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The Effects of Different Immersion Media on the Compressive Behaviour of Arenga Pinnata-Silicone Biocomposite

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Abstract

Arenga Pinnata (AP) is a natural fiber that possesses strong potential in replacing synthetic fibers in the future. By employing AP as a reinforcement for silicone rubber, results showed promising values in terms of sealing and cushioning applications due to the high elastic property of silicone rubber paired with the excellent seawater resistance of AP fibers. This study aimed solely to determine the compressive behaviour of *Arenga Pinnata – Silicone* (AP-Sil) in various immersion media. Firstly, AP-Sil specimens ranged from 0wt.%, 4wt.%, 8wt.%, 12wt.%, and 16wt.% fiber compositions were prepared. The specimens were then soaked in different immersion mediums (water, and seawater) under room temperature conditions. They were then tested by ASTM D349 and ASTM D575. It was found that higher fiber content will result in greater compression set values and can withstand much higher compressive stress. Also, water-soaked showed better results than that seawater-soaked. Neo-Hookean hyperelastic constitutive model was also simulated using the Excel Solver tool to obtain the material constant values. Results showed that the model could predict the compressive behaviour of AP-Sil biocomposite well.

Discipline: Material Science.

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1 Introduction

Arenga Pinnata (AP) fiber is known for its excellent seawater-resistant properties thus making it suitable for harsh environment applications (Ticoalu et al., 2014). The addition of this fiber to a composite matrix like silicone rubber would prove to be useful as it has the capability to increase the overall properties of silicone rubber (Kamarul Bahrain et al., 2018). The said seawater-resistant property possessed by AP will prove useful as it will not jeopardize the overall composite itself when used in sealing applications. Also, AP filler addition towards silicone poses better swelling behaviour in which the swelling of *Arenga Pinnata – Silicone* biocomposite (AP-Sil) showed a reduction in swelling rate in comparison to pure silicone rubber further proving the suitability of this fiber to be the perfect candidate of filler addition for sealing in composite materials (Kamarul Bahrain & Mahmud, 2019).

AP-Sil is a composite material with AP fiber as a reinforcement and pure silicone as the matrix. Being an elastomer, silicone rubber generally has good temperature stability with weak mechanical strength (Nunes, 2011; Yan et al., 2015). When bonded with AP, AP-Sil showed promising results for sealing and cushioning applications (Bahrain et al., 2017). The sealing application involves joining of two substances together while having a sealant compressed in between. Similarly, cushioning application offers the same concept of compressive force acting on the item (in this case, AP-Sil composite product). An analysis of the compressive behaviour of AP-Sil has been conducted to observe the sealing capabilities of AP-Sil (Bahrain et al., 2017) between unsoaked and water-soaked AP-Sil specimens. Hence, to broaden the field of study of the compressive properties of this biocomposite, by implying the sealing application of AP-Sil in the marine sector, different immersion media must be taken into consideration. So, this paper studies the compressive behaviour of AP-Sil when exposed to different immersion media. Compression tests will be conducted to relate the behaviour of AP-Sil when exposed to water and seawater while adapting the Neo-Hookean hyperelastic constitutive model to investigate the hyperelastic behaviour of the materials. This study will contribute towards the properties of AP-Sil in exhibiting sealing capabilities while also promoting a green material alternative in marine applications.

2 Literature Review

Arenga Pinnata is a name given to a natural forest species that originated from the Palmae family. In the early 19th century, before being named *Arenga Pinnata*, this plant had a number of other scientific names like *Saguerus rumphii* and *Arenga saccharifera Labill* (Bismarck, A., Mishra, S. and Lampke, 2005). The most common name for AP is sugar palm. Coming from the *Arecaceae* family, sugar palm is native to tropical countries like Malaysia, Indonesia, the Philippines, and India. There are more than 100 local names given to the sugar palm tree. Among the popular ones are *enau* and *kabung*. The fiber is blackish in color and has an appearance almost similar to a lock of hair. It is best known for its seawater-resistant properties which drew the attention of many sailors to produce ship cordages ropes (Ishak et al., 2013). The fiber can also be used to produce filters, brushes, brooms, cushions and many more. The vast applications of AP indicate the fiber has the acceptable strength to withstand harsh environments like rainy, hot, and humid weather which grants AP the advantage over other natural fibers (Misri et al., 2010).

AP biocomposite is a composite material that involves the fiber of the AP plant as a reinforcement and another substance as a matrix. The study of composite materials has been more and more focused on AP biocomposite. This can be seen that in recent years, there are plenty of studies conducted on this biocomposite. There was a study done using thermoplastic polyurethane as a matrix which involves the testing of moisture absorption, swelling, and density test (Atiqah et al., 2017). Other matrices used together with AP fiber composite studies include phenolic (Rashid et al., 2017), sugar palm starch (Sahari et al., 2013), and epoxy (Khalid & Abdullah, 2013; Khudhur et al., 2013).

AP-Sil is a biocomposite that has strong market potential as well as commercial value. Some known applications in which AP-Sil can be fully utilised include daily-application tools such as non-slip mats, coasters, racket grip, etc. Such discoveries can contribute to a decrement in synthetic fiber usage and dependency. This indirectly promotes a new contribution towards bio-friendly materials which is safe for both humans and the environment. Also, it was proven that AP filler addition to silicone pose better swelling behaviour in which the swelling of AP-Sil showed a reduction in swelling rate in comparison to pure silicone rubber (Kamarul Bahrain & Mahmud, 2019).

Bahrain et al. have conducted research on the sealing capabilities of AP fiber infused with silicone. They conducted a comparative study between soaked (with engine oil) and unsoaked specimens of this biocomposite with different fiber compositions and pure silicone. It was found that soaked specimens produced greater compressive strength and lower compression set to that of unsoaked specimens. This made AP-Sil suitable for sealing especially in oily environments (Bahrain et al., 2017). A study was conducted to analyse the compressive behaviour between silicone rubber and vapour grown carbon nanofiber (VGCNF)/silicone composite. Results revealed that at 20% compressive strain, the increment of filler content increases the modulus (M. A. Raza et al., 2011). The identical relationship can be found in (Mohsin Ali Raza et al., 2011) where the paper studied the graphite nanoplatelet (GNP)/silicone composite. Both studies recorded an increment of compressive modulus and ultimate compressive strength values when filler was added to pure silicone. This shows that a compressive test is crucial and needs to be done in order to observe the capability of the material in withstanding any compressive load. Different filler loading could either enhance or reduce the mechanical properties of the materials.

3 Method

3.1 Materials Preparation

The preparation of the specimen was first involved in retrieving raw AP fibers from Kuala Pilah, Negeri Sembilan, Malaysia. Upon harvesting, the fibers were washed off and immediately dried for a period of 24 hours, similar to the procedure of past research (Kamarul Bahrain & Mahmud, 2019). The next process involves crushing and milling the uncured fibers using the crushing machine and planetary mono machine. Crushing was done to reduce the entanglements between the fibers whilst the milling process turned existing fibers into powders with micro-scale grain size.

The powders will then be sieved via a vibratory sieving machine to extract the grain size of the powders to 160μm or less. Any grains of powders which was left above the sieve were milled again and re-sieved so that they can achieve the targeted grain size. The reduction of the grain size of the fibers is crucial since the hydrophobic nature of silicone prevents the fiber from mixing together thus this process is required to allow the filler and matrix to be bonded together.

The process of obtaining the fiber's density was done via the usage of a pycnometer. The average density, ρ of AP fibers was recorded to be 1505 kg/m^3. The test was conducted after the sieved powders were oven-dried at 120°C for 24 hours. The bonding of AP-Sil can be achieved by mixing the fiber compositions into the silicone mixture. The different compositions of fibers comprised 4%, 8%, 12%, and 16wt.%.

For 0% composition, Ecoflex 00-30 Platinum Cure was selected as the primary source of silicone rubber. The mixing procedure of Ecoflex 00-30 involved having both parts requiring identical volume (1:1 scale of Part A and Part B used) to ensure the perfection of the specimens created. The mixture was then stirred together in roughly one to three minutes in a single direction while making sure the sides and bottom of the container scraped periodically. It was then poured into a mould and left at room temperature condition for 4 hours to cure. The mould used for making the specimen is a cylindrical-shaped mould that follows the standard used for the rubber testing method. The said standard is ASTM D395 which is the standard test method for rubber property-compression set. Each specimen bears the dimension of 29±0.5mm in diameter and 12.5±0.5mm in depth.

Similar to that of the procedure of pure silicone (0 wt.%) specimens, AP-Sil specimens (4%, 8%, 12%, and 16% composition) use an identical method but with the fibers added to the container before both parts A and B of Ecoflex 00-30 were mixed. Having the fiber mixed results in different volumes of Ecoflex 00-30 needed to fill the mould. All cured specimens are then immersed with different immersion media. These media are seawater (ρ = 1025 kg/m^3), and water (ρ = 997 kg/m^3). The immersion process lasts 7 days.

3.2 Experimental Testing

Two tests were conducted in this paper; compression set test (ASTM D349) and compression test (ASTM D575). Usage of compression jig was required for ASTM D349 whereas ASTM D575 was conducted via 3382 Universal Testing Machine 100kN (Instron, USA, 2008).

For ASTM D349, specimens were compressed at a quarter of their size (see *Figure 1*). Through this testing, values of compression set if each specimen variation were calculated based on Equation (1).

$$C = \frac{t_0 - t_i}{t_0 - t_n} \times 100\% \qquad (1),$$

where t_0 is the initial thickness of the specimen, t_i is the final thickness after testing and t_n is the thickness during testing. A compression set is an irrecoverable deformation on release from compression. It depends on compression strain (or compression stress), duration, and temperature (Wypych, 2017).

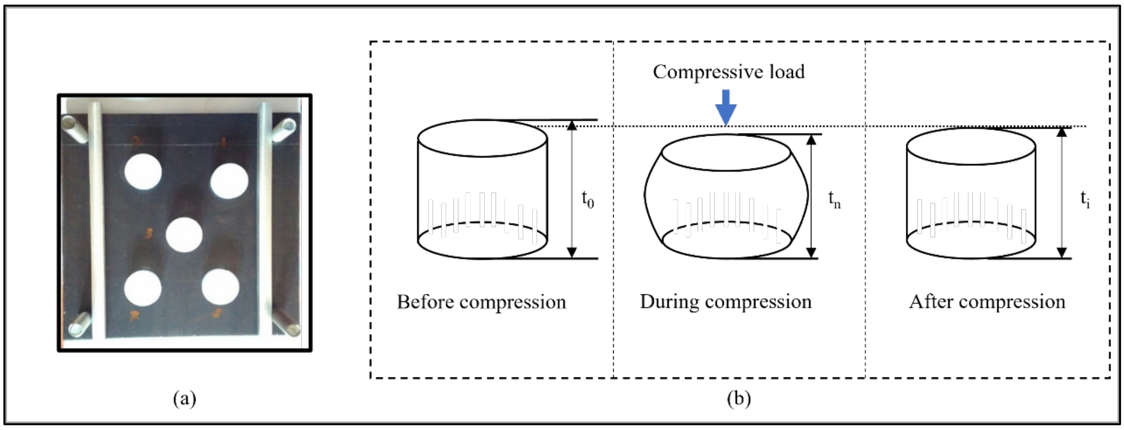

Figure 1: (a) Specimen placed at compression jig, (b) Specimen before-during-after compression set test.

For ASTM D575, this process requires the specimens to be compressed up to 25% of their thickness, (see *Figure 2*). ASTM D575 specifically stated the required thickness of the specimen to be 12.9±0.5mm. The goal of this test is to obtain the values generated by the machine during testing. Specifically, values of compressive stress and compressive strain are needed in order to plot stress-stretch curves for numerical analysis. The speed of the gauge was set to 13 mm/min.

Figure 2: Specimen undergoing compression test

3.3 Quantifying Compressive Properties

The hyperelastic constitutive equation, Neo-Hookean was selected as it is the most basic and most common hyperelastic model in demonstrating the compressive behaviour of silicone reinforced with various AP fiber compositions (Equation (2)).

$$\sigma_E = 2C_1\left(\lambda - \frac{1}{\lambda^2}\right) \qquad (2),$$

where σ_E is the engineering stress and λ is the extension ratio (stretch ratio). The material constant from the equation is denoted as C. λ values must be calculated manually via Equation (3).

$$\lambda = 1 + \varepsilon \qquad (3),$$

where ε is the strain. Values of σ_E and ε are obtained from the compression test. This analysis used Excel Solver add-in whereby parameters of σ_E and λ were included into Equations (2) to obtain the values of material constants.

4 Result and Discussion

From this study, it was found that the compression set ratio of AP-Sil possesses greater value than that of pure silicone. In view of immersion media, at 16 wt% AP fiber composition, the compression set ratio of seawater-soaked AP-Sil tops the chart with 14.70 % whereas waterfalls in place with 14.39 %. Likewise, greater fiber content also reduces the elastic property of silicone rubber which in turn, made silicone biocomposite stiffer in nature.

It is known that silicone rubber, as an elastomer, is generally resistant to water due to the nature of its hydrophobicity. Even so, some chemicals like solvents, concentrated acids and oils might prove otherwise. From the chart in Figure 3, it is found that increasing the fiber content has increased the amount of permanent deformation. The presence of AP fiber as a filler has reduced the rubber chain mobility of the biocomposite. This results in the composite having a weaker ability to retain its original thickness. A similar curve trend for the amount of permanent deformation was also shown by (Bahrain et al., 2017) when immersing silicone biocomposite in engine oil. Figure 3 shows the compression set ratio of AP-Sil specimens immersed in water and seawater.

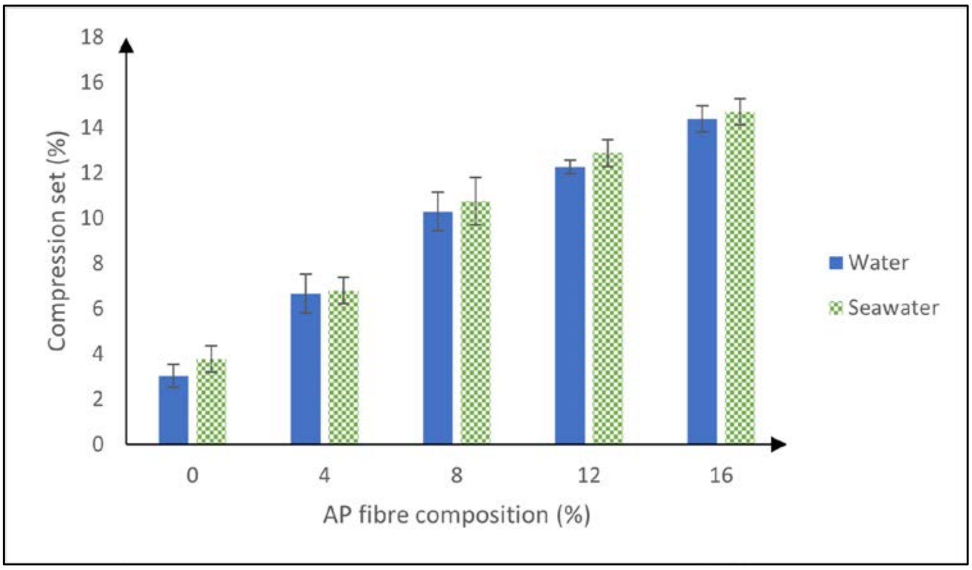

Figure 3: Amount of permanent deformation (Compression set) of immersed AP-Sil.

In the compression test, the calculated stretch, λ and engineering stress, σ_E values were plotted. The stress-stretch plots were constructed to compare the compressive stress of each fiber composition when subjected to 25% compressive strain.

A relationship can be seen whereby greater fiber content led to greater compressive strength. Upon closer inspection, the slope of each graph gets steeper with the increment of AP fiber. This nonlinear pattern was also demonstrated by Farshad (Farshad & Benine, 2004). Taking immersion media into consideration, at 16 wt% AP reinforced, water-soaked seemed to be the most effective in terms of cushioning effect since it can withstand the highest amount of compressive stress in comparison with seawater (94.29 kPa, and 85.74 kPa respectively). Also, water-soaked AP-Sil proved to be best in terms of sealing application as well which can be seen at compression set test where they yield the least amount of permanent deformation. This also shows that at 16 wt%, the silicone biocomposite is stiffer in nature when compared to pure silicone or other fiber compositions (4, 8, 12 wt%). This trend can also be seen in (Mohsin Ali Raza et al., 2011) and (Abdullah et al., 2020) in which both deduced the increased values of compressive modulus and ultimate compressive strength when fillers were added to pure silicone. Figures 4, and 5 show the stress-stretch relationships between AP-Sil in different fiber compositions when immersed in water, and seawater respectively.

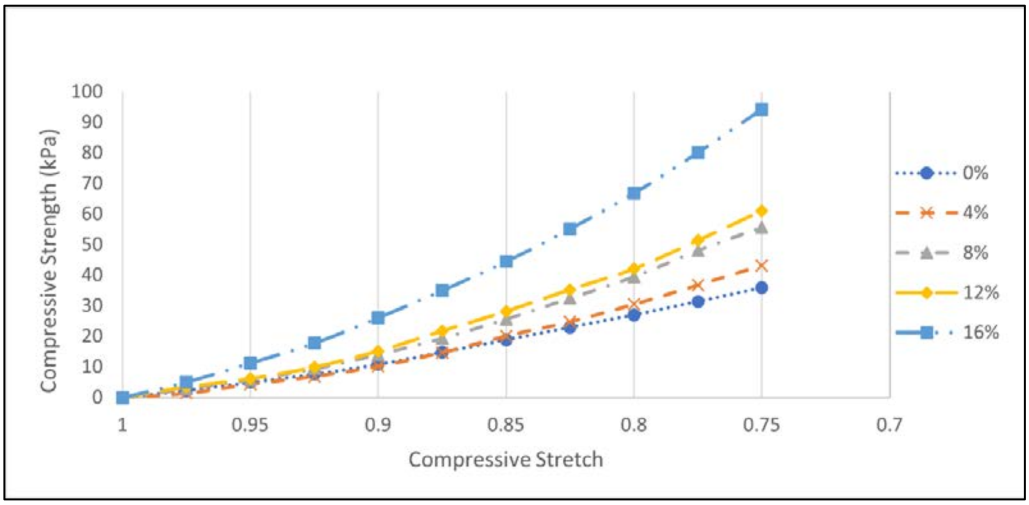

Figure 4: Compressive behaviour of AP-Sil (immersed in water)

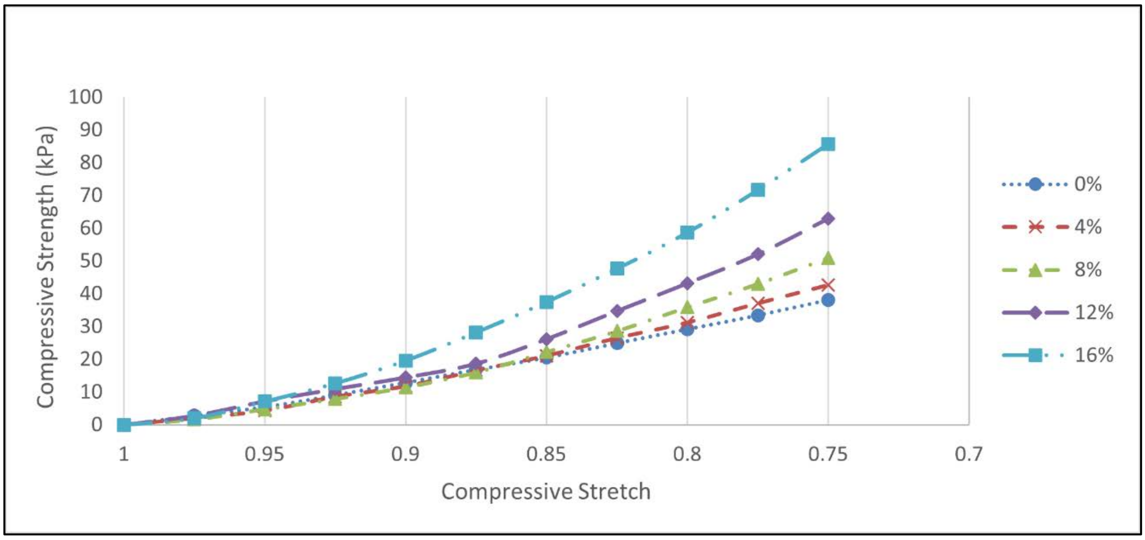

Figure 5: Compressive behaviour of AP-Sil (immersed in seawater)

Neo-Hookean hyperelastic constitutive model was simulated in every single stress-stretch plot of the conditions. Results indicate that the simulated model was able to mimic the behaviour of the experimental data of pure silicone and AP-Sil. The generated curve has identical nonlinear concave upwards behaviour similar to that of experimental data when immersed in different immersion media (Figures 6, and 7). In terms of material constant, Neo-Hookean showed a consistent increase in negative value as the slope increased. Comparing the material constant values, the pure silicone state recorded a lesser negative amount than that of AP-Sil which indicates that the stiffness properties of the silicone biocomposite increase as has been described on the specimens' compressive strength. This has also been proven by (Bahrain et al., 2017) whereby the values of material constant increase as silicone biocomposite gets stiffer.

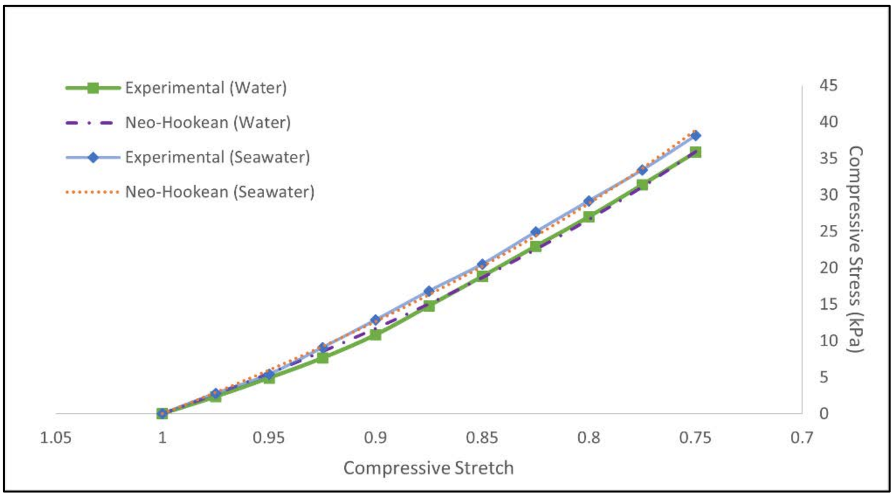

Figure 6: Experimental versus Simulated Stress-Stretch curve for Pure Silicone.

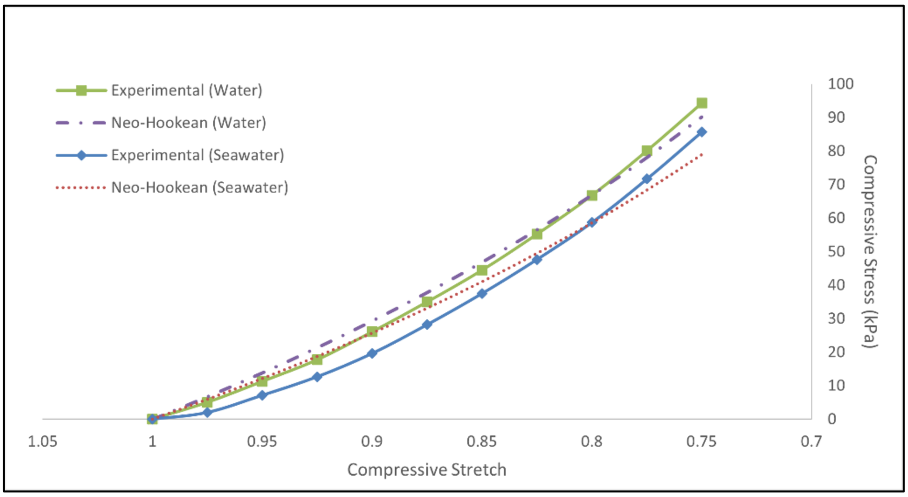

Figure 7: Experimental versus Simulated Stress-Stretch curve for 16wt.% AP-Sil.

Table 1: Material Constants for Neo-Hookean model

Material Constant	Fiber Composition (wt%)	Immersion Media	
		Seawater	Water
C1	0	-18.91	-17.49
	16	-38.45	-43.87

5 Conclusion

This present work has presented the effect of different immersion mediums on the compressive behaviour of AP-Sil. AP-Sil underwent two compression tests. One test was the compression set test (in accordance with ASTM D395) and the other was the compression test (in accordance with ASTM D57). In general, the higher fiber content will result in greater compression set values. It can be deduced that seawater-soaked AP-Sil has greater compression set ratio compared to water-soaked AP-Sil with a very little margin. In contrast, pure silicone produced the least compression set ratio which shows a greater ability in returning to its original thickness. On the other hand, soaked AP-Sil showed greater stiffness by having the ability to withstand higher compressive stress. Results in this study indicate that when exposed to both water and seawater at a prolonged time, AP-Sil will still be able to retain its shape thus making it suitable for sealing applications even in the marine sector since both water and seawater proved to show a near identical result in terms of their compressive behaviour. In the numerical analysis section of this research, Neo-Hookean hyperelastic constitutive model was plotted at each of the stress-stretch experimental data via the Excel Solver tool. From the curve fits, material constants generated showed increasing values as the fiber content increased. Neo-Hookean model could also predict the compressive deformation well since the simulated data are very close to the experimental data. This study has proved that the addition of AP fiber as filler for silicone rubber has enhanced the properties of silicone biocomposite.

6 Availability of Data and Material

Data can be made available by contacting the corresponding author.

7 Acknowledgement

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