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Effect of moisture exposure and elevated temperatures on impact response of *Pennisetum purpureum*/glass-reinforced epoxy (PGRE) hybrid composites

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Abstract

A *Pennisetum purpureum*/glass-reinforced epoxy (PGRE) hybrid composites was comprehensively characterised to assess its impact response behaviour at room temperature (RT), under moisture exposure, and elevated temperatures. The untreated, 5 and 10% alkali-treated PGRE composites were fabricated using hybridised *Pennisetum purpureum*/woven E-glass fibres and epoxy resin. An instrumented IMATEK IM10 drop weight impact tester was utilised to characterise the impact responses of the prepared hybrid composites. The specimens were subjected to water exposure for 50, 100, 200, and 400 h and before arranged with a low-velocity impact test. In addition, the tests were repeated at 40, 60, and 80 °C to examine the effects of elevated temperatures. The results indicate that the untreated PGRE composite yielded the highest peak load impact response at all energy levels. The stiffness of the composites found to decrease substantially with increasing temperatures, which increases the absorbed energy and peak deflection causing extensive damage to the specimens.

27 **Keywords:**

28 Impact response

29 *Pennisetum purpureum* fibre

30 Hybrid composites

31 Moisture absorption

32 Temperature exposure

33 _____

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1. Introduction

Modern industry such as marine, military, aerospace, and mechanical is driven to implement fibre reinforced composites [1]. Once the composites exposed to impact damage, high cost is needed and tough to repair it [2]. Two types of fibres are commonly employed in engineering applications; natural and synthetic, though natural fibres yield exceptional mechanical properties with the added advantage of being lightweight materials with high specific strength. Thus, to ensure the environmental sustainability and lessen the use of polluting and high carbon footprint production of human-made fibres; the replacement of synthetic with natural fibres in engineering applications is the interest of the research study. Natural fibre composites typically use plant-based fibres, such as kenaf, jute, sisal, hemp, flax, and more recently *Pennisetum purpureum* or also locally known as Napier grass fibre [3–8].

A hybrid fibre reinforced composite is an amalgamation of two or more types of fibres in a single polymer matrix, thus resulted in enhanced specific properties compared to a single reinforced polymer composite. In recent times, reinforcements in hybrid composites have been presented because of their dimensional stability and superior mechanical [9]. The performance of hybrid composites is governed by their fibre-matrix interfacial bonding, matrix, length and shape of individual fibres, and the volume fraction of synthetic or natural fibres used [10,11]. Inexpensive and low-grade fibres can cause hybrid composites more tolerant to damage and cut the overall costs, whereas more costly fibres with a high specific modulus provide load-bearing capacities and improved stiffness. Thus, hybridisation of fibres in composites may enhance the stiffness and strength, improve impact and fatigue resistance and instantaneously reduce the weight and overall cost of the material [12].

Engineering building and constructions are often exposed to impact-related stress during manufacturing, maintenance, and service operations[13]. Studies have shown that laminated composite structures are even more at perils to impact-related damage than steel structures [14]. In most studies, scholars have focused on the effects of varying parameters, fibre architecture, and thickness of the composites [15,16]. However, fewer studies have been performed concerning the influence of moisture exposure and elevated temperatures on the residual strength of natural/synthetic fibre hybrid composites under low-velocity impact event. In composite structures, the design process is used to mitigate the internal impact damage and effects of the impact load. This is because the routine visual examination is not suitable to be used to detect inner damage due to impact loading. The damage can develop under impact loading and cause severe strength reductions. In an industrial setting, the limitations of the composite materials are particularly significant due to the unpredictable impact performance of composite structures [17]. The primary factor influencing the impact performance of composites is the type and properties of the fibres in the composites materials. By governing the stiffness of the fibre, the local stress dissemination caused by impact loading can be controlled. Furthermore, the fibre arrangement, fibre-loading and stacking arrangement also affect the impact performance of the composite [18].

The effect of moisture exposure on composites has been widely investigated [19–21]. The mechanical properties of these materials and the influence of moisture exposure are greatly influenced by the fibres length and hybridisation fractions used for reinforcement [22]. Duigou et al. explored the ageing of flax/polylactic acid biocomposites in seawater over a period of two years. Their investigation determined the best fibre characteristics to be used in boat manufacturing materials [23]. Studies regarding the mechanical and ageing behaviour of fibre bundles indicated that the changes in the mechanical properties of biocomposites were

primarily due to weight gain from moisture absorption [24]. The process of inducing ageing from load-unload cycles used in this study meant at underlining initial damage to biocomposites, with the authors suggesting that damage can be caused by fibre bundle division instigated by their interlaminar crack and washing out of soluble components. To improve fibre-matrix interphase in polymer composites, materials with chemically treated *Pennisetum purpureum* have been previously developed [25].

Evaluating the influence of temperature on the impact behaviour and the subsequent residual strength of polymer composites is imperative because their use in load-bearing structures exposes them to temperatures that could be higher than ambient temperatures during maintenance operations. Variation in temperature significantly influences the impact response of polymer composites [26]. Low-velocity impact considerably reduces the performance of the polymer composites, so the initial in-plane stiffness is crucial. Im et al. inspected the effect of temperature on the impact resistance of matrix cracking and interfacial delamination damage of carbon fibre/epoxy and carbon fibre/polyether ether ketone cross-ply composites subjected to low-velocity impact [27]. Their results showed a direct relationship between the impact energy and evolution of delamination area at varying temperatures. Similarly, Dhakal et al. studied the influence of temperature on the impact damage in jute/polyester[28]. They established that temperatures and impact velocity significantly affect energy absorption as well as impact and post-impact damage features. Nonetheless, Kang et al. who investigated the influence of temperature on the damage resistance of glass/epoxy laminates due to low energy impact at 40 to 80 °C [29] indicated a lesser effect on the impact response of composite laminates.

Recently, the comprehensive study on *Pennisetum purpureum* fibre as reinforcement of polymer composites and the mechanical properties of PGRE composite were investigated in

previous publications [8,30,31]. However, the effect of moisture exposure and elevated temperatures on the low-energy impact of PGRE composites has yet to be examined. Therefore, the current investigations were carried out to assess the impact responses of PGRE composites at room temperature (RT), under moisture exposure, and elevated temperatures. By comprehensively assessing their impact responses, the study is envisaged to provide evidence towards composite development and potential structural applications.

2. Materials and experimental methods

2.1 Materials

Pennisetum purpureum fibre, woven glass fibres, and epoxy were used to fabricate the hybrid *Pennisetum purpureum*/glass-reinforced epoxy (PGRE) composite. *Pennisetum purpureum* grass or locally known as Napier grass was harvested from a local plantation in Beseri, Perlis, Malaysia. Woven E-glass fibres were procured with dimensions of 350×350 mm per ply. EpoxAmite 100 epoxy resin was used as a matrix and mixed with a hardener at a ratio of 100 g epoxy: 28.4 g hardener. The properties of the fibres and epoxy materials are tabulated in Table 1.

Table 1. Properties of fibres and epoxy resin

Properties	Materials		
	<i>Pennisetum purpureum</i> fibre	Glass fibre	Epoxy
Density (g/cm^3)	0.36	2.5	1.1
Strength (MPa)	73	2000-3000	55
Modulus (GPa)	6	70	1.75
Elongation at break (%)	1.4	2.5	6
References	[32]	[33]	[34]

2.2 Specimen preparation

Pennisetum purpureum fibres were extracted from the stems of the plant using a laboratory-scale water retting process. The *Pennisetum purpureum* fibres were treated for 6 h using alkali (NaOH) solutions with concentrations of 5 and 10% at a liquor ratio; 40:1. All details regarding the fibre extraction and alkali treatment procedure have been described in previous publications [25]. The PGRE composites were fabricated using a vacuum infusion technique. The volume fractions of the *Pennisetum purpureum*, glass fibre and epoxy resin were opted at 24, 6, and 70%, respectively. The volume fractions of the fabricated composites were computed using a method reported in [35]. The hybrid reinforced composite samples comprised of either untreated, 5%, or 10% alkali-treated *Pennisetum purpureum* fibres.

2.3 Experimental procedure

An instrumented IMATEK IM10 drop weight impact tester was used to describe the impact responses of the PGRE composites. The total mass of impactor was 9.68 kg. The diameter of the striker was 10 mm with a hemispherical impact head, and its mass was 0.71 kg. A square specimen of 70-mm $\times$ 70-mm $\times$ 5-mm (length $\times$ width $\times$ thickness) was clamped between two metal features with a central circular opening at the centre where the impact event took place, as shown in Fig. 1. The different impact energy was obtained by changing the height of the dropping weight of the machine with three energy levels; 7.5, 15, and 22.5 J. Five replicates of hybrid composites for each of the untreated, 5%, and 10% treated *Pennisetum purpureum* were tested. A data acquisition system recorded the force as a function of time for each test. The built-in software was used to compute the peak load, absorbed energy, and deflection experienced by the specimen. To investigate the effects of moisture exposure, the specimen was submerged in distilled water at room temperature

(25°C) for 50, 100, 200, and 400 h in accordance with ASTM D570-10 [36]. Finally, the specimen was also tested in the environmental chamber at 40, 60, and 80 °C to examine the effect of elevated temperatures on the composites.

Fig. 1. Specimen held and clamped during the drop impact tests.

3. Results and discussion

3.1. Impact response of the PGRE composites

The load-displacement curves of PGRE composites samples at energy levels of 7.5, 15 and 22.5 J shown in Fig. 2. The materials of these PGRE composites were composed of either the untreated, 5 or 10% alkali treated *Pennisetum purpureum* fibres. To characterise the impact resistance of the PGRE composites, the peak load and stiffness has been obtained from the curves for comparison with conventional reinforcing fibres. The peak load indicates the maximum load of composite be able to sustain before suffering significant damage. In natural environments, the composite materials become brittle, and it was assumed that the elastic deformation occurred with absorbed energy to the peak load. The reflected waves of the peak load for each specimen were observed in Fig. 2. According to the Abu Seman et. al., this wave occurred due to the effect of unidirectional of natural fibres disturbed the propagating waves entering the fibre structures which triggers internal reflections inside the composites [37].

Fig. 2(a) shows the load-displacement curves of the PGRE composites at energy levels of 7.5 J were evaluated. The curves indicate that the specimens fail at average peak load were 4.72, 2.89, and 2.84 kN for the untreated, 5, and 10% alkali-treated PGRE composites, respectively. The reduction in peak load is about 40% for the alkali-treated PGRE composites, respectively. At this energy level, a similar pattern can be seen for 5 and 10% alkali-treated PGRE composites. The displacement of untreated, 5 and 10% of alkali-treated PGRE composites were 2.61, 3.95, and 3.94 mm, respectively. The closed loop of the curves as indication of no penetration of the composite samples occurred.

Fig. 2(b) illustrates the load-displacement curve of the PGRE composites at energy level of 15 J. The average peak loads of untreated, 5 and 10% alkali-treated PGRE composites were 4.81, 4.13, and 4.29 kN, respectively. For the alkali-treated PGRE composites shows the increment of energy level increased the peak load. The reduction of the peak load for alkali-treated PGRE composites was lower than 15%. The stiffness of 5 and 10% alkali-treated PGRE composites were quite similar. The displacements of untreated, 5 and 10% alkali-treated PGRE composites at the peak load were 4.33, 5.58, and 5.44 mm, respectively.

In Fig. 2(c) the load-displacement curves of the PGRE composites at the energy level of 22.5 J is shown. The average peak loads of untreated, 5 and 10% alkali-treated PGRE composites at this energy level were determined to be 5.23, 4.08, and 4.18 kN, respectively. The displacement at peak loads of untreated, 5 and 10% alkali-treated PGRE composites were 5.19, 6.66, and 5.14 mm, respectively. The trend is somewhat similar for all of the three curves, as the curves show no rebound at 22.5 J compared to at 7.5 and 15 J. This indicates that the specimens were penetrated or perforated at this energy level.

a) Load vs displacement at 7.5 J

b) Load vs displacement at 15 J

c) Load vs displacement at 22.5 J

Fig. 2. Load as a function of displacement of the PGRE composites at different applied energies (a) 7.5 J, b) 15 J, and c) 22.5 J.

In general, significant reductions of peak load were observed for the alkali-treated PGRE composites. This reduction is owed to the elimination of hemicellulose, lignin, waxes, and other impurities that weaken the impact strength of the hybrid composites. The load direction of the drop weight impact test was perpendicular to fibre bundles. Therefore, the treatment of the fibres did not improve the impact strength of the composites. These results differed from the tensile and flexural strength data previously reported [25], which indicates that the alkali treatment enhanced the fibres and matrix interfacial adhesion. The improved tensile strength occurred because the specimens were subjected to the load parallel to fibre bundles. For the flexural strength, even though the direction was perpendicular to the fibre bundles, the subjected load response differed from the drop weight impact test because it was influenced by the potential energy of the weight. Therefore, it can be established that the alkali treatment

of the fibres, in fact, weakens the impact strength of the PGRE composites. However this phenomenon against to the sisal/epoxy composites which exhibited the alkali treatment of the sisal fibre improved fibre-matrix interaction in order to produce higher impact strength [38].

The results for energy absorption of the PGRE composites are shown in Fig. 3. The absorbed energy of the samples is lesser than the corresponding impact energy of 7.5J were 6.3, 6.6, and 6.6 J for untreated, 5, and 10% alkali-treated PGRE composites, respectively. These differences are likely due to excessive energy (elastic energy), retained in the impactor and used to rebound the impactor from the non-perforated samples. At 15 J, the absorbed energy of the untreated PGRE composite was 13.2 J compared to 14.5 and 14.2 J for the samples of 5, and 10% alkali-treated PGRE composites, respectively. This indicates that untreated PGRE composites require more elastic energy to rebound the impactor.

Fig. 3. Energy absorption of the PGRE composites at different energy levels

At 22.5J, the absorbed energies of untreated, 5, and 10% alkali-treated PGRE composites were 21.3, 21.3, and 20.7 J, respectively. The lowest energy absorbed was observed for the 10% alkali-treated PGRE composites indicating that the samples were

entirely perforated. However, for the untreated and 5% alkali-treated PGRE composites, only penetration occurred at this energy level. The growth in damage area is an essential sign of the severity of the damage incurred from impact loading. The damaged area grows with increasing impact energy for most composites. Furthermore, the composite's residual strength after the impact test is essentially dependent on whether the damage is localised or non-localized. Azouaoui et al. (2010) reported that delamination cracks preferentially propagate over the matrix-rich region, which is moderately less resistant to cracking than the fibre pathway [39]. The analysis of surface damage modes are presented in

Table 2

Table 2 for the samples at energy levels of 7.5, 15, and 22.5 J. The impacted surfaces show damage as circular-shaped indentations caused by the dropped hemispherical head. The depth of this indentation increases with higher impact energies, and no visible cracks or perforations were observed on the front faces at 7.5 J. At higher energies, the crack propagates along the direction of the fabric textures, as is apparently visible in the images of

the samples tested with 15 and 22.5 J of impact energy. From the images of the impacted surfaces, the untreated PGRE composites present less damage area, while a clearer tendency towards the direction of damage was shown in the other samples. With regards to the extension of the damage to the back of the sample, which involves the entire thickness of the sample, it was more noticeable on the untreated PGRE composite when higher impact energies were applied.

Table 2. Damage area of the PGRE composites at different impact energy levels.

Composites/ Energy Level	untreated PGRE composites	5% PGRE composites	10% PGRE composites
7.5 J
15 J

22.5 J

3.2 Effect of moisture exposure on the impact damage of the PGRE composites

Table 3 shows the peak load distribution of the PGRE composite at different immersion times, demonstrating the effect of moisture exposure on impact response. The peak load of the PGRE composite decreased with higher immersion times at each of the impact energies. This indicates that the exposure to moisture for 50, 100, 200, and 400 h influences the impact properties of the samples. The peak load values decreased with increasing immersion times due to degradation of the matrix strength by moisture. The untreated PGRE composite shows the lowest peak load at 7.5 J under all immersion conditions. The value was similar to that of the 10% alkali-treated PGRE composite at energy level of 7.5 J. However, it was different for 5% alkali-treated PGRE composites, where 15 J showed the lowest peak load for the samples immersed for 50, 100, 200, and 400 h. The peak load decreases for the alkali-treated PGRE composite with immersion time, and the high concentration alkali treatment resulted in the lowest peak load. The different energies were observed to have a smaller impact on the peak load when compared to immersion time. The reduction of peak load suggests that the impact strength of the PGRE composites declined. The absorbed water molecules within the composites due to moisture exposure weaken the intermolecular hydrogen bonding between the cellulose molecules in the fibre [40]. Thus, interfacial bonding between the fibre and matrix degraded, causing in the declined impact strength of the PGRE composites. The conduct of the polymer chains molecules, as well as the hydrogen bonds and Van der Waals

interactions, greatly affect the capacity of the composites to tolerate external stress [41]. As water molecules permeate the PGRE composite, hydrolysis and plasticisation of the matrix occurred, impairing the bonding within the polymer chains [42]. Consequently, the interfacial bonding deteriorates and bond between polymer chains is impaired, which then reduces the stiffness of the PGRE composites [43].

The energy absorption of the untreated, 5 and 10% alkali-treated PGRE composites at different immersion times and applied impact energies are tabulated in Table 4. The absorbed energy increased slightly with longer immersion times for all PGRE composites at 7.5 J. The untreated and 10% alkali treated PGRE composites at 15 J slightly increased with longer immersion times. However, absorbed energies of the 5% alkali-treated PGRE composites exhibited minor fluctuations with small changes between the dry, 50, 100, 200, and 400 h immersion samples. For the 22.5 J applied energy impact, the absorbed energy decreased with longer immersion times. The absorbed energy of the untreated PGRE composite was reduced by 6% from 21.12 J of the dry sample to 19.7 J after 400 h of immersion. The absorbed energy of the 5% alkali-treated PGRE composite was approximately 28% less at 21.22 J at RT to 15.34 J after immersion for 400 h. Finally, the 35% reduction of the absorbed energy for the 10% alkali-treated PGRE from 20.6 J under dry conditions to 13.48 J after 400 h of immersion. Based on these results, at 22.5 J applied energy, the untreated PGRE composite absorb more energy than the 5 and 10% alkali-treated PGRE composites. The brittle nature of constituents of the composite may explain the behaviour of the untreated *Pennisetum purpureum*, glass fibres, and epoxy matrix, where they become more brittle after immersion in water [44]. Moisture exposure for 50, 100, 200, and 400 h exerted a definite influence on the impact response of the composites.

Furthermore, the data regarding the distribution of peak deflection for the PGRE composite subjected to 7.5, 15 and 22.5 J of applied energy are listed in Table 5. The peak deflection of the untreated PGRE composite exhibits an increasing trend with immersion time at each of the applied energy levels. However, the peak deflection of the PGRE composites with both types of alkali-treated *Pennisetum purpureum* fibres did not show the same trend. An increasing trend for applied energy at 7.5 J was observed, but a decreasing trend can be seen for applied energy levels of 15 and 22.5 J.

Table 3. Distribution of peak load of the PGRE composites.

Peak Load (kN)															
Hybrid	7.5J					15J					22.5J				
Composites	Dry	50h	100h	200h	400h	Dry	50h	100h	200h	400h	Dry	50h	100h	200h	400h
Untreated	4.68	3.00	2.99	2.47	2.26	4.81	3.03	2.99	2.94	2.92	4.68	3.03	2.99	2.47	2.26
5%	3.01	2.41	2.35	2.26	2.25	4.26	2.07	2.00	1.77	1.53	3.01	2.41	2.35	2.26	2.25
10%	2.82	2.81	2.52	2.04	2.03	4.47	3.00	2.81	2.53	2.17	2.82	2.81	2.52	2.04	2.03

Table 4. Distribution of absorbed energy of the PGRE composites.

Energy Absorbed (kJ)															
Hybrid	7.5J					15J					22.5J				
Composites	Dry	50h	100h	200h	400h	Dry	50h	100h	200h	400h	Dry	50h	100h	200h	400h
Untreated	6.30	6.49	6.50	6.53	6.70	13.23	14.00	14.21	14.26	14.31	21.12	21.03	20.50	20.14	19.70
5%	6.66	6.69	6.82	6.91	7.06	14.53	14.10	14.26	14.27	14.28	21.22	21.03	20.49	15.90	15.34
10%	6.62	6.84	6.85	6.94	7.00	14.05	14.19	14.28	14.32	14.32	20.60	20.46	19.35	14.47	13.48

Table 5. Distribution of peak deflection of the PGRE composites.

Peak Deflection (mm)															
Hybrid	7.5J					15J					22.5J				
Composites	Dry	50h	100h	200h	400h	Dry	50h	100h	200h	400h	Dry	50h	100h	200h	400h
Untreated	2.65	3.83	3.68	4.01	4.44	4.15	4.90	5.34	5.07	6.67	4.99	6.33	7.13	7.23	7.30

5%	3.66	3.85	4.58	4.54	4.22	5.53	4.90	4.15	4.70	4.28	6.78	6.26	5.07	4.75	4.27
10%	3.96	4.42	4.06	4.22	4.04	4.34	5.46	4.62	5.21	4.88	5.36	6.32	6.51	5.69	5.65

Table 6 shows the damaged area of the PGRE composite with 22.5 J of applied impact energy. The untreated PGRE composite display less damage area at all immersion times compared to the 5 and 10% alkali-treated PGRE composite. For longer immersion times, the cracks tend to propagate along the direction of the fabric textures. The alkali-treated PGRE composite was wholly perforated after immersion for 200 and 400 h, whereas the untreated PGRE composites were not perforated. Micromechanics damage such as interfacial debonding between the fibres and matrix due to moisture exposure may result in the decline of the global stiffness and local strength of the hybrid composite. The degraded stiffness and strength of the moisture-exposed composites caused the composites to crack easily with larger crack formation due to the toughness reduction of the wet (aged) composite caused by impacts that can be more clearly seen in the dry composites [45]. The reduced stiffness and strength of the wet composite also reduced the amount of absorbed energy compared to that of the dry composites.

Table 6. Damage area of the PGRE composites subjected to different immersion times.

Composites/ Time immersion	untreated PGRE composites	5% PGRE composites	10% PGRE composites
400 h

200 h

100 h

50 h

3.3 Effect of elevated temperatures on the impact response of the PGRE composites

Fig. 4(a) shows the peak load of the untreated, 5 and 10% alkali-treated *Pennisetum purpureum*/glass-reinforced epoxy (PGRE) composites subjected to impact tests at room temperature (RT) and 40, 60, and 80 °C for 7.5, 15, and 22.5 J of applied energy. At RT, the untreated PGRE showed the higher peak loads compared to the 5 and 10% alkali-treated PGRE composites at all energy levels. It can be observed that the peak load of the untreated PGRE composite at RT were 4.7, 4.8, and 5.2 kN for 7.5, 15, and 22.5 J of applied energy, respectively. The peak loads slightly decreased at 40 °C, and the ranges of peak load showed a slight difference in their energies. However, the ranges of peak load were greater at 60 and 80 °C. The peak load at 60 °C decreased to 2.5, 3.0, and 4.0 kN for 7.5, 15, and 22.5 J of applied energy, respectively. For the specimens at 80 °C, the peak loads were 2.5, 3.0, and

4.0 for 7.5, 15, and 22.5 J of applied energy, respectively. The 5 and 10% alkali-treated PGRE composites at RT and elevated temperatures showed a reduction in the peak load. However, negligible changes in the peak load were observed between the 5 and 10% alkali-treated PGRE composites concerning increasing impact temperature. Thus, it can be concluded that a decrease in peak load occurred at elevated temperatures. This substantial reduction in peak load is evident at 60 °C, which is near to the glass transition temperature, T_g of the material at approximately 63–67 °C. For the RT and 40 °C impacted specimens, the peak load remained nearly constant, which might be because at elevated temperatures, softening or plasticisation of the matrix enhances the impact damage resistance. This phenomenon is associated with the investigation of the impact properties of the jute/UP composites when the impact temperature is higher than the T_g , the softening of matrix occurred by the decrease in the percentage of hits corresponding to matrix [28].

The distribution of absorbed energy of the untreated, 5 and 10% treated PGRE composites are shown in Fig. 4(b). It was apparent that the absorbed energy slightly increases at elevated temperatures in the increasing order $40 < 60 < 80$ °C. At increasing absorbed energies, the superior impact damage tolerance of the specimens can be credited to the stronger and tougher *Pennisetum purpureum* fibres. However, the absorbed energy of the PGRE composite was similar between untreated, 5, and 10% alkali-treated PGRE composites for their respective temperature and energy. This shows that the treated fibres do not significantly influence the absorbed energy of the respective composites. The distribution of peak deflection of the untreated PGRE composite increases with higher impact temperatures, as shown in Fig. 4(c). As the temperature increases, the stiffness of the material was considerably degraded which increases the peak deflection triggering extended damage to the specimens. Although the peak deflection shows an increasing trend with temperature, the

magnitude of the peak deflection was lower compared to those of the other two cases even at elevated temperatures. Hence, the 5% alkali-treated PGRE composite specimens exhibited the highest toughness among all three composites. A lesser degree of peak deflection can be seen for the 10% alkali-treated PGRE composite from RT to 40 and 60 °C. The absorbed energy and peak deflection increase with higher impact temperatures, as shown in Fig. 4(b) and (c).

385

a) Distribution of peak load of PGRE composites

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b) Distribution of absorbed energy of PGRE composites

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c) Distribution of peak load of PGRE composites

Fig. 4. Impact properties of the PGRE composites at elevated temperatures

Table 7 shows the indented fracture observed by optical inspection of PGRE composite specimens impacted at 22.5 J. Minor matrix cracks can be seen on the impacted composites and fibre straining on the rear face was observed on the surfaces, showing increased damage area. Damage at the rear surface of the specimen is more visible for all specimens at each energy level. At higher temperatures, the specimens tested at 60 and 80 °C, the damage pattern is more apparent and extended. Therefore, the damaged area and delamination increase with the test temperature. Similar findings were reported by Dhakal et al. noticed that the temperature significantly influences the impact damage of jute/UP laminates composites [28].

Table 7. Damage area of the PGRE composites at different temperatures.

Composites/ Temperature	untreated PGRE composites	5% PGRE composites	10% PGRE composites
80 °C

60 °C

40 °C

3.4 The mechanical properties of natural fibres and hybrid composites

The mechanical properties of *Pennisetum purpureum* fibre and other more common natural fibres reinforced epoxy composites and their impact response of are tabulated in Table 8 and Table 9 respectively. The table review indicates that the tensile and flexural properties of *Pennisetum purpureum* fibres are comparable with other natural fibres listed as reinforcement in polymer composites. In the previous study, the hybridisation of the *Pennisetum purpureum* with glass fibres shows significant improvement in the mechanical properties of the composites [46]. Previous research investigation reported that the natural fibres composites show potentials in automobiles such as door panels, hat racks, package trays, sun visors, seat backs and exterior/underfloor panelling [47], and also has been used in interior materials in aerospace industries [48].

Table 9 tabulated the comparison of the impact response between PGRE with other hybrid composites at 15 and 40 J, impact energy. The peak load of PGRE was slightly higher than Flax/carbon composites, although the energy absorption of the flax/carbon was lower than PGRE composites. It can be concluded that the PGRE shows promising impact properties compared to Flax/carbon composites at the same impact energy. The peak load of

PGRE was performed higher compared to Jute/glass composites at the same energy provided. Lastly, the impact response of PGRE can be claimed better than Basalt/flax composites even the peak load and energy absorption of PGRE were lower than Basalt/flax composites. This is due to the impact energy for Basalt/flax is more than doubled that of PGRE composites. Therefore the impact properties of the PGRE are comparable to other hybrid composites.

Table 8. Mechanical properties of natural fibres reinforced epoxy composites

Properties / Natural fibre reinforced epoxy composites	Oil palm fibre	Sugar palm fibre	Bamboo fibre	Kenaf fibre	<i>Pennisetum purpureum</i> fibre
Tensile Strength (MPa)	25-30	43-50	30-32	58-124	21-50
Tensile Modulus (MPa)	1.3-1.4	3.3-3.9	3.3	6.8-14.4	2.5-5.9
Flexural Strength (MPa)	40-45	78-98	80-85	230-300	47- 66
Flexural Modulus (MPa)	3-3.3	2.9-7	3.6-4.6	5.6-5.8	4-6
References	[49]	[50,51]	[52,53]	[54,55]	[25]

Table 9. Impact properties of hybrid epoxy composites

Properties / Natural fibre reinforced epoxy composites	Flax/carbon	Basalt/Flax fibre	Jute/Glass	PGRE
Impact energy	15	40	15	15
Peak load(N)	4776	6900	3500	4850
Energy absorption	11.20	20	14	14
References	[10]	[56]	[57]	-

4. Conclusions

The effects of alkali treated *Pennisetum purpureum* fibre, moisture exposure, and elevated temperature of the untreated, 5, or 10% alkali-treated hybrid PGRE composite on the low-velocity impact behaviour of the composites was investigated.

a) A significant reduction of peak load was observed for the alkali-treated PGRE composite.

This was likely due to the removal of the hemicellulose, waxes, lignin, and other impurities which reduced the impact strength of the composites. The load direction of the drop-weight impact test was perpendicular to the fibre bundles. Therefore, the fibre treatment did not improve the impact strength of the composites.

b) The peak load of the composites decreased with longer immersion times at each applied energy. This indicates that the moisture content under dry, 50, 100, 200, and 400 h immersion conditions influenced the impact properties. The peak load values decreased with increasing immersion time due to degradation of the matrix strength by the moisture and resulted in easy fracture of specimens under impact loading. The peak load decreased with the addition of alkali-treated PGRE composite for particular immersion times during testing, and the high concentration alkali treatment produced the lowest peak load. The reduced stiffness and strength of the moisturised composites caused cracking with extended crack sizes due to the more extensive toughness reduction of the humid composite than that of the dry composites.

c) As the temperature increased, the stiffness of the material was significantly reduced, which influenced the absorbed energy and peak deflection, causing extended damage to the specimens. Though the absorbed energy increased with temperature, the magnitude of the absorbed energy was lower than those of the other two cases at elevated temperatures. Thus, the PGRE composite possesses the highest toughness among all the three samples.

At higher temperatures, the specimens tested at 60 and 80 °C, the damage pattern was more visible and extended. Therefore, the damaged area and delamination increase with increasing test temperature.

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Highlight

1. The PGRE with untreated *Pennisetum purpureum* fibres yielded highest the peak load.
2. The peak load of the PGRE decreased with longer immersion times.
3. The reduced stiffness and strength of the moisturised PGRE caused cracking.
4. The stiffness of the PGRE reduced considerably as the temperature increased.
5. The damaged area and delamination increases with increasing test temperature.