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Research Article

The Effect of Vulcanization Temperature on the Properties of Natural Rubber Latex to Prepare the Suturing Training Pad

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ABSTRACT

This study focuses on the controlled curing method for preparing natural rubber latex as a suturing training pad. Local natural rubber latex was transformed into pre-vulcanized rubber latex using a chemical. The natural rubber sheets were cured at temperatures of 30 ± 2 °C, 40 ± 2 °C, and 50 ± 2 °C for 7 days under controlled conditions. Various properties, including stress-strain curves, hardness, crosslink density, swelling, and crosslinking behavior, analyzed using FT-IR spectra, were examined. The FT-IR spectra indicated a decrease in the signal of the C=C bond and an increase in the C-S bond, demonstrating the crosslinking behavior. As the curing temperature increased, crosslinking also increased, resulting in enhanced stress-strain properties at break, higher Young's modulus, greater strain hardening, and increased hardness. Additionally, crosslink density increased while swelling decreased. A curing temperature of 30 ± 2 °C was selected for preparing the natural rubber sheet for use as a suturing training pad. The performance of this rubber sheet was tested and compared with a commercial silicone skin suture practice sheet. The results showed that no cracking occurred around the pinholes, and the rubber surface could be sutured without tearing. A nylon suture placed on the rubber surface demonstrated a tight closure, similar to that of the silicone skin suture practice sheet.

1. Introduction

Suturing skills are crucial for students training in medical labs. To practice suturing, these labs often use simulation materials designed to mimic real skin. For instance, Cheung *et al*. (2014) created a simulation material using 3D modeling software, which was then printed with silicone rubber. Boyajian *et al*. (2019) explored a method for creating suture training materials using medical-grade silicone and 3D printing techniques. Similarly, Gallagher *et al*. (2020) developed a silicone material designed specifically for skin suture task training, utilizing a 3D printer. In addition, Serdinšek *et al*. (2019) constructed a model of the pelvic floor, including the uterus/vaginal cuff, bladder, both ureters, and associated ligaments using a variety of materials such as sponge foam paper, felt fabric, chenille stems, foam, plastic ties, and fabric glue. Moreover, Khantasa-Ard (2024) stated that the materials used to create the suture training pad include

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a plate of polyurethane leather. Meanwhile, polymer suture materials are often expensive and involve complex manufacturing processes, and sponge materials are prone to tearing. Despite these advances, animal materials are still commonly used for suturing practice. For example, Wei *et al*. (2014) trained students using chicken thighs, while La and Caruso (2013) employed porcine models for suturing training. However, these animal-based simulation materials have significant downsides, including their perishable nature and degradation over time. To address these issues, there is growing interest in using local natural rubber latex as an alternative to animal, polymer, and sponge materials for suturing practice.

Natural rubber sheets possess excellent elastic properties, characterized by a flexible texture due to rubber chain interactions and crosslinking (Wietor and Sijbesma, 2008; Smitthipong *et al*., 2013; Suntako, 2014; Xu *et al*., 2016). Additionally, they are low-cost materials. Natural rubber has been used to create medical training materials, such as sponges designed for practicing basic surgical skills (Gonzalez-Navarro *et al*., 2021; Ige *et al*., 2012). Additionally, a blend of silicone rubber and natural rubber has been developed as a material for birthing models used in childbirth simulation (Panmanee *et al*., 2023). Furthermore, using thin sheets of natural rubber as suturing materials offers a viable option for medical students, providing them with an accessible tool for practice. This approach also adds value by creating a new product through a simple manufacturing process.

This project aims to develop a suturing practice material sheet using locally sourced natural rubber latex. The approach involves a straightforward production process and a controlled curing method, with the intent of creating an alternative to common skin simulation materials used in medical laboratories. Fourier Transform Infrared Spectroscopy (FT-IR) was employed to investigate the crosslinking of the rubber sheets, as well as to analyze the crosslink density and swelling properties related to the interactions within the rubber chains via a sulfur vulcanization system. Additionally, the tensile strength and hardness properties were examined to assess the stability of the rubber sheet's surface. The performance of the natural rubber sheet was compared to that of a commercial silicone skin suture practice sheet, specifically regarding the effects of pinhole and nylon sutures on the surface. As a result, the natural rubber sheet was effectively developed as a suturing training pad for medical students' laboratories.

2. Materials and Methods

2.1 Controlling the curing temperature for preparing natural rubber latex as a suturing training sheet

The local natural rubber latex was prepared as a concentrated rubber latex and mixed with a chemical formulation, as detailed in Table 1. This mixture produced pre-vulcanized rubber latex at a concentration of 40%. A sheet mold was filled with the pre-vulcanized rubber latex to create a natural rubber sheet, which served as suturing training material with a thickness of 1 mm and 6.0 ± 2.0 mm for the samples used for hardness properties. The sheets were then dried in a hot air oven at temperatures of 30 ± 2 °C, 40 ± 2 °C, and 50 ± 2 °C for 7 days under controlled curing conditions. Once dried, the natural rubber sheets were removed from the mold, resulting in suturing training sheets.

Table 1 The chemical formulation to prepare the pre-vulcanized rubber latex

Materials and Chemicals Dispersion	Source	Parts per hundred rubber [phr]	*Average Particle size
40 % Natural rubber latex concentration	Local Narathiwat province, Thailand	100	-
50% white seal Zine Oxide dispersion	Polymer Innovation Co., Ltd. Thailand	2.0 ± 0.2	0.5 microns
60% ultra fine Sulfur dispersion	Polymer Innovation Co., Ltd. Thailand	1.0 ± 0.2	< 1.5 microns
50% ZMBT, Zinc 2-Mercaptobenzo- thiazole dispersion	Polymer Innovation Co., Ltd. Thailand	0.8 ± 0.02	< 1.5 microns
50% ZDEC, Zinc Diethyldithiocarba mate dispersion	Polymer Innovation Co., Ltd. Thailand	0.6 ± 0.02	< 1.5 microns

* Data sheets

2.2 Fourier transform infrared spectroscopy (FT-IR) analyzed the crosslink reaction

The natural rubber sheets were cured using a sulfur vulcanization system and a temperature-controlled curing method to investigate the changes in crosslink reactions involving the C=C bond and C-S bond within the natural rubber. Fourier Transform Infrared (FT-IR) spectroscopy was employed to identify the signal peaks corresponding to the C=C and C-S bonds. The rubber sheet samples were cut into 1 cm x 1 cm pieces. The attenuated total reflection (ATR) mode on a Bruker Tensor spectrometer was utilized, covering a wavenumber range from 4000.12 to 400.15 cm^{-1}, with a resolution of 2 cm^{-1}. The FT-IR spectra were analyzed using OPUS software and recorded.

2.3 The stress-strain properties of a natural rubber sheet

The tensile testing machine (model H 10KS, manufactured by Hounsfield Test Equipment, Tinius Olsen Ltd, UK) The testing samples were prepared using die D and in accordance with ASTM D412. The tensile testing machine was used at a crosshead speed of 50 ± 5 mm/min for 1 mm thick rubber sheets.

2.4 Young modulus at linear proportionality or elastic region

At low strain, the tensile behavior of natural rubber sheets follows Hooke's law. The modulus of elasticity or Young's modulus was calculated in terms of slope on the stress-strain curve in the linear proportionality or elastic region as follows in Eq. (1) (Roylance, 2001)

$$E = \frac{Stress}{Strain} = \frac{\sigma}{\varepsilon} = slope = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (1)$$

where E is Young's modulus or modulus of elasticity, σ is stress (MPa), ε is strain

2.5 Strain hardening of the stress-strain curve

The resistance to deformation was measured in terms of the strain hardening parameter of the stress-strain curve, according to the equation by Roylance (2001) is

$$\log(stress) = \log(c) + n\log(strain) \quad (2)$$

$$\log(\sigma) = \log(c) + n\log(\varepsilon) \quad (3)$$

where n is strain hardening parameter, c is constant, σ is stress (MPa), ε is strain

2.6 The hardness properties on a natural rubber sheet surface

The shore hardness properties of samples (rubber sheet and silicone sheet) were measured according to ASTM D2240 using a type A Durometer (Digital hardness tester, toyoseiki Co. Ltd, Japan). The testing was conducted at 26 ± 2 °C room temperature with a constant load applied to samples that were 6.0 ± 2.0 mm in thickness. Three different points on the surface of samples were measured. After the indenter made contact with the sample surface for 30 second, the hardness readings should be recorded. Hardness tests of the samples were reported on the Shore A scale.

2.7 Determination of the crosslink density and swelling properties

Crosslink density of a natural rubber sheet was determined according to ASTM: D3616 – 95 and the Flory–Rehner equation (Paul and John, 1943; Xu *et al*., 2016; Kumnuantip and Sombatsompop, 2003) as follows in Eq. (4) and (5)

$$\frac{-\ln(1-V_r) - V_r - \chi V_r^2}{2V_s\left(V_r^{\frac{1}{3}} - \frac{2V_r}{f}\right)} = \eta_{swell} \quad (4)$$

where V_r is volume fraction of rubber in swollen gel, χ is rubber-toluene solvent interaction parameter (0.3795), V_s is molar volume of the toluene (106.2 cm^3/mol), η_{swell} is cross-link density of the rubber (mol/cm^3), f is functionality of the crosslinks (being 4 for sulfur curing system)

$$V_r = \frac{\frac{w_d - w_f}{\rho_r}}{\frac{w_d - w_f}{\rho_r} + \frac{w_s - w_d}{\rho_s}} \quad (5)$$

where w_d is the weight of the de-swollen sample, w_f is the weight of the filler in the compound, w_s is the weight of the swollen sample, ρ_s is the density of the toluene solvent (0.87 g/cm^3), ρ_r is the density of the rubber (0.91 g/cm^3)

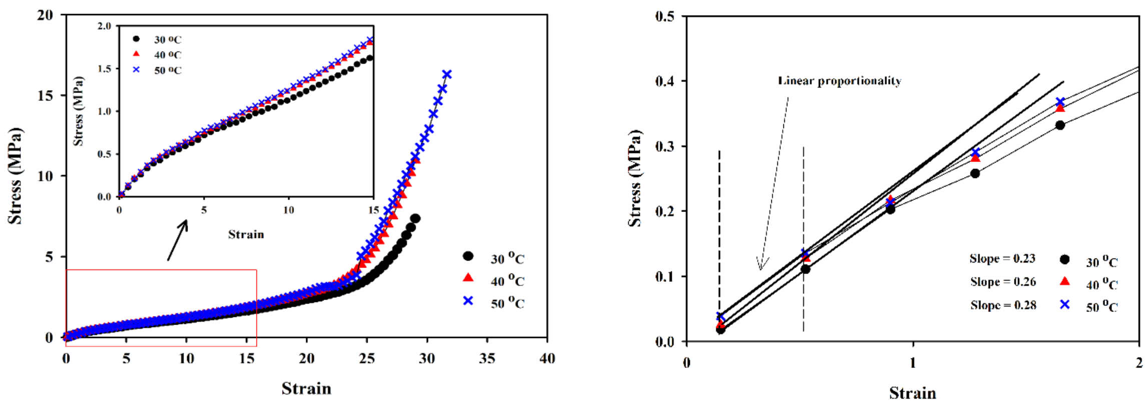
The swelling behavior of a natural rubber sheet was investigated by cutting the sheet and weighing it to 0.40 ± 2 g. The samples were immersed in toluene solvent in a 25 mL bottle for 48 h at 25 ± 2 °C. The weight of samples was measured before immersion in the toluene solvent (dry samples) and after immersion in toluene (swollen samples). The swollen samples were taken out, and excess solvent on the surface was removed and weighed. The swelling percent at a given time (Q_t) (Kumnuantip and Sombatsompop, 2003) was calculated from Eq. (6) and according to ASTM: D3616 – 95.

$$Q_t = \frac{\frac{(w_t - w_o)}{w_o}}{M_w} \times 100 \quad (6)$$

where w_o is the weight of dry sample, w_t is the weight of swollen sample, M_w is the molar mass of toluene (92.14 g/mol)

3. Results and Discussion

The natural rubber sheet was vulcanized using a sulfur cure system at temperatures of 30 ± 2 °C, 40 ± 2 °C, and 50 ± 2 °C, following a controlled curing temperature method. The properties of the stress-strain curve (Fig. 1(a)) indicated that the stress at break increased, while Young's modulus, represented by the slope of the stress-strain curve in the linear proportionality (elastic region), also showed an increase (Fig. 1(b) and Table 2). Additionally, the strain hardening parameter increased with rising curing temperatures (Fig. 2 and Table 2).



(a) (b)

Figure 1 The stress-strain curve of a natural rubber sheet was cured at 30 ± 2 °C, 40 ± 2 °C, 50 ± 2 °C using sulfur vulcanization system.

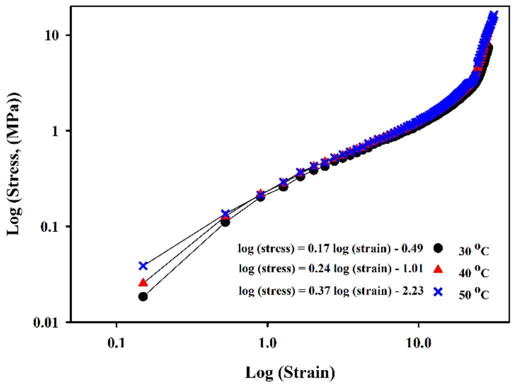


Figure 2 Strain hardening parameter of the stress-strain curve (log) of a natural rubber sheet was cured at 30 ± 2 °C, 40 ± 2 °C, 50 ± 2 °C using sulfur vulcanization system.

Table 2 The Young's modulus at linear proportionality and strain hardening parameter of a natural rubber sheet

Curing temperature (°C)	Young's modulus, E (MPa)	Strain hardening parameter, n
30	0.23	0.17
40	0.26	0.24
50	0.28	0.37

Meanwhile, the hardness properties of the surface of a rubber sheet demonstrated that an increase in curing temperature resulted in higher hardness. This was compared with the hardness properties on the surface of a silicone skin suture practice sheet (a commercial product) (Fig. 3).

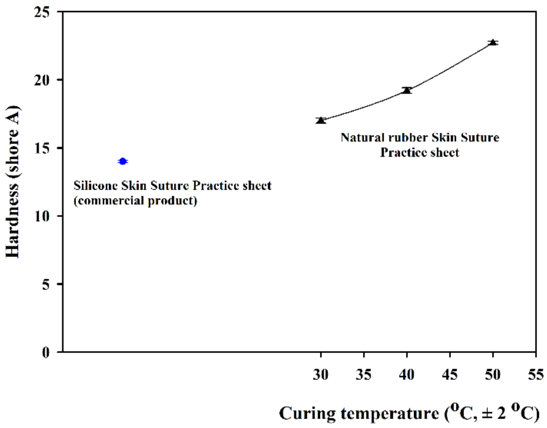


Figure 3 The hardness properties and a curing temperature at 30 ± 2 °C, 40 ± 2 °C, 50 ± 2 °C using sulfur vulcanization system of a natural rubber sheet and silicone skin suture practice sheet (commercial product)

The crosslinking density and swelling properties of the rubber sheet (Fig. 4) indicate that the crosslink density increased while the swelling decreased as the curing temperature increased.

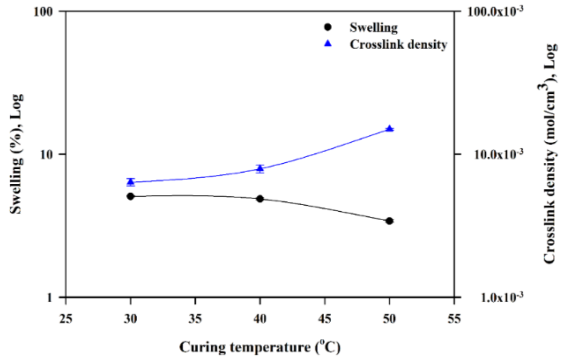


Figure 4 The crosslink density and swelling properties of a natural rubber sheet

FT-IR spectra (Fig. 5) and Table 3 showed that the absorbance peak at 1664.44 cm^{-1} indicates the C=C bond (Coran, 1965; Kishore and Pandey, 1986; Lu and Hsu, 1987; Rai *et al.,* 2006; Posadas *et al.,* 2010; Milani *et al.,* 2013; Sébastien *et al.,* 2015; Kruželák *et al.*, 2016; Bornstein and Pazur, 2020) decreased while the peak at 1134.58 cm^{-1} assigns the C-S bond (Coran, 1965; Kishore and Pandey, 1986; Lu and Hsu, 1987; Rai *et al.*, 2006; Posadas *et al.*, 2010; Milani *et al.*, 2013; Sébastien *et al.*, 2015; Kruželák *et al.*, 2016; Bornstein and Pazur, 2020) increased as the curing temperature increased.

Table 3 The absorbance (a.u.) ratio of FT-IR spectra at C-S bond and C=C bond of a natural rubber sheet

Curing temperature (°C)	Absorbance (a.u.) ratio	
	C-S bond at 1134.58 cm^{-1}	C=C bond at 1664.44 cm^{-1}
30	1.10	1.22
40	1.29	1.09
50	1.34	1.05

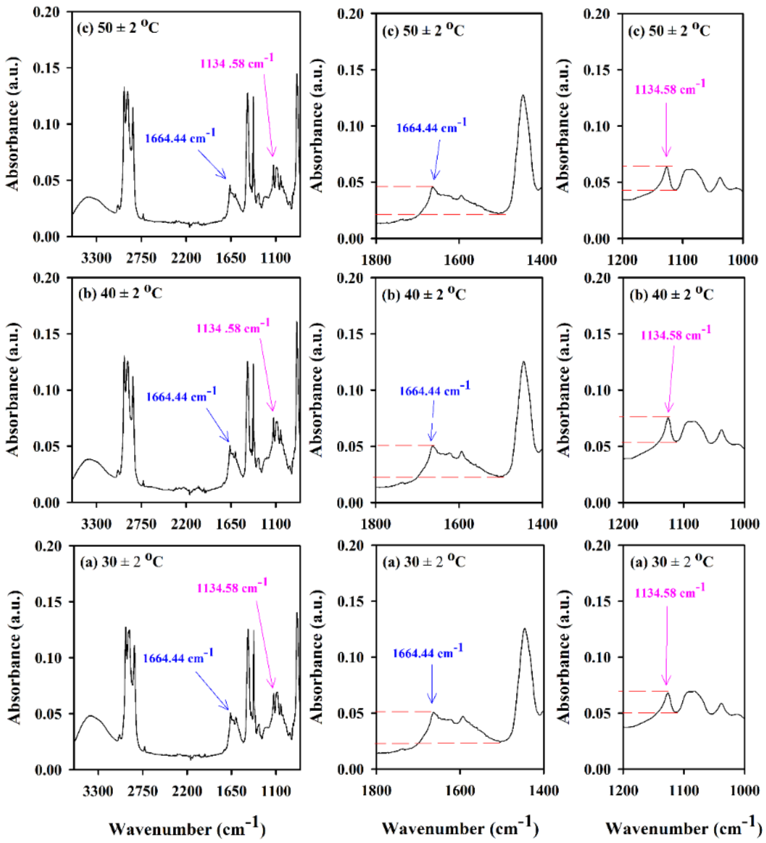


Figure 5 FT-IR of a natural rubber sheet was cured at (a) 30 ± 2 °C, (b) 40 ± 2 °C, (c) 50 ± 2 °C

(a) 1 day (b) 3 days (c) 7 days

Figure 6 The 1 mm thickness samples of the natural rubber sheet were cured at 30 ± 2 °C for 7 days. (a) 1 day, (b) 3 days, (c) 7 days

The application of a natural rubber sheet as a suturing training pad was tested and compared to a silicone skin suture practice sheet (a commercial product). The natural rubber sheet was cured at a temperature of 30 ± 2 °C (as shown in Fig. 6), using a sulfur vulcanization. This method was selected to prepare the suturing training sheet, as illustrated in Fig. 7, because the hardness properties of the rubber sheet closely resemble those of the silicone skin suture practice sheet. Furthermore, the stress-strain curve properties of the rubber sheet indicate that its Young's modulus, hardening parameter, and hardness are low. As a result, it is well-suited for easy suturing with a pinhole and nylon suture on its surface.

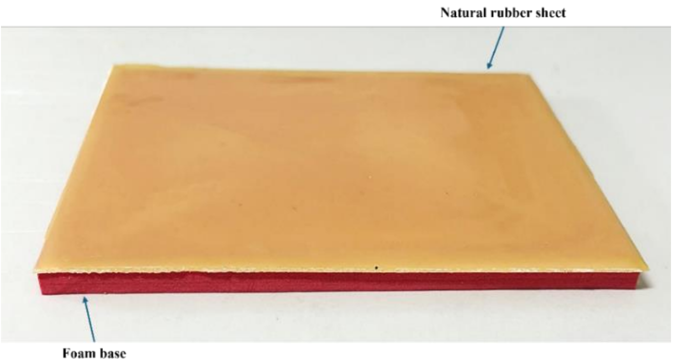
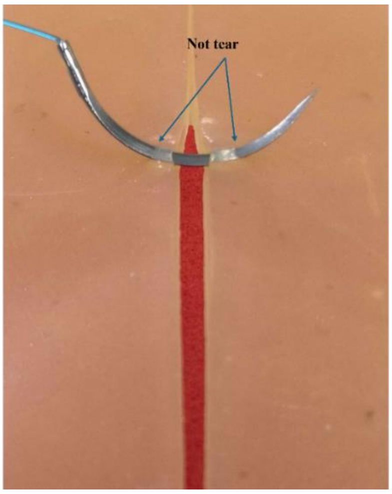
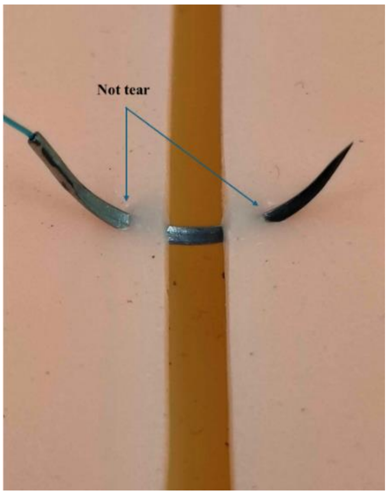


Figure 7 The natural rubber sheet of 1 mm thickness on the foam base is used as a suturing training sheet.

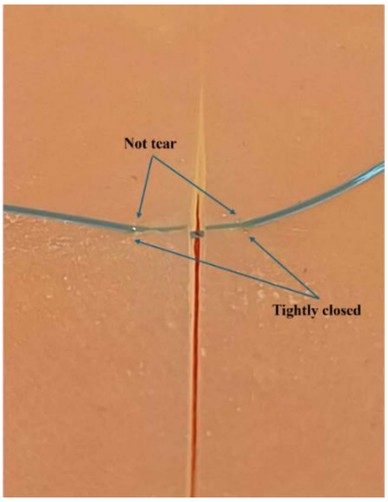


(a) Natural rubber sheet surface

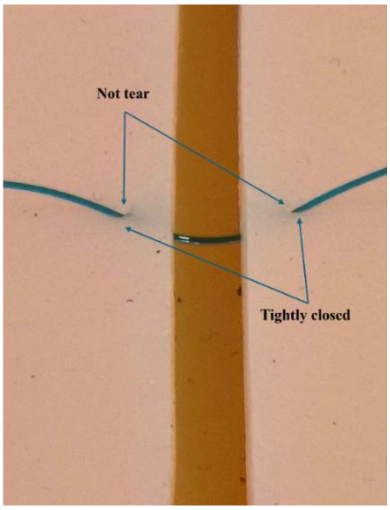


(b) Silicone skin suture practice sheet surface (commercial product)

Figure 8 Photo (10 x optical) of a surface around the pinhole via sutured (a) natural rubber sheet and (b) silicone skin suture practice sheet (commercial product)



(a) Natural rubber sheet surface



(b) Silicone skin suture practice sheet surface (commercial product)

Figure 9 Photo (10 x optical) presented tightly closed on around nylon suture of (a) natural rubber sheet surface and (b) silicone skin suture practice sheet surface (commercial product) via sutured

The natural rubber sheet was cut in half with a scalpel blade, as shown in Fig. 8(a). The two separated parts were then sutured together, demonstrating that the area around the pinhole did not tear, thanks to the elastic properties of the material, which allowed it to recover with linear proportionality. Figure 9 illustrates the tightly closed area formed by the nylon sutures. A comparison of the surfaces of a natural rubber sheet (Figs. 8(a) and 9(a)) and a silicone suture practice sheet (a commercial product) (Figs. 8(b) and 9(b)) revealed similar characteristics during suturing with a pinhole and nylon sutures. This indicates that natural rubber sheets are effective for use as suturing training materials.

For discussion, the sulfur vulcanization of natural rubber mainly occurred on the rubber chain at C=C bond (Coran, 1965; Kishore and Pandey, 1986; Lu and Hsu, 1987; Rai *et al*., 2006; Posadas *et al*., 2010; Milani *et al*., 2013; Smitthipong *et al*., 2013; Sébastien *et al*., 2015; Kruželák *et al*., 2016; Bornstein and Pazur, 2020). The increase in curing temperature resulting in the reaction between sulfur and C=C bond increased. FT-IR spectra showed that an unsaturated C=C (Str.) bond converted to a saturated C-C bond and C-S bond (Coran, 1965; Kishore and Pandey, 1986; Lu and Hsu, 1987; Rai *et al*., 2006; Posadas *et al*., 2010; Milani *et al*., 2013; Smitthipong *et al*., 2013; Sébastien *et al*., 2015; Kruželák *et al*., 2016; Bornstein and Pazur, 2020), confirming the crosslink reaction in the natural rubber chain. Based on the analysis of crosslink density and swelling properties, the low swelling of rubber sheets suggests a rigid movement of the rubber chain segments due to a high level of crosslinking. Conversely, high swelling indicates lower crosslinking and allows for easier movement of the entangled rubber chain segments. Consequently, as the crosslink density increases, the mechanical properties of natural rubber sheets improve, including stress-strain at break, Young's modulus, strain hardening, and hardness. Additionally, during the suturing process, the natural rubber sheet exhibited durability around pinholes and nylon sutures on its surface. It did not tear and maintained elastic behavior in a linear proportional manner, thanks to the effective interactions of crosslinks within the natural rubber chains, achieved through optimized curing chemicals. Natural rubber sheets offer numerous advantages and properties that make them quite appealing. They can serve as a new type of suturing training material, providing a substitute for traditional skin simulation materials used in suturing training for skilled students. These suturing training sheets were crafted using local natural rubber latex at a temperature of 30 ± 2 °C, or room temperature. This approach not only reduces costs and energy consumption but also simplifies the production process, making it more economical compared to commercial silicone sheet products (priced at 6 USD per piece). By utilizing local natural rubber latex, this method also adds value to the material.

4. Conclusion

The development process to prepare local natural rubber latex involved using controlled curing temperature to create a suturing training material. This material aims to replace a common skin simulation product used in medical students' labs. The local natural rubber latex was mixed with chemicals to produce pre-vulcanized natural rubber sheets at controlled curing temperatures of 30 ± 2 °C, 40 ± 2 °C, and 50 ± 2 °C for 7 days. Various properties of the rubber sheets were studied, including the stress-strain curve, stress-strain at break, Young's modulus, strain hardening, hardness, crosslink density, and swelling properties. Additionally, the crosslinking reaction was analyzed using FT-IR spectroscopy. The results indicated that increasing the curing temperature led to improvements in stress-strain at break, Young's modulus in the elastic region, strain hardening, and hardness properties. As the crosslink density increased, the swelling of the rubber sheets decreased as well. FT-IR spectra showed a decrease in the absorbance peak of the C=C bond and an increase in the C-S bond. The optimal process identified was curing at 30 ± 2 °C for 7 days to prepare the natural rubber sheet as a suturing training material. A comparative study of the rubber sheets during suturing revealed that their surface properties were similar to those of a commercially available silicone skin suture practice sheet. Consequently, natural rubber sheets can effectively replace common skin simulation materials used for suturing training. This application not only helps add value to local natural rubber latex but also introduces a cost-effective product that is easy to prepare at low temperatures, ultimately saving costs and energy. The cost of the natural rubber sheets for suturing training is approximately $0.10 for 3 pieces, significantly lower than that of a silicone skin suture practice sheet, which costs $18 for 3 pieces.

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