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*Article*

# Development of a Suture Pad for Medical Training from Silk Fiber Reinforced Polydimethylsiloxane Composite

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**Abstract.** The aim of this research is to develop a suture pad simulating human skin for suturing practice. The suture pad was fabricated with layers of artificial dermis and subcutis which reproduced the mechanical properties of skin. The main focus of this study was to reinforce polydimethylsiloxane with silk fiber to create a realistic dermis. The effects of silk fiber amount and aspect ratio on the mechanical properties of the suture pads were investigated. Results revealed that the tensile strength and modulus of the composite increased in relation to fiber content and aspect ratio. Composites with silk fiber exhibited higher tear resistance to suture thread compared with pure polydimethylsiloxane. Furthermore, the hardness of the composites was improved with the addition of silk fiber. It was found that polydimethylsiloxane composite reinforced with 2 phr of silk fiber with an aspect ratio of 1000 showed a hardness value similar to that of human skin. These results indicate that silk fiber reinforced polydimethylsiloxane composites can realistically simulate human skin and have the potential to be used as suture pads for medical training.

**Keywords:** Suture pad, silk fiber, polydimethylsiloxane, medical training.

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# 1. Introduction

Surgical care operation has been an essential part of health care worldwide for over a decade. While surgical procedures are intended to save lives, unsafe surgical care can cause substantial harm. Demand for better surgeons in the future leads to demand for better learning apparatus which can, in turn, improve the performance of medical students while reducing the cost of learning. One such item, the suture pad, is commonly used to practice suturing in learning environments in preference to a real human body. In the design of suture pads, simulating the mechanical properties of human skin is crucial for realistic practice.

Skin forms a barrier from inhospitable environments and has three general layers consisting of the epidermis (the outer layer), dermis (the middle layer) and subcutis (the layer that mostly consists of fat). The epidermis and subcutis are soft; the dermis, however, is harder, providing tensile strength and elasticity to the skin through an extracellular matrix composed of collagen fibrils, microfibrils, and elastic fibers [1]. The dermis determines most of the mechanical properties of the whole skin and is formed of a composite of natural fibers. Therefore, this research outlines the fabrication of a composite which mimics skin structure, consisting of a matrix of fibers.

Commercially available suture pads are based on polydimethylsiloxane because of its high flexibility and low toxicity [2]. Polydimethylsiloxane is widely used in medical practice apparatus because of its ability to simulate human body parts [3]. However, polydimethylsiloxane has poor mechanical properties which limit its realism. Fiber reinforced composites are used commonly in engineering because of their superior properties [4-6]. The fibers in these composites usually form bundles or filaments. Therefore, even if several fibers break, the load is redistributed to others, which lessens the chance of complete failure [7]. Many factors affect the mechanical properties of fiber reinforced composites including aspect ratio, critical fiber length, fiber loading, and fiber orientation [3]. S.R. Ryu *et al.* [8] found that the tensile strength of nylon fibers with aspect ratios in the range of 0-500 increased alongside aspect ratio, reaching maximum strength at an aspect ratio of 400.

Natural fiber reinforced composites have gained increasing interest because of their eco-friendly properties and ready availability [9-12]. These natural fibers include jute, silk, coir and sisal. Not only are these abundant renewable materials but they also have similar or often superior properties to synthetic fibers [2, 9, 12]. The integration of biodegradable plant-based fibers has been proposed to improve the mechanical properties of polydimethylsiloxane as well [13-15]. However, their naturally highly hydrophilic surfaces have low interfacial bonding with polydimethylsiloxane, and thus further surface treatments had to be applied to improve their compatibility [13-15].

Kaewprasit *et al.* investigated amino acid composition within different types of silk fibers, including a report on their hydrophilicity and hydrophobicity [16]. The report showed high hydrophobicity in three different silk fibers, implying better compatibility with polydimethylsiloxane. Silkworm silk fibers have unique mechanical properties and biocompatibility. They are also commonly used in bioengineering structures in which they serve as model light-weight and inert fibers for composites [10-12]. Cheung, H. Y. *et al.* [10] reported the effect of length and fiber content on the mechanical properties of polylactic acid composites filled with silk fiber. Their results showed that hardness increased linearly with fiber content then decreased as fiber length exceeded 5 mm. Therefore, the amount and aspect ratio of short silk fibers in polydimethylsiloxane pads are essential factors achieving realistic skin simulation.

This study aims to develop a suture pad simulating human skin based on silk fiber reinforced polydimethylsiloxane. The effects of silk fiber content and aspect ratio on the mechanical properties of the composites are examined. The resulting suture pad is also evaluated by experienced medical staff.

# 2. Experimental

## 2.1. Materials

Materials used in this research included polydimethylsiloxane resin, silicone oil, and degummed silk fiber. Polydimethylsiloxane resin is condensation-cured room-temperature-vulcanized (RTV) silicone. Polydimethylsiloxane resin was supplied by Mat Wealth Co., Ltd from Taiwan under the product name RTV 2-230 MW. Silicone oil was obtained from Resin Rungart Co., Ltd. Silk fiber was degummed Thai silk purchased from Chul Thai Silk Co., Ltd. The silk fiber had a density of 1.230 g $cm^{-3}$ and diameter of 11.724 μm.

## 2.2. Specimen Preparation

Silk fiber reinforced polydimethylsiloxane composites were prepared with different aspect ratios and amounts of silk fiber to simulate the dermis. Silk fiber aspect ratios were in the range of 500–1500 and silk fiber content was in the range of 0-5 phr. Polydimethylsiloxane was mixed with 20 phr of silicone oil and then stirred to achieve uniform dispersion. Room temperature curing agent was added to the mixture at 1 phr and immediately stirred. Next, the silk was added to the mixture and carefully stirred. The compound was poured into an aluminum mold with dimensions of 15 x 15 x 1 cm. The mixture was put inside a vacuum oven at room temperature to remove void bubbles.

## 2.3. Suture Pad Fabrication

The suture pad was prepared with 2 layers for suture test evaluation. The first (dermis) layer was made from silk fiber reinforced polydimethylsiloxane composite with a thickness of about 2 mm. The second (subcutis) layer was made of 50% polydimethylsiloxane and 50% silicone oil, with a thickness of 8 mm as shown in Fig. 1.

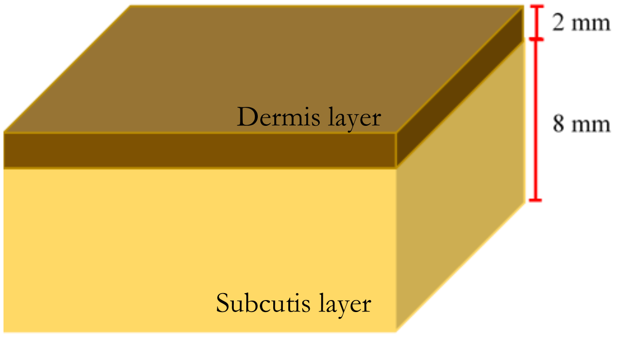


Fig. 1. Silk fiber reinforced polydimethylsiloxane suture pad.

### 2.4. Characterization

Density was measured by calculating the difference between theoretical and actual density. The composites were cut into small samples of 3 x 3 cm² and their actual density was measured using a hydrometer and the water displacement method. Actual density was calculated based on Eq. (1):

$$\rho_{actual} = \frac{A}{A-B} \times \rho_o \tag{1}$$

where $A$ and $B$ are the weight of the composite sample in the air and in water, respectively. $\rho_o$ is the density of water (1.00 g cm$^{-3}$)

Theoretical density was calculated following the mixing rule principal using to Eq. (2):

$$\rho_{theoretical} = \frac{1}{\frac{\omega_f}{\rho_f}+\frac{\omega_m}{\rho_m}} \tag{2}$$

where $\omega_f$ and $\omega_m$ are the weight fractions of silk fiber and polydimethylsiloxane, respectively. $\rho_f$ and $\rho_m$ represent the density of silk fiber (1.230 g cm$^{-3}$) and polydimethylsiloxane (1.128 g cm$^{-3}$), respectively.

For mechanical property evaluation, a sample was prepared following ASTM D 412 Type C [17]. The tensile test was conducted with an Instron Universal Testing Machine with a load of 1 kN and testing speed of 500 mm min$^{-1}$. Three samples were tested for each variable. Maximum strength, young modulus, and strain at break were then examined.

A hardness test was carried out with a Shore A durometer following ASTM D2240 [18]. The samples were tested five times for each variable at each different concentration of silk fiber reinforcement.

Samples of 3 x 3 cm were prepared to perform a suture tread resistance test. Two specimens were then sutured using suture equipment consisting of a sharp suture needle and thread of monofilament nylon NC 242 2-0 purchased from Nutri Plus Intertrade Co., Ltd. The sutured samples were tested for an extension of 0.5 cm while their resistance towards suture thread was observed.

## 3. Results and Discussion

### 3.1. Density Measurement of Silk Fiber Reinforced Polydimethylsiloxane Composites

Density measurement is used to analyze the dispersion of silk fiber within the polydimethylsiloxane matrix. The absence of air voids inside the composite sample implies an evendispersion of reinforcing filler in the matrix. The relative air void volume can be calculated from the difference between the theoretical and actual density of the silk fiber reinforced polydimethylsiloxane composite. The theoretical density of a composite is the maximum density it can achieve without voids. The actual density of the composite can be calculated in accordance with the Archimedes principle, in which the weight of water displaced is equal to the difference between the weight of the solid in air and water. The ratio of the weight of water displaced to the density of water is the same as the ratio of the weight of the sample to its density. The minimal differences between the theoretical and actual densities of the composites indicated low air content, thus implying well-fabricated samples. Theoretical density values were calculated according to the rule of mixture.

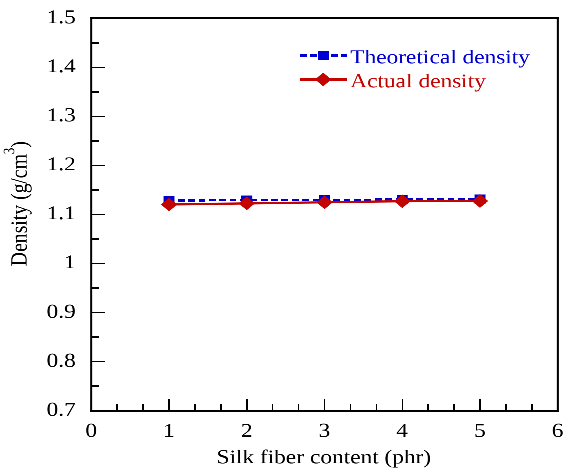


Fig. 2. Theoretical and actual densities of silk fiber reinforced polydimethylsiloxane composite with different fiber content.

Differences between theoretical and actual densities of silk fiber reinforced polydimethylsiloxane samples is presented in Fig. 2. There was no significant change in density across different silk fiber concentrations, which was due to the relatively parity between silk fiber and PDMS density.

Actual density was no different from calculated theoretical density, indicating relatively low air voids inside the composite samples. This result implied well prepared and well dispersed mixtures in the composites. Negligible air voids inside the samples show that the composites have almost none of the defects that commonly appear in polydimethylsiloxane products [19].

### 3.2. Mechanical Properties of Silk Fiber Reinforced Polydimethylsiloxane Composites

The tensile strength and modulus of silk fiber reinforced polydimethylsiloxane filled with 1 phr of silk fiber at different aspect ratios of 500, 1000, and 1500 were carried out, with results shown in Fig. 3. The results showed higher tensile strength with increased silk fiber aspect ratio. This result was expected, as fibers which adhere each other resist strain on the matrix. Thus, longer fibers are able to better reinforce the matrix against a tension load. The tensile strengths of the composites were 2.26, 2.37 and 3.11 MPa for the three different aspect ratios of 500, 1000 and 1500, respectively. As the aspect ratio of the fiber increased from 500 to 1000, tensile strength increased by 4%, while an increase from 500 to 1500 gave 37% more tensile strength. A similar result was reported by Valentini *et al.* [12].

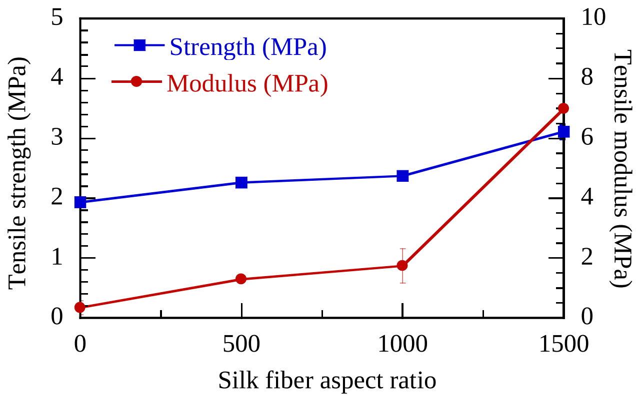


Fig. 3. Tensile strength and modulus of silk fiber reinforced polydimethylsiloxane with various silk fiber aspect ratios.

Tensile modulus or Young's modulus was calculated from the initial slope of the stress-strain curve. As seen in Fig. 3, the tensile modulus of silk fiber reinforced polydimethylsiloxane composites increased from 0.3 MPa for the unfilled network to 1.3 MPa at 1 phr of silk fiber with aspect ratio of 500. The tensile modulus increased modestly to 1.7 MPa at the aspect ratio of 1000 then jumped to 6.9 MPa at aspect ratio 1500. Valentini *et al.* reported a similar result; the tensile modulus increased substantially in conjunction with the fiber length [12]. This result implied that longer fibers could reduce the gaps in the composite network, thus improving the ability of the composite to withstand deformation upon tension load. However, fibers that were too long generated more air gaps as the became entangled, and thus mechanical properties decreased. Composites with longer fibers exhibited lower tensile modulus than those with shorter ones because fiber entanglement caused uneven distribution in the composite network [8]. Therefore, a decrease in tensile modulus indicates uneven distribution of fibers within the network. Our results suggested good silk fiber distribution within the polydimethylsiloxane composite.

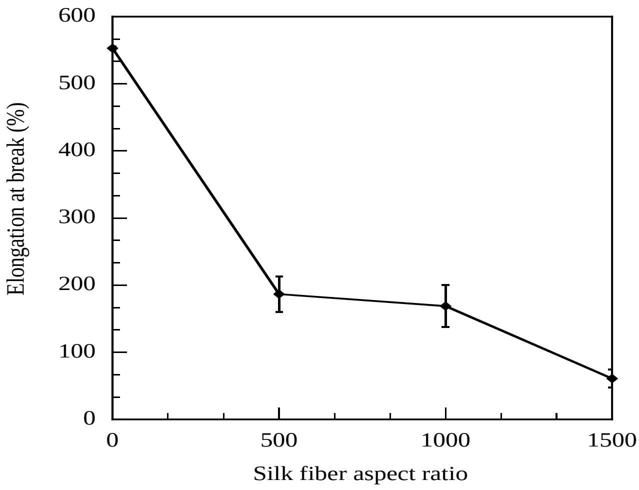


Fig. 4. Elongation at break of silk fiber reinforced polydimethylsiloxane with various silk fiber aspect ratios.

The elongation at break of silk fiber reinforced polydimethylsiloxane is also affected by fiber aspect ratio. As shown in Fig. 4, higher fiber aspect ratios resulted in decreased elongation at break values. Unfilled polydimethylsiloxane showed the highest elongation at break of 554%, which then decreases to 176%, 175%, and 55% as silk fiber with aspect ratios of 500, 1000 and 1500, respectively, is added. This was because the entangled fibers resisted the elongation of the composite.

From these results, the optimal fiber aspect ratio for further study of the effect of silk fiber content set at 1000 due to it having high enough tensile strength and modulus values. Longer fibers have high entanglement when mixed randomly inside the network [8]. This fiber entanglement made it too hard to penetrate the suture pad with thread and needle, and although shorter fiber reduced the probability of fiber entanglement, in principle the increased distance between each fiber would result in less entanglement and a less effective barrier to hold suture thread.

Figure 5 illustrates the relationship between silk fiber content, tensile strength and modulus of silk fiber reinforced polydimethylsiloxane composites.

It was found that tensile strength of the composite increased with fiber contents. As silk fiber content in polydimethylsiloxane composite increased from nothing to 1, 2, 3, 4 and 5 phr, the tensile strength of the composites increased from 1.93 MPa to 2.37, 2.46, 2.57, 3.02 and 3.63 MPa, respectively. The enhancement in tensile strength in this research was greater than that reported by Valentini *et al.,* in which the tensile strength of the polydimethylsiloxane composite with 10 mm silk fiber at 1% concentration was only 1.2 MPa, which is 50% lower than that value obtained in this research [12].

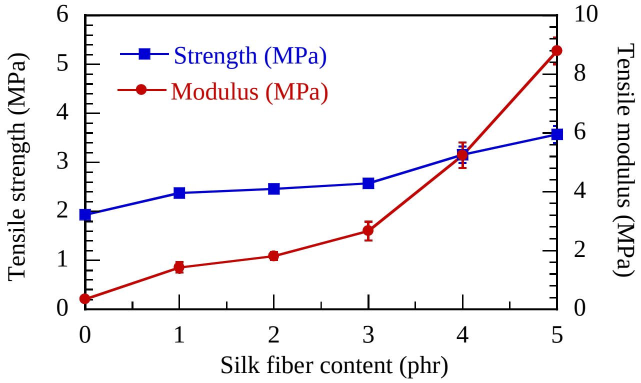


Fig. 5. Tensile strength and modulus of silk fiber reinforced polydimethylsiloxane with different silk fiber content.

Tensile modulus of polydimethylsiloxane reinforced with short silk fiber with various fiber content is also illustrated in Fig. 5. From the figure, the tensile modulus of the composites increased alongside silk fiber content. The increasing tensile modulus implied good interaction between polydimethylsiloxane with silk fibers as filler reinforcement. Thus, an increase of silk fiber content produced a stiffer composite. The modulus values of silk fiber reinforced polydimethylsiloxane obtained from this research were relatively close to the modulus of real thigh skin, being in the range of 2-12 MPa [20].

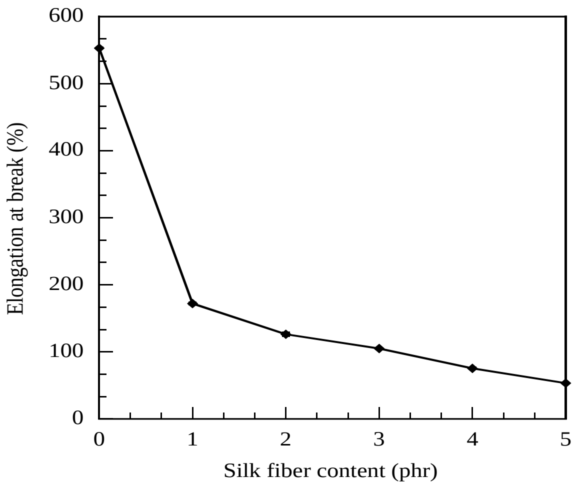


Fig. 6. Elongation at break of silk fiber reinforced polydimethylsiloxane with different silk fiber content.

Figure 6 shows the relationship between elongation at break of silk fiber reinforced polydimethylsiloxane and silk fiber content, with elongation at break decreasing with fiber content. Elongation at break was measured as 553, 172, 126, 104, 75 and 53 in composites with 0, 1, 2, 3, 4 and 5 phr of silk fiber, respectively. This result is due to the semi-crystalline property of silk fiber with elongation at 4-26% [11]. A similar result with short fiber reinforced rubber was reported by Sang-Ryeoul Ryu *et al.*; while fiber aspect ratio and content increase, the distance between rubber molecules decrease, which causes a decrease in elongation at break [8].

The tensile strength and modulus of real human skin are in the range of 1.2 to 30 MPa and 2 to 12 MPa, respectively. These mechanical properties have such a wide range as they are affected by many factors such as skin part, age and sample freshness [20, 21]. Because of this, real human skin's mechanical properties cannot be defined as an exact value. The mechanical properties of the polydimethylsiloxane reinforced with silk fiber in this research were in the same range as those of real human skin. This result suggested that the silk fiber reinforced polydimethylsiloxane composite showed good suitability to simulate real human skin for suture pads.

### 3.3. Hardness of Silk Fiber Reinforced Polydimethylsiloxane Composites

The hardness test was carried out using a Shore A durometer with composite samples with different silk fiber content and aspect ratios. Table 1 shows the hardness values of the composites.

Table 1. The effect of varying fiber aspect ratio and content on the hardness of silk fiber reinforced polydimethylsiloxane composites.

| Silk fiber content (phr) | Silk fiber aspect ratio | Shore A value (HA) |
|---|---|---|
| 0 | 0 | 14.9 ± 1.4 |
| 1 | 500 | 31.8 ± 5.5 |
| 1 | 1000 | 34.9 ± 3.9 |
| 1 | 1500 | 48.3 ± 4.4 |
| 2 | 1000 | 40.5 ± 5.6 |
| 3 | 1000 | 49.5 ± 6.1 |
| 4 | 1000 | 55.7 ± 3.3 |
| 5 | 1000 | 64.4 ± 1.7 |

It is clear that the hardness of the composites was improved by 113-224% with only 1 phr of silk fiber. Moreover, the hardness values of the composites were also enhanced by 113-332% with the incorporation of 1-5 phr silk fiber with an aspect ratio of 1000. Higher aspect ratios and content provided harder composites as a result of the high entanglement of the rigid fibers [8]. High entanglement of fiber was the main reason for the higher strength of the material, but it also makes it have low elongation at break, as shown in Fig. 4. The hardness of the material plays an important role for its application as suture pads. The texture of the suture pad needs to be similar to real human skin. A hardness test of human skin conducted by S. Derler *et al.* showed that average human skin hardness is approximately 40 HA [22]. Therefore, polydimethylsiloxane composite reinforced with 2 phr of silk fiber, with a hardness value of 40.5 ± 5.6, is about as hard as real human skin.

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### 3.4. Tear Resistance of Silk Fiber Reinforced Polydimethylsiloxane Composites

The tear resistance test was conducted by medical staff and doctors with a sample sutured using nylon suture thread. Our silk fiber reinforced polydimethylsiloxane composite exhibited better suture thread resistance than other suture pads available commercially at the time. However, the continuous addition of silk fiber into the polydimethylsiloxane increased the stiffness and hardness of the sample composite, which in turn made it hard to suture.

A practical suturing procedure was conducted to determine an appropriate hardness as well as the theoretical comparison to real human skin described in section 3.3. The suturing process requires the needle and nylon thread to easily penetrate the suture pad, while not adversely affecting the overall integrity of the samples. Composite samples with lower silk fiber content were softer, which allowed the suture needle and nylon thread to penetrate the network. On the other hand, this softer material showed low durability in the suture thread resistance test shown in Fig. 7.

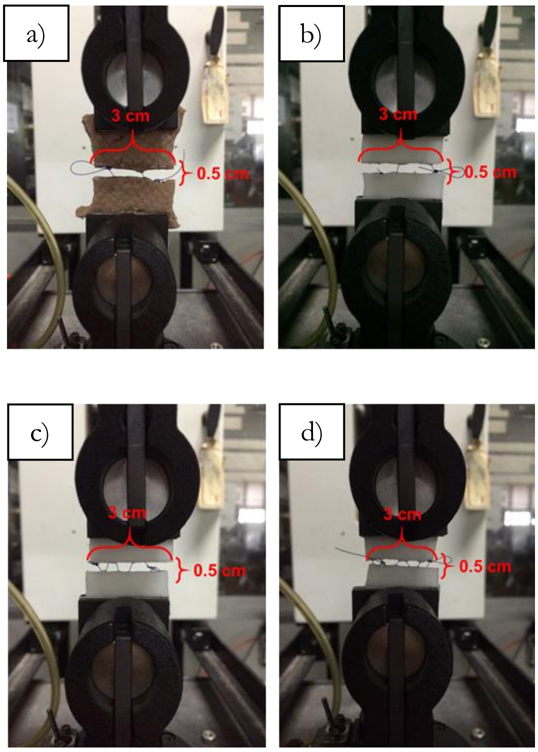


Fig. 7. Suture thread resistance in a) a commercial suture pad, b) 1 phr, c) 2 phr, and d) 3 phr of silk fiber reinforced polydimethylsiloxane composites.

At higher fiber concentrations, the composites were hard to suture because the distance between the fiber was minimal and its entanglement obstructed the needle and thread.

### 3.5. Physical Evaluation Silk Fiber Reinforced Polydimethylsiloxane Suture Pad

Suture pads with two different layers representing dermis and subcutis layers were fabricated. The upper dermis layer was produced from polydimethylsiloxane reinforced with 2 phr of silk fiber whereas the subcutis layer was fabricated from polydimethylsiloxane without silk fiber. The upper layer is flexible but still be able to maintain a hardness similar to that of real human skin. The flexibility of the suture pad lies in the lower layer since the upper layer only about 2 mm thick. A suturing evaluation was performed on the suture pad with a sharp needle and nylon thread.

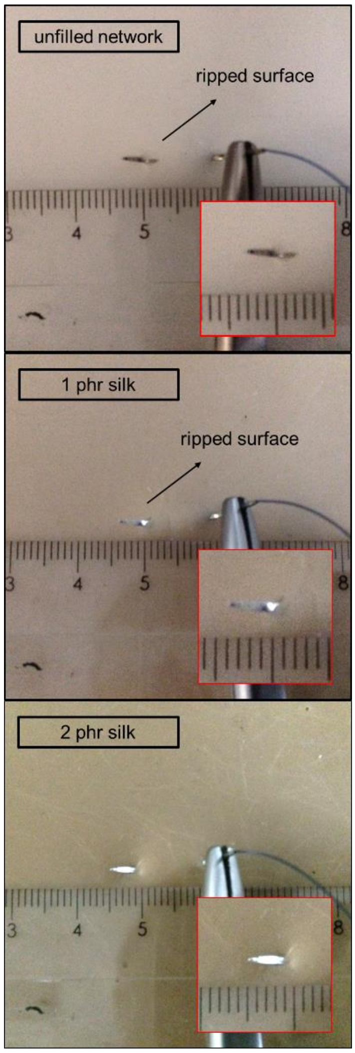


Fig. 8. Suture equipment evaluation of unfilled and filled networks of polydimethylsiloxane.

The suturing test evaluates the durability of the suture pad against suture needles commonly used for human skin.

As shown in Fig. 8, the suturing process left unfilled polydimethylsiloxane with a ripped surface, whereas the silk fiber reinforced polydimethylsiloxane showed a less ripped surface, indicating an enhancement in the tear resistance of the suture pad with the addition of silk fiber. These results suggested that the silk fiber played a role as a barrier against the suture needle. The polydimethylsiloxane filled with 2 phr of silk fiber showed an absence of ripped surfaces, which implied the composite with 2 phr of silk fiber has enough durability for application as a suture pad.

The material cost of a 10 x 10 cm suture pad made of silk fiber reinforced polydimethylsiloxane having a was estimated to be only \$0.0143 per $cm^2$. In comparison, the market prices of some commercially available suture pads iare shown in Table 2. It is clear that cost of the suture pad developed from this research is much lower than commercially available suture pads.

Table 2. Price list of commercially available suture pads.

| Product name | Price (\$ $cm^{-2}$) | Ref |
|---|---|---|
| Present study (material cost) | 0.0143 | - |
| Ergode | 0.037 | [23] |
| BornToEdu | 0.067 | [23] |
| Brosan | 0.11 | [23] |
| Skin Model Suture | 0.2 | [24] |
| Skin Suture Pad | 0.29 | [24] |

## 4. Conclusions

In this study, the successful development of a suture pad made of polydimethylsiloxane reinforced with silk fiber is outlined. The effects of silk fiber aspect ratio and content on the tensile properties, hardness and tear resistance of the composite were investigated. Density measurement confirms good dispersion of silk fibers in the polydimethylsiloxane network, showing negligible air voids inside the composite samples. Tensile strength and modulus of the composite were enhanced with the addition of silk fibers, increasing in tandem with fiber aspect ratio and content, whereas elongation at break of the composites decreased. This result suggested splendid interfacial bonding between silk fiber and polydimethylsiloxane. Furthermore, a tear resistance test using suture thread revealed significant enhancements in durability, although the excessive addition of silk fibers made the composite stiffer and therefore harder to suture. The hardness of polydimethylsiloxane reinforced with 2 phr of silk fibers was most similar to that of human skin. Therefore, the developed silk fiber reinforced polydimethylsiloxane showed high potential for use as a suture pad for medical trainees to practice on.

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