from those of the other fibers, and their composites react to applied stresses in various processes (Pai and Jagtap, 2015). Therefore, the selection of fibers between the spikelet and stalk of the palm oil tree is crucial to develop sandwich-structured glass. This is because the matrix attachment and the reinforcement features determine the quality of the fiber-based composites (Tamanna et al., 2021). In general, matrices are homogeneous and monolithic materials that enable the incorporation of fillers to produce a composite (Lee et al., 2021). The matrix plays a vital role in sustaining the fibers at a preferable location and orientation. In addition, it becomes a transfer medium for load or stress and, at the same time, conserves the fibers from environmental impairment. Meanwhile, fibers act as filler or reinforcing phases and emerge as the main load or stress-bearing elements. The appropriate combination of matrix and fibers determines the quality and net shape of the composites (Bichang'a et al., 2022). Therefore, enhancing workability between the matrix and filler by changing the surface state of the fibers can improve the mechanical properties of composites (Chaiwong et al., 2019).

An integration of two or more elements produces materials with outstanding mechanical properties (Ashby, 2011). According to Lee et al. (2021), the synergy between the matrix and fibers in a composite system depends on its interface conditions. In another study, Pai and Jagtap (2015) reported that fibers possessed hygroscopic features and should be dried adequately before being blended with the polymer matrix, given that air may get entrapped in the composites. The dispersion of fibers within the matrix becomes intricate because fibers may be attracted to water (hydrophilic), and polymers may avoid water (hydrophobic). In addition, the formation of agglomeration weakens the mechanical features of the composites as the number of fibers increases. According to Lascano et al. (2021), the structure is deprived of its stability and causes premature material failure due to a lack of coordination between the core and the facesheets as the outer faces.

In the present study, the sandwich-structured glass without fibers as a filler in the interlayer part (labeled as SiE glass) possessed compressive strength, with a value of 280.60 MPa. Meanwhile, the sandwich-structured glass containing epoxy and spikelet fibers in the interlayer part (labeled as SiEF (spikelet) 250 glass) exhibited a higher compressive strength, with a value of 402.46 MPa. The sandwich-structured glass containing epoxy and stalk fibers in the interlayer part (labeled as SiEF (stalk) 250 glass) exhibited a slightly lower value of compressive strength, with a value of 363.83 MPa. The higher compressive strength possessed by the sandwich-structured glass containing epoxy and spikelet fibers in the interlayer part (SiEF (spikelet) 250 glass) implied the higher capacity of spikelet fibers to be used as a filler or a reinforcement agent in the structured glass (Fidelis et al., 2013). This was because fibers from the spikelet of EFB exhibited a higher strength than that of the stalk of EFB (Nafu et al., 2015). Furthermore, the lower value of compressive strength for the sandwich-structured glass containing stalk fibers was due to the coarse or rough fiber surface, which resulted in an inefficient interfacial bonding between matrix and fibers.

Ashraf et al. (2021) demonstrated the mechanical properties of the sandwich structure made of flax/glass hybrid composite facesheet and honeycomb core. They found that a glass fiber composite with a compressive strength value of 148.40 MPa gave optimum compressive strength due to greater stiffness and larger fiber volume fragment of glass than that of flax fiber. Meanwhile, Al-Fatlawi et al. (2021) reported a lightweight sandwich plate comprising a fiber-reinforced plastic (FRP) honeycomb core and woven glass fiber with epoxy resin as facesheets possessed a compressive strength of 550 MPa. They suggested that these types of material elements and the arrangement of the designated material provided a minimal weight and good mechanical properties. In the present study, the sandwich-structured glass containing epoxy and spikelet fibers possessed a slightly lower compressive strength value of 402.46 MPa compared to the previously reported sandwich plate comprising a FRP honeycomb core and woven glass fiber with epoxy resin with a compressive strength value of 550.00 MPa. However, our method of developing sandwich-structured glass using simple interlayer structure arrangements, organic fibers as filler elements, and a feasible assembly process are beneficial to the production of glass structures with an acceptable impact resistance.

3.5 Generation of cracks on the glass surface

The sandwich structure is one in which the composite material is made up of different layers by combining two rigid materials of different ranges of thickness and a lightweight core (Komorek et al., 2022). This design has important features such as a high strength-to-weight ratio, a high stiffness-to-weight ratio for bending, good resistance features toward corrosion, high flexural and transverse shear stiffness, and an extremely low weight that significantly reduces the total weight (Rajak et al., 2019). Different materials, including glass, ceramic, mud, and glaze, show the formation of surface crack patterns. The formation of these cracks is stimulated by the contraction of the object's surface area (Iben and O'Brien, 2009). Nevertheless, the generation of fractures on the glass surface is affected by the strength of the glass. The degree of fracture stress predominantly alters the crack patterns that develop when distributing cracks cut through the glass surface. The magnitude of stored elastic strain energy in the glass is determined by its strength and fracture stress. Therefore, the crack expansion depends on the stored elastic strain energy from a fracture (Bradt, 2011). In general, the maximum energy that can be absorbed by the material implies deformation or deflection, which is a mode of failure (Balaganesan et al., 2017). The process is driven by the delamination mechanism and, subsequently, is followed by the rupture of the matrix and breakage of the fibers (Ameur et al., 2019).

Figure 6 shows the physical appearance of glass after being subjected to compressive testing. Some deformations on the glass were formed during the interaction. It could be observed that all the sandwich-structured glasses remained intact, with the formation of fractures in a certain area of the glass surface. In the present study, sandwich-structured glass containing epoxy and stalk fibers showed the formation of spalling mode fractures. This generation of fractures was mainly close to the top facesheet area. Spall is the dynamic fracture that occurs due to tensile stresses arising from the synergy of spreading waves. Compressive waves moving from the energy deposition surface of a body intersect those reflecting from the rear surface, generating internal ruptures or spallation under certain conditions, in which the tensile stresses are adequately high. There are four stages of damage accumulation. In the first stage, the nucleation of voids or cracks occurs at the existing defect locations. Then, in the second stage, the individual voids or cracks grow. Afterwards, the voids or cracks undergo a coalescence process. Finally, the last stage leads to fragmentation (Jarmakani et al., 2010).

Shock waves with an energy arising from the point of impact caused damage to the glass surface. In a certain situation, wherein the object hits the glass surface, stretching and compression processes occur, which lead to the breaking of the glass (Tiwari et al., 2019). If the impact originated from low-impact energy (not a projectile impact with high momentum), the formation of radial cracks on the glass surface is likely to occur. Therefore, radial cracks are generated on the opposite side of the force where the load was applied, and the radial cracks spread from the origin of the impact. However, the radial cracks will be impeded if they intersect an existing fracture line (Harshey et al., 2017). Our findings are in good agreement with Bradt's (2011) findings, in which the emanation of radial cracks from an impact crush zone was reported to be due to the impact of a blunt object. In another study, Jacob et al. (2004) suggest that fibers from the spikelets of EFB possess greater strength compared to those of stalk fibers. Therefore, sandwich-structured glass containing epoxy and stalk fiber in the interlayer part showed the formation of prominent fractures on the glass surface. However, sandwich-structured glass containing epoxy and spikelet fibers in the interlayer part showed the formation of vague fractures on the glass surface. In the present study, the distribution of applied stresses was accomplished by using epoxy and oil palm fibers as core materials in the interlayer part. Therefore, the mechanical properties can be improved by using a suitable design of sandwich-structured glass with the utilization of organic fiber as a filler and epoxy as an adhesive material in the interlayer part of the glass.

(a) (b) (c)

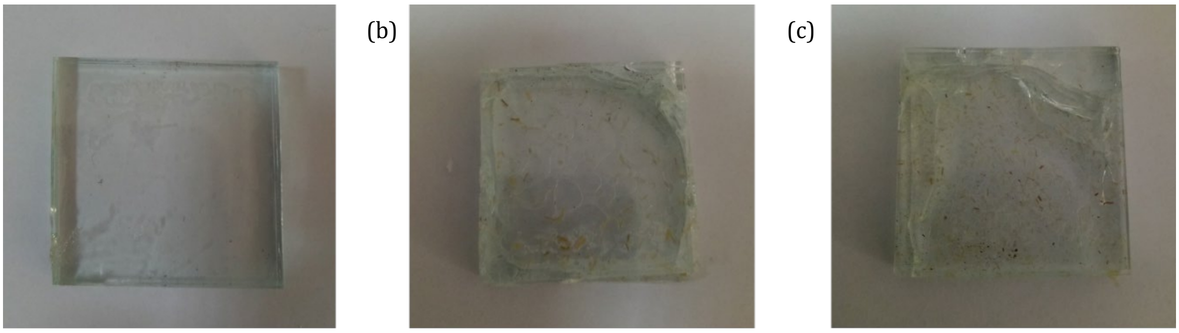

Figure 6. The physical appearance of a sandwich-structured glass after being subjected to stress. The interlayer part contained (a) epoxy, (b) epoxy and spikelet fiber with a size of 250 μm, and (c) epoxy and stalk fiber with a size of 250 μm

4. CONCLUSION

A single-layered silicate glass showed acceptable chemical stability, with a weight loss value of 1.24% and 3.33% when it was immersed in distilled water and ammonium hydroxide solution, respectively. The physical appearance of sandwich-structured glass containing epoxy in the interlayer part showed a yellowish color with the desired transparency. The incorporation of the spikelet and stalk fibers in the interlayer part slightly reduced the transparency of the sandwich-structured glass. The SEM image showed the formation of fibrils in helical spirals in the spikelet fibers due to the chemical treatment. The SEM image of the stalk fibers showed the appearance of a rougher surface than that of the spikelet fibers. The EDX spectra affirmed the detection of C, O, Si, Au, and Mg elements. The mechanical properties of the sandwich-structured glass increased from 280.60 MPa to 402.46 MPa with the incorporation of organic fibers as fillers and epoxy as an adhesive material in the interlayer part of the glass. The findings showed that the distribution of applied stresses by the interlayer part of the sandwich-structured glass caused variations in the crack patterns on the glass surface. The sandwich-structured glass containing organic fiber and epoxy can be used as an impact-resistant material in the construction sector.

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