# Physical and Mechanical Properties of Bamboo-Silicone Biocomposites (BaSiCs)

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Silicone rubber biocomposites were prepared with 0%, 4%, 8%, 12%, and 16% bamboo fiber as reinforcement. The compressive set behavior of the samples was compared between the samples that were tested before and after immersion in water. The compression set values for the samples that were immersed in the water were lower than the samples that were not immersed in the water. The moisture absorption rate of the bamboo-silicone biocomposites (BaSiCs) increased as the bamboo fiber content increased. As the bamboo fiber content in the BaSiCs increased, the impact energy and the deflection at peak load values decreased and increased, respectively. The results from this study showed that the addition of bamboo fiber into silicone rubber composites can substantially affect its compressive strength, moisture absorption, and impact strength. This study provided essential knowledge to the development of BaSiCs for cushioning applications, such as shoe insoles.

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## INTRODUCTION

Due to the unique structure of polysiloxane, silicone rubber possesses exemplary characteristics such as biocompatibility, oxidation resistance, thermal stability, climate resistance, low surface tension, and unique high permeability. Nevertheless, silicone rubber has weak intermolecular forces among its polymer chains, which confines its mechanical strength and applications (Xu *et al*. 2010). Many efforts have been made to improve the mechanical properties of silicone rubber (Gu and Zhou 1998; Kaneko and Yoshida 2008; Wang *et al.* 2008). One of the developed methods involves employing cellulose fiber as reinforcement in the silicone matrix.

In recent years, composite industries have focused on the use natural fibers rather than synthetic fibers because of their biodegradable properties and environmentally friendly nature (Arpitha and Yogesha 2017). Previous studies have found that the reinforcement of silicone rubber with *Arenga pinnata* (Bahrain *et al.* 2017), kenaf (Nishino *et al.* 2003; Ismail *et al.* 2019), and banana fibres (Amir *et al.* 2017) can maintain the material properties, which can offer many benefits. Natural materials based on cellulosic fibers have been commonly used in recent studies compared to other types of fiber because of their wide availability, strong mechanical properties, and relatively low cost (Ganicz *et al.* 2020). Natural fibers are used in many applications in accordance with their specific properties such as durability, thermal stability, tensile strength, and other criteria. Different fiber types have their own mechanical and chemical properties that can be used to tailor the product to meet certain conditions (Abidin *et al*. 2020). Bamboo (*Gigantochloa albociliata*) is a firm and compact plant that is widely produced in Malaysia. Bamboo is a natural fiber that can instil many benefits in a wide range of consumer products. Thanks to its abundance, bamboo is a strong candidate amongst the most important non-timber woodland assets on the planet. For practical engineering design, the load-bearing capacity of bamboo fibers reinforced into resin (hard biocomposites) has been studied by Zhong *et al.* (2014) and others. Nevertheless, the physical and mechanical behavior of silicone matrix reinforced with bamboo fibers (soft biocomposites) have not been reported widely.

In this study, bamboo was applied as a method to reduce foot ulcerations. For patients with diabetes, the risk of delayed wound healing after developing foot ulcers has become a serious issue in the public health care system. A study has been conducted on using the catappa fibre blends with epoxidized natural rubber to investigate the capability of the biocomposite to be used as insole application (Ahmad and Baharum 2019). They found that the tensile strength was optimum at 15% of fibre loading while the modulus strength is increased as the fibre content increases. The water absorption was also observed to be increased as the fibre loading was increased, which is favorable towards insole applications. Adding natural fibres can also offer improvement in footwear components. A study conducted on multilayer fabrics utilizing calf and pig leather added with cellulose fibre had shown positive results with respect to thermal relief, and the material also became more wear-resistant and absorbent (Nam and Lee 2019). Still, no study has been reported on the effect of using bamboo fiber in the silicone rubber insoles commonly used by diabetic patients, so bamboo's healing effect for diabetic patients with foot ulcers has remained unexplored. Bamboo fiber and silicone rubber may be employed to fabricate an insole that can reduce foot wounds from spreading and developing into ulcers. Therefore, the aim of this study was to determine an optimal and safe concentration of bamboo fiber that can be mixed with the silicone rubber matrix for effective wound healing properties while investigating the mechanical and swelling behavior of the bamboo-silicone biocomposites (BaSiCs).

## EXPERIMENTAL

### Materials

The bamboo (*G. albociliata*) was placed into an oven for 24 h at 70 °C to remove all the moisture. The bamboo was then cooled at 27 °C for the composite preparation. The bamboo was then crushed using a jaw crusher. A Planetary Mono Mill (FRITSCH GmbH, Idar-Oberstein, Germany) was used to refine the crushed bamboo for 3 h and the fine particulate bamboo was sieved with a vibratory sieve shaker (Retsch GmnH, Haan, Germany) having a 0.25 mm mesh size frame to obtain fine bamboo powder. The mass of the bamboo fiber was measured with a Mettler Toledo AG245 analytical balance (Columbus, OH, USA) for each composition according to the volume of sample that was required for each test condition.

For the fabrication process, silicone Ecoflex 00-30 platinum cure (Smooth-On, Macungie, PA, USA) was used as the matrix material. The product was comprised of a silicone elastomer and a silicone elastomer crosslinker. To develop pure silicone rubber, the two parts were mixed at a 1:1 ratio. The bamboo powder was mixed with the silicone solution at addition levels of 4, 8, 12, and 16 wt.%. The solution was then poured into the mould and allowed to cure for at least 4 h. The BaSiCs were prepared to form several samples for each test. The compression strength, compression set test, moisture absorption, and impact strength were measured.

## Characterization

*Compression test*

To obtain the maximum strength of each BaSiC, a compression test was performed on each sample using an Instron universal testing machine (Norwood, MA, USA). The BaSiC samples were subjected to compressive loading to determine the compressive strength with and without immersion in seawater, according to the ASTM standard D575 (2018), at a speed rate of 1.3 mm/min. The average compressive properties from the five samples were then identified and compared to pure silicone rubber.

*Compression set test*

To determine the effect of the bamboo fiber content on the compression set behavior of the silicone biocomposites, the compression set test was carried out. Once the compressive strength of the samples has been measured, the compression set test was performed based on the ASTM standard D395 (2018). The thickness of the original specimen was measured and then placed between spacers in the compression device. The specimen was compressed to 25% of its original height, and spacers were used to accurately measure the compression. Within 2 h of assembly, the compression device was placed in an oven at a specified temperature for the suggested time periods of 22 and 70 h. After the sample was removed from the oven, it was cooled for 30 min before measuring the final thickness using a Mitutoyo ABSOLUTE 573 digital caliper (Kanagawa, Japan). The compression set was expressed as a percentage, as seen in Eq. 1,

$$Compression\ Set\ (\%) = \left[\frac{(t_o - t_i)}{(t_o - t_n)}\right] \times 100 \quad (1)$$

where $t_o$ and $t_i$ are the original and final thickness measurements of the sample, respectively, and $t_n$ is the thickness of the space bar that was used in the test.

*Moisture absorption test*

Five samples with dimensions of 50 mm × 50 mm × 2 mm for each bamboo fiber composition were made according to the procedures outlined by Namitha *et al.* (2013). The initial weights of the samples were recorded before they were soaked in 100 mL of distilled water in a beaker for 24 h. Subsequently, the samples were wiped to remove the excess water from the surface and then weighed again. The quantity of water absorbed by each BaSiC was determined based on the difference in the initial and post-soak weights of the samples. The volume of the moisture absorption was expressed as a percentage, as seen in Eq. 2 (Namitha *et al.* 2013),

$$Volume\ of\ Moisture\ Absorption\ (\%) = \frac{\frac{(w_f - w_i)}{\rho_w}}{\left[\frac{(w_f - w_i)}{\rho_w}\right] + \left[\frac{w_i}{\rho_c}\right]} \times 100 \quad (2)$$

where $w_i$ and $w_f$ are the initial and final weights of the sample, respectively, and $\rho_w$ and $\rho_c$ are the densities of the water and the composite, respectively.

*Impact test*

The impact strength for the BaSiC samples were conducted according to the ASTM standard D3763 (2018), which is designed to provide the impact energy *vs.* the striker displacement response of polymers in the form of flat test specimens. The falling weight impact test was used. The impact test is used to evaluate the ability of a material to resist cracking when a load is applied rapidly, thereby conveying the material's potential and kinetic energy. In this study, a 3 kg weight was dropped at a given initial impact velocity in the center of a clamped polymer disk with an impact height of 32 cm. The impact load, the impact energy, and the deflection were determined as the striker moved down.

## RESULTS AND DISCUSSION

### Compression Test

To separate the effects of the mechanical behaviors, compression tests of the samples with and without immersion in water were performed, as can be seen in Table 1. The stiffness and strength of the BaSiC samples were noticeably higher than the pure silicone rubber when tested under the same conditions.

**Table 1.** Compressive Strength of the BaSiCs

| Content of Bamboo Fiber (wt%) | Max. Stress (KPa) without Immersion in Water | Max. Stress (KPa) with Immersion in Water |
|---|---|---|
| 0 | 30.8 | 30.8 |
| 4 | 35.2 | 41.8 |
| 8 | 39.6 | 44.0 |
| 12 | 46.2 | 63.8 |
| 16 | 63.8 | 70.4 |

Figures 1 and 2 show the strength curves of the BaSiC samples compared to the pure silicone. The strength of the BaSiC samples increased with the addition of the bamboo fiber, as can be seen in Fig. 3. The results indicated that the addition of the bamboo fiber into the silicone improved the silicone compression strength, which made it harder to break under compression (Bai *et al.* 2017). As shown in Fig. 2, the 16% BaSiC sample had a higher compressive strength when immersed in water (70.4 KPa) compared to the 16% BaSiC that was not immersed in water (63.8 KPa). Similar results were observed in a study on the compressive strength for bamboo fiber reinforced composites, commercial bamboo scrimber, and laminated bamboo lumber (Gong *et al*. 2016). This study found that the compressive strength of bamboo fiber reinforced composites was 0.6 times, 0.3 times, and 1.0 times higher than that of raw bamboo, commercial bamboo scrimber, and laminated bamboo lumber, respectively.

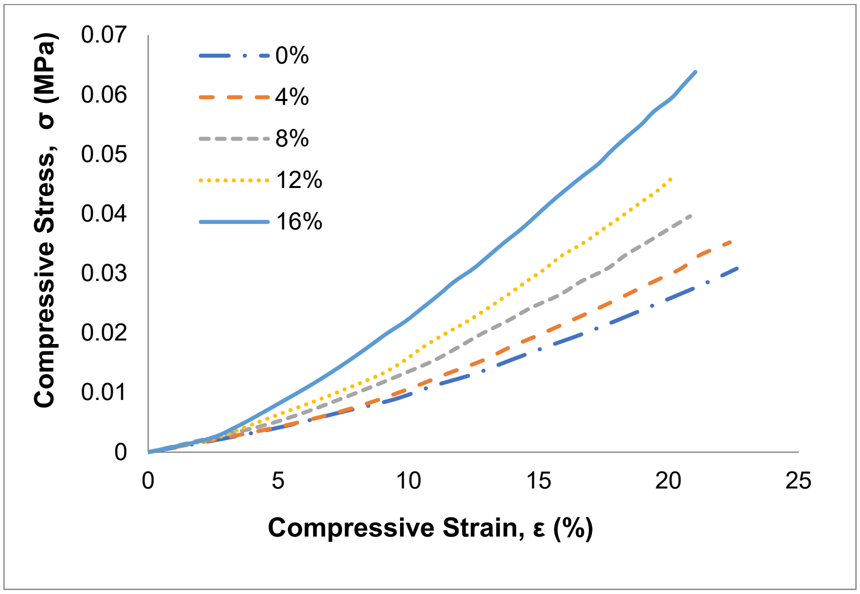


**Fig. 1.** Average compressive strength of the BaSiCs that were not immersed in water

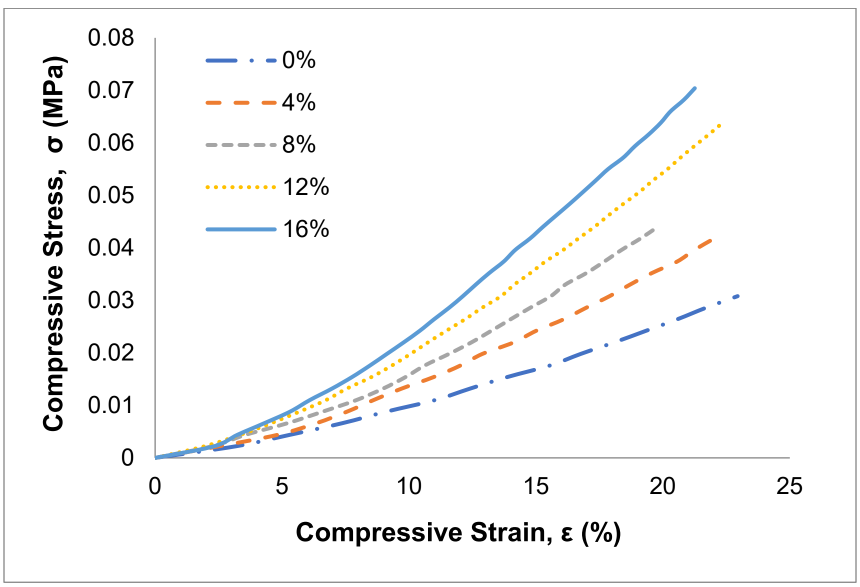


**Fig. 2.** Average compressive strength of the BaSiCs that were immersed in water

## Compression Set Properties

The compression set test determines the elastic properties of an elastomer. The compression set behavior depicts the reduction in the thickness after a material is aged in compression, so it expresses the capability of the material to be restored to its initial thickness. An insole will be subjected to a compressive load for a certain period. The compression set becomes visible when the compressive load is removed, and the original thickness is not recovered after a long time. This loss of resiliency or memory may reduce the performance of an elastomeric insole and cushioning pad over a long period of time. At a compression set of 0%, the insole material would maintain its original height. At a compression set of 100%, the material would become fully deformed and unable to return to its original thickness when the load is removed (Bai *et al*. 2017). Figure 3 shows the compression set tests that were performed for the BaSiC samples with 0%, 4%, 8% 12%, and 16% of bamboo fiber contents that were tested before and after immersion in water.

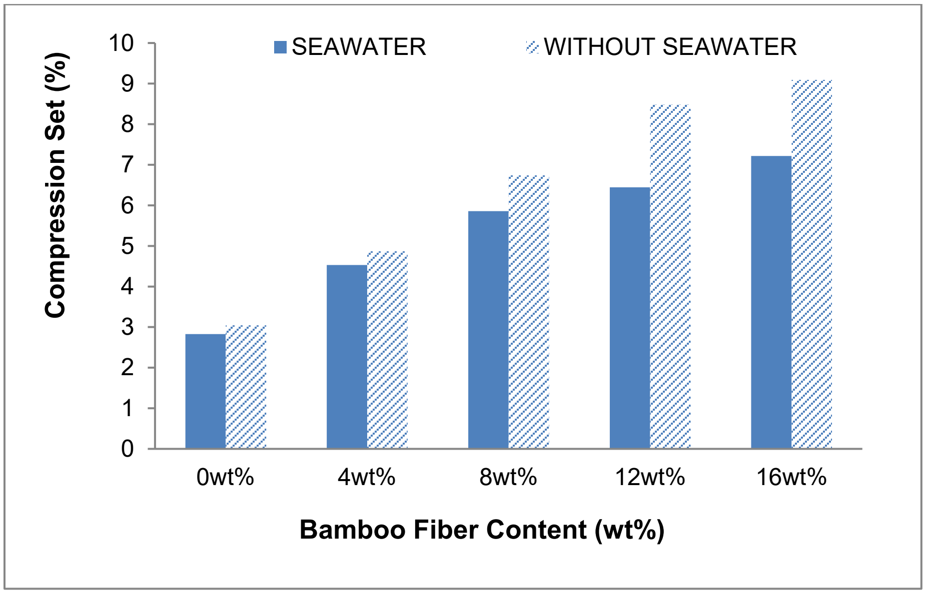


**Fig. 3.** Compression set values (%) of the BaSiCs with and without immersion in water

The samples that were tested after they were immersed in the seawater had lower compression set values than the samples that were not immersed in the seawater. This suggests that as the fiber composition of the BaSiC increases, the elasticity of the silicone rubber chain mobility decreases, and the compression set value increases as a result of the higher matrix stiffness (Bahrain *et al.* 2017). Therefore, the stiffness of the BaSiC samples increased as the bamboo fiber content increased. This behavior was observed in previous studies where silicone rubber composites with higher fiber contents yielded stronger compression set values (Bahrain and Mahmud 2019). The same result was also observed in a comparison study of pure rubber and carbon black-filled compound conducted by Mostafa *et al*. (2009), where it was found that the compression set value increased as the carbon black percentage in the pure rubber increased. However, these values are still in a low range of compression set when compared to other experiments where much higher compression set percentages were reached (Arroyo *et al.* 2003; Ziraki *et al.* 2017). Similar to Arroyo's results, the compression set values of the BaSiC samples were lower after they were immersed in the water. This is probably because the absorption of the seawater by the fiber improved the mobility of the rubber chain of the silicone and thus enhanced the elasticity of the samples. This was supported by the moisture absorption test results that are explained in the next section.

## Moisture Absorption Test

After the BaSiC samples were immersed in distilled water for 24 h, the volume percentage (%) of moisture absorption by the silicone was recorded (Fig. 4).

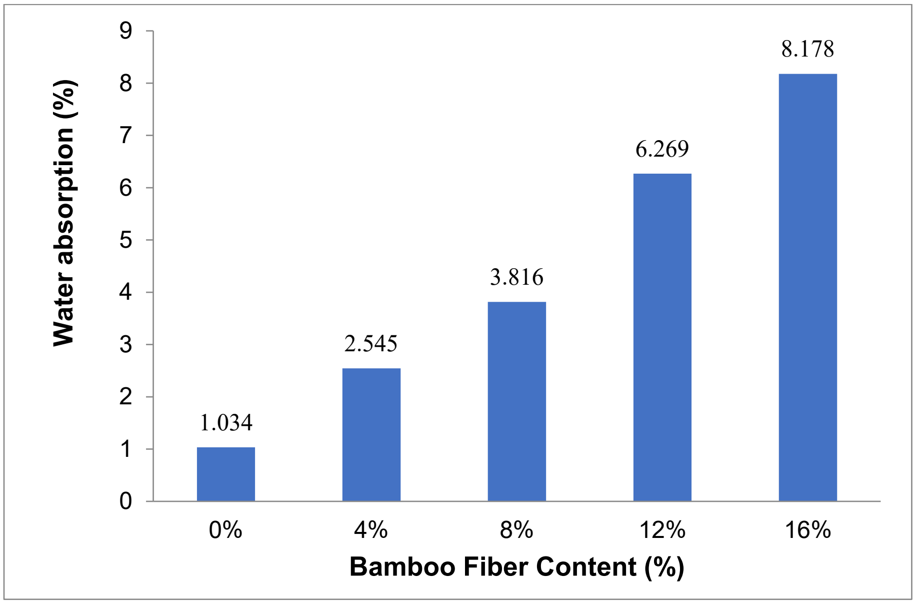


**Fig. 4.** Moisture absorption rates (%) of the BaSiC samples

Moisture absorption tests were carried out to investigate how much water could be absorbed by the samples. The water absorption rate had a clear dependency on the bamboo fiber content in the BaSiC samples. As shown in Fig. 4, higher bamboo fiber contents in the BaSiC samples resulted in higher moisture absorption rates. Bamboo fibers are naturally porous and comprised of countless of hydroxyl groups, vascular bundles, and parenchyma tissues. Therefore, the hygroscopic nature of bamboo facilitated the higher moisture absorption levels (Li *et al*. 2016) which increased the moisture absorption rate. Other studies found that the moisture absorption rate of silicone composites increased significantly as the fiber reinforcement percentage increased (Namitha *et al.* 2013; Ismail *et al.* 2019).

## Impact Analysis

Due to its unique and desirable properties, the application of silicone rubber for impact strength benefits has gained increasing attention. Silicone rubber has greater weather and radiation resistant properties compared to other high damping rubbers, and it is thermally stable due to the higher energy of the silicone and oxygen bonding in its main chain (Yu *et al*. 2019). One of the crucial parameters that were analyzed in this study was the average impact energy (*J*) *vs.* the composition and the deflection at peak load (mm) *vs.* the composition, as can be seen in Fig. 5.

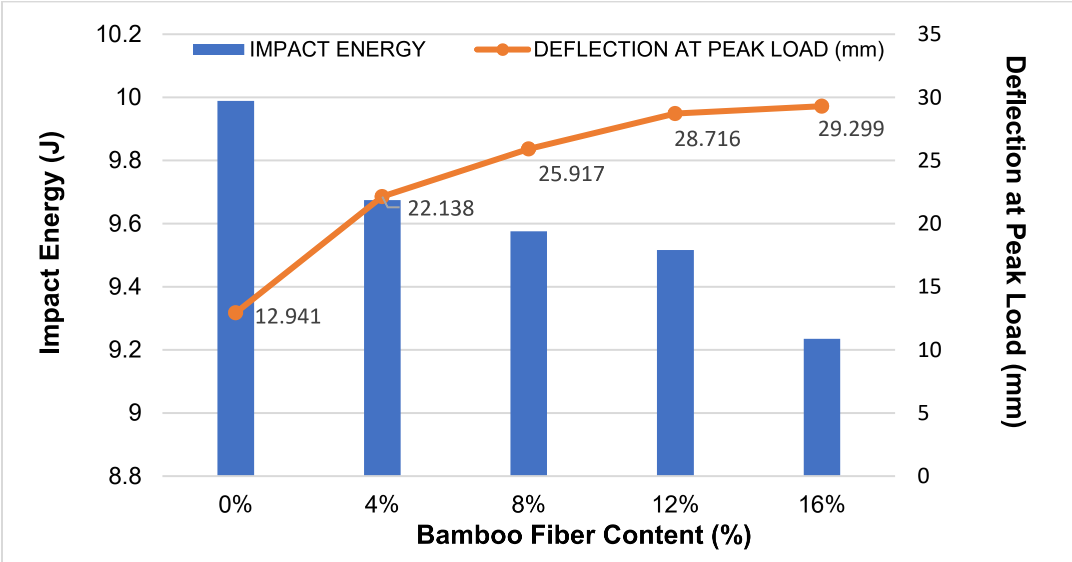


**Fig. 5.** Impact energy (J) and the deflection at peak load (mm) of the BaSiC samples at various bamboo fiber addition rates

In this experiment, a 3 kg impactor at a falling impact height of 32 cm was applied to indicate the amount of energy that was exerted on the samples. The graph in Fig. 5 shows that the impact energy decreased as the bamboo fiber content in the BaSiC samples increased. The pure silicone samples with 0% bamboo fiber were entirely elastic, so a greater amount of energy was required to break the elastomer chain (Soever *et al*. 2011). The trend of the curve in Fig. 5 is similar to the study by Chern *et al.* (2014), which shows the decreasing energy when more oil palm fibers were added. According to Park and Balatinecz (1997), this phenomenon occurs as the added fiber tends to hinder deformation and ductile mobility of polymer molecules. Subsequently, Ismail *et al*. (2019) studied the impact strength of kenaf, bamboo and kenaf/bamboo hybrid composites and found that the use of kenaf in bamboo hybrid composites yielded better impact properties. The maximum deflection was achieved at the highest bamboo fiber content level (Table 2). This finding indicates that the higher bamboo fiber content led to the increment of peak load magnitude, due to the enhancement of the material strength between the fiber reinforcement and the silicone matrix. Therefore, the ductile nature of the BaSiCs and the relationship between the fibers and the matrix play an important role to achieve effective bonding, which can result in good mechanical properties for the designed material.

**Table 2.** The Average Impact Energy and the Deflection at Peak Load of the BaSiCs with 0%, 4%, 8%, 12%, and 16% Bamboo Fiber Content

| Bamboo Fiber Content (%) | Average | |
|---|---|---|
| | Deflection at Peak Load (Mm) | Impact Energy (J) |
| 0% | 12.941 | 9.989 |
| 4% | 22.138 | 9.674 |
| 8% | 25.917 | 9.576 |
| 12% | 28.716 | 9.516 |
| 16% | 29.299 | 9.235 |

Figure 6 illustrates the damaged samples after they were exposed to the impact load. There was an obvious crack propagation between the sample with high (12% to 16%) and low (0% to 8%) levels of bamboo fiber addition. The images of the damaged surfaces for the different samples were similar. However, the BaSiC with 16% bamboo fiber addition clearly had small fragmentation from the focal point of the sample, which was the point where the stress concentration of the puncture was the highest. The 16% BaSiC sample appeared to be a more solid structure with better stiffness properties compared to the other BaSiC samples. In shoe insole applications, the aim of the design is to provide a material that can remain substantially intact despite constant impact.

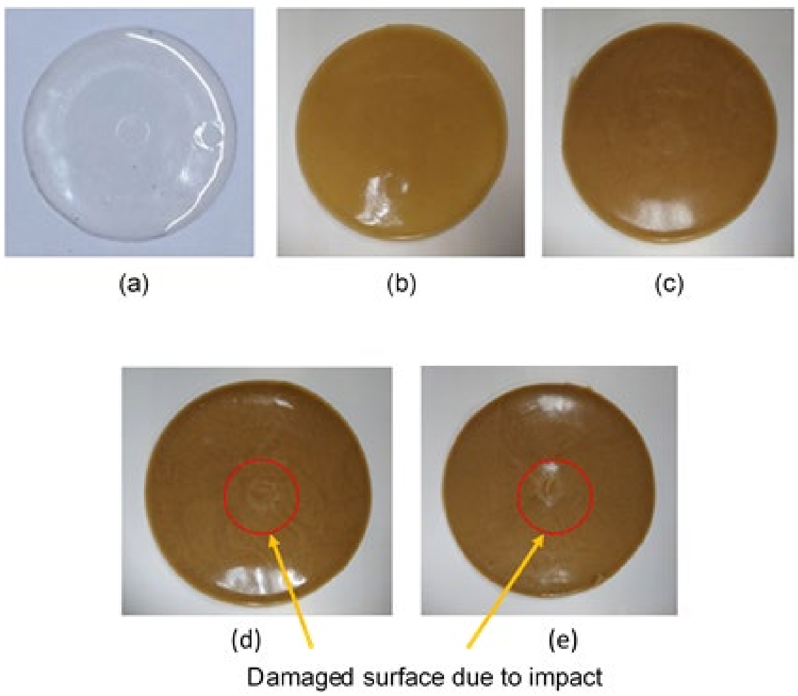


**Fig. 6.** Damaged surface of the BaSiC samples with (a) 0%, (b) 4%, (c) 8%, (d) 12%, and (e) 16% of bamboo fiber

## CONCLUSIONS

1. The mechanical (compression and compression set) properties of the bamboo-silicone biocomposite (BaSiC) samples were determined. The samples that were immersed in the water revealed higher compressive strength values and lower compression set values than the BaSiC samples that were not immersed in the water.
2. The compression strength of the BaSiCs increased as the bamboo fiber content increased.
3. The compression set values of the BaSiC samples increased as the bamboo content increased. Lower compression set values contribute to better cushioning for applications such as shoe insoles.

4. The moisture absorption rates of the BaSiC samples rose as the bamboo fiber addition increased. The moisture absorption rate is important for insole applications, so this relationship should be considered in the production of insoles particularly for diabetic patients.
5. The impact test destroyed the 16% BaSiC sample. Further testing should be conducted with a larger impactor to mimic the size of human feet and to better predict the impact imparted by a walking motion.

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