

Effect of Gamma Radiation on the Mechanical Properties of Natural Fabric Reinforced Polyester Composites

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Abstract

Two types of composites: (1) pineapple fabric reinforced polyester resin (pineapple/PR) and (2) jute fabric reinforced polyester resin (jute/PR) were prepared and the mechanical properties investigated for various gamma radiation doses ranging from 100-500 krad. Properties like tensile strength, Young's modulus, elongation-at-break, bending strength, bending modulus and impact strength were increased significantly by 19%, 32%, 45%, 32%, 47% and 20%, respectively, at a dose of 300 krad for pineapple/PR, and by 47%, 49%, 42%, 45%, 52% and 65%, respectively, at a dose of 200 krad for the jute/PR composite in comparison to the non-irradiated composite. Gamma radiation improved the mechanical properties, but overdoses of radiation even caused a reduction in them.

Key words: fabric reinforced composites, pineapple fabric, jute fabric, polyester resin, gamma radiation, mechanical properties.

Introduction

With the strong emphasis on environmental awareness, natural fibres have recently attracted researchers as an alternative for synthetic materials. In the field of composites, natural fibres provide multiple advantageous properties as reinforced material over conventional reinforcement materials like biodegradability and availability [1]. Moreover, these natural fibres possess low density, light weight, low cost, high mechanical strength, good thermal stability, and lower abrasion of equipment during processing [2, 3]. Therefore, the total global natural fibre composite material market in 2016 was US\$ 531.3 million and was expected to increase by 11% annually over the next 5 years [4]. Generally, plant fibres are used as a reinforced polymer matrix due to the above-mentioned properties and recyclability [5].

Agriculture is a global source of renewable materials for bio-composites [6], among which pineapple leaf fibre (PALF) and jute fibre exhibit excellent mechanical properties. PALF exhibits high specific strength and stiffness, containing a higher percentage of cellulose (70-82%) and a comparatively low microfibrillar angle (14°) [7]. Jute fibre is bastfibre and comprises bundled ultimate cells, each containing spirally oriented micro-fibrils bound together. It has good thermal and electrical insulation characteristics, appreciable toughness, and wide commercial availability at low cost [8]. Although jute fibre has excellent mechanical and physical properties, it is highly inconsistent in properties, which

depend on the geographic origin, climatic growth conditions and processing techniques [9]. Usually thermosetting resins like epoxy, polyester, polyurethane, phenolic, etc. are the most commonly used matrixes in composite manufacturing, for their sufficient mechanical properties at an acceptable price level [10]. Many researchers have investigated and recommended jute fibre reinforced composites in the last decade, where jute fibre has been used as reinforcing material to make a composite or hybrid composite [11]. Although the use of fibre as a reinforcing material is very common for textile reinforced polymer composites, the use of fabric, especially woven fabric, as a reinforcing material can be a wise selection because of its high productivity, huge possibility of structural customisation, good mouldability into complicated shapes, and the elimination of cold storage [12]. However, among all the advantages mentioned-above, natural fibre reinforced composites exhibit some disadvantages like hydrophilicity [13]. Therefore, a composite of hydrophilic reinforced fibre (low surface tension) with a hydrophobic or non-polar polymer matrix (high surface tension) results in a lack of good interfacial adhesion and poor resistance to humidity absorption, consequently leading to poor mechanical properties compared to pure polymer [14]. Physical or chemical treatment on the surface can overcome this problem by changing the surface structure and surface energy of the fibre [15]. Among the chemical treatments, plasma treatment is used to improve hydrophilicity and hydrophobicity, as well as make changes to mechanical properties and antimicrobial

activity in the composite materials [16]. Mukhopadhyay, S. et al. applied gamma radiation to modify a sisal fibre surface to improve the adhesion between sisal fibres as reinforcement and polypropylene as the matrix of the fibre composite [17]. Physical treatment such as ionising and non-ionising radiation can introduce better surface cross-linking between the natural fibre and matrix as well as reduce its hydrophilic nature through the hydrophobic matrix [18].

The application of ionising radiation i.e. x-rays, UV rays & gamma ray are becoming more widespread every year because of their several advantages, such as continuous operation, minimum time requirement, less atmospheric pollution, curing at ambient temperatures, increased design flexibility through process control, etc [19]. J. Wiener et al. investigated the effect of UV irradiation on the mechanical properties of both natural (cotton) and synthetic fabrics (polyester, polypropylene, and polyamide) before and after nano-TiO₂ incorporation, and the result showed an improvement in tensile strength for cotton [20]. Gamma radiation also plays an important role in the surface modification of natural fibre reinforced composites. It is the process by which an object is exposed to gamma radiation to increase the interfacial bonding strength by uniform distribution of radical initiating sites throughout the thickness of the irradiated samples [21]. Few researches have been done on the effect of gamma radiation on natural fibre reinforced composites [14, 22, 23]. Haydaruzzaman et al investigated the effect of gamma radiation on the performance of jute fabric-reinforced polypropylene composites and found that the gamma irradiated composite better mechanical properties than other non-irradiated composites [18]. Md. Asadul Hoque et al. studied the effect of γ (Gamma)-radiation on the mechanical properties of raw and a polyethylene glycol modified bleached jute reinforced polyester composite and found similar results [22]. Water repulsion and mechanical properties were improved in a jute/PALF hybrid composite by gamma radiation, as investigated by Raghavendra Supreeth B. S et al. [10]. Marina Cardoso Vasco et al also investigated the gamma radiation effect on sisal/polyurethane composites and found an improvement in the bending modulus [14]. Gonzalo Martínez-Barrera et al discovered an improvement in the compressive strength and modulus of elasticity

Table 1. Specifications of jute and pineapple fabric.

Quality parameters	Jute fabric	Pineapple fabric
Weave	Plain	Plain
Yarn linear density, tex	98	74
Density in warp, cm ⁻¹	21	25
Density in weft, cm ⁻¹	11	13
Surface area, g/m ²	338	310

of polypropylene fibre reinforced polymer concrete by gamma radiation [24]. The insulating properties of composites were also improved by gamma radiation, as investigated by Khan et al. [25].

In this study, gamma radiation was used to improve the mechanical properties of two types of composites: (1) pineapple fabric reinforced polyester resin composite (pineapple/PR) and (2) jute fabric reinforced polyester resin composite (jute/PR). They were irradiated with gamma radiation and the effects on their mechanical properties were investigated and compared. Although gamma radiation application to fibre reinforced composites is not new, the effect of gamma radiation on the pineapple fabric reinforced composite and jute fabric reinforced composite and their comparison are novel work.

Materials and methods

Materials

PALF (Pineapple Leaf Fibre) was collected from Modhupur and Tangail, Bangladesh, and jute fibre from Kazipur and Sirajganj, Bangladesh. Jute fabric and pineapple fabric were manufactured in Bangladesh by the Jute Research Institute, Dhaka, both of which manufactured in plain weave. Unsaturated polyester resin and methyl ethyl ketone peroxide (MEKP) were purchased from Nasim Plastic Industries Limited, Dhaka, Bangladesh. MEKP was used as a catalyst.

Methods

Fabrication of composite

The composites were prepared by the hand lay-up technique. Pineapple and jute fabric were used as reinforcing material for pineapple/PR and jute/PR composites, respectively. The fabrics were cut to dimensions of 30 cm × 30 cm and taken for reinforcing. A glass plate of 40 cm × 40 cm dimensions was placed in a suitable environment. Mylot paper of similar dimensions to the glass plate was cut and placed on it. According to fabric weight, polyester resin was put in

a beaker and 2% MEKP added. These two chemicals were mixed vigorously with an agitator. 1/3 of the mixture was poured onto the mylot paper and spread over an area similar to that of the pineapple fabric with a plastic spreader. Then one-ply pineapple fabric was placed onto the polyester resin mixture and rolled with a handroller. Again 1/3 of the mixture was poured onto the previous ply and rolled. Then, with the same process, polyester resin solution was poured over the two plies of fabric one by one. Finally, it was sandwiched with two pieces of mylot paper and a handroller driven over it. The whole swatch was covered with two glass plates, and a dead weight of 15 kg was loaded on the arrangement for 4 hours. Finally, the dead weight was unloaded, and the two layers of mylot paper were separated from the composite. The same procedure was done for all the samples. Thus, pineapple and jute reinforced polyester composites were obtained.

Sampling

The thicknesses of the samples were recorded by digital slide callipers. The average results of three readings from different places along the sample were taken for measuring each thickness. The thickness of all the samples of both composites was the same as for pineapple/PR – 1.62 ± 0.02 mm and for jute/PR – 1.35 ± 0.02 mm. 10 samples (5 for pineapple and 5 for jute) were prepared with the same dimensions (60 × 15 mm) for irradiating with 5 different gamma radiation doses i.e. 100 krad, 200 krad, 300 krad, 400 krad and 500 krad.

Gamma radiation

For the gamma radiation, a Co – 60 gamma source (model gamma beam 650 No.11R) was used. It is capsule type, housed in a cavity and raised by a remote controlled electromechanical system. Its strength is about 65 Kci. The gamma beam is loaded with source GBS-98, which comprises 36 double encapsulated capsules. The resultant composites were irradiated by γ -ray with different

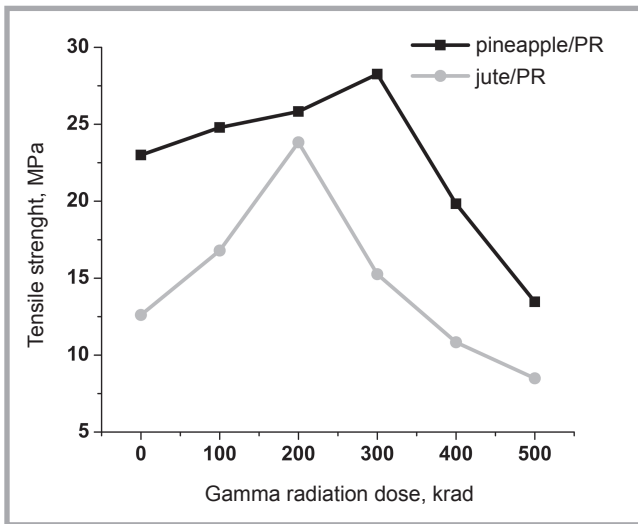


Figure 1. Effect of gamma radiation on the tensile strength of pineapple/PR and jute/PR composites.

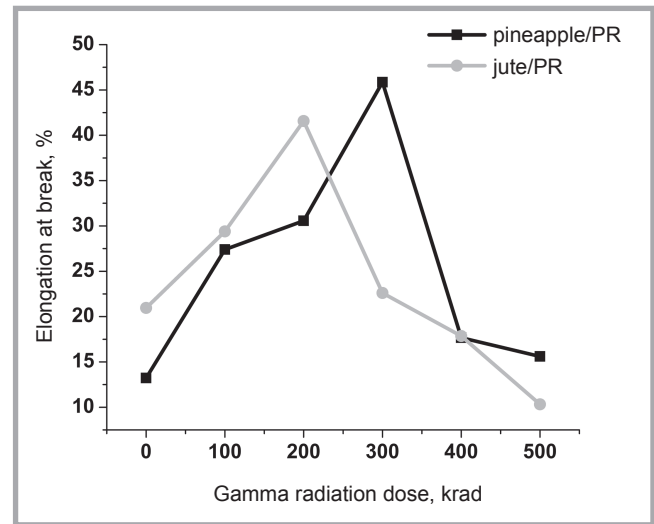


Figure 2. Effect of gamma radiation on the elongation properties of pineapple/PR and jute/PR composites.

doses (i.e. 100 krad, 200 krad, 300 krad, 400 krad and 500 krad) using this source. After treating with gamma rays, the samples were prepared for mechanical testing.

Mechanical tests

Tensile properties, such as the tensile strength (TS), elongation at break percentage (EB%) and Young's modulus (Y) of the composites prepared were evaluated by a universal testing machine (UTM) (Model: H50KS-0404, HOUNSFIELD, series S, UK) at the Institute of Radiation and Polymer Technology Laboratory, Bangladesh Atomic Energy Commission, Dhaka, Bangladesh. The specimens were prepared according to the ASTM D638 standard. A crosshead speed of 10 mm/min and gauge length of 50 mm were maintained. Equations (1), (2) and (3) were used for measuring the tensile strength, elongation at break percentage and Young's modulus, respectively [26].

$$\text{Tensile strength, (TS)} = \frac{F_{max}}{A} \text{ MPa} \quad (1)$$

Where, F_{max} = maximum load applied to the sample and A = cross-sectional area of the sample.

The percentage of elongation-at-break was obtained by the following relation:

$$\begin{aligned} \text{Elongation at break, EB(\%)} &= \\ &= \left(\frac{\Delta L_b}{L_0} \right) \times 100\% \end{aligned} \quad (2)$$

Where, ΔL_b = extension at break point and L_0 = original length of the sample.

$$\text{Young's modulus, (Y)} = \frac{dI_f}{d\varepsilon} \text{ MPa} \quad (3)$$

Where, $d\sigma$ = stress at yield point and $d\varepsilon$ = strain at yield point.

A bending test was carried out to determine the bending (BS) and bending modulus (BM) using the same universal testing machine. The bending strength and modulus was calculated by Equations (4) and (5), respectively.

$$\text{Bending strength, BS} = \frac{3FL}{2bd^2} \text{ MPa} \quad (4)$$

Where, F is the load (force) at the fracture point (N), L the length of the support span, b width, and d is thickness.

$$\text{Bending modulus, BM} = \frac{L^3 F}{4wh^3 d} \text{ MPa} \quad (5)$$

Where, w and h are the width and height of the sample, L the distance between the two outer supports, and d is the deflection due to the load F applied in the middle of the sample.

A dynamic impact test was conducted to evaluate IS on the un-notched mode composite specimens according to ASTM D 6110-97 using an Impact tester (HT-8041B IZOD, Pendulum type, Taiwan). Mechanical property measurement for each composite was repeated four times for accuracy.

Results and discussion

Tensile strength

Figure 1 depicts the effect of gamma radiation on the tensile strength (TS) of both composites. The tensile strength of the pineapple/PR composite increases

by a maximum of 19% (28.26 MPa) after being treated with a gamma radiation dose of 300 krad from a non-irradiated composite. Further increasing of the gamma radiation dose from the maximum of 400 krad and 500 krad decreases the strength by 13% and 41%, respectively. The tensile strength of the jute/PR composite also shows similar types of results. It increases up to 47% (23.81 MPa) after treatment with 200 krad but after that started to decrease. In comparison, jute/PR is affected more by the gamma radiation as it increases the TS by up to 47%, whereas for pineapple/PR it is by a maximum of 19%.

Elongation at break

Figure 2 reveals the effect of gamma radiation on the elongation properties of the composites. It is found that the elongation at break (EB%) of the pineapple/PR composite increases by up to 45.85% from that of the non-irradiated composite when treated with gamma radiation of 300 krad, after which it starts to decrease. The jute/PR composite shows a similar trend as the elongation percentage increases by up to 41.55% from that of the non-irradiated composite at a gamma dose of 200 krad, and then decreases.

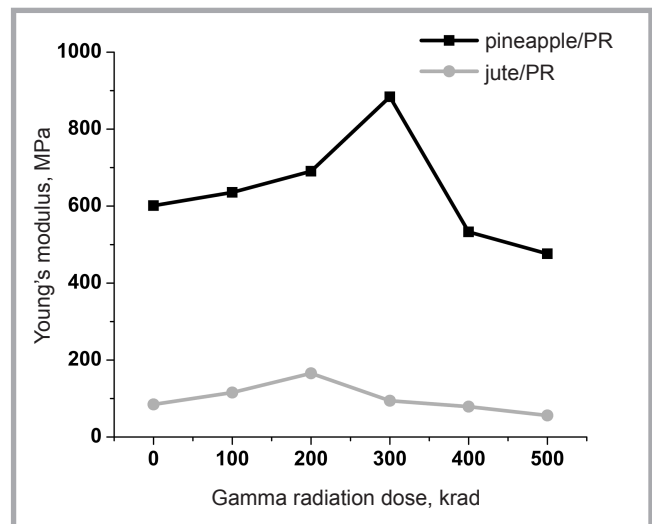
Young's modulus

From Figure 3, it is clearly seen that the Young's modulus of the pineapple composite increases by a maximum of 32% (884 MPa) from that of the non-irradiated composite at a gamma radiation dose of 300 krad, and further increasing of the gamma radiation dose decreases

es the modulus by 11% (533 MPa) and 21% (476 MPa) from the maximum at a gamma radiation dose of 400 krad and 500 krad, respectively. The Young's modulus of the jute composite increases by up to 49% (165.4 MPa) after being treated with a gamma radiation dose of 200 krad over that of the non-irradiated composite. But after that, when treated with 300 krad, it starts to decrease. In comparison, jute/PR is affected more by the gamma radiation as it increases the modulus by up to 49%, whereas for pineapple/PR it is by a maximum of 32%. However, the large improvement in elongation properties of both composites by 45.85% for pineapple/PR and 41.55% for jute/PR is still open to question. This problem has not been analysed yet in others papers and needs deeper analysis, which will be the topic of our further investigations.

Gamma radiation is a very strong type of ionising radiation source and has a very strong penetration power into materials. It can affect the internal structure of the fibre-matrix and produce three types of reactive species in the composite i.e. ionic, radical and peroxide. This may increase the intra-chain bond in the fibre and matrix, which can make a highly oriented polymeric structure and may contribute to better fibre-matrix bonding. Peroxide species are produced when polymers are irradiated in the presence of oxygen. In this case, both the polymer matrix and cellulosic fibres may undergo a chain scission, and thus the polymer molecules may be broken into smaller fragments. Afterwards, the rupture of chemical bonds yields fragments of large polymer molecules. Another

Figure 3. Effect of gamma radiation on the young's modulus of pineapple/PR and jute/PR composites.



reactive species, radical, is produced in the cellulose chain by hydrogen and hydroxyl abstraction. Gamma radiation also ruptures some carbon-carbon bonds and produces radicals. These free radicals may react to change the chemical structure of the polymer and physical properties of the materials. It also may undergo cross-linking among the molecules to form a large molecule [27, 28]. Gamma radiation may also remove moisture from the composite, resulting in better adhesion between the fibre and matrix [23, 25].

It is observed that tensile properties increase with gamma radiation up to a certain dose and then decrease due to the two opposing phenomena, namely, photocross-linking and photodegradation, which take place simultaneously under gamma radiation. At lower doses, free radicals are stabilised by a combination reaction, resulting photo-cross-linking.

The higher the number of active sites generated on the polymeric substrate, the greater the grafting efficiency. This inter cross-linking between neighbouring molecules by gamma radiation forms a larger molecule, which results in an improvement in tensile properties [23]. In the pineapple/PR composite maximum values were obtained at a dose of 300 krad and in the jute/PR composite at 200 krad for all tensile properties, after which it started to decrease, due to photodegradation in the polymer chain. At higher radiation the main chain may be broken down and the polymer may degrade into small fragments, which results in a decrease in tensile properties. It can also be observed from all the figures that the tensile properties at a dose of 500 krad decrease even more than for the untreated composites, which may be due to the severe degradation of polymer molecules at the higher radiation dose.

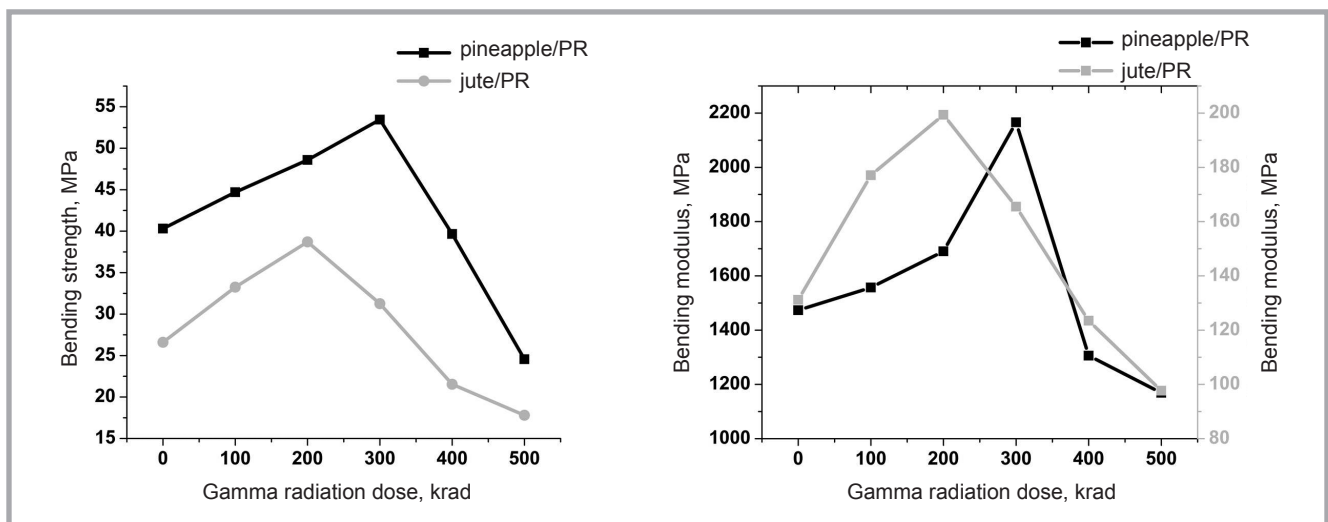


Figure 4. Effect of gamma radiation on the bending strength and bending modulus of pineapple/PR and jute/PR composites.

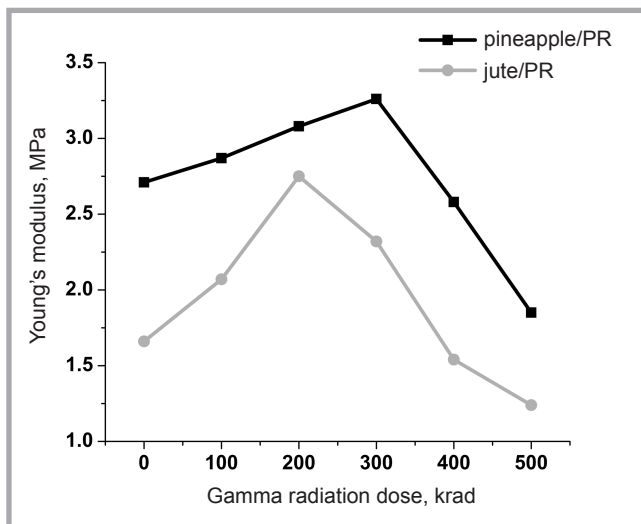


Figure 5. Effect of gamma radiation on the impact strength of pineapple/PR and jute/PR composites.

Bending properties

Figure 4 shows the variation in the bending strength and bending modulus of both composites, respectively, for various dosages of gamma irradiation. With a gamma radiation dose of 100 krad, the values of the bending properties show a slight improvement over those of non-irradiated composites. It is observed from the figures that with an increase in the gamma radiation dose up to 300 krad for the pineapple/PR and up to 200 krad for the jute/PR composite, the values of the bending strength and bending modulus show an improvement due to the cross-linking of molecules and formation of highly oriented polymeric structures. A further increase in the radiation dose decreases the values of the bending strength and bending modulus due to chain degradation. The highest value of bending strength (53.45 MPa) and bending modulus (2165.8 MPa) are obtained for a gamma radiation dosage of 300 krad in the pineapple/PR composite. In the jute/PR composite the maximum value of bending strength (48.69 MPa) and bending modulus (421.77 MPa) is obtained for a gamma radiation dose of 200 krad. Thus gamma radiation dosages of 300 krad and 200 krad are considered as the optimum for pineapple/PR and jute/PR composites, respectively, for better bending properties.

The bending strength and modulus increase by about 32.59% and 47%, respectively, for the pineapple/PR composite at a gamma radiation dose of 300 krad over those of non-irradiated composites. Similarly, in the jute/PR composite the bending strength and modulus increase by about 43% and 52%, respectively, over those of non-irradiated composites

at a gamma radiation dose of 200 krad. At 500 krad the bending properties decrease past those of non-irradiated specimens for both composites, which might be due to the severe destruction of the polymer molecules.

Impact strength

Figure 5 depicts the effect of gamma radiation on the impact strength of both composites. As the gamma radiation dose increases, the impact strength of both composites increases over that of non-irradiated composites. But after a certain level of dosage, both composites show the opposite trend, as the impact strength decreases along with an increasing radiation dose. In the pineapple/PR composite the maximum value of impact strength is obtained – 3.26 KJ/m² at a dose of 300 krad; but further increasing of the gamma radiation dose decreases the impact strength; and even at a dose of 500 krad it decreases the impact strength past that of the non-irradiated specimen. A similar trend is seen in the jute/PR composite, where the impact strength increases up to 65% over that of non-irradiated composites at a gamma radiation dose of 200 krad; but its further increasing decreases the impact strength.

The impact strength also shows a similar trend to that of tensile and bending properties for both composites, as discussed above. Gamma treatment increases the bond strength by producing active sites, which also increases the cross-linking between fibres, resulting in an increase in the impact strength. But a further increase in the radiation dose decreases the values of impact strength due to the degradation of the main polymer chain caused by over radiation.

Conclusions

In the present study, research was conducted to investigate the effect of gamma radiation on the mechanical properties of pineapple/PR and jute/PR composites. Results show a significant improvement in all mechanical properties with the increasing of the gamma radiation dose over those of non-irradiated composites. The highest value of tensile strength (TS), Young's modulus (Y), elongation at break (EB), bending strength (BS), bending modulus (BM) and impact strength (IS) for the pineapple/PR composite were found to be 28.26 MPa, 884 MPa, 45.85%, 53.45 MPa, 2165.8 MPa and 3.26 kJ/m², respectively, at a gamma radiation dose of 300 krad, while for the jute/PR composite the highest values were found to be 23.83 MPa, 165.4 MPa, 41.57%, 38.71 MPa, 199.37 MPa and 2.75 kJ/m², respectively, at a gamma radiation dose of 200 krad. This dramatic improvement is due to the cross-linking between fibre molecules, intra-chain bonding and the better adhesion of fibre and matrix obtained by gamma radiation. But further increasing of the gamma dose decreases the mechanical properties as overdoses may degrade the main polymer chain by breaking the molecules into small fragments. Hence, 300 krad for the pineapple/PR composite and 200 krad for the jute/PR composite are the optimum gamma radiation doses found in this experiment. From the discussion above, there is no doubt that gamma radiation improves all the mechanical properties significantly; but the optimum dose must be maintained because overdose can reduce those properties.

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