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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Characteristic Properties and Behavior under Flexural and Impact Loadings of Packaging-Waste/E-Glass/Epoxy Sandwich Composites for Construction Applications

Yapı Uygulamaları için Atık-Ambalaj/E-Cam/Epoksi Sandviç Kompozitlerin Eğilme ve Darbe Yükleri altındaki Karakteristik Özellikleri ve Davranışları

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Abstract

Using textile structural composites improves day by day in various industries due to their high specific strength and modulus, good fatigue and corrosion resistance. The most important reasons for the increased use of textile structural composites are the increased expectations for product performance and demand for lightweight materials in global markets. Rapid economic growth, urbanization, rising in population and welfare level lead to an increased amount of waste production. In Turkey, the annual average of solid waste is 25 million tons and 20% of this waste consists of packaging wastes. In this study, a new sandwich material was developed for construction applications with low cost and high performance by using box wastes as core and E-Glass woven fabric as sheet materials. The mechanical properties of sandwich composites were investigated by 3-point flexural test and their impact behavior was compared after low-velocity impact tests in different energy levels. The core material had a negligible flexural strength. The flexural load of sandwich composites was dramatically higher than those of face material. Low-velocity impact results showed that absorbed energy and damaged area increased with increasing impact energy. It could be concluded that the developed sandwich composites absorb more energy with small damaged areas and therefore can be considered as damage resistant materials for constructional applications such as door and siding.

Keywords: Sandwich composites, Packing-waste, E-Glass/epoxy composites, Flexural strength, Impact resistance

Öz

Tekstil yapısal kompozitlerin kullanımı, yüksek özgül dayanım ve modülü, iyi yorulma ve korozyon direncinden dolayı, çeşitli endüstrilerde günden güne artmaktadır. Tekstil yapısal kompozitlerinin kullanımının artmasının en önemli nedenleri, küresel pazarda ürün performansı ve hafif malzemelere olan talebin artmasıdır. Hızlı ekonomik büyüme, kentleşme, nüfus ve refah düzeyindeki artış, atık miktarının da artmasına yol açmaktadır. Türkiye'de yıllık ortalama katı atık miktarı 25 milyon tondur ve bu atığın %20'sini ambalaj atıkları oluşturmaktadır. Bu çalışmada inşaat uygulamaları için, çekirdek olarak atık karton kutu ve dış yüzey malzeme olarak E-Cam dokuma kumaşın kullanıldığı düşük maliyetli ve yüksek performanslı yeni bir sandviç malzeme geliştirilmiştir. Sandviç kompozitlerin mekanik özellikleri 3-nokta eğilme testi ile incelenmiş ve farklı enerji seviyelerinde düşük hızlı darbe testlerinden sonra darbe davranışları karşılaştırılmıştır. Çekirdek malzeme ihmal edilebilir bir eğilme dayanımı göstermiştir. Sandviç kompozitlerin eğilme yükü, dış yüzey malzemelerden çok daha yüksektir. Düşük-hız darbe sonuçları, absorbe edilen enerjinin ve hasarlı alanın artan darbe enerjisiyle birlikte arttığını göstermiştir. Geliştirilen sandviç kompozitlerin daha az hasarlı bölge ile daha fazla enerji absorpladığı belirlenmiş ve bu nedenle kapı ve dış cephe kaplama gibi inşaat uygulamaları için hasara dayanıklı malzemeler olarak kabul edilebileceği sonucuna varılmıştır.

Anahtar Kelimeler: Sandviç kompozitler, Atık-ambalaj/E-Cam/epoksi sandviç kompozitler, Eğilme dayanımı, Darbe direnci.

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I. INTRODUCTION

Textile structural composites have been used in many industrial areas since 1940s, mainly due to developments in thermoset-based polymers, from aerospace to automotive. It is due to the lightness, high strength and modulus, high fatigue resistance and corrosion resistance of composite materials, as well as their production in complex geometric shape parts. [1]. Composites are used extensively in construction industry, from prefabricated houses to bridges [2]. The most used areas of composite materials in construction industry are facade cladding panels and siding materials. Facade claddings can be produced as single-walled or double-walled panels and polyurethane foam can be used for insulating purposes in core part of sandwich composites [3]. Sandwich composites are designed by placing a different material between two layers in a different form. These structures consist of a thick and low density core material between thin and stiff faces. Core materials include foams and aluminum, Nomex and polypropylene (PP) structures in honeycomb or corrugated forms [4]. Honeycomb sandwich constructions are used in where high mechanical strength is required [5, 6]. Some detailed studies were performed by researchers about the mechanical and impact properties of sandwich composites. Cabrea et al. produced sandwich composite by combining PP cores with PP faces in the tubular unit cell structure. It was stated that PP/PP sandwich composites exhibit a more ductile behavior and flexural strengths of these structures are lower compared to E-glass/PP constructions [7]. Xu et al. produced sandwich composites by comprising cores in a wavy beam structure. Sandwich composites showed a face wrinkling-based failure under flexural load which caused by insufficient core resistance [8]. Lascoup et al. developed a sandwich composite that consists of the PU foam core structure with E-glass faces in which the structure is reinforced by an angular stitching through-the – thickness. Stitching density and stitching width are stated as important process parameters [9]. Brandt et al. reported that 3D reinforced sandwich composites exhibit a high potential for damage tolerance and energy absorption capability. The mechanical performance of these materials are influenced by the design parameters. However, it was stated that the crimp caused by weaving process is also an important factor on the mechanical properties [10]. Guan et al. studied both the experimental and numerical effects of stitching on ballistic performance of sandwich composites. The results showed that the stitching had no significant effect on the ballistic strength of the sandwich composites [11]. Meo et al. produced sandwich composites by using Nomex honeycomb core and carbon/epoxy faces. The impact strength of the sandwich composites measured under different energy levels. The energy absorption of Nomex honeycomb was eight-times higher than that of the carbon/epoxy faces [12].

The common feature of commercially produced core materials is their high cost. Nowadays, there is a growing interest in waste-based composites because of the strong need for new low-cost materials which also contribute to recycling. Rapid economic growth, urbanization, rising in population and welfare level lead to an increased amount of wastes. In Turkey, the annual average of solid waste is 25 million tons and 20% of this waste consists of packaging wastes. The amount of packaging placed on the market is 2.5 million tons per year in Turkey. The recycled amount of packaging is about 2 million tons [13]. It could be stated that there is a successful recycling of packaging waste. However, there is not any effort on manufacturing high value added products using these wastes. The novelty of this study is using box wastes as core materials of sandwich structures with E-glass/epoxy faces to obtain low-cost, high-performance and recycled sandwich composites for construction applications.

II. MATERIALS AND METHODS

2.1 Manufacturing of Sandwich Composites

E-glass twill (2/2) woven fabric made from 300 tex fibers was used as face materials of sandwich composites. The areal weight of fabric was 288 g/m^2 and the thickness of fabric was 0.34 mm. The warp/weft density of fabric was 6 ends/10 cm. A corrugated cell type box waste was used as core material. The areal density of box was 0.59 kg/m^2 and the thickness of box was 6.20 mm. Sandwich composites (SC) are produced according to the hand lay-up method using epoxy resin (Hexion, MGS LR160) and hardener (Hexion MGS LH160) in the ratio of 100/25. Curing occurred at 20°C for 24 hours. Figure 1 shows the manufacturing stages of the sandwich composite. For sandwich composite production, the waste box (C) was firstly cut to dimensions of 30x30 cm. E-glass woven fabric are cut in the same dimensions as 4 layers for each faces (F). Teflon films were used on both surfaces for easy releasing of composite. Figure 2 shows the view of produced box waste/E-glass/epoxy sandwich composite. The thickness values of face, core and sandwich composite materials were 1.88 mm, 6.20 mm and 9.73 mm, respectively.

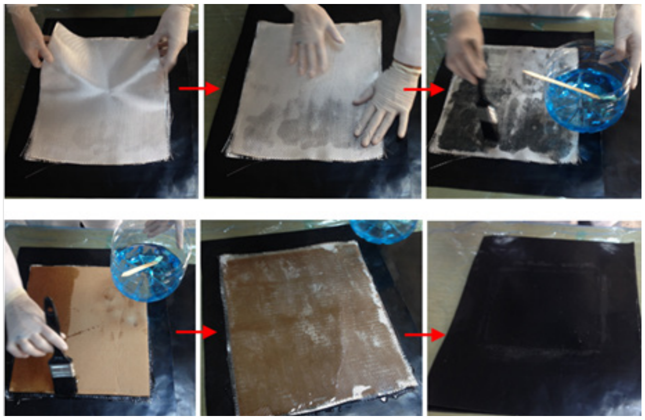

Figure 1. Production stages of the sandwich composite.

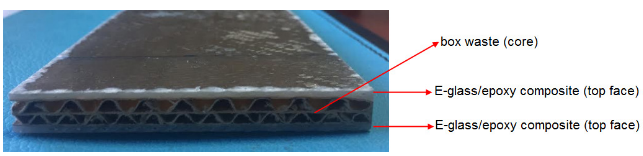

Figure 2. The view of produced box waste/E-glass/epoxy sandwich composite.

2.2 Performed Tests

Density measurements of sandwich composites were performed according to ASTM D792-13 [14] by using a density meter (Precisa®, XP205). The density of the specimens was calculated by measuring the weight of the specimens in the air and in the distilled water at 23±2°C. The composite fiber fraction was measured by burn-off test of ASTM D3171-15 [15] at 650°C for 2 hours. Fiber volume fraction of face composites was calculated by using Equation (1).

$$V_f = [(W/F)/(w/c)] \times 100 \quad (1)$$

where; V_f is volume based fiber fraction (%), W is fiber weight (g), w is composite weight (g), F is fiber density g/cm^3), c is composite density (g/cm^3).

Flexural properties of sandwich composites were measured according to 3-point flexural test method of ASTM C393-16 [16]. The flexural tests of the sandwich composites were performed on a Zwick-Roell tester. The dimension of the test specimen was 75 mm x 250 mm. The support span length was 200 mm and test speed was 6 mm/min. Figure 3 shows the views of core, face and sandwich composite during flexural test.

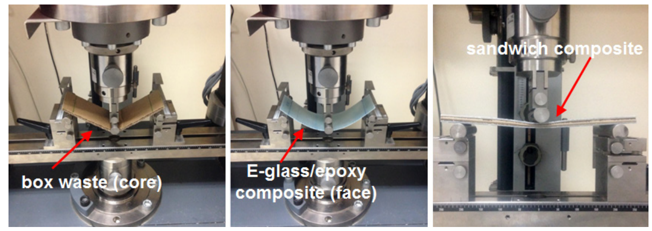

Figure 3. The views of core, face and sandwich composite during flexural test.

Drop-weight impact tests were performed in four different energy levels as 5J, 10J, 20J, 30J and 50J according to ASTM D7136-15 [17] using a CEAST 9350 impact tester. The specimen size was 100 mm x 150 mm. The mass of hemispherical impactor was 5.05 kg and the diameter of impactor was 12 mm. The illustration of impact test machine was given in Figure 4. Peak force and peak deformation values were obtained from impact test. Absorbed energy was calculated by software automatically. After impact test, the front and back face damaged area measurements were conducted on image processing software (BAB Bs200Doc, Turkey). The dent depths of sandwich composites were also measured after impact tests as shown in Figure 4(b).

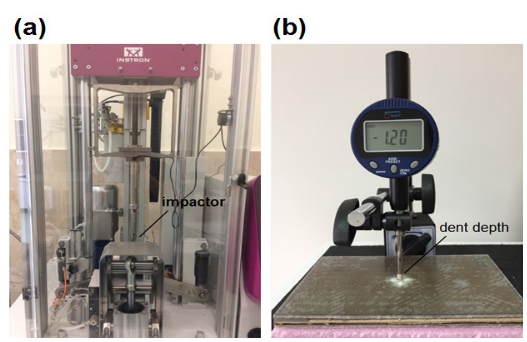

Figure 4. The illustration of impact test machine (a) and dent depth measurement (b).

The flexural strength (2), modulus (3) and strain (4) of sandwich composites were calculated according to the equations of ASTM D790-90 [18] which are given below:

$$S = 3PL/2bd^2 \quad (2)$$

$$E = L^3 m/4bd^3 \quad (3)$$

$$\varepsilon = (l_1 - l_0)/l_0 = \Delta l/l_0 \quad (4)$$

where; S is the stress in the outer fibers at mid-span (N/m^2), P is the load at a given point on the load-deflection curve (N), L is the support span (m), b is the width of beam tested (m), d is the depth of beam tested (m), E is the modulus of elasticity in flexural (N/m^2), m is the slope of the tangent to the initial straight-line portion of the load-deflection curve (N/m) of deflection. ε is the flexural deflection (%), Δl is the elongation (m) and l0 is the initial length (m).

The core shear strength (5) and facing stress (6) of sandwich composites were calculated according to the equations of ASTM C393-16 [16] which are given below:

$$F_s^{ult} = \frac{P_{max}}{(d+c)b} \quad (5)$$

$$\sigma = \frac{P_{max}\,S}{2t\,(d+c)\,b} \quad (6)$$

where; F_s^{ult} is the core ultimate strength (MPa), P_{max} is the maximum force prior to failure (N), t is the nominal facing thickness (mm), d is the sandwich thickness (mm), c is the core thickness, b is the sandwich width (mm), σ is the facing stress (MPa) and S is the span length (mm).

The absorbed-energy was calculated by software of impact tester according to equation (7):

$$E_A = \frac{1}{2} m\,(v_i^{\,2} - v_r^{\,2}) \quad (7)$$

where; E_A, is absorbed-energy (J), m is the impactor mass (kg), v_i is the velocity of impact (m/s) and v_r, rebounding velocity (m/s).

III. RESULTS AND DISCUSSIONS

The density, thickness and fiber fraction values of core, face and sandwich composites are presented in Table 1. The thickness of sandwich composite was higher than those of the core and face materials as excepted. The fiber volume fraction of E-glass/epoxy face composite was not high because of using hand lay-up method. And also, the void content of E-glass/epoxy face composite was quite high due to the hand lay-up method. Both fiber volume fraction and void content had obvious effects on the mechanical properties of composites. Density of core material was lower than those of E-glass/epoxy face composite and sandwich composite, as expected. Sandwich composite showed quite low density and areal weight which provide high specific strength.

Table 1. The physical properties of the sandwich composites.

Material type	Thickness (mm)	Density (g/cm^3)	Areal weight (kg/m^2)	Fiber volume fraction (%)	Void content (%)
C	6.20 ± 0.08	0.15 ± 0.03	0.59 ± 0.04	-	-
F	1.88 ± 0.06	1.49 ± 0.09	2.68 ± 0.11	41.40 ± 0.78	5.00 ± 0.492
SC	9.73 ± 0.07	0.62 ± 0.02	6.59 ± 0.16	-	-

The results of flexural and core shear test of sandwich composites are presented in Table 2. Figure 5 shows the load-extension behavior of sandwich composites. As seen in Figure 5, the maximum flexural load of sandwich composite was about 19 times higher than that of core material and about 6.5 times higher than that of E-glass/epoxy face composite. The packaging-waste/E-glass/epoxy sandwich composite was failed by buckling of the panel after flexural load which was generally caused by insufficient panel thickness and core stiffness. E-glass/epoxy face composite showed a more ductile flexural behavior compared to the sandwich composite which confirmed by high deflection. This was probably due to the high support span length of flexural test. However, E-glass/epoxy face composite showed a considerably higher flexural strength compare to sandwich composite. The flexural strength of core material was negligible.

Table 2. Flexural test results and core shear test results of sandwich composites.

Material type	Load (N)	Deflection (%)	Flexural strength (MPa)	Core shear strength (MPa)	Facing stress (MPa)
C	31.20 ± 0.29	180.79 ± 35.45	3.19 ± 0.08	-	-
F	91.88 ± 6.28	2495.96 ± 119.54	103.27 ± 6.51	-	-
SC	587.75 ± 18.32	55.31 ± 3.24	24.70 ± 0.78	0.49 ± 0.01	26.06 ± 1.45

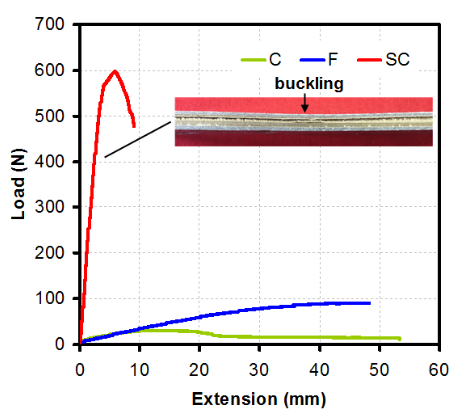

Figure 5. The load-extension behaviour of sandwich composites.

The flexural test results of developed sandwich composite was compared with a produced sandwich composite in literature by using woven glass/PP fabric as face and a 80 kg/m^3 PP honeycomb as core material [7]. The core shear strength of packaging-waste/E-glass/epoxy sandwich composite was 0.49 MPa while the core shear strength of woven glass/PP-honeycomb sandwich composite was 0.14 MPa. These results indicated that the core shear strength of packaging-waste/E-glass/epoxy sandwich composite was about 3.5 times higher than that of woven glass/PP-honeycomb sandwich composite. The facing stresses of packaging-waste/E-glass/epoxy sandwich composite and woven glass/PP-honeycomb sandwich composite were 26.06 MPa and 30 MPa, respectively. Considering the price/performance properties of both sandwich composites, it is possible to achieve the similar performance properties with 30% low-cost by using waste box.

Table 2 presents the impact test results of sandwich composites for 5J, 10J, 20J, 30J and 50J. Figure 6 shows the force-time, force-deformation, energy-time histories of the sandwich composites. Peak force values of sandwich composites were varied from 1783.0 N to 4889.75 N. The peak forces of sandwich composites increased by increasing impact energy levels. At 50J impact energy, the sample was fully perforated. At 30J impact energy, the sandwich composite was partly perforated in which the front face and core were fully perforated while the back face had a severe damage. Since the sandwich composites were perforated at 30J and 50J, their force-time histories were different from those of the 20J, 10J and 5J impacted samples. As seen in Figure 6(a), there were two-peaks were obtained in force-time history of sandwich composites. In peak-1, some matrix-cracks, minor fiber breakages and fiber-matrix delamination were probably occurred. After that the peak force could be reached to its maximum value which defined as peak-2.

Table 5. The impact test results of sandwich composites.

Impact energy	Velocity (m/s)	Peak force (N)	Peak deformation (mm)	Absorbed energy (J)	Damaged area (mm^2)		Dent depth (mm)
					Front face	Back face	
5J	1.43	1783.0	7.53	1.48	90.36	-	0.25
10J	2.02	2466.1	10.22	5.62	189.71	-	0.71
20J	2.85	4507.1	14.78	11.64	288.61	58.29	1.57
30J	3.49	4475.9	16.85	27.79	287.12 (pf*)	214.55 (pf)	5.05
50J	4.51	4889.8	19.29	41.45	267.82 (fp**)	315.24 (fp)	10.73

* pf: partly perforated, ** fp: fully perforated

Peak deformation values of sandwich composites were varied from 7.53 mm to 19.29 mm. Peak deformation values also increased with increasing impact energy levels which indicated that the sandwich composites showed more deflection at higher impact energy levels. The absorbed energy values of sandwich composites were varied from 1.48J to 41.45 J. As shown in Figure 6(c), sandwich composite showed an energy-drop from 5J to 30J energy levels after achieving the peak force because of elastic-recovery. However, there was no an energy-drop at 50J as a consequence of fully perforation that did not give any chance to elastic-recovery of the sandwich composite.

Figure 7(a) shows the damaged areas of sandwich composites on both front and back faces after impact test by considering the peak loads. As seen in Figure 7(a), damaged areas generally increased by the increase in impact energy levels. There were no damaged areas observed on back faces of the sandwich composites at 5J and 10 J impact energy levels while the sandwich composite showed a small back face damaged area at 20 J. The front face damaged areas and peak forces of sandwich composites at 20 J and 30 J impact energy levels were almost same while the sandwich composite showed a 3.7 times higher back face damaged area at 30J. This was due to the partly perforation occurred on front face of sandwich composite at 30J. It can be concluded that the impact damage threshold of sandwich composite was 30J. At this impact energy level, sandwich composite showed a permanent deformation which partly occurred on the front face. Figure 7(b) shows the dent depths of sandwich composites after impact test by considering the absorbed energy. The dent depths of sandwich composites increased with an increase in impact energy levels. The more damage in sandwich composite caused the more energy absorption, as expected.

Figure 8 shows the views of front and back face damaged areas of sandwich composites. Impact load caused multiple-fiber-breakages and severe fiber/matrix delamination on front face. Besides these failures, the fiber pull-out was observed at the back faces of sandwich composites. It can be concluded that the core material restricted the damaged area and increased the energy absorption of the sandwich composites which resulted as relatively damage resistant materials.

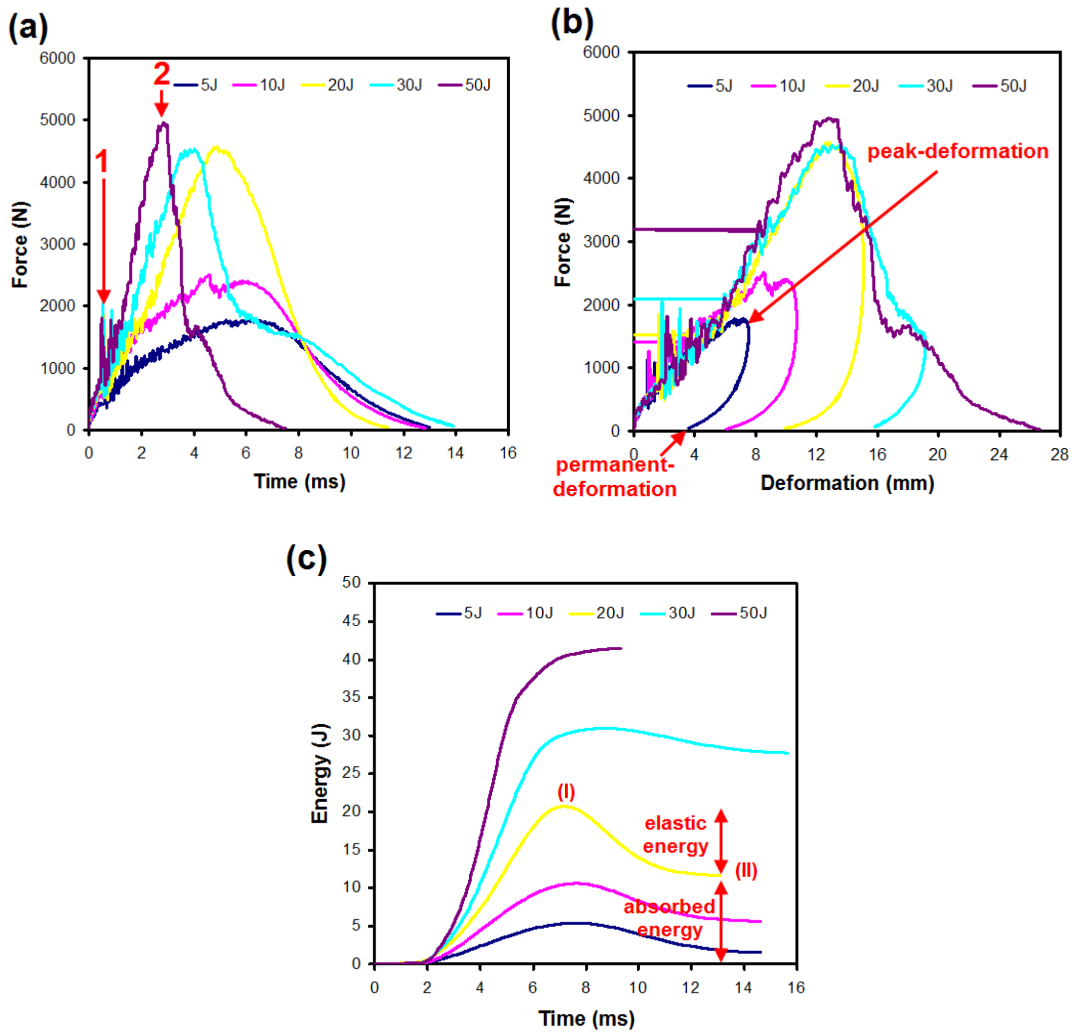

Figure 6. Force-time (a), force-deformation (b), energy-time history (c) of sandwich composites.

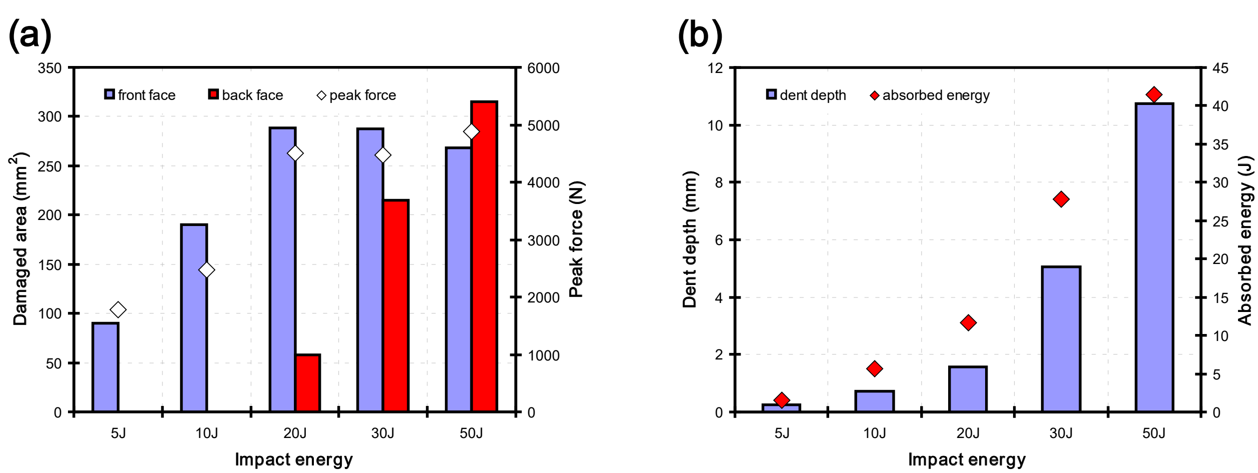

Figure 7. Damaged area-peak force (a), dent depth-absorbed energy (b) of sandwich composites.

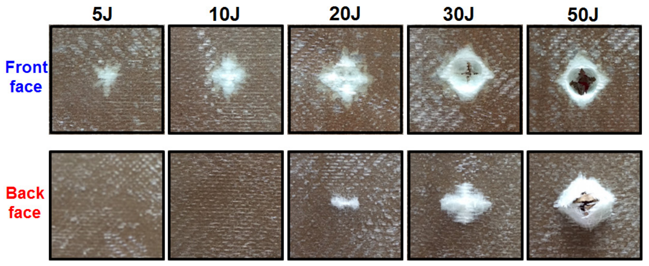

Figure 8. Front and back face damaged area views of sandwich composites.

IV. CONCLUSIONS

A novel packaging-waste/E-glass/Epoxy sandwich composite was developed and its flexural and impact properties were investigated. This sandwich composite had an important contribution to recycling process of packaging wastes in a different perspective. The packaging-waste/E-glass/epoxy sandwich composite showed quite low density and areal weight which provide high specific strength. The compatible flexural test results were obtained compared to literature with quite low-cost. The maximum flexural load of sandwich composite was about 19 times higher than that of the core material and about 6.5 times higher than that of the E-glass/epoxy face composite. The flexural load caused a panel buckling type failure on the sandwich composite which was probably caused by insufficient panel thickness and core stiffness. The peak forces, peak deformations and absorbed energy values of sandwich composites increased with increasing impact energy levels. Because of the fully-perforation at 50J, there was not any elastic-recovery occurred. The damaged areas and dent depths of sandwich composites were generally increased by the increase in impact energy levels, as expected. The more damage in sandwich composite caused the more energy absorption. The impact damage threshold of sandwich composite was determined as 30J in which the sandwich composite showed a partly-perforation on its front face. It can be concluded that the core material restricted the damaged area and increased the energy absorption of the sandwich composites which resulted as relatively damage resistant materials. Using thicker box as core material and filling the cells of box with rigid foams to overcome the buckling type failure and to increase the damage tolerance of sandwich composite could be the subject of future work. By this way, it could be possible to contribute the potential thermal and sound insulation properties of sandwich composites especially using as siding components in constructional applications. The thermal insulation properties of these new sandwich composites will be also investigated in future researches.

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