Effect of Gamma Radiation on Compressive Properties of Kevlar/Oil Palm Empty Fruit Bunch Hybrid Composites

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The compressive strength of irradiated hybrid composite materials was investigated *via* compression testing. The hybrid composites consisted of Kevlar fibre, oil palm empty fruit bunch (EFB) fibre, and epoxy. The hand lay-up method was used to fabricate the samples. The samples were then irradiated with different gamma radiation doses: 25 kGy, 50 kGy, and 150 kGy. Compression tests were performed in accordance with ASTM D695 (2015). Compressive strength in Group 1 increased to 30.4 MPa at 25 kGy. At 50 kGy, the compressive strength further increased to 39.6 MPa. Compressive strength for Group 2 also increased to 58.7 MPa when the radiation increased to 50 kGy. The compressive modulus showed the same trend in compressive strength for both Group 1 and Group 2. It was observed that the exposure of hybrid Kevlar/oil palm EFB/epoxy hybrid composites improved the compressive properties of the materials. Furthermore, a difference in the thickness and layering pattern also influenced the compressive strength with different doses. At 150 kGy, both layering patterns showed a degradation of compressive properties.

Keywords: Compressive strength; Gamma radiation; Hybrid composites

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INTRODUCTION

Compressive strength is a mechanical test that measures the amount of maximum compressive load that materials can withstand before failure. The objective of compression testing is to determine the behaviour of the material by measuring various parameters such as compressive strength, yield strength, compressive modulus, *etc*. These parameters may help to determine the suitability of the material for specific applications.

Researchers have investigated the compressive strength properties of Kevlar-reinforced fibre composites. Muhammad *et al.* (2015) investigated the compressive properties of a Kevlar hybrid with carbon and glass composites. Salman *et al.* (2015) concluded that the presence of Kevlar fibre enhanced the properties of glass fibres. The compressive strength of different types of composite materials, Kevlar/glass fibre reinforced epoxy resin and carbon/glass fibre reinforced epoxy resin with multi layers were investigated (Salman *et al*. 2015). From the work, it was concluded that the compression strength obeyed the rule of number of layers and types of hybrid fibre-reinforced polymer matrix composites. Ankolekar *et al.* (2015) studied the compressive strength of 10 wt.%

Kevlar reinforcement with Bisphenol A. epoxy resin. However, in the above studies, the effect on radiation towards the properties of compression were not investigated.

Hybrid Composites

Composites have vast usage in engineering applications. Currently, laminated composites are becoming very popular in the area of aeronautics, wind energy, and the automotive industry (Maier *et al*. 2014). Hybrid composites can also be used for security, such as producing an armour (Radif *et al*. 2011).

Hybrid composites, containing both synthetic and natural fibres for reinforcement, are becoming increasingly in demand across many industries. Generally, studies on the effects of mechanical properties of various hybrid composites has increased. Rashid *et al.* (2011) evaluated the mechanical properties of hybrid composite between coir and Kevlar. Studies on hybrid between kenaf and Kevlar were conducted by Yahya *et al*. (2014). In his work, the effect of kenaf volume content and fibre orientation on tensile and flexural properties of kenaf-Kevlar hybrid composites were studied. Tshai *et al*. (2014) investigated the mechanical properties of hybrid fibre polyactide acid composite with empty fruit bunch (EFB) and chopped glass strand. Al-Mosawi *et al*. (2012) evaluated the impact strength, tensile strength, flexural strength, and hardness of hybrid composites between palms and Kevlar fibres. Hybrid composites consisting natural and natural fibres have also gained wide interest such as hybrid between kenaf and sugar palm (Bachtiar *et al.* 2015), jute with oil palm (Jawaid *et al.* 2013), coir and oil palm (Zainudin *et al.* 2014) and many more.

Ionising Radiation

Ionising radiation, especially from the gamma source, offers several benefits such as a continuous operation, less atmospheric pollution, and minimal time requirement compared to various alternative treatments (Shubhra and Alam 2011). Exposure of material to radiation offers benefit to the material. It may be used as one of the methods to enhance the properties of the materials such as composite materials. In contrast, it is known that polymer matrices are usually radiation sensitive, which can be significantly affected by certain amounts of radiation exposure (Wu *et al*. 2013). As a result, this situation might lead to the degradation of properties and thus cause serious engineering problems. Consequently, the investigation of radiation's effect on polymer matrices and composites is essential when developing any new matrix resin. Studies on the influence of ionising radiation on the mechanical properties of various materials have been performed (Shubra *et al.* 2010; Jovanovic *et al*. 2013; Hassan *et al.* 2014; Campos *et al.* 2015). Haydaruzzaman *et al*. (2009) studied the effect of gamma radiation on composites with natural fibres.

Table 1 summarizes the application of ionising radiation to various materials. From the studies, it is shown that radiation doses play an important role in observing the effect of radiation to the material. The effects to the material exposed varies with the radiation dose. The studies also showed that there are advantages in exposing the materials to radiation. It enhanced the mechanical properties: tensile and flexural strength of the materials (Shauddin *et al.* 2014). Palm *et al*. (2015) studied the influence of the ionising radiation on the mechanical properties to the Wood-Plastics Composites and the studies showed that there was an increased in the strength of the material after being irradiated at a certain dose.

Table 1. Previous Research on Ionising Radiation to Various Materials

No.	Authors	Material	Radiation Dose
1.	Hoffman and Skidmore 2009	Epoxy/carbon-fibre composite	0.5 MGy, 1.0 MGy, and 2.0 MGy
2.	Martinez-Barrera *et al*. 2013	Luffa fibres	50 kGy and 100 kGy
3.	Naim *et al*. 2017	PVC/ZnO polymer composites	5 kGy to 40 kGy
4.	Vasco *et al*. 2017	Sisal/polyurethane composites	25 kGy
5.	Raghavendra Supreeth *et al.* 2015	Pineapple leaf fibre (PALF)/jute composites	1 kGy to 20 kGy
6.	Sekulic *et al*. 2006	Carbon/epoxy composites	12 MGy and 20 MGy
7.	Hoque *et al.* 2017	Raw and polyethylene glycol-modified bleached jute reinforced polyester composites	2 kGy to 14 kGy
8.	Shauddin *et al*. 2014	Jute caddice/polyethelene composites	2.5 kGy to 12.5 kGy
9.	Palm *et al*. 2015	Wood-plastic composite	0 kGy, 50 kGy, 100 kGy, 150 kGy, 200 kGy, and 250 kGy
10.	Severiano *et al*. 2010	Wood	25 kGy, 50 kGy, and 100 kGy
11.	Zhang *et al.* 2016	Ultrafiltration membrane	0 kGy to 75 kGy
12.	Wu *et al*. 2013	Epoxy/glass fibre composite	1 MGy, 5 MGy, and 10 MGy

Testing involved in the studies were flexural, physical and thermal testing. Limited studies were conducted on the irradiation effect of hybrid composites on compressive strength. Thus, the objective of this work is to investigate the compressive strength of hybrid composite-laminated plates comprised of Kevlar/oil palm fibre with epoxy resin that have been irradiated with different doses of gamma radiation.

EXPERIMENTAL

Materials

The materials used in this work were oil palm EFB fibre and Kevlar fibre with epoxy resin Zeepoxy HL002TA and hardener HL002TB. The Kevlar fibre was in woven form, while the oil palm EFB was in fibre mat form. The oil palm EFB was procured from HK Kitaran Sdn. Bhd., Malaysia.

Fig. 1. Kevlar twill fabric

Fig. 2. Oil palm EFB compressed fibre mat

The Kevlar fiber and the epoxy resin were supplied by ZKK Sdn. Bhd., Malaysia. The Kevlar fibre used was plain-woven hexcel aramid of high performance fabric Style 706 (Kevlar KM-2, 600 denier; DuPont Kevlar, Ashtabula, OH, USA) with the real density of 180 g/m^2. Figures 1 and 2 show the fibres that were used in this work.

Laminated composite fabrication methods

Two sets of composites were fabricated. The first set of composites was comprised of oil palm EFB fibre mat and woven Kevlar fibre. In the first set, the oil palm EFB fibre was sandwiched between two layers of Kevlar fibre. The second set consisted of oil palm EFB fibre mat and woven Kevlar fibre. In this set, the woven Kevlar fibre was sandwiched between the oil palm EFB fibre. The layering pattern of the hybrid composites is shown in Fig. 3.

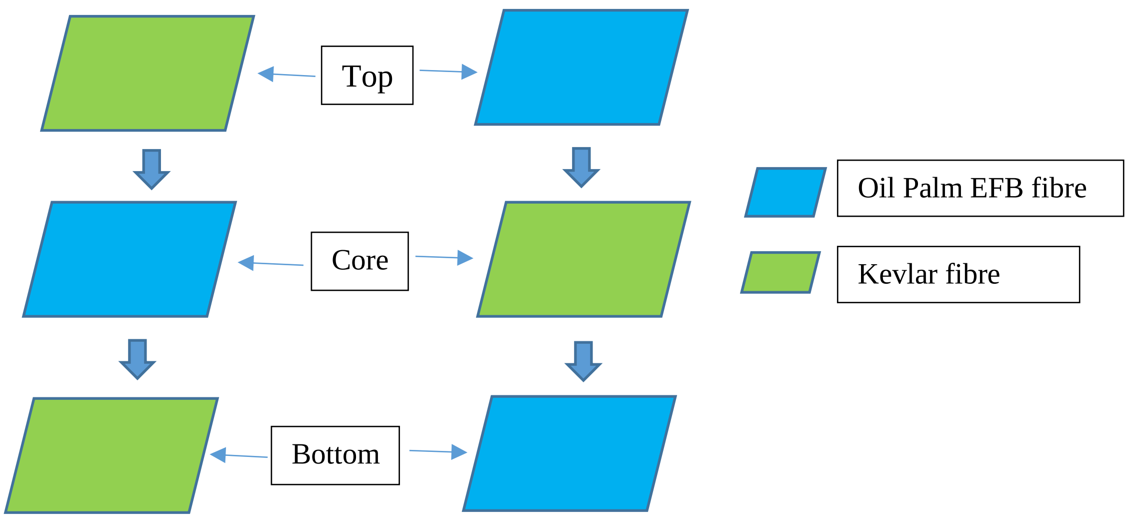


Fig. 3. The layering pattern of the hybrid composites

Material preparation

The hand lay-up technique was used to prepare the samples. A carbon steel mould with dimensions of 300 mm × 200 mm was used. The mould cavity was coated with glazing wax that acted as the releasing agent. All of the composites were impregnated with the epoxy resin in the mould. The mould was closed and pressed to remove the excess resin and left at room temperature for 24 h for curing. After removal from the mould, the composites were placed into the oven for 3 h at 80 °C for the post curing process. This was to ensure that the resin in the composites was completely dry.

Methods

Gamma irradiation

Before the composites were cut into specific dimensions, the samples were irradiated into a gamma cell using Co-60 radioactive material with different radiation doses; 25 kGy, 50 kGy, and 150 kGy. The samples were irradiated at the SINAGAMA radiation facility at the Malaysian Nuclear Agency, Malaysia under conditions of room temperature and ambient humidity.

Compression test

Before the test, the samples were cut into two sets of dimensions. The first set was 12.7 mm × 12.7 mm × 8 mm of the specimens and the second sets of specimens were 12.7mm x 12.7 mm x 12 mm. The compressive test was conducted in accordance to ASTM D695 (year) as shown in Fig. 4 with a crosshead speed of 1.3 mm/min.

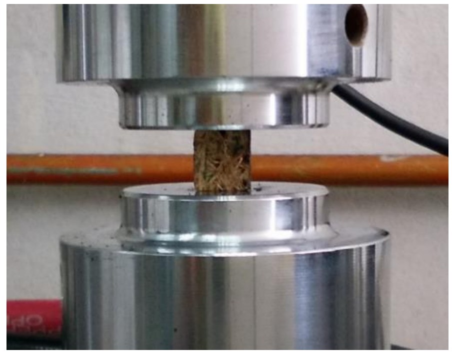


Fig. 4. Compression test of the hybrid composites

In Table 2, Group 1 shows the radiation dose for the specimens. For Group 1 specimens, oil palm EFB fibres were sandwiched between the Kevlar fibres. Two layers of Kevlar fibres were the exterior in the lamination. The layering pattern for Group 1 were Kevlar/oil palm EBF/Kevlar (K/OP/K). The thickness achieved for Group 1 was 8 mm. Group 2 shows the radiation dose for the specimens. The layering pattern for Group 2 specimens was different from that of Group 1. Two layers of oil palm EFB fibres were the exterior and one layer of Kevlar fibre in the interior of the laminations. The layering pattern for Group 2 was oil palm EFB/Kevlar/oil palm EFB (OP/K/OP). The thickness achieved for Group 2 was 12 mm.

Table 2. Radiation Dose for Group 1 and Group 2 Specimens

Radiation Dose (kGy)	**Group 1** Thickness = 8 mm	**Group 2** Thickness = 12 mm
Without radiation	P 101	P 201
25 kGy	P 102	P 202
50 kGy	P 103	P 203
150 kGy	P 104	P 204

RESULTS AND DISCUSSION

Figures 5 and 6 depict the compressive behavior of Groups 1 and 2, respectively. Both groups showed the same trend for compression behavior. However, Fig. 6 shows that Group 2 produced more consistent results than Group 1, which may be due to the layering pattern of the hybrids.

The compression strength for hybrid oil palm EFB/Kevlar/oil palm EFB showed the highest values of 39.6 MPa (Table 3). Based on the results from Table 3, it was observed that when hybrid Kevlar/oil palm EFB/Kevlar composites were irradiated with 25 kGy of gamma radiation, the compressive strength increased to 30.4 MPa.

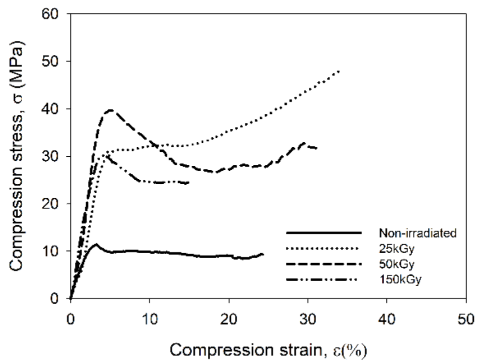


Fig. 5. Compression behavior for Group 1

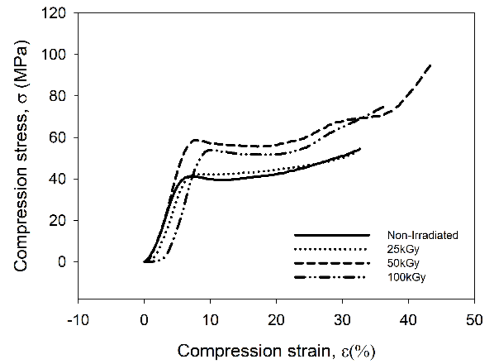


Fig. 6. Compression behavior for Group 2

When the specimens were further irradiated up to 50 kGy, the compressive strength increased to 39.6 MPa. With further irradiation up to 150 kGy, the compressive strength was reduced to 32.7 MPa. Hybrid composites with the configuration of oil palm EFB/Kevlar/oil palm EFB showed higher compressive stress compared to composites laminated on Kevlar/oil palm EFB/Kevlar. For the specimens without irradiation, the compressive stress for the composites of oil palm EFB/Kevlar/oil palm EFB was 40.8 MPa. As the doses increased, the compressive stress for Group 2 also increased. However, both laminates from Groups 1 and 2 experienced a decrease at 150 kGy.

Table 3. Variation of Compressive Stress and Strain at Break with Radiation Dose

Radiation Dose (kGy)	Compressive Strength (MPa)		Compressive strain at break (%)	
	Group 1	Group 2	Group 1	Group 2
0	12.31 ± 1.97	40.77 ± 2.53	4.15 ± 0.78	7.61 ± 0.70
25	30.43 ± 2.10	43.59 ± 6.30	5.25 ± 1.21	8.33 ± 0.15
50	39.61 ± 0.56	58.74 ± 0.50	5.18 ± 0.22	7.84 ± 0.74
150	32.66 ± 2.61	54.53 ± 1.61	4.46 ± 0.31	8.47 ± 1.36

For Group 2 in Table 3, the compression strain at break increased when the doses increased. The results showed the same trend as in the results from Group 1. The sample that was not irradiated with gamma radiation showed a lower reading for both Group 1 and Group 2, which were 4.15% and 7.61%, respectively. At doses of 25 kGy, the compression strain increased to 5.25% and 8.33% for Group 1 and Group 2, respectively. Given the radiation dose at 50 kGy, the strain at break for Group 2 decreased to 7.84% and the compression strain at break for Group 1 decreased to 5.18%. Both groups decreased the compression strain at 150 kGy in which Group 1 was 4.46% and Group 2 8.47%.

From Table 3, the compressive stress and compressive strain for Group 1 were lower than for Group 2. This was due to the difference in thickness of the two groups where for Group 1 the thickness was 8 mm while in Group 2 the thickness was 12 mm. Because the thickness of Group 2 was higher the compressive strength showed a higher compressive strength compared to Group 1. Group 2 was the composites with presence of Kevlar fibre in the middle layer that showed a higher compressive stress. This finding supports the results obtained by the work of Muhammad *et al*. (2015).

From the results above, it was observed that when the samples were irradiated with gamma radiation, the compressive strength increased as compared to the samples that were not irradiated. These results applied to both Group 1 and Group 2 samples. This shows that the effect of ionising radiation can improve their properties (Campos *et al*. 2015). This may be due to a consequence of cross-linking of the polymeric chain that is caused by ionizing radiation (Campos *et al*. 2015). The effect of radiation shows that gamma radiation could be an alternative technique for surface treatment that can improve mechanical properties (Zhang *et al*. 2008). However, further improvements of its compressive properties were only observed in the lower radiation doses, such as at 50 kGy. This phenomena may be due to new bonds that occur from the cross-linking process at lower radiation doses (Zhang *et al*. 2008).

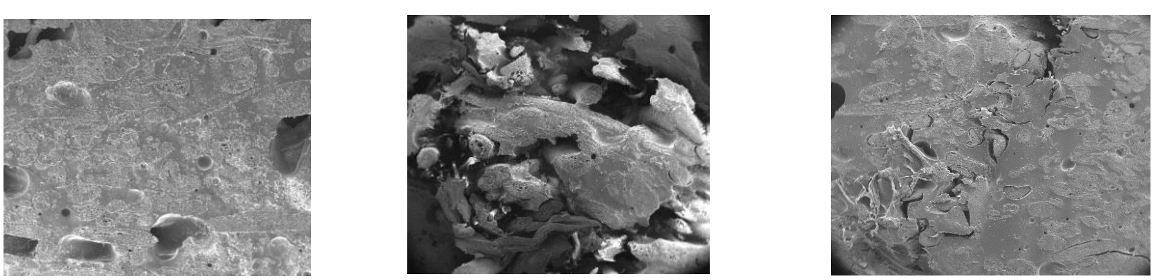
At higher radiation doses, the compression strength and strain at break decrease notably. This is because at higher radiation doses significant bond scission occurs (Zhang *et al*. 2008). Bond scission process is responsible for decreasing the mechanical strength of composites. From the results, the high radiation dose for this particular hybrid composite materials that shows the degradation of composites was at 150 kGy. The results agreed with the work of Hassan *et al.* (2014) where the elongations exhibited a dramatic decrease at dose range up to 150 kGy.

Table 4. Variation of Compressive Modulus with Radiation Dose

Radiation Dose (kGy)	Compressive Modulus (MPa)	
	Group 1	Group 2
0	398.00 ± 37.96	967.00 ± 138.09
25	1009.00 ± 71.52	1016.48 ± 136.13
50	1386.00 ± 97.65	1262.81 ± 36.69
150	1115.43 ± 154.27	1219.85 ± 68.06

Table 4 shows the variation of compressive modulus with radiation dose. In Groups 1 and 2 the compressive moduli without any exposure to radiation were 398 and 967 MPa, respectively. The modulus increased when the radiation was increased to 50 kGy for both group. However, at higher doses of 150 kGy, both Group 1 and Group 2 experienced the same trend as in the results in the compressive stress and compressive strain testing.

Figure 7 shows the SEM images for Group 1. Before compression, the samples exhibited flat surfaces, as shown in 7(a). After compression, many fibre pull-out features were observed in samples without radiation as depicted in 7(b). This contributes to low compression strength.

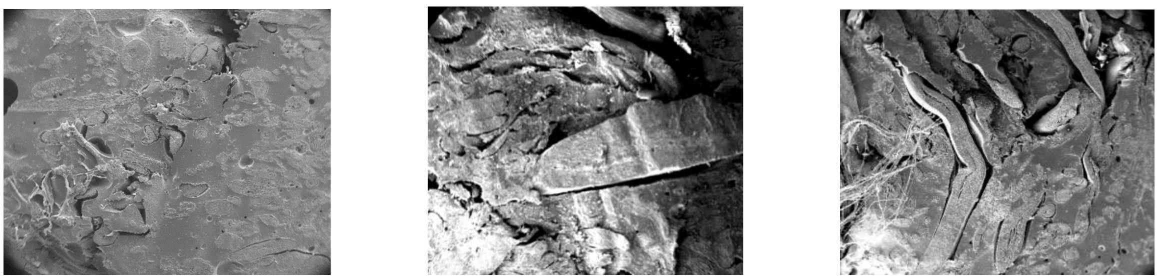


7(a) 7(b) 7(c)

Fig. 7. SEM images for Group 1: 7(a) before compression 7(b) after compression (without radiation) 7(c) after compression (with radiation)

However, samples exposed to radiation less fibre pull out observed as shown in 7(c). More flat surface observed and this lead to higher compression strength as compared to without radiation.

The SEM micrograph in Fig. 8 shows the surface of Group 2 before compression and after compression. In Fig. 8(a), flat surface and a layer of Kevlar is observed. After compression, the samples without radiation shows more fibre crack and fibre pull out features. This contributes to low compressive strength. However, as shown in 8(c), a flat surface is observed and this contributes to higher compression strength as compared to samples with radiation.



8(a) 8(b) 8(c)

Fig. 8. SEM micrograph for Group 2: 8(a) before compression 8(b) after compression (without radiation) 8(c) after compression (with radiation)

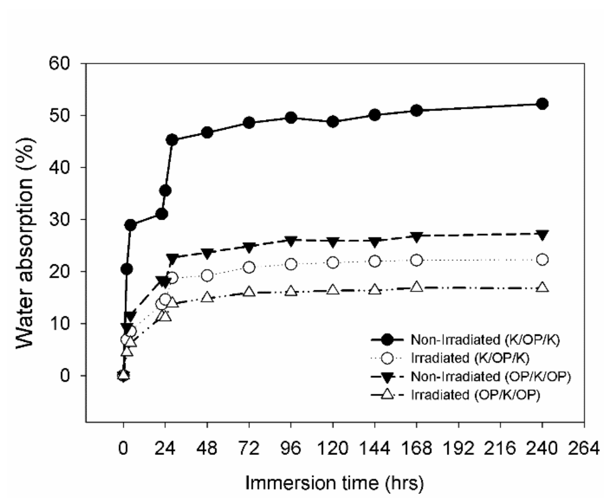


Fig. 9. Variations of water absorption with immersion time

Water uptake experiments were conducted for irradiated and non-irradiated samples for hybrid Kevlar /Oil Palm EFB / Kevlar and Oil Palm EFB / Kevlar / Oil Palm EFB. Figure 9 shows the same trend as in the work of Khalil *et al.* (2011). As shown in Fig. 9, the layering pattern for Kevlar /Oil Palm EFB /Kevlar and layering pattern Oil Palm EFB /Kevlar /Oil Palm EFB, both non-irradiated showed higher water absorption as compared to hybrid Kevlar /Oil Palm EFB /Kevlar and hybrid Oil Palm EFB /Kevlar/Oil Palm EFB when irradiated. Water uptake for non-irradiated Kevlar /Oil Palm EFB /Kevlar was 45% and with radiation was about 18%. Hybrid Oil Palm EFB /Kevlar /Oil Palm EFB that is not irradiated had less water being absorbed, which was 22% as compared to the same hybrid pattern but with radiation which is only 15%. The results showed that irradiated hybrid composites had less water uptake compared to non-irradiated hybrids. This implies that cross-linking took place due to the radiation and that it improved the compressive strength of the hybrid composites.

CONCLUSIONS

1. This work investigated the effect of different radiation doses on the compressive properties of Kevlar/oil palm EFB/epoxy hybrid composites. The hybrid composites appeared to be resistant to a dose of 50 kGy for Group 1 (with Kevlar on the outside) and Group 2 (with EFB on the outside). Group 1 have lower compressive strength than Group 2. This may have been due to the difference of thickness between Group 1 and Group 2.
2. Both Group 1 and Group 2 showed a degradation in compressive properties at 150 kGy.
3. These findings can be attributed to the cross-linking and the chain scission of the epoxy matrix due to the irradiation process from gamma radiation.
4. The results indicated that gamma radiation would be an efficient method to enhance the compressive properties in the hybrid composites by improving the fibre-matrix adhesion. Therefore, the results obtained can contribute to the new knowledge on the compressive properties of gamma irradiated hybrid Kevlar/oil palm EFB/epoxy composites.

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REFERENCES CITED

Al-Mosawi, A. I., Al-Maamori, M. H., and Wetwet, Z. A. (2012). “Mechanical properties of composite material reinforcing by natural-synthetic fibers,” *Academic Research International* 3(3), 108-112.

Ankolekar, P., Hawal, T. T., Naik, R. J., and Anil, T. R. (2015). “Reinforcement effect of Kevlar fabric on the mechanical properties of epoxy resin,” *International Research Journal of Engineering and Technology* 2(5), 402-405.

ASTM D695-02a (2015). “Standard test method for compressive properties of rigid plastics,” ASTM International, West Conshohocken, PA.

Bachtiar, D., Siregar, J. P., Sulaiman, A. S., and Rejab, M. M. R. (2015). “Tensile properties of hybrid sugar palm/kenaf fibre reinforced polypropylene composites,” *Applied Mechanics and Materials* 695, 155-158. DOI: 10.4028/www.scientific.net/AMM.695.155

Campos, L. M. P., Boaro, L. C., Santos, L. K. G., Parra, D. F., and Lugao, A. B. (2015). "Influence of ionizing radiation on the mechanical properties of BisGMA/TEGDMA based experimental resin," *Radiation Physics and Chemistry* 115, 30-35. DOI: org/10.1016/j.radphyschem.2015.06.003

Hassan, M. M., Aly, R. O., Hasanen, J. A., and Sayed, E. S. F. E. (2014). "The effect of gamma irradiation on mechnical, thermal and morphological properties of glass fiber reinforced polyethylene waste/reclaim rubber composites," *Journal of Industrial and Engineering Chemistry* 20, 947-952. DOI: org/10.1016/j.jiec.2013.06.027

Haydaruzzaman, Khan, R. A., Khan, M. A., Khan, A. H., and Hossain, M. A. (2009). "Effect of gamma radiation on the performance of jute fabrics-reinforced polypropylene composites," *Radiation Physics and Chemistry* 78(11), 986-993. DOI: org/10.1016/j.radphyschem.2006.06.011

Hoffman, E. N, and Skidmore, T. E. (2009). "Radiation effects on epoxy/carbon-fiber composite," *Journal of Nuclear Materials* 392, 371-378. DOI: 10.1016/j.jnucmat.2009.03.027

Hoque, M. A., Bhuiya, M. A. K., Saiduzzaman, M., Islam, M. A., and Khan, M. A. (2017). "Effect of γ (gamma)-radiation on mechanical properties of raw and polyethylene glycol-modified bleached jute reinforced polyester composite," *World Journal of Engineering* 14(2), 108-113. DOI: 10.1108/wje-06-2016-0006

Jawaid, M., Khalil, H. P. S. A., Hassan, A., Dungani, R., and Hadiyane, A. (2013). "Effect of jute fibre loading on tensile and dynamic mechanical properties of oil palm epoxy composites," *Composites Part B: Engineering* 45(1), 619-624. DOI: org/10.1016/j.compositeb.2012.04.068

Jovanovic, V., Samarzija-Jovanovic, S., Dekic, B., Dekic, V., Konstaninovic, S., Markovic, G., and Marinovic-Cincovic, M. (2013). "Effect of γ-irradiation on the thermo-oxidative behaviour of nano-silica based urea-formaldehyde hybrid composite with 4-chloro-3-nitro-2h-chromen-2-one," *Composites Part B: Engineering* 45, 864-870. DOI: org/10.1016/j.compositesb.2012.07.025

Khalil, H. P. S. A., Jawaid, M., and Bakar, A.A. (2011). "Woven hybrid composites: Water absoption and thickness swelling behaviours," *BioResources* 6(2), 1043-1052. DOI:10.15376/biores.6.2.1043-1052

Maier, A., Schmidt, R., Oswald-Tranta, B., and Schledjewski, R. (2014). "Non-destructive thermography analysis of impact damage on large-scale CFRP automotive parts," *Materials* 7(1), 413-429. DOI: 10.3390/ma7010413

Martinez-Barrera, G., Vigueras-Santiago, E., Martinez-Lopez, M., Rieiro, M. C. S., Ferreire, A. J. M., and Brostow, W. (2013). "Luffa fibers and gamma radiation as improvement tools of polymer concrete," *Construction and Building Materials* 47(#), 86-91. DOI: 10.1016/j.conbuildmat.2013.05.038

Muhammad, N., Jumahat, A., and Ali, N. M. (2015). "Effect of hybridization on compressive properties of woven carbon, glass and kevlar hybrid composites," *Jurnal Teknologi* 76(9), 75-80. DOI: 10.11113/jt.v76.5655

Naim, A. A., Alnaim, N., Ibrahim, S. S., and Metwally, S. M. (2017). "Effect of gamma irradiation on the mechanical properties of PVC/ZnO polymer nanocomposites," *Journal of Radiation Research and Applied Sciences* 10, 165-171. DOI: 10.1016/j.jrras.2017.03.004

Palm, A., Smith, J., Driscoll, M., Smith, L., and Larsen, L. S. (2015). "Influence of ionizing radiation on the mechanical properties of a wood-plastic composite," *Physics Procedia* 66, 595-603. DOI: 10.1016/j.phpro.2015.05.079

Radif, Z. S., Ali, A., and Abdan, K. (2011). "Development of a green combat armour from rame-Kevlar-polyester composite," *Pertanika Journal of Science & Technology* 19(2), 339-348.

Raghavendra Supreeth, B. S, Vinod, B., and Sudev, L. J. (2015). "Effect of gamma irradiation on mechanical properties of natural fibers reinforced hybrid composites," *International Journal of Science Technology and Engineering* 2(4), 15-23.

Salman, S. D, Hassim, W. S. W., and Leman, Z. (2015). "Experimental comparison between two types of hybrid composite materials in compression test," *Manufacturing Science and Technology* 3(4), 119-123. DOI: 10.13189/mst.2015.030407

Sekulic, D. R., Djordjevic, I. M., Gordic, M. V., Burzic, Z. H., and Stevanovic, M. M. (2006). "Gamma radiation effects on mechanical properties of carbon/epoxy composites," *Materials Science Forum* 518, 549-554. DOI: 10.4028/www.scientific.net/MSF.518.549

Severiano, L. C., Lahr, F. A. R., Bardi, M. A. G., Santos, A. C., dan Luci, D. B., and Machado, L. D. B. (2010). "Influence of gamma radiationon properties of common Brazilian wood species used in artwork," *Progress in Nuclear Energy* 52, 730-734. DOI: 10.1016/j.pnuene.2010.04.008

Shauddin, S. M., Shaha, C. K., and Khan, M. A. (2014). "Effects of fiber inclusion and γ radiation on physico-mechanical properties of jute caddies reinforced waste polyethylene composite," *Journal of Polymer and Biopolymer Physics Chemistry* 2(4), 91-97. DOI: 10.12691/jpbpc-2-4-6

Shubhra, Q. T. H., and Alam, A. K. M. M. (2011). "Effect of gamma radiation on the mechanical properties of natural silk fiber and synthetic E-glass fiber reinforced polypropylene composites: A comparative study," *Radiation Physics and Chemistry* 80(11), 1228-1232. DOI: org/10.1016/j.rad.phys.chem.2011.04.010

Shubra, Q. T. H., Alam, A. K. M. M., Khan, M. A., Saha, M., Saha, D., and Gafur, M. A. (2010). "Study on the mechanical properties, environmental effect, degradation characteristics and ionizing radiation effect on silk reinforces polypropylene/natural rubber composites," *Composites Part A: Applied Science and Manufacturing* 41(11), 1587-1596. DOI: org/10.1016/j.compositea.2010.07.007

Tshai, K. Y., Chai, A. B., Kong, I., Hoque, M. E., and Tshai, K. H. (2014). "Hybrid fibre polylactide acid composite with empty fruit bunch: Chopped glass strands," *Journal of Composites* 2014(#), 1-7. DOI: org/10.1155/2014/987956

Vasco, M. C., Neto, S. C., Nascimento, E. M., and Azevedo, E. (2017). "Gamma radaition effect on sisal/polyurethane composites without coupling agents," *Polimeros* 27(2), 165-170, DOI: 10.1590/0104-1428.05916

Wu, Z. X., Li, J. W., Huang, C. J., Huang, R. J., and Li, L. F. (2013). "Effect of gamma irradiation on the mechanical behaviour, thermal properties and structure of epoxy/glass-fiber composite," *Journal of Nuclear Materials* 441(1-3), 67-72. DOI: org/10.1016/j.jnucmat.2013.05.041

Yahya, R., Sapuan, S. M., Jawaid, M., Leman, Z., and Zainudin, E. S. (2014). "Effects of kenaf contents and fiber orientation on physical, mechanical, and morphological properties of hybrid laminated composites for vehicle spall liners," *Polymer Composites* 36(8), 1469-1476. DOI: 10.1002/pc.23053

Zainudin, E. S., Yan, L. H., Haniffah, W. H., Jawaid, M., and Alothman, O. Y. (2014). "Effect of coir fiber loading on mechanical and morphological properties of oil palm fibers reinforced polypropylene composites," *Polymer Composites* 35(7), 1418-1425.

DOI: 10.1002/pc.22794

Zhang, X., Niu, L., Li, F., Yu, S., Zhao, X., and Hu, H. (2016) "Effet of gamma-ray irradiation at low doses on the performance of PES ultrafiltration membrane," *Radiation Physics and Chemistry* 127, 127-132. DOI: 10.1016/j.radphyschem.2016.06.030

Zhang, Y. H, Huang. Y. D., Liu, L., and Cai, K. L. (2008). "Effects of γ-ray radiation grafting on aramid fibers and its composites," *Applied Surface Science* 254(#), 3153-3161. DOI: 10.1016/j.apsusc.2007.10.081

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