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RESEARCH ARTICLE

Leucaena-Silicone Biocomposite: Experimentation, Quantification and Prediction of Mechanical Properties for Potential Applications in Medicine and Healthcare

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ABSTRACT – Silicone rubber, in general, possesses super soft physical behavior, which is not suitable for structural applications. Therefore, this study aims to introduce an innovative biocomposite material combining Leucaena and Silicone, named LeuSiC, to establish its physical and mechanical properties for possible medical applications. Various Leucaena fiber compositions ranging from 0 wt% to 16 wt% were mixed with pure silicone rubber, where density, compression set, and uniaxial tensile behavior were experimentally investigated following ASTM standards. The Ogden hyperelastic constitutive was employed to quantify the tensile behavior of LeuSiC via material constants, μ and material exponent, α. Additionally, the tensile properties of LeuSiC were also predicted using Artificial Neural Network (ANN). The results revealed that the material constants, μ value, increased with higher Leucaena fiber composition, indicating stiffness increment. In contrast, increasing fiber composition reduced the tensile strength and flexibility of LeuSiC. In terms of prediction using ANN, the results proved the capability of the constructed neural network model, where the error was less than 0.4%. The quantified and predicted properties of μ and α range from 5.4 to 55.9 kPa and 2.16 to 3.0 respectively, suggest that LeuSiC has the potential to mimic and be made into synthetic connective tissues.

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1. INTRODUCTION

Silicone rubber is recognized for its noteworthy features, such as being biocompatible, resistant to rust, stable in heat, adaptable to different climates, has smooth surfaces and can allow substances to permeate through its unique structure made of polysiloxane [1]. Additionally, silicone rubber is made up of molecular chains with siloxane bonds (Si-O), which gives superior properties compared to other natural rubbers, specifically by its ability to withstand heat, stable chemically and possesses electrical conductivity [2]. Other than that, silicone is also known for its ability to insulate electricity and allow light to pass through [3]. It can withstand both high and low temperatures and exposure to various chemicals. Additionally, silicone does not have any adverse reaction with biological tissues, which makes it safe for use in medical applications [4]. Despite its advantages, silicone rubber's main drawback is its weak bonds between polymer chains, which affect its strength and possible applications. Researchers have put considerable effort in improving silicone rubber's strength, with various studies focusing on methods like integrating cellulose fiber to strengthen the silicone structure [5]. Furthermore, it shares similarities with natural rubber (NR), which is extensively used in a variety of products, including rubber bands, gloves and condoms, because of its outstanding properties in terms of elasticity, strength and resistance to many corrosive substances [6].

Composite materials are developed to enhance the performance of the original individual materials [7]. Two parts are typically involved, which are the matrix and reinforcing components. Composites consisting of synthetic resin and natural reinforcing materials have gained popularity in recent times [8]–[10]. Recently, researchers have been paying more attention to natural fibers because they have the potential to reinforce materials, and synthetic fibers can be expensive. Natural fibers come from plants or animals, which means they can be easily found and are environmental friendly in contrast to synthetic fibers [11]. Natural fibers have been increasingly chosen as a component in composites because they can compete with other materials based on their strength relative to their weight. Although natural fibers may not match synthetic fibers in mechanical strength, they offer several advantages, such as their vast availability, lower density and cost, and higher modulus [12]. Thus, using natural fibers in composite materials can help decrease reliance on non-renewable resources. Additionally, natural fibers are more cost-effective than conventional reinforcing fibers such as glass and carbon [13].

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In this study, Leucaena was selected as the natural fiber due to its potential as a green material functioning as a biofiller. Leucaena leucocephala, also known as the white leadtree, is a rapid-growing tree found in the Fabaceae lineage and native to Central and South America. It is commonly seen across tropical and subtropical regions globally. Leucaena leucocephala, known locally as ‘Petai Belalang’, has impressed many with its high-density wood production, rapid growth, and strong adaptability [14]. Leucaena is capable of growing up to 20 meters tall, accessing nutrients and water through its deep roots. Its leaves are rich in protein, making them valuable as livestock feed, and its nitrogen-fixing ability enhances soil fertility, acting as green manure. Leucaena is remarkably resistant to drought and can endure dry spells for up to 7 months, though growth may slow in low-humidity conditions [15]. A recent study has determined the use of Leucaena leucocephala as a suitable substitute in the production of particleboards [16]. Its widespread availability, cost-effectiveness, and environmentally friendly nature make it a desirable choice for countless products, ranging from automotive to construction industries and, in this case, its potential use as a component in biocomposite for potential synthetic skin.

Previous studies have attempted to address the weak mechanical and structural properties of silicone rubber by incorporating various reinforcing materials, such as cellulose fibers, to improve silicone’s mechanical properties. Natural fiber-reinforced composites have gained attention due to their sustainability, cost-effectiveness and potential to enhance the material performance [17]-[18]. Despite these advancements, there remains a lack of research exploring the integration of Leucaena fiber into silicone-based biocomposites. Studies have primarily focused on other natural fibers like bamboo, coir and kenaf, leaving a gap in understanding the potential of Leucaena as a reinforcing agent. Additionally, while artificial neural networks (ANN) have been used to predict the properties of conventional composites [19]-[20], their application in modeling the mechanical behavior of Leucaena-silicone biocomposites is still underexplored.

To bridge this research gap, the present study introduces a new biocomposite material named LeuSiC, which combines Leucaena fibers with silicone to enhance the physical and mechanical properties of potential biomedical applications. The research aims to experimentally determine the physical and mechanical characteristics of this biocomposite and provide a better understanding of Leucaena-silicone biocomposites. Additionally, the use of ANN models in predicting material properties, specifically for the newly developed LeuSiC biomaterial, is introduced and discussed. By doing so, this study provides insights into the potential applications of LeuSiC in biomedical engineering, particularly in synthetic connective tissue development. The remaining sections of the paper are organized as follows: Section 2 presents the materials and methods used for fabricating Leucaena-silicone biocomposite materials, including experimental investigations of their physical and mechanical properties and the prediction of material properties using ANN models. Section 3 presents the results and discussion. Finally, Section 4 summarizes the conclusions and key findings of the study.

2. MATERIALS AND METHODS

2.1 Leucaena-Silicone Biocomposite Fabrication

The silicone used in this study was Ecoflex 00-30, a two-part formulation consisting of a base (Type A) and a hardener (Type B), which was mixed in a ratio of 1:1. Density measurements for both the silicone rubber and Leucaena fibers were conducted using a Micromeritics pycnometer (AccuPyc II 1340, U.S.A., 2013).

Table 1. Measurement of weightage for each leucaena-silicone biocomposite sample

Volume of Mold (cm^3)	Weight Percentage	Leucaena Fiber (g)	Silicone Rubber (cm^3)	
			Type A	Type B
Density test				
1.2 cm^3	0%	0	0.600	0.600
	4%	0.07056	0.576	0.576
	8%	0.14112	0.552	0.552
	12%	0.21168	0.528	0.528
	16%	0.28224	0.504	0.504
Uniaxial Tensile Test				
6 cm^3	0%	0	3.000	3.000
	4%	0.3528	2.880	2.880
	8%	0.7056	2.760	2.760
	12%	1.0584	2.640	2.640
	16%	1.4112	2.520	2.520
Compression Set Test				
8.521 cm^3	0%	0	4.260	4.260
	4%	0.5010	4.090	4.090
	8%	1.0020	3.920	3.920
	12%	1.5030	3.749	3.749
	16%	2.0040	3.579	3.579

The Leucaena fibers were obtained from locally cultivated Leucaena trees at the university farm in Jengka, Pahang. Leucaena preparation involves several steps, starting with trimming the stems and removing the bark. The trimmed Leucaena stems were first air-dried, followed by oven-drying at 100°C for 24 hours. After drying, the Leucaena was crushed into chips and further processed with a milling machine to produce a fine powder. The powdered Leucaena underwent milling multiple times and was finally sieved to achieve uniform particles sized at 100 µm. In this study, compositions with 0wt%, 4wt%, 8wt%, 10wt%, 12wt%, and 16wt% of Leucaena fiber content, relative to the total weight of the composite, were produced by obtaining the mass required and the density of leucaena fibers of 1.47g/cm^3. An electronic balance (Mettler Toledo, AG245, ±0.03 mg) was used to measure fiber weight. The process involved careful control to ensure accurate proportions of the fiber weight and precise formulation of the fiber-matrix mixture. The fiber was then mixed with a silicone rubber matrix in a cup, and the solution was transferred into the density mold, compression mold and tensile mold according to each ASTM standard. Finally, the mixture in the molds was cured for 4 hours at ambient conditions. A total of 75 specimens were produced for testing, with 25 specimens allocated for the density test, 25 for the tensile test and another 25 for the compression test. Table 1 shows the weightage compositions of each sample.

2.2 Physical and Mechanical Properties

2.2.1 Density measurements

Density testing was conducted in accordance with ASTM D792 - Test Method A, a standard procedure for evaluating solid plastics in water [21]. This method facilitates the comparison of plastic sample consistency by analyzing physical changes during immersion. Distilled water was used for immersion during the test. The Specific Gravity Measuring Kit (AD-1653, Japan) was utilized to conduct the investigation. Eq. (1) was used to find the density of each specimen. Figure 1 illustrates the dimensions of the specimen mold of 20 mm x 20 mm x 3 mm. A total of 25 specimens were made for testing, with 5 samples in each set.

$$\rho = \frac{\mathrm{A}}{\mathrm{A}-\mathrm{B}} \times (\rho_o - d) + d \tag{1}$$

ρ represents the density of the specimens, ρ_o represents the density of water (0.99651 g/cm^3), d represents the density of air (0.001 g/cm3), while A and B represent the weight of the specimen in air and water, respectively.

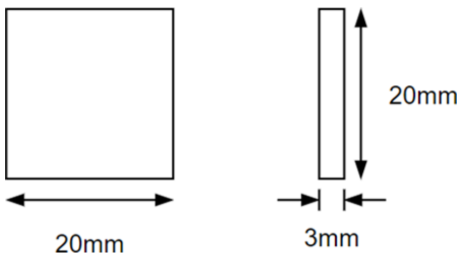

Figure 1. Dimension for specimens undergoing density test following the ASTM D792 standard

2.2.2 Uniaxial tensile test

The tensile test followed the specific guidelines set by ASTM standard ASTM D412 [22]. Figure 2 illustrates the dimensions of the specimens used for testing. Each specimen underwent testing using the SHIMADZU AG-IS 50kN Universal Testing Machine. The Universal Testing Machine had standard crosshead and load cell accessories, and a speed of 500mm/min was maintained. The accessories included the SHIMADZU SFL-50KNAG Code B with CAL cable. Measurement accuracy was maintained at Standard-Precision Type (1/500, ±1%). The precision was within ±1% of the specified test force. The accuracy range was applicable within the 1/500 to 1/1 load cell rating.

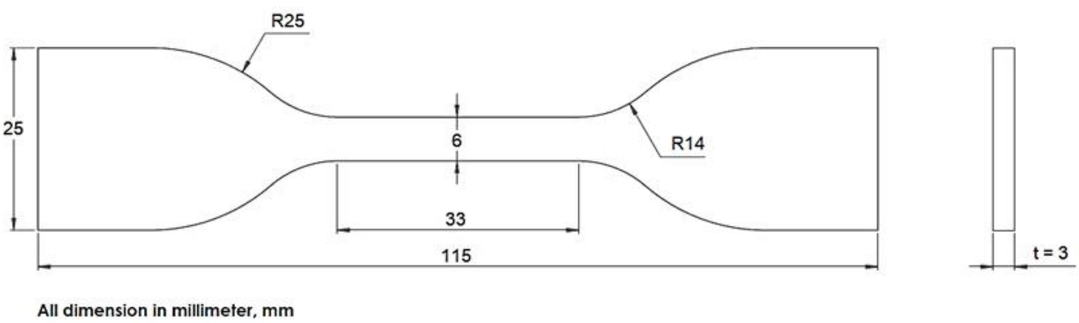

Figure 2. Dimension of the specimens following ASTM D412

2.2.3 Compression set test

The compression test for the Leucaena-silicone biocomposite was conducted according to the ASTM D395 standard [23]. Soft specimens in Figure 3 were shaped into cylinders, measuring 12.9 mm thick and 29 mm in diameter. Following the ASTM D395 standard, the specimens were compressed to 25% of their original thickness. Compression set values were calculated using Eq. (2). The specimens underwent compression for 22 hours at ambient conditions. Thickness measurements were taken before, during, and after 30 minutes of the compression test.

$$C = \frac{t_o - t_i}{t_o - t_n} \times 100\% \tag{2}$$

Based on the equation above, C represents the compression test values, t_o is the initial thickness of the specimen, t_i represents the final thickness of the specimen after testing and t_n is the thickness of the specimen during testing.

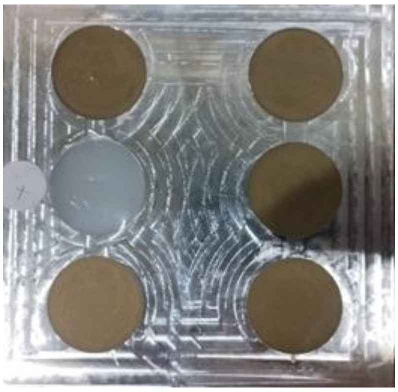

Figure 3. Sample image of the specimens poured into the mold for compression testing following ASTM D395 standard

2.3 Leucaena-Silicone Biocomposite Fabrication

2.3.1 Investigation of deformation behavior of the specimens based on the Ogden hyperelastic model

As the composites exhibited soft and highly elastic characteristics akin to rubbery materials, they were treated as hyperelastic materials in this study. The stress-stretch relationship was modeled using a hyperelastic constitutive model. Specifically, the Ogden hyperelastic model was applied to depict the deformation behavior of the biocomposite material specimens. The Ogden hyperelastic model is shown in Eq. (3) with the assumption that the materials are hyperelastic, isotropic and incompressible [24].

$$\sigma_E = \frac{\mu}{\lambda}\left(\lambda^{\alpha} - \lambda^{-\frac{\alpha}{2}}\right) \tag{3}$$

In this context, σ_E denotes the engineering stress (in MPa), α and μ represent the material constant (in MPa) that stands for stretch ratio, and ε indicates strain (in m/m). Equation 3 expresses the association between engineering stress and stretch ($\sigma_E - \lambda$). The engineering stress-strain ($\sigma_E - \varepsilon$) data acquired was then altered to engineering stress–stretch ($\sigma_E - \lambda$) relation using Eq. (4) [25].

$$\lambda = 1 + \varepsilon \tag{4}$$

Finally, a curve fitting technique was conducted using the engineering stress and stretch data points from the investigation to find the best curve that corresponds to the data as based on Eq. 4. These matching curves help to depict the mechanical properties of the materials effectively through material constant parameters. Validated data sets were used to establish engineering stress-stretch data sets and determine Ogden material constants, μ and material exponent, α for the Leucaena-Silicone biocomposites. The curve-fitting technique was then obtained using the Solver Tool in Microsoft Excel to determine the values of material constants, μ and exponent, α. These values represent the obtained elastic properties that demonstrate the nonlinear behavior of the silicone biocomposites. The stress-stretch curves for the Leucaena-Silicone biocomposites were then plotted based on the determined μ and α values, illustrating their tensile properties and hyperelastic behavior.

2.3.2 Prediction of the hyperelastic Ogden material constant using ANN

For the prediction of hyperelastic Ogden material constant, the properties used are outlined in Table 2. The ANN model developed for this purpose was made up by fully connected layers, including one input and output layer and two hidden layers. The training function utilized the Levenberg–Marquardt backpropagation algorithm, and the Tansig neural transfer function was used as the activation function of the hyperbolic tangent sigmoid transfer function. Figure 4 shows the Network window created after all values were inserted, as shown in Table 2. The network was trained with 44 sets of data and 8 sets of data for network validation. The three inputs were represented by weightage, load and elongation. Meanwhile, the two outputs obtained were material constant μ and α.

Table 2. Properties and parameters for the present ANN model

Parameter	Value
Input data	3
Target data	2
Network Type	Cascade-forward backdrop
Number of Layers	2
Number of Neurons	8
Activation Function	Transig
Network	Network1

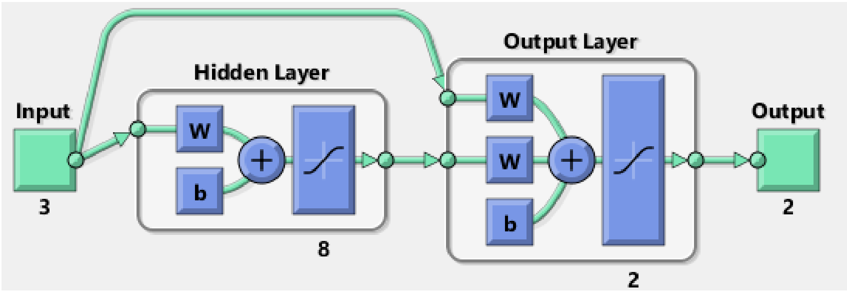

Figure 4. The model network diagram for prediction and validation of the network

3. RESULTS AND DISCUSSION

3.1 Density of the Leucaena-Silicone Biocomposite

The average density for different filler compositions was obtained, as shown in Figure 5. These values were calculated using Eq. 1 and evaluated against the density of the Leucaena filler. Pure silicone rubber specimens (0wt%) had the lowest density at approximately 1.0243 g/cm3. The insert in Figure 5 shows a clear trend where the density values increased with higher filler content. Incorporating Leucaena filler influenced the silicone rubber's density, leading to an increase with greater filler loading. Sanyang et al. [26] discovered that the density of sugar palm starch/polylactic acid bilayer films rose notably to 1.35 g/cm3 with loadings of up to 80wt%. Similarly, [27] observed a similar trend when glass fiber was incorporated with Arenga pinnata fiber reinforced epoxy composite, resulting in a density increase of up to 1.4 g/cm3. In this study, the addition of 16wt% filler was nearly saturated, indicating that the biocomposite material had the highest density value. However, this density was still considerably lower compared to the densities presented by [28], [29].

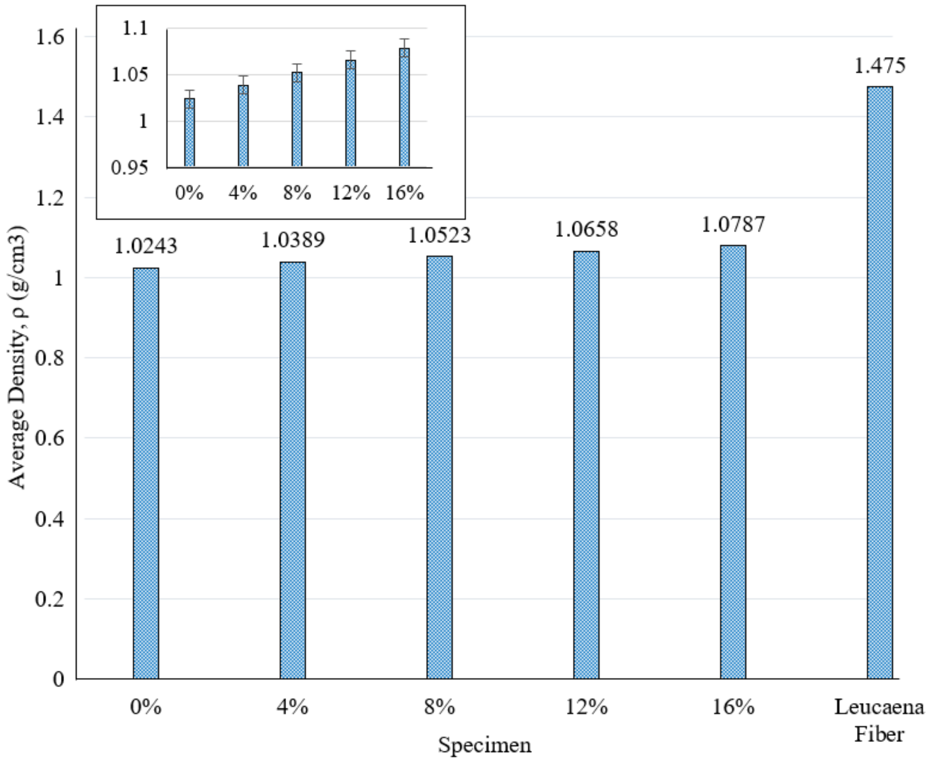

Figure 5. Average density values for various specimens with different compositions in comparison to Leucaena fiber. The small figure focuses on LeuSiC and the respective error bar, highlighting the increasing trend

The increasing density with filler content trend aligns well with the principle that introducing solid fillers into a polymer matrix typically increases the composite's overall density due to the higher density of the filler compared to the based material [30]. The increase in density also suggests improved packing efficiency within the matrix, leading to reduced void content and better fiber-matrix interaction [31]. However, it is important to note that excessive filler loading can lead to agglomeration, which may introduce structural inhomogeneities and impact other mechanical properties.

3.2 Tensile Properties of the Leucaena-Silicone Biocomposite

Figure 6 shows different data for various fiber compositions under the uniaxial tensile test. Adding Leucaena filler to silicone rubber greatly improves its elastic response for both small and large stretches. The curve becomes more linear as the Leucaena fiber content increases. Pure silicone rubber (0wt%) exhibits the most noticeable nonlinear elastic curve compared to other compositions. Pure silicone rubber stretches quickly, even under relatively light loads of tension, leading to greater elongation than mixed compositions. The gradient of the curve increases steadily with more fibers added to the composite, indicating increased stiffness.

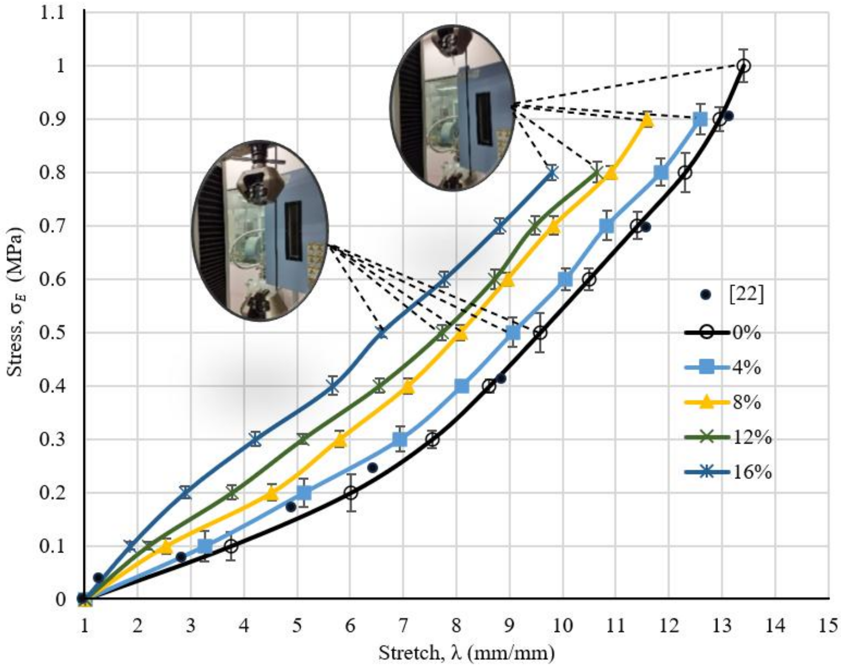

Figure 6. A graph comparing the engineering stress against the stretch ratio for the leucaena-silicone biocomposite samples

The results indicate that increasing the Leucaena fiber content enhances the stiffness of the biocomposite, as evidenced by the steeper stress strain curves in Figure 6. This is consistent with the classical composite theory, which states that the modulus of elasticity increases with filler content due to the higher stiffness of reinforcing fibers compared to the polymer matrix. It is concluded that the presence of Leucaena fiber in the composite contributes to its resistance against deformation during tensile loading. However, a trade-off was observed in terms of tensile strength and flexibility. While Leucaena fibers contributed to the stiffness of the composite, they also restricted polymer chain mobility, leading to a decrease in elongation at break. This trend is supported by studies of fiber-reinforced elastomers, where the reinforcement phase acts as a stress concentrator and reduces the overall ductility of the material [28].

The study by Bahrain et al. [29] similarly reported a comparable trend, observing a reduction in tensile strength with the increase of Arenga Pinnata fiber content in silicone rubber. This is because silicone polymer chains typically display weak intermolecular interactions, leading to reduced mechanical strength, but the addition of filler or fiber inhibits the movement of these chains by occupying the spaces between them. Besides that, Azmi et al. [7] recorded similar trends in which the ES powder increases as the tensile strength decreases. This is suggested to occur due to the resistance to deformation from the filler in the composite, as it is difficult to shift alongside the polymer chains, making it stiffer.

Qualitatively, the graph for pure silicone obtained in the current study is closely similar to the graph for pure silicone presented by Bahrain et al. [29], as shown in Figure 6. The average percentage difference was found to be less than 5%, validating the reliability of the current experimental data. In addition, to validate the tensile properties measured in this study, the results were compared with those from other studies that have measured the tensile properties of the same pure silicone (Ecoflex 00-30 Platinum Cure Silicone Rubber). The percentage difference in tensile properties is presented in Table 3. In all cases, the percentage difference is approximately 5%, proving that the experimental results of the current study are acceptable.

Table 3. Comparison of tensile stiffness of pure (0 wt%) Silicone 00-30 Platinum Cure with previous studies

Authors	Tensile Stiffness (kPa)	Percentage Difference (%)
Current study	30.30	-
Othman et al. [25]	31.7	4.52
Noor et al. [32]	32.0	5.46

3.3 Quantification of Tensile Properties α and μ Based on Experiments and Numerical Analysis

The Ogden constitutive equation was used to determine the material constant for both pure silicone and the Leucaena-silicone biocomposite. This equation helps to represent the nonlinear behavior of these materials. Values of the Ogden material constant, μ and α, are recorded in Table 3.

Table 3. Tensile properties obtained via Ogden constitutive equation

Fiber weightage composition	Ogden (kPa)	
	μ	α
0 wt%	5.4	3.0051
4 wt%	9.5	2.7956
8 wt%	18.9	2.5748
12 wt%	32.0	2.3606
16 wt%	55.9	2.1624

For application purposes, Table 4 shows the measured material coefficient and exponent, μ and α of the Leucaena-silicone biocomposite in comparison to the properties of other materials and organs presented by other studies. It is important to note that pure silicone exhibits low tensile stiffness (very weak), making it unsuitable for many applications. Therefore, this study has reinforced silicone rubber with various weight percentages of Leucaena fiber to enhance its tensile stiffness. As demonstrated in Table 4, the material constants, μ and α, of the newly developed Leucaena-silicone biocomposite fall within the suitable range for several potential medical applications, i.e., synthetic connective tissue and synthetic skins.

Table 4. Material constants α and μ for potential application

Material Constant		Material Type	Reference
μ (kPa)	α		
5.4	3	Pure silicone	Current study
9.5 to 55.9	2.16 to 2.79	Leucaena-Silicone Biocomposite	Current study
10	26	Human Skin	[33]
11	9	Human Skin	[34]
153 to 180	15.15 to 18.34	Fresh Goat Skin (unshaved)	[35]
185	41	Connective tissue	[36]
400	12	Pig skin	[34]
400 to 7500	12	Porcine skin	[37]
1827	15.89	Goat leather	[35]
2100 to 8000	2.5	Silicone Rubber (Sil8800)	[38]
3500	14.82	Bovine leather	[35]

Based on Tables 3 and 4, the results show that μ, which represents the material stiffness, increased with fiber content, ranging from 5.4kPa for pure silicone to 55.9kPa at 16wt% fiber composition. Conversely, the exponent α decreased with the increase of fiber content, suggesting a shift from highly nonlinear hyperelastic behavior towards a more linear elastic response. These findings align with existing literature on rubber composites, where the increased filler content leads to higher stiffness but reduced strain energy storage capacity [39]. The observed decrease in α indicates that the biocomposite becomes less strain-sensitive, which is a desirable trait for applications requiring controlled deformation under load, such as biomedical implants and synthetic connective tissues [40].

3.4 Compression Set

Compression set testing was conducted to evaluate the material's ability to recover its original shape after being compressed for a prolonged period. The results are presented in Figure 7, displaying how average compression set values increase with higher filler loading. This behavior suggests that the addition of Leucaena fiber reduces the elasticity of the silicone rubber, which correspondingly causes the stiffness to increase. This is further attributed to the lower elasticity of pure silicone rubber when compared to the 16 wt % of Leucaena-silicone biocomposite.

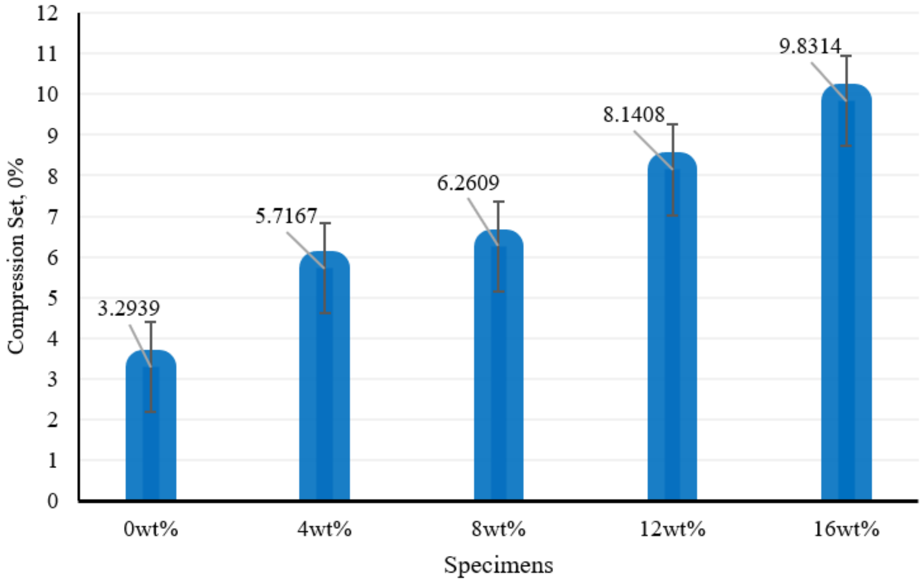

Figure 7. Average compression sets values of pure silicone (0 wt%) against various Leucaena-Silicone Biocomposite specimens

The compression set behavior can be explained using the rubber elasticity theory, which states that a cross-linked polymer network exhibits elastic recovery due to entropy-driven molecular reorganization. This is because the cross-link density of the composite makes the polymer chains move less and stiffens the composite. When compressed, the polymer chains squeeze together, causing the fillers to move. This shift in filler position prevents the silicone rubber from returning to its original shape. Therefore, when the Leucaena fiber is increased, the compression set also increases. For this study, an increase in the composition of fiber leads to an increase in plastic deformation, which contributes to the high compression set value. This is further corroborated by Jinlin et al. [41], who indicated that constant compression displacement is initially attributed to the elastic strain. However, as time progresses, despite the similar overall strain, the material's elastic deformation inclines towards plastic deformation.

3.5 Predicted Tensile Properties α and μ by ANN

The regression plot of Network 1 is displayed in Figure 8. The findings of the regression plot obtained from the network included the training, validation, test and overall data. Figure 8 indicates the predicted values obtained after the network was trained. The colored lines indicate the actual relationship of the network. The dotted line lies behind the colored line because the actual relationship shows an excellent relationship between the target and the output. The correlation coefficient R^2 for the training and validation phases is equal to one (1). It shows that the slope has a perfect fit, and the output is the same outcome as the target. However, the correlation coefficient, R, of the test value is 0.99999, which is almost equal to 1.

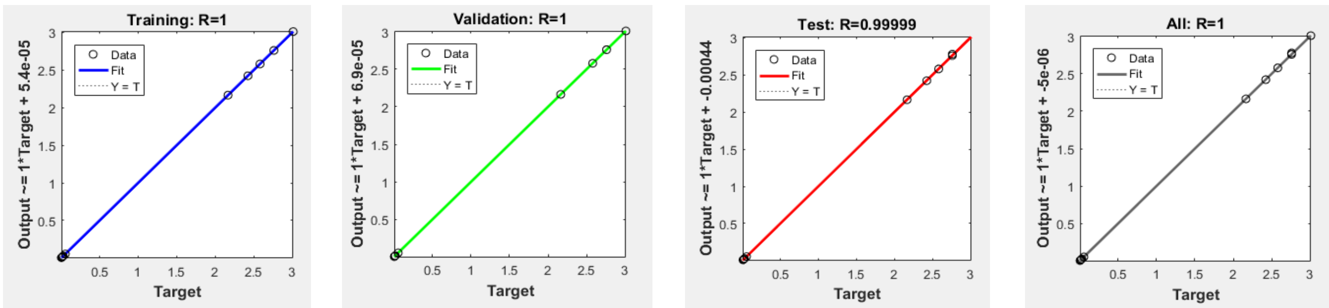

Figure 8. The regression analysis of ANN for Network 1

Another study reported by Patar et al. [42] showed a similar trend of the regression plot pattern in forecasting the material constant of the silicone biocomposite. Other than that, a previous study by Mohammadi et al. [43] also reported a small difference in values, which showed a high accuracy in correlation coefficient values. Therefore, the relationship between coefficient values for the training and validation should be close to 1 to indicate the network accuracy. Figure 9 depicts the validation performance of Mean Square Error (MSE) versus Epochs (iteration) for ANN models. In general, the error decreases as the epochs increase. Figure 9 shows a stop at 2.1798x10-7 at epoch 11. Mohammadi et al. [43] stated that the error decreases over time during training, and the algorithm discontinues once the authentication error rises for six successive repetitions or if the highest error per epoch limit is reached. The validation performance can improve as the epoch increases and more data is being inputted in the training process [44]. The MSE values explain that when the MSE values are near zero, the network is well-trained.

Table 5 shows the percentage error of the material constant for the Ogden model. The predictions of the ANN are comparable to the experimental data. The highest percentage error was 0.352 % at 8 wt% for Leucaena fiber. The lowest percentage error was found to be 0.002%, observed at 16 wt% of Leucaena fiber. The trend increased as fiber composition increased, which can be observed from 0 w% to 8 wt%. In fact, the highest target recorded for ANN prediction was 2.577 MPa and 0.018 MPa.

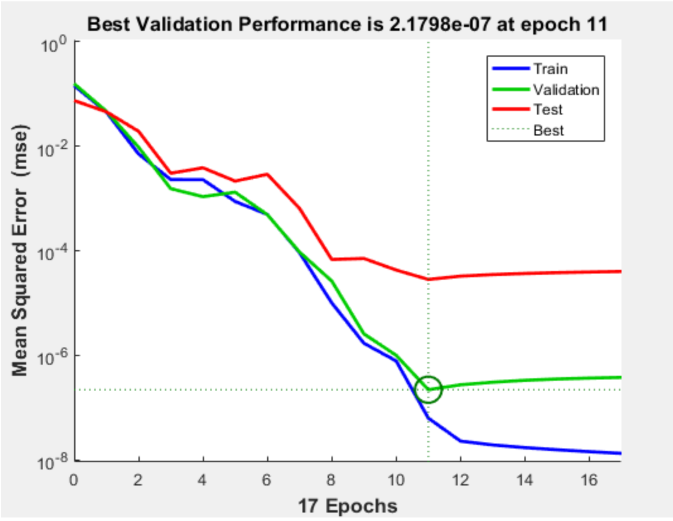

Figure 9. Best validation performance of network 1

Table 5. The percentage error (%) and comparison of output material constant between the experimental values and the ANN model

Input			Target: Material Constant				Percentage Error, %	
Weightage	Load, kPa	Elongation, mm	Experimental, MPa		ANN model, MPa			
			α	μ	α	μ	α	μ
0	5.978	279.420	3.009	0.005	3.009	0.005	0.007	0.007
0	5.978	279.630	3.007	0.005	3.009	0.005	0.067	0.067
0	6.301	310.477	3.009	0.005	3.009	0.005	0.007	0.007
0	5.903	280.450	3.009	0.005	3.009	0.005	0.007	0.007
4	9.188	264.650	2.758	0.011	2.758	0.011	0.005	0.005
4	9.248	266.402	2.758	0.010	2.758	0.011	0.014	0.014
4	10.817	299.572	2.758	0.010	2.759	0.011	0.033	0.033
4	9.275	267.158	2.768	0.010	2.758	0.011	0.345	0.345
8	6.250	200.685	2.575	0.019	2.577	0.018	0.098	0.098
8	6.278	201.589	2.577	0.019	2.577	0.018	0.031	0.031
8	6.241	200.401	2.568	0.019	2.577	0.018	0.352	0.352
8	6.244	200.493	2.578	0.019	2.577	0.018	0.045	0.045
12	7.813	221.440	2.412	0.029	2.421	0.029	0.340	0.340
12	7.852	222.552	2.412	0.029	2.421	0.029	0.348	0.348
12	7.845	222.364	2.422	0.028	2.421	0.029	0.062	0.062
12	7.852	222.549	2.414	0.029	2.421	0.029	0.265	0.265
16	6.250	154.670	2.160	0.056	2.164	0.056	0.182	0.182
16	6.248	154.617	2.163	0.056	2.164	0.056	0.081	0.081
16	6.226	154.083	2.163	0.056	2.164	0.056	0.074	0.074
16	7.786	183.793	2.164	0.056	2.164	0.056	0.002	0.002
						Average	0.118	0.118

The artificial neural network (ANN) developed in this study was used to predict the material constants μ and α with high accuracy, as indicated by the regression analysis in Figure 8. The correlation coefficient R^2 values approached 1, which confirmed the robustness of the model. The ANN model has successfully captured the nonlinear relationship between input parameters like fiber content, load and elongation with the corresponding mechanical properties. The predictive capabilities of the ANN model are significant because it eliminates the need for extensive experimental testing and provides an efficient means of estimating material properties for different compositions. This aligns with previous studies that have demonstrated that ANN-based modeling is an effective tool for predicting the mechanical behavior of composite materials with minimal error [45]-[47].

4. CONCLUSIONS

There is an emerging need for innovative and cost-effective development of new materials for medical and biomedical applications, particularly in enhancing physical and mechanical properties. Silicone rubber typically exhibits extremely soft physical properties, which limits its suitability for structural applications in biomedicine and healthcare. In this study, a combination of Leucaena and silicone was used to fabricate an innovative biocomposite material with enhanced physical and mechanical properties tailored for specific medical and biomedical applications.

The key material properties, including density, compression and uniaxial tensile behavior, were experimentally investigated in accordance with ASTM standards. The Ogden hyperelastic model was applied to depict the deformation behavior of the biocomposite material specimens. The use of ANN models in predicting material properties, specifically for the newly developed LeuSiC biomaterial, was introduced and discussed, with a focus on the prediction of tensile properties. The following are the key summaries of the theoretical and experimental investigations: (1) The incorporation of Leucaena fibers influenced the properties of the silicone rubber both physically and mechanically, with higher fiber compositions at 16 wt% leading to increased density and compression set values; (2) Incorporating Leucaena fiber improved the elastic response of the silicone rubber, making the stress-strain curve more linear with the increase of fiber content. However, tensile strength and the stretch ratio of the Leucaena-Silicone Biocomposite were inversely proportional to the fiber composition due to the inhibition of silicone polymer chain movement by the filler; (3) The Ogden hyperelastic constitutive model effectively represented the nonlinear behavior of the biocomposite while the material constants (μ) and material exponent (α) were determined through curve-fitting techniques which showed a decreasing trend for α and an increasing trend for μ as fiber composition increased; (4) The developed ANN model exhibited high accuracy in forecasting the material constants μ and material exponent α with a percentage error of 0.118%, showcasing its potential for providing reliable predictions as more data sets become available; and (5) The material constant, μ and material exponent, α, of the newly developed Leucaena-silicone biocomposite have potential medical application, i.e., synthetic connective tissue and human skin.

The findings of this study contribute significantly to the understanding and innovative development of natural fiber-reinforced biocomposites, which show considerable potential for applications in biomedicine and healthcare, including innovative design and development of medical and biomedical devices. This work contributes a fundamental step towards the innovative development of eco-friendly biocomposites that may address current challenges in biomedical engineering and medical treatments. The successfully developed Leucaena-Silicone biocomposite, LeuSiC, exhibits promising physical and mechanical properties that can be further investigated for specific applications in biomedicine and healthcare. Future research should focus on comprehensive clinical investigations of LeuSiC to assess its vivo performance, biocompatibility, and long-term stability. Additionally, the optimization of the manufacturing process and the exploration of potential modifications to enhance specific properties should also be investigated in detail.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

M.H. Hidzer (Conceptualization; Methodology; Validation; Formal analysis; Data curation; Investigation; Software; Visualization; Writing - original draft; Writing - review & editing)

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W.M.N. Wan Abdul Rahman (Conceptualization; Methodology; Investigation; Resources; Writing - review & editing; Funding acquisition)

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