Research Paper

Effect of Chemically Modified Banana Fibers on the Mechanical Properties of Poly-Dimethyl-Siloxane-Based Composites

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A R T I C L E   I N F O

A B S T R A C T

The study presents the mechanical properties of polymer-based composites reinforced with chemically modified banana fibers, by alkalization in different concentrations of sodium hydroxide (NaOH). The fiber weight fraction has a great effect on the mechanical properties of the composites. Stiff composites were obtained at 6 wt% fiber fractions with Young's modulus of 254.00 ±12.70 MPa. Moreover, the yield strength was 35.70 ±1.79 MPa at 6 wt% fiber fractions. However, the ultimate tensile strength (UTS) and toughness of the composites were obtained at 5 wt% fiber fractions. Statistical analyses were used to ascertain the significant different on the mechanical properties of the fibers and composites. The implication of the results is then discussed for potential applications of PDMS-based composites reinforced with chemically modified banana fibers.

1   Introduction

A composite-based material comprised of two or more different materials with identifiable interfaces between the matrix and the reinforced material [1]. Thus, the combination gives rise to different physical and chemical phases, separated by a distinct interface and the overall effect enhances the mechanical properties of the new structure [1, 2]. Composite materials

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are characterized by low weight, high fatigue strength, good resistance to corrosion [2], and improved resistance to abrasive wear, hardness and impact strength [3].

Polymer-based matrices have been limited by poor mechanical properties that render polymers inadequate for most engineering applications [4]. An elastomeric polymer such as poly-dimethyl-siloxane (PDMS) particularly has large strain but with low strength and stiffness and cannot stand the test of any structural application. The associated weaknesses in the mechanical properties of polymers can be improved by reinforcing with natural fibers [5].

Polymer matrix composites (PMC) are commonly used due to their low cost and simplicity in fabrication [6]. Apart from the conventional Fiber materials such as aramid, Kevlar and glass fibers, natural fibers such as hemp, bamboo, kenaf, flax, and jute are increasingly applied for reinforcement [7-13] to study their effect on the mechanical properties of the composites.

Most PMC are made by embedding strong fibers, such as carbon, aramid, glass, or natural fibers in a polymer matrix [14, 15]. Natural fibers are based on cellulose and therefore offer advantages of biodegradability, low density, nonabrasive nature, and low cost [16].

The amount of hemicellulose controls the moisture absorption, biodegradation, and thermal degradation properties of natural cellulosic fibers, while lignin has been reported to be the most thermally stable constituents [17]. However, lignin is very sensitive to ultraviolet (UV) radiation and it is also responsible for the degradation of fibers under ultraviolet radiation [17]. The chemical composition of natural fibers has been reported [18]. Moreover, fiber reinforced polymer composites (FRPC) possess high specific moduli and specific strengths and are widely used in many structural applications including aerospace, sporting goods, automobile, civil and marine structures [19]. Mechanical properties of natural fiber materials (flax, hemp, jute, bamboo, sisal, and choir) have been extensively studied [20].

Though natural fibers could provide important properties such as low density, appropriate stiffness, high disposability, and renewability [8], they are however challenged with relatively high moisture absorption. Recent studies show that natural fibers could be good candidates for reinforcement. However, they should be appropriately treated for practical applications [21].

Significant improvements in mechanical properties of natural fibers have also been achieved with chemical modification of fibers in order to promote appropriate bonding at the fibers matrix-interface [22]. Fiber surface treatments can improve the interfacial adhesion between the fiber surface and the matrix [21]. Alkali treatment is a known method used for the chemical treatment of natural fibers. The type of alkali treatment may include potassium hydroxide (KOH), lithium hydroxide (LiOH), sodium hydroxide (NaOH) and their concentrations influence the degree of swelling and the degree of lattice transformation into cellulose [23]. The cellulose content determines the mechanical properties of the fibers [24]. Mishra et al. (2003) [23] reported 5% treated NaOH fiber reinforced polyester composites with improved tensile strength than 10% NaOH treated composites. The tensile strength of composite decreased drastically after a certain optimum NaOH concentration. Moreover, acetylation was used in surface treatments of fibers [25]. Acetylation treatment of sisal fiber improved the fiber-matrix adhesion [23]. Similarly, the mechanical properties of composites reinforced with wood fibers and polyvinyl-chloride (PVC) or polystyrene (PS) as resins were improved by an isocyanate treatment [26].

2   Materials and Methods

2.1 *Materials*

Banana stem (obtained from the pseudo-stem of a banana plant) was harvested from the Kwara State University (KWASU) teaching farm, Malete, Nigeria. Sylgard 184 kit silicone elastomer base with curing agent were procured from DOW Corning Corporation (Midland, U.S.A.). NaOH, ethanol (100%) and distilled water were procured from a chemical laboratory (Labtrace) in Ilorin, Nigeria.

Metallic molds were fabricated with mild steel for used (Fig. 1). The molds were obtained with respective dimensions (L = 12 mm, W = 2.5 mm, B = 0.6 mm). The molds were then used to fabricate specimens for mechanical characterizations.

(a)   (b)

Fig. 1– (a) Fabricated Mild Steel Mold and (b) Mild Steel Molds filled with Polymer Samples.

2.2 Experimental Procedures

2.2.1   Fiber Preparation

Banana stems were obtained and transported to the Materials Science and Engineering Laboratory at KWASU. The dried outer layers of the stems were slightly pilled off before cutting into uniform lengths of slabs. The samples were then pre-warmed at 80˚C for 25 min to increase the rate of fermentation. The pre-warmed samples were subsequently submerged in distilled water for 9 days. Due to the fermentation, it was easy to remove exposed fibers from the samples. The fibers were properly washed with 2 v% of detergent solution (in 500 ml distilled water) to remove contaminants as well as adhering's. Fibers were then dried in a laboratory oven (Uniscope Sm905, Sergifriend Medicals, England) at moderate temperature (100˚C for 2 h), ready for chemical treatment.

2.2.2   Fiber Treatment

Alkali solutions of NaOH were prepared at 6 wt% of NaOH (dissolved in distilled water at a concentration of 3.6 mg/ml), 8 wt.% of NaOH (dissolved in distilled water at a concentration of 6.3 mg/ml), and 10 wt.% of NaOH (dissolved in distilled water at a concentration of 10.2 mg/ml). The obtained fibers were then soaked at room temperature for 24 h. The treated fibers were then removed from the alkali solutions, washed severally with distilled water to remove any alkali solution and particulates sticking on the fiber surface. Diluted acetic acid (2 v% in 1500 ml distilled water) was then used to wash the modified fibers, to neutralize the NaOH on the surfaces. The fibers were then dried in an oven at 100°C for 6.5 h. The average diameters of the fibers were determined using a digitized micrometer screw gauge. The reactions equation below explained what took place as a result of alkali treatment [30].

$$Fiber - OH + NaOH \rightarrow Fiber - O^-Na^+ + H_2O \tag{1}$$
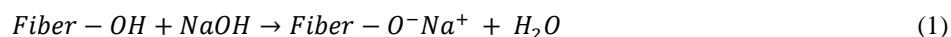
2.2.3   Fiber Pullout Test

The average fiber strengths were obtained using a mechanical testing machine (Instron 825, university avenue, Norwood) (Fig. 2a). For every set of fibers, 5 specimens were tested to determine the average fiber bundle strength at room temperature. The fiber bundle tensile strength was performed using a computer controlled Instron machine with a gauge length of 40 mm at a crosshead speed of 0.05 mm/min. The data from the load-extension curves were then used to describe the stress-strain curves. The tests for fiberpull-out (Fig. 2b) were similarly carried out by testing for at least 5 fibers.
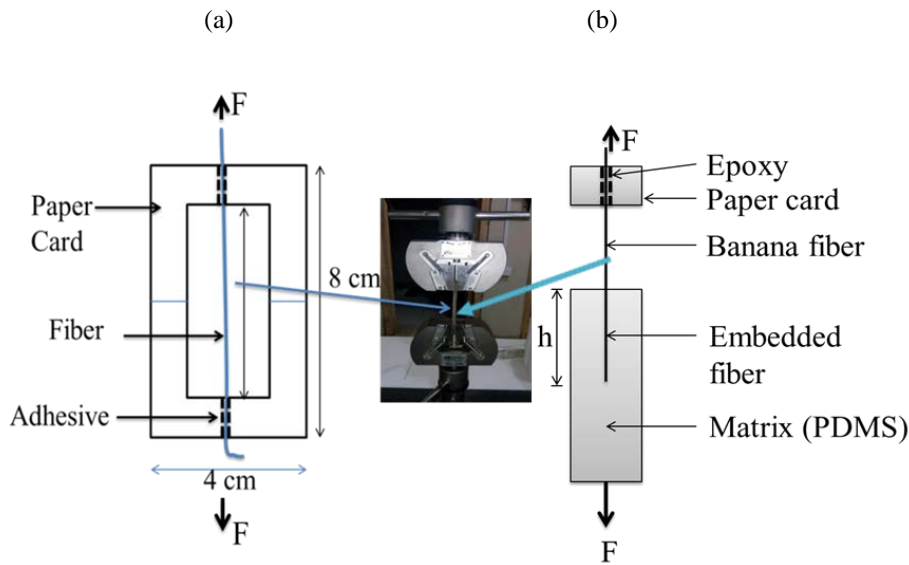
Fig. 2 – Illustrations: (a) Specimen for the Test for Fiber Strength and (b) Specimen for Fiber Pullout Test.

Following the fiber pullout test, the shear strength at the fiber-matrix interface (τ) was obtained by:

$$\tau = \frac{F}{2\pi rhn} \tag{2}$$

where F is the maximum load at failure, h is the length of the embedded fiber, n is the repeated number of fibers, r is the fiber radius and π is a constant which assumed circular diameter fibers. The critical length (L_c) was then obtained as follows:

$$L_c = \frac{\sigma_f d}{2\tau} \tag{3}$$

where σ_f is the fiber strength in tension, d is the diameter of the fiber, τ is the shear strength at the fiber-matrix interface. The optimal fiber length used during the reinforcement was ($L > L_c$).

2.2.4 Composite Fabrication

The designed composites were guided by the rule of mixture. For randomly oriented fibers, an orientation efficiency factor, n_o was introduced [31]. The fiber orientation factors accounted for the average decrease in composite strength in any given direction due to the randomness of the fibers. Hence, the rule-of-mixture for composite strength and modulus for shot fibers were modified by [32]:

$$\sigma_c = \sigma_m w_m + \eta_f \eta_o \sigma_f w_f \tag{4}$$

$$E_c = w_m E_m + \eta_f \eta_o w_f E_f \tag{5}$$

where σ_c is the strength of the composite, σ_m is the matrix tensile stress at maximum load (MPa), w_m is the weight fraction of the matrix , η_f is the fiber efficiency factor, η_o is the fibers orientation factor, σ_f is the fiber tensile stress at maximum load (MPa) and w_f is the weight fraction of the fibers. Typical value of η_o are 0.375 for random in-plane two-dimensional arrays and 0.2 for three-dimensional random arrays. For an aligned longitudinal whiskers/fibers, the value of η_f is assumed to be between 0 and 1 [32].

During the composite fabrications, sylgard 184 kit silicon elastomer base with a curing agent (a crosslinker) were obtained and mixed vigorously at different ratios of 5:1 v/v% and 10:1 v/v%. Fibers were reinforced at 4, 5 and 6 wt.%. The mixtures were vigorously stirred and then de-gassed with a vacuum oven, set at -50 in.Hg equivalent with no heat for 1h, 15min. Meanwhile, during the degassing process, the oven was vented and at 15 min intervals. This causes bubbles to easily disappear and hence reduces the duration of degassing.

The molds were then positioned on flat platforms, while the degassed PDMS-fibers blends were then poured gently into the fabricated molds. The rheological property of PDMS enables the samples to flow, taken the shape of the molds. The samples were then cured at 80˚C for 3 h with the vacuum oven (without creating any further vacuum). The samples were then allowed for 12 h before unmoulding.

2.2.5   *Optical Characterization*

The obtained fibers (treated and untreated) and PDMS-based composites were examined with an optical microscope. Morphological characteristics of the samples were compared.

2.2.6   *Mechanical Characterization of Composites*

PDMS (control samples), as well as PDMS-based composites, were subjected to tensile mechanical tests at a loading rate of 1.0 mm/sec with a gauge length of 40 mm. The data from the load-extension curves were used to describe the stress-strain behaviours (eqn. 6a). The Young's modulus and modulus of resilience (taken to the point of yielding) were obtained at the elastic region, respectively [33]:

$$E = \frac{\sigma}{\varepsilon} \tag{6a}$$

$$U_r = \frac{1}{2}\sigma_y\varepsilon_y = \frac{\sigma_y^2}{2E} \tag{6b}$$

where σ is the stress, ε is the strain, E is the elastic modulus (the gradient of the stress versus strain curve, Pa), U_r is the modulus of resilience for the linear elastic behaviour (strain energy per unit volume, J/m^3 or Pa), σ_y is the yield strength and ε_y is the strain at yielding. The toughness, which is the area under the curve up to the point of fracture [33] was computed by assuming the ductile behaviour of materials.

$$U_t = \frac{1}{2}(\sigma_y + \sigma_{ut})\varepsilon_f \tag{7}$$

where σ_y is the yield strength, σ_{ut} is the ultimate tensile strength, and ε_f is the strain at the point of failure. The Vickers hardness of the samples was characterized with Matsuzawa micro Vickers hardness tester (MMT-X Series, Matsuzawa Co. Ltd, Toshima, Akita Pref, Japan).

2.2.7   *Statistical Analysis*

Statistical analyses were carried out on the mechanical properties of the banana fibers, PDMS matrices, and PDMS-based composites for at least at three independent times. The average values ± standard errors (SE) were then reported [34]. Analyses were done using Minitab software package (Minitab16, Minitab Inc., State College, PA, USA). Statistical significances of the data were established from the difference in the means at a significant level of 5%, unless otherwise stated. One way ANOVA tests were performed on the effect of chemical modification on the strength of fibers as well as test the effect of fiber weight fractions on composites strengths. Moreover, two-way analysis of variance was performed on the effects of crosslinker ratio on the stiffness, yield strength, ultimate tensile strength, toughness, modulus of resilience and hardness of the PDMS-based composites.

3   Results and discussion

Optical images of the banana fibers treated with NaOH and untreated fibers are presented (Fig. 3). The alkali treatments removed impurities adjoining the fiber materials. Thus, the alkali solution removed contaminants as well as adhering's to fiber surfaces. The optical images of the treated fibers reveal micro-defects at the surface of some sections of the fibers. Randomness in fiber orientations was observed in the samples (Figs. 4a-d). The images clearly revealed the presence of fibers within the polymer matrices in greater quantities with higher wt.% fiber ratios.
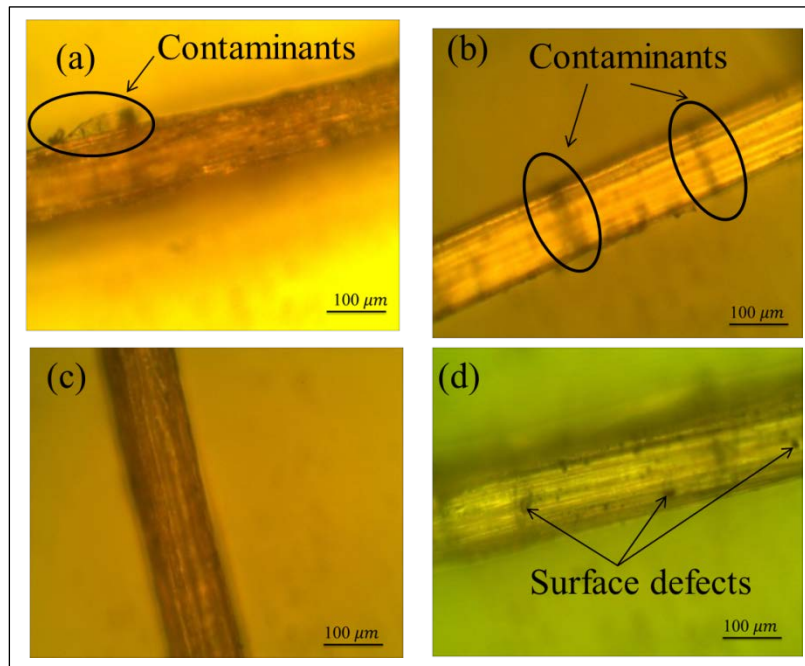
Fig. 3 –Optical Micrographs of Fibers:(a) untreated fiber, (b) 6wt% NaOH (c) 8 wt% NaOH and (d) 10 wt% NaOH treated fiber.
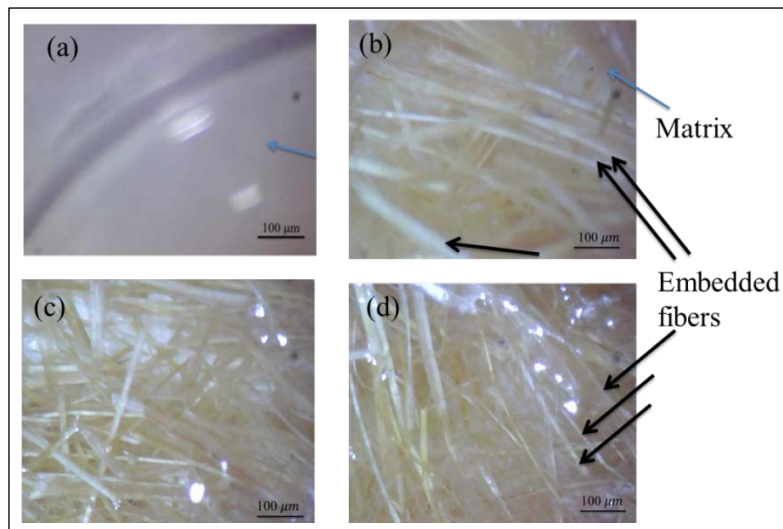

Fig. 4 – Optical Micrographs of the Banana Fibers Reinforced PDMS Composites (5:1 crosslinker ratio): (a) Control (Matrix) (b) 4wt% fibers; (c) 5wt% fibers and (d) 6 wt% fibers.

Mechanical properties of treated fibers with NaOH at different concentrations were compared with the untreated (control) specimen (Figs. 5a-d).

The optimal NaOH concentration needed for improved mechanical properties such as Young's modulus (E), ultimate tensile strength (UTS) and toughness (U) were fibers treated with 8 wt.% NaOH (Concentration of 6.25 mg/ml). The optimized E, UTS, and U were 1683 ± 84.15 MPa, 261 ± 13.05 MPa and 38734.38 ± 1936.71 MJ/m^3, respectively, while the untreated reported 670 ± 33.50 MPa, 84.95 ± 4.25 MPa and 9378.25 ± 468.91 MJ/m^3 for E, UTS and U, respectively.

The above properties increased steadily up to 6.25 mg/ml concentration of NaOH treatment. Further increase in the concentration of NaOH and beyond 8 wt% caused the mechanical properties to drop. For instance, the stiffness of fibers decreased beyond 8 wt.% NaOH (6.25 mg/ml) treatment. This shows that, chemical modification at 24 h was optimized at 6.25 mg/ml of NaOH.
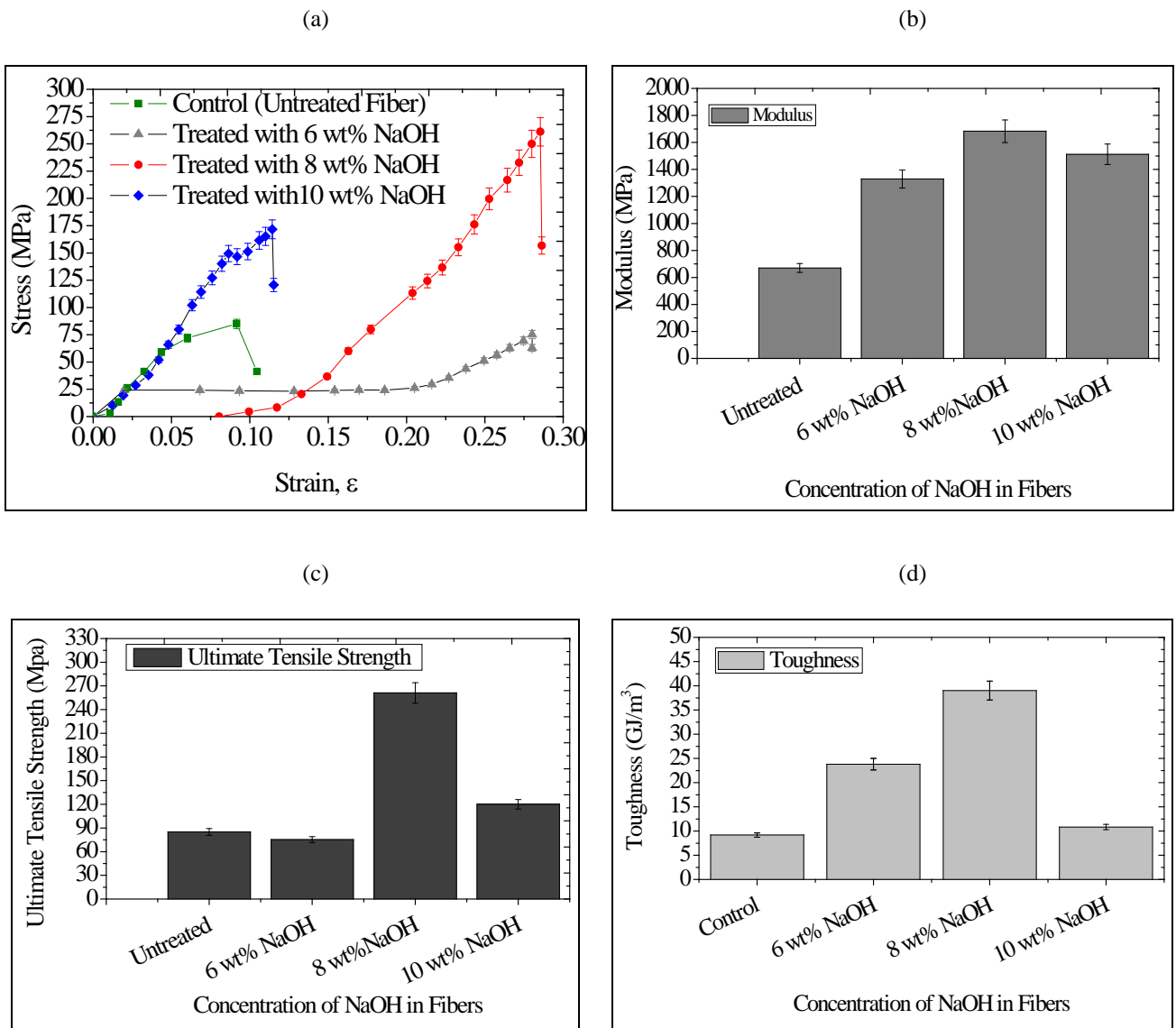
(a)   (b)

(c)   (d)

Fig 5 -Mechanical Properties of Treated Fibers with NaOH at different Concentrations: (a) Stress-strain curves, (b) Young's Modulus, (c) Ultimate Tensile Strength (UTS) and (d) Toughness of Fibers.

Stress-strain curves for the PDMS-based composites are presented (Figs. 6a-b) for different ratio of sylgard and crosslinker. Polymer chains were linked together by a non reversible chemical reaction that created chemical bonds (covalent bonds) to form a three-dimensional network.

Comparisons of E, UTS and yield strength (YS) for PDMS-based composites are presented (Figs. 7a-c). There were great improvements in E with the effect of crosslinker concentration.

The result (Fig. 7a) gave a stiffer material with higher E (307.80±11.50 MPa) at 5 wt.% fiberratio for 5:1 ratio as compared with 229.92±15.39 MPa for 10:1 at 5 wt.% fiber ratio. The PDMS 5:1 matrix-to-fiber ratio contained twice the amount of a curing agentas compared to the 10:1. This created a highly crosslinked network which gave a stiff material as compared to PDMS 10:1. However, the results (Figs. 7b and 7c) revealed that the stiffer materials yielded earlier with increasing fiber ratio above 5 wt.%. PDMS-based composites with sylgard to crosslinker ratios of 10:1 recorded a higher value of YS (35.7±1.79 MPa) as compared to YS (28±1.40 MPa) for the 5:1. This explained that stiff materials turn to be brittle and could yield easily. Despite that, UTS was improved for 10:1 (43.63±2.18 MPa) at 5 wt.% fiber fraction than the 5:1 ratio (30.44±1.52 MPa), the results obtained at 6 wt.% was similar for the two category of specimens (~41 MPa).
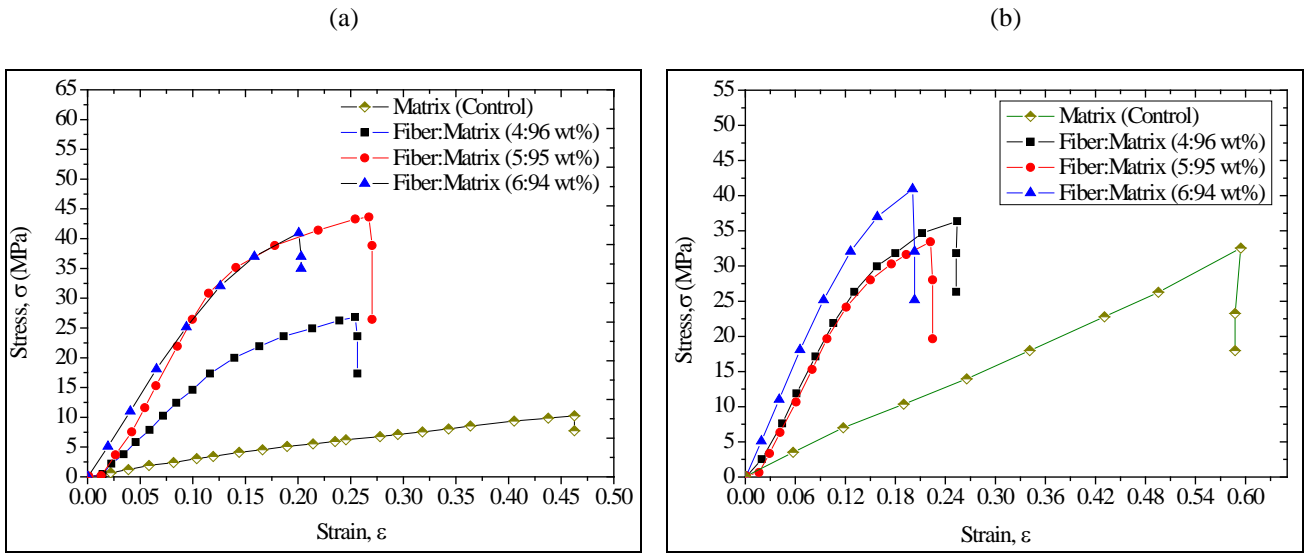
(a)   (b)

Fig 6- : *Stress-Strain Curves for Composites: (a) PDMS with 10:1 Crosslinker ratio and (b) PDMS with 5:1 Crosslinker ratio.*
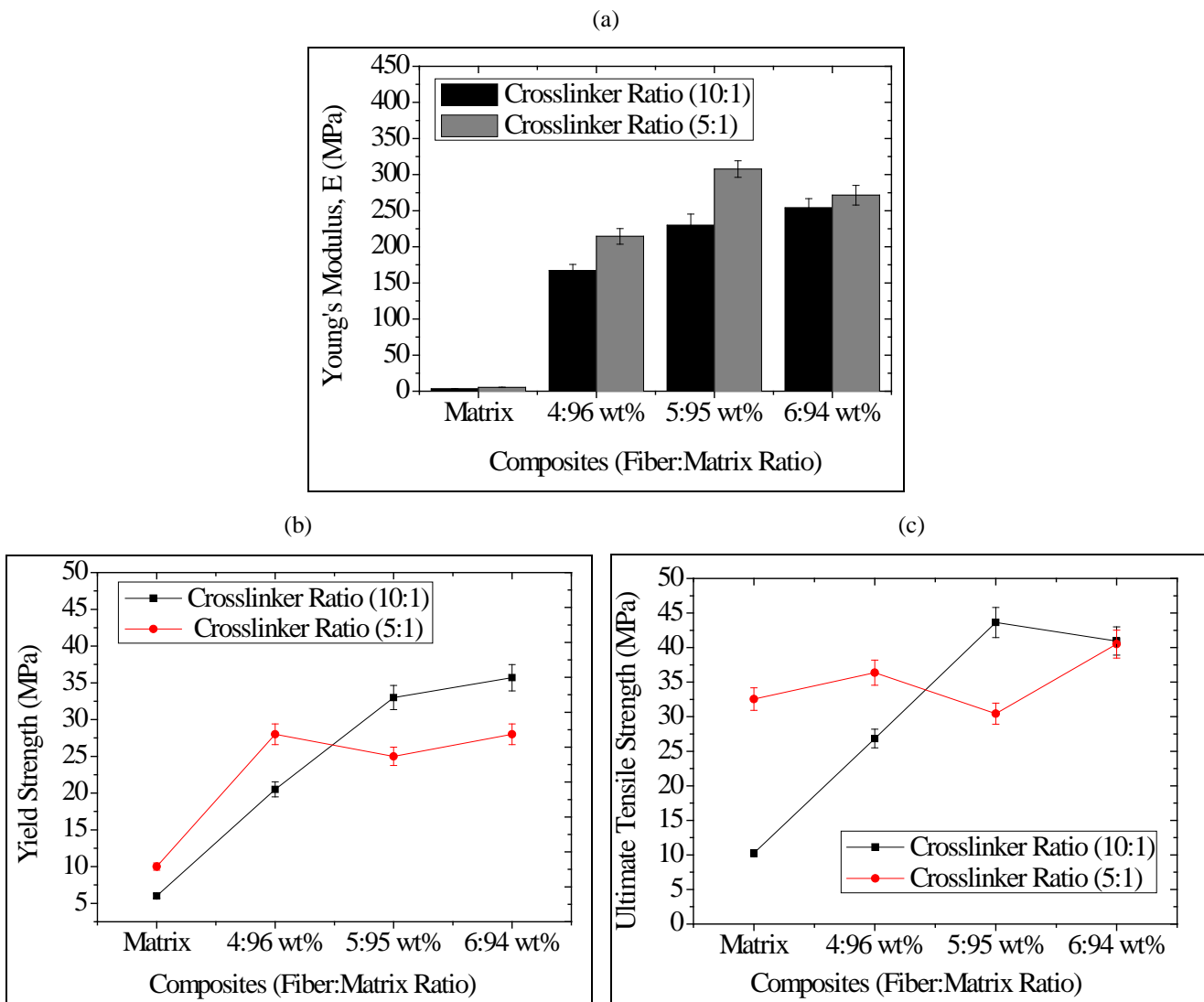
(a)

(b)   (c)

Fig. 7-*Mechanical Properties of PDMS-Based Composites: (a) Young's Modulus of PDMS-Based Composites (MPa), (b) Yield Strength (MPa) and (C) Ultimate Tensile Strength (MPa).*

The modulus of resilience (Ur) (Fig. 8a) and toughness (Ut) (Fig. 8b) described the capacity of the materials (fibers, matrices, and composites) to absorb energy during elastic deformation and then recover upon unloading. Thus, the modulus of resilience is essentially the strain energy per unit volume involved to stress a material from an unloaded state up to the point of yielding. The result (Fig. 8a) indicated that the presence of fiber decreased the modulus of resilience. This is possible because the reinforced materials become stiffer and hence can lead to brittleness as compared to the matrix phase alone. There was a significant effect on the Ur due to crosslinker ratio (Fig. 8a). Ur of 24.27±1.21 MPa was reported for 5:1 as compared to 10.71±0.54 MPa. However, there was no greater effect when the composites were compared. Similarly, Figure 8b showed the effect of fiber fraction as well as crosslinker ratio on the Ut of PDMS-based composites. The Ut of specimens increases to optimum at 5 wt.% of fiber fraction in the PDMS matrix. On average, the Ut of all samples (10:1) reduces at fiber concentration beyond 5 wt.% (with Ut =10.36±0.52 MPa). However, the Ut forthe5:1 began to decrease drastically from 0wt.% fiber fraction (only matrix) at 12.64±0.63 MPa down to 6.15±0.31 MPa and 6.87±0.34 MPa at 5 wt.% and 6 wt.% of fiber fractions, respectively.

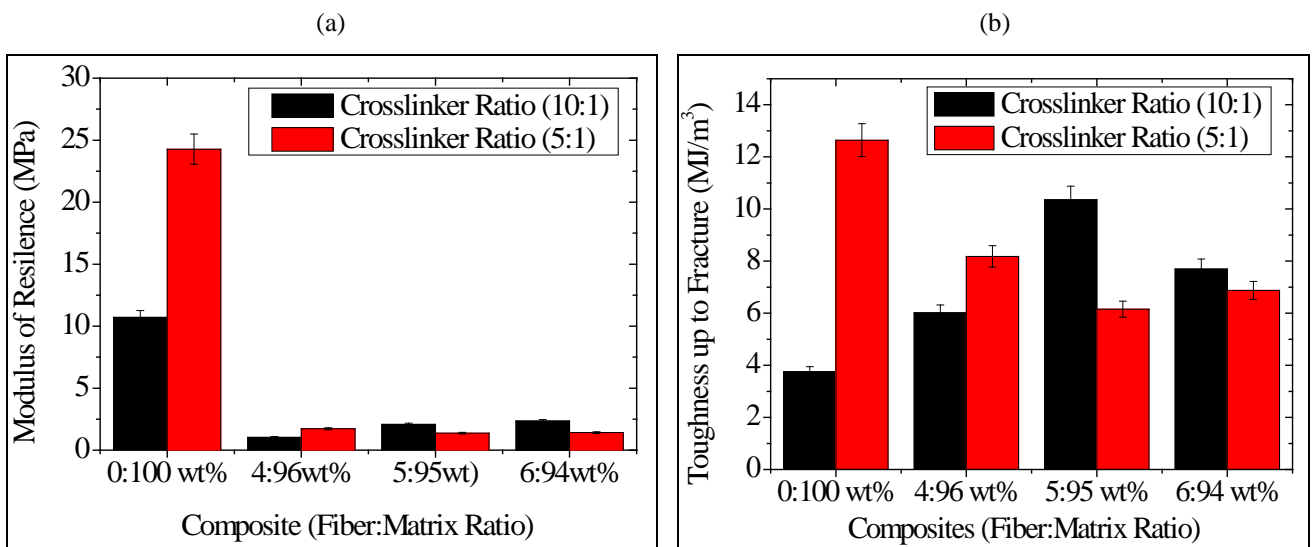(a)   (b)

Fig.8- Toughness: (a) Modulus of Resilience of PDMS-Based Composites and (b) Toughness up to Fracture.

Incorporation of treated banana fibers in PDMS matrix increases the UTS, E, and YS to a greater extent. This is because the fibers increase the stiffness of the composites which cause effective stress transfer from matrix to the interface. The high bonding strength between fiber and matrix was also important. The reduction in the tensile strength, E, Ur or and Ut with increasing fibers fraction is as a result of imperfect interfacial bonding between filler and matrix. Thus, the increase in fiber fraction in PDMS matrices produced stiff composites which later reduce the ductility of the specimens. This is due to the high ratio of fiber-fiber interacting with each other, other than fiber-matrix interaction.
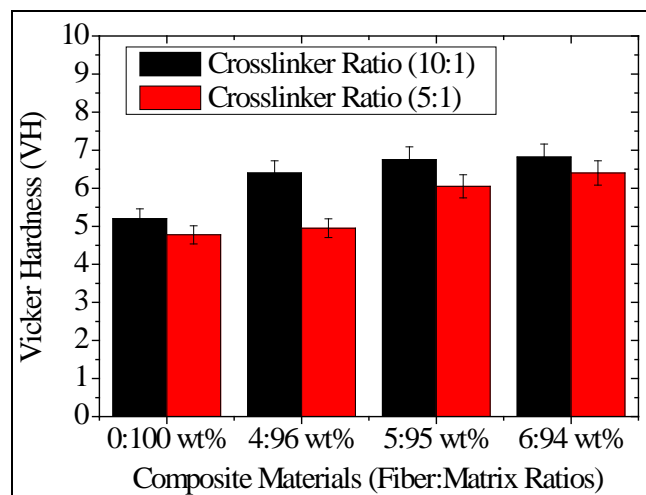

Fig.9 - Vickers Hardness of PDMS-Based Composites.

The Vickers's hardness's of the composites (Fig. 9) were found to steadily increase with increased in fiber weight fraction from 5.2±0.26 VH for PDMS matrix (control sample with no fibers) to an optimum value of 6.82±0.341 VH at 6 wt.% fiber fraction for 10:1 specimen. Though the trend was the same for the 5:1 specimen, however, the hardness values decreased for the 5:1 specimen with 4.8±0.24 VH reported for the control sample and 6.4±0.32 VH was the optimum at 6 wt.% fiber fractions.

From the statistical analysis; the ANOVA test revealed a significant difference between the mean effects of the untreated fibers (control) and that of the different treatment of NaOH on the fiber strength (Table 1a). Thus, a post hoc test was carried out to check the existence of the significant differences between the fiber strength of the untreated and treated NaOH (Table 1b). The post hoc test then revealed there was a significant difference in fiber strength at 0.05.

Table 1a: Fiber Strengths (Mpa)

ANOVA Result	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	103399.279	3	34466.426	11.976	.000
Within Groups	184185.416	64	2877.897		
Total	287584.695	67			

Table 1b: Post Hoc Tests Result on Fiber Strengths (MPa).

Multiple Comparisons

Dependent Variable: Result
LSD

(I) Fiber Strengths (MPa)	(J) Fiber Strengths (MPa)	Mean Difference (I-J)	Std. Error	Sig.	95 % Confidence Interval	
					Lower Bound	Upper Bound
Untreated	NaOH Treated-6 wt%	2.4513	18.4324	0.895	-34.3716	39.2741
	NaOH Treated-8 wt%	-88.7108*	18.6857	0.000	-126.0399	-51.3818
	NaOH Treated-10 wt%	-58.7781*	18.6857	0.003	-96.1072	-21.4491
NaOH Treated-6 wt%	Untreated	-2.4512	18.4324	0.895	-39.274	34.3716
	NaOH Treated-8 wt%	-91.1621*	18.1431	0.000	-127.4071	-54.9171
	NaOH Treated-10 wt%	-61.2294*	18.1431	0.001	-97.4744	-24.9844
NaOH Treated-8 wt%	Untreated	88.7108*	18.6857	0.000	51.3818	126.0399
	NaOH Treated-6 wt%	91.1621*	18.1431	0.000	54.9171	127.4071
	NaOH Treated-10 wt%	29.9327	18.4004	0.109	-6.8264	66.6918
NaOH Treated-10 wt%	Untreated	58.7781*	18.6857	0.003	21.4491	96.1072
	NaOH Treated-6 wt%	61.2294*	18.1431	0.001	24.9844	97.4744
	NaOH Treated-8 wt%	-29.9327	18.4004	0.109	-66.6918	6.8264

*The mean difference is significant at the 0.05 level.

The one-way ANOVA results for 5:1 specimen revealed no significant difference between the mean effects of the different fiber matrix ratios on the composite strength. This implies that the different fiber matrix ratio does not significantly affect the overall composite strength, however, in reality; a slight difference in the composite strength cannot be overlooked (since the composite strength is measured in the orders of 10^6 Pascal). Moreover, the one-way ANOVA test for 10:1 specimens revealed significant differences between the mean effects of the different fiber matrix ratio on the composite strength (Table 2a). This implied that the different fiber-matrix ratio had an effect on the overall composite strength at a significant level of 0.05. A post hoc test was then performed to verify the significant difference between the fiber-matrix ratios. The post hoc test (Table 2b) revealed the mean differences were significant at the 0.05 level.

Table 2a: Composite Strengths (MPa) Control (matrix 10:1)

ANOVA Result	*Sum of Squares*	*Df*	*Mean Square*	*F*	*Sig.*
Between Groups	3189.751	3	1063.250	8.696	.000
Within Groups	7335.995	60	122.267		
Total	10525.747	63			

Table 2b: Post Hoc Tests on Composite Strengths of Composites.

Multiple Comparisons

Dependent Variable: Result
LSD

(II) Composite Strength (MPa)	(J) Composite Strength (MPa)	Mean Difference (I-J)	Std. Error	Sig.	95 % Confidence Interval	
					Lower Bound	Upper Bound
Control (Matrix 10:1)	Fiber:Matrix Ratio (4:96wt%)	-11.6526*	3.9093	0.004	-19.4725	-3.8326
	Fiber:Matrix Ratio (5:95 wt%)	-17.4954*	3.9093	0.000	-25.3154	-9.6755
	Fiber:Matrix Ratio (6:94 wt%)	-17.0816*	3.9093	0.000	-24.9015	-9.2616
Fiber: Matrix Ratio (4:96 wt%)	Control (Matrix 10:1)	11.6526*	3.9093	0.004	3.8326	19.4725
	Fiber:Matrix Ratio (5:95 wt%)	-5.8429	3.9093	0.140	-13.6628	1.9771
	Fiber:Matrix Ratio (6:94 wt%)	-5.4290	3.9093	0.170	-13.2489	2.3909
Fiber: Matrix Ratio (5:95 wt%)	Control (Matrix 10:1)	17.4954*	3.9093	0.000	9.6754	25.3154
	Fiber:Matrix Ratio (4:96 wt%)	5.8429	3.9093	0.916	-1.9771	13.6628
	Fiber:Matrix Ratio (6:94 wt%)	0.4138	3.9093	0.000	-7.4061	8.2337
Fiber: Matrix Ratio (6:94 wt%)	Control (Matrix 10:1)	17.0816*	3.9093	0.170	9.2616	24.9015
	Fiber:Matrix Ratio (4:96 wt%)	5.4290	3.9093	0.916	-2.3909	13.2489
	Fiber:Matrix Ratio (5:95 wt%)	-0.4139	3.9093	0.916	-8.2337	7.4060

*The mean difference is significant at the 0.05 level.

Moreover, the two-way ANOVA revealed that both the composites and the crosslinker ratio have no significant effect on the toughness (up to fracture). This implies that the cross-linking ratio does not significantly affect the toughness of the resulting composite, although, in reality, a slight difference in the toughness of the composite is really big (order of 10^6 Pascal). However, the two-way ANOVA revealed that the composite had a significant effect on the stiffness (Table 3a), while the crosslinker ratio had no significant effect. Thus, a post hoc test was carried out to test the significant difference between the mean effects of the composites.

Table 3a: Two Way Analysis of Variance Copy of Effects of Crosslinker Ratio on Toughness Up to Fracture

Tests of Between-Subjects Effects
Dependent Variable: Results

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	482.236[a]	5	96.447	6.232	.081
Composites	2.187	3	.729	.047	.984
Crosslinker Ratio	4.541	1	4.541	.293	.626
Error	46.430	3	15.477		
Total	528.666	8			

[a] R Squared = .912 (Adjusted R Squared = .766)

Two-way ANOVA test revealed the effect of fiber weight fraction on the stiffness of the composite with great significant differences (Table 4a). However, there was no significant difference with crosslinker ratio on the stiffness of the composite. Similarly, post hoc test determined the significant difference between the mean effects of the composite's stiffness due to fiber weight fraction (Table 4b).

Test for the significant difference on; the modulus of resilience (Table 5a), ultimate tensile strength (Table 5b), and yield strength (Table 5c) due to polymer cross-linked ratio are presented (Table 5a). However, one-way ANOVA result indicated no significant difference between the mean effects of the different fiber-matrix ratios on the composite strength. However, a slight difference in the composite strength cannot be overlooked since the composite strengths are measured in the orders of 10^6 Pascal. Similarly, two-way ANOVA results showed that both the composites and the crosslinker ratio had no significant effect on the modulus of resilience, the ultimate tensile strength (Table 5b) and the yield strength (Table 5c).

Table 4a: Copy of Significant Difference in Stiffness Due to Crosslinker Ratio on Composites

Tests of Between-Subjects Effects
Dependent Variable: Results

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	364534.578[a]	5	72906.916	237.587	.000
Composites	92432.897	3	30810.966	100.406	.002
Crosslinker Ratio	1.037	1	1.037	.003	.957
Error	920.591	3	306.864		
Total	365455.170	8			

[a] R Squared = .997 (Adjusted R Squared = .993)

Based on observed means. The error term is Mean Square (Error) = 306.864. *The mean difference is significant at the 0.05 level.

Table 4b: Post Hoc Tests on the Significant Difference in Stiffness Due to Crosslinker Ratio.

Multiple Comparisons (10:1)
Dependent Variable: Result
LSD

(I) Composite Stiffness (MPa)	(J) Composite Stiffness (MPa)	Mean Difference (I-J)	Std. Error	Sig.	95 % Confidence Interval	
					Lower Bound	Upper Bound
Control (Matrix)	Fiber:Matrix (4:96 wt%)	213.2800*	17.5175	0.001	-269.0286	-157.5314
	Fiber:Matrix (5:95 wt%)	-243.9800*	17.5175	0.001	-299.7286	-188.2314
	Fiber:Matrix (6:94 wt%)	-272.9600*	17.5175	0.001	-328.7085	-217.2114
Fiber:Matrix Ratio (4:96 wt%)	Control (Matrix)	-213.2800*	17.5175	0.001	157.5314	269.026
	Fiber:Matrix (5:95 wt%)	-30.7000	17.5175	0.178	-86.4486	25.0486
	Fiber:Matrix (6:94 wt%)	-59.6800*	17.5175	0.042	-115.4286	-3.9314
Fiber:Matrix Ratio (5:95 wt%)	Control (Matrix 10:1)	243.9800*	17.5175	0.001	188.2314	299.7286
	Fiber:Matrix (4:96 wt%)	30.7000	17.5175	0.178	-25.0486	86.4486
	Fiber:Matrix (6:94 wt%)	-28.9800	17.5175	0.197	-84.7286	26.7686
Fiber:Matrix Ratio (6:94 wt%)	Control (Matrix 10:1)	272.9600*	17.5175	0.001	217.2114	328.7086
	Fiber:Matrix (4:96 wt%)	59.6800*	17.5175	0.420	3.9314	115.4286
	Fiber:Matrix (5:95 wt%)	28.9800	17.5175	0.197	-26.7686	84.7286

Table 5a: Copy of Test for Significant Difference on Modulus of Resilience Due to Crosslinker Ratio on Composites

Tests of Between-Subjects Effects
Dependent Variable: Results

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	648.641[a]	5	129.728	5.334	.099
Composites	376.352	3	125.451	5.158	.106
Crosslinker Ratio	19.861	1	19.861	.817	.433
Error	72.965	3	24.322		
Total	721.606	8			

[a] R Squared = .899 (Adjusted R Squared = .730)

Table 5b: Copy of Test for Significant Difference on Ultimate Tensile Strength Due to Crosslinker Ratio on Composites

Tests of Between-Subjects Effects
Dependent Variable: Vickers hardness

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	284.587[a]	5	56.917	483.020	.000
Composites	3.272	3	1.091	9.256	.050
Crosslinker	1.121	1	1.121	9.515	.054
Error	.354	3	.118		
Total	284.941	8			

[a] R Squared = .999 (Adjusted R Squared = .997)

Table 5c: Copy of Test for Significant Difference on Yield Strength Due to Crosslinker Ratio on Composites.

Tests of Between-Subjects Effects
Dependent Variable: Results

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	9014.792[a]	5	1802.958	15.927	.023
Composites	424.389	3	141.463	1.250	.429
Crosslinker Ratio	41.314	1	41.314	.365	.588
Error	339.608	3	113.203		
Total	9354.400	8			

[a] R Squared = .964 (Adjusted R Squared = .903)

The rule of mixture applied during the design of the PDMS-based composites shows that incorporating stiff and strong banana fibers would provide higher moduli and strength to the PDMS matrix. From the mechanical results reported, the optimized mechanical properties such as moduli, hardness, toughness, and strengths can be investigated by varying the weight fraction of the reinforced fibers. It was observed that mixing PDMS and banana fibers above 6 wt.% was almost not feasible due to higher viscosities experienced during mixing, especially with increasing fiber weight fraction. The increase in polymer viscosity makes it very difficult to ensure homogeneity as the weight fraction of the reinforcements is increased beyond 5 wt.%. Two-way analysis of variance test performed to test the significance different the Vickers hardness of PDMS-based composites at different crosslinker ratio is presented (Table 6).

Table 6: Two-Way Analysis of Variance Test Performed to Test the Significance of the Different Composites and Crosslinker Ratio on the Vickers Hardness.

Tests of Between-Subjects Effects
Dependent Variable: Results

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Model	5017.175[a]	5	1003.435	31.500	.009
Composites	681.165	3	227.055	7.128	.070
Crosslinker Ratio	2.205	1	2.205	.069	.810
Error	95.565	3	31.855		
Total	5112.740	8			

[a] R Squared = .981 (Adjusted R Squared = .950)

4 Concluding Remarks

Chemically treated fibers improved the mechanical properties of the banana fibers which then increased the ultimate tensile strength, yield strength, Young's modulus and Vickers hardness of the composites.

The toughness values reported shows the ability of the composite materials to sustain sufficient loadup to the points of fracture. Specimen geometries, as well as the manner of load application, are important in toughness determinations. In other to avoid any disparity in results, similar geometries were used to fabricate samples with the aid of the molds. Loading rates were also maintained for each sample under the tensile stress-strain test analysis. The tough specimens display good strength and ductility. The tougher specimens were optimized with the samples reinforced with 5 wt% fiber fractions. Thus, for a material to be tough, it must display both strength and ductility. Most often, ductile materials are tougher than brittle ones. This explained why the toughness reduced with increasing amount of fiber weight fraction above 5 wt%. Though the fibers embed provided stiffness, higher fiber ratio caused fiber-fiber interaction instead of more fiber-matrix interaction. Hence, reduces the overall toughness of the composites.

From the statistical analysis; there was significant difference between the mean effects of the untreated fibers with respect to the different treatments of NaOH concentrations on the fiber strength (Table 1a). Post hoc test was then carried out to ascertain the existence of the significant differences between the fiber strength of the untreated and that of the NaOH treated fibers (Table 1b).

Moreover, one-way ANOVA test for 10:1 specimen revealed the existence of significant differences between the mean effects of the different fiber-matrix ratios on the composite strength (Table 2b). This confirmed the significant effect of the different fiber-matrix ratios on the composite strengths at a significant level of 0.05. The significant difference between the fiber-matrix ratios was then cross-checked with the post hoc test (Table 2c).

Also, two-way ANOVA test revealed a significant effect of fiber weight fraction on the stiffness of the composite (Table 4b), while the crosslinker ratio had no significant effect on composite stiffness. Similarly, post hoc test determined the significant difference between the mean effects of the composites stiffness due to fiber weight fraction (Table 4b). However, one-way ANOVA results for 5:1 specimen indicated no significant difference between the mean effects of the different fiber-matrix ratios on the composite strength. This implies that the different fiber matrix ratio does not significantly affect the overall composite strength. Meanwhile, in reality; a slight difference in the composite strength cannot be overlooked. This is because the composite strengths are measured in the orders of 10^6 Pascal. Similarly, two-way ANOVA results showed that both the composites and the crosslinker ratio had no significant effect on the modulus of resilience, the ultimate tensile strength, and the yield strength.

In polymer matrix composites such as PDMS, a load applied on the matrix are usually transmitted to the incorporated fibers (strong and stiff) by shear stresses, in which case the fibers supports a greater part of the load than the matrix. Hence, the maximum loads sustained by polymer matrix composites are usually attributed to the fibers. This was similarly reported for polymer matrix composites especially those with observed low matrix strengths and moduli [32]. Hence, fiber properties

can have great effects on the composite properties, while the matrix serves as a binder to ensure fibers do not interact directly. Hence, fiber-matrix bonding then enables the transmission of stresses between the matrix and fibers by shear.

The results show that chemically modified natural fibers such as banana fibers can find an application in toughening soft polymers such as elastomeric PDMS to find applications where toughness and crack growth resistance could be offered. However, the selected PDMS composite must have a balance of strength, stiffness, toughness, and resistance to any environmental effect. The study thus, agreed that composite materials play major roles in most engineering applications due to their enhanced strength and modulus. The properties measured were greatly affected by the fiber weight fraction with optimized properties obtained at fiber content of 8 wt%, while a similar result was obtained in recent studies on polyethylene matrix with 10 wt% [35].

The ultimate tensile strengths of banana fibers have been reported to be within 54-754 MPa [36]. The current work agreed with this study in terms of the ultimate tensile strength of treated banana fibers (at 8 wt% NaOH), which was obtained to be 270 MPa. The ultimate tensile strength of banana fiber epoxy-based composite was reported to be 112.58 MPa (at 50-50 wt% ratios) [37], while an ultimate tensile strength of 43.63 MPa was reported in the current study at 92-8 wt% of matrix-to-fibers ratio when reinforced with PDMS. This great difference is attributed to the stiff nature of a cured epoxy (3-6 GPa) [38] as well as the higher ratio of fibers incorporated in the former report as compared to the soft nature of PDMS (which is an elastomer) with elastic modulus less than 5 MPa. Effort by Namdari and Rizvi (2018) [39], investigated PDMS-based composites reinforced with metal fibers with the aim of manipulating its surface texture and functionality. Though this sounds great, it was still not conclusive to compare the result since the PDMS-composite then was formed with metal fibers. However, future work would seek to investigate the effect of using different natural fibers on a common matrix. This is currently outside the scope of the current paper.

The backbone of PDMS offers a siloxane bonds (-Si-O-Si), which are very stable with a binding energy of 433 KJ/mol. PDMS (a silicon rubber) thus exhibits higher heat resistance as well as maintain chemical stability. This makes it a preferred material for electrical insulation instead of organic polymers [39]. The hydrophobic nature of PDMS therefore provides protection for the fibers against water. The outside coil structure of PDMS is made of methyl groups which offer free mobility (rotation) and hence provide distinct interfacial properties, good flexibility and above all offers sufficient environmental protections to embedded fibers.

Acknowledgments

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