journal of the mechanical behavior of biomedical materials 160 (2024) 106716

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Mechanical and optical properties assessment of an innovative PDMS/beeswax composite for a wide range of applications

Ronaldo Ariati [a], Andrews Souza [b,d,h], Maria Souza [b], Andrea Zille [c], Delfim Soares [d,e], Rui Lima [b,f,g], João Ribeiro [a,h,i,*]

[a] *Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253, Bragança, Portugal*
[b] *MEtRICs, Mechanical Engineering Department, University of Minho, Campus de Azurém, 4800-058, Guimarães, Portugal*
[c] *2C2T - Centre for Textile Science and Technology, University of Minho, Campus de Azurém, 4800-058, Guimarães, Portugal*
[d] *CMEMS – UMinho, Universidade Do Minho, 4800-058, Guimarães, Portugal*
[e] *LABBELS – Associate Laboratory, Braga, Guimarães, Portugal*
[f] *CEFT, Faculdade de Engenharia da Universidade Do Porto (FEUP), Rua Roberto Frias, 4200-465, Porto, Portugal*
[g] *ALiCE, Faculty of Engineering, University of Porto, Porto, Portugal*
[h] *Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253, Bragança, Portugal*
[i] *Laboratório Associado para a Sustentabilidade e Tecnologia Em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253, Bragança, Portugal*

ARTICLE INFO

Keywords:
Polydimethylsiloxane (PDMS)
Beeswax
Mechanical properties
Optical properties
Wettability
Biocompatibility
Biodegradable

ABSTRACT

Polydimethylsiloxane (PDMS) is an elastomer that has received primary attention from researchers due to its excellent physical, chemical, and thermal properties, together with biocompatibility and high flexibility properties. Another material that has been receiving attention is beeswax because it is a natural raw material, extremely ductile, and biodegradable, with peculiar hydrophobic properties. These materials are applied in hydrophobic coatings, clear films for foods, and films with controllable transparency. However, there is no study with a wide range of mechanical, optical, and wettability tests, and with various proportions of beeswax reported to date. Thus, we report an experimental study of these properties of pure PDMS with the addition of beeswax and manufactured in a multifunctional vacuum chamber. In this study, we report in a tensile test a 37% increase in deformation of a sample containing 1% beeswax (BW1%) when compared to pure PDMS (BW0%). The Shore A hardness test revealed a 27% increase in the BW8% sample compared to BW0%. In the optical test, the samples were subjected to a temperature of 80 °C and the BW1% sample increased 30% in transmittance when compared to room temperature making it as transparent as BW0% in the visible region. The thermogravimetric analysis showed thermal stability of the BW8% composite up to a temperature of 200 °C. The dynamic mechanical analysis test revealed a 100% increase in the storage modulus of the BW8% composite. Finally, in the wettability test, the composite BW8% presented a contact angle with water of 145°. As a result of this wide range of tests, it is possible to increase the hydrophobic properties of PDMS with beeswax and the composite has great potential for application in smart devices, food and medicines packaging films, and films with controllable transparency, water-repellent surfaces, and anti-corrosive coatings.

1. Introduction

Smart materials have been studied by researchers due to the properties of absorption and transmission of light with external stimuli, thus creating new mechanisms, such as transmittance devices that allow users to control the incidence of light and heat (Tan et al., 2021; Wang et al., 2021; Liu et al., 2021). Polydimethylsiloxane (PDMS) has received primary attention for a wide range of applications, due to its excellent features of transparency, biocompatibility, and flexibility, among other properties (Liu et al., 2021; Yun et al., 2022; Zhang et al., 2017; Oh et al., 2021). Polydimethylsiloxane excels among a wide range of silicones due to its excellent optical properties and biodegradability. Another very important global factor that has brought satisfactory results to the environment is the use of biodegradable products. Among the

---

* Corresponding author.Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253, Bragança, Portugal.
E-mail address: jribeiro@ipb.pt (J. Ribeiro).

https://doi.org/10.1016/j.jmbbm.2024.106716
Received 18 March 2024; Received in revised form 26 August 2024; Accepted 1 September 2024

biodegradable materials, beeswax also belongs to the materials of natural origin These materials are utilized due to their excellent chemical and thermal properties (Smith et al., 2021; Yamamoto et al., 2016; Ren et al., 2020; Dinker et al., 2017; Cavallaro et al., 2015; Amin et al., 2017; Zeng and Taylor, 2020). PDMS is a synthetic silicone rubber belonging to organosilicon polymers, while beeswax comes from a metabolic process of the bees through the abdominal segments. Both PDMS and beeswax retain non-toxic and biodegradable characteristics (Zhai et al., 2021; Akther et al., 2020; Heo et al., 2020; Xu et al., 2021; Cheng et al., 2018; Higazy et al., 2022; Selim and A.A). Another notable impact factor present in the use of beeswax is that it is a natural and sustainable raw material (Khanzadi et al., 2015; Reis et al., 2017).

There is a growing interest in the studies of these materials due to the wide range of applications in different fields. Both PDMS and beeswax are relevant in applications in the food, cosmetic, pharmaceutical, and medicinal industries (Fratini et al., 2016; Ploy Klangmuang, 2016; Felicioli et al., 2017; Soleimanian et al., 2017; Bernal et al., 2005; Szulc et al., 2020; Wardhono et al., 2019; Luo et al., 2021; Farias and Khan, 2021). In the case of PDMS, the range extends to the areas of mechanical and civil engineering solutions, electronic devices, and biomedical employment (Qian et al., 2018; Adiguzel et al., 2017; Yi et al., 2020; Wang et al., 2020; Nazari et al., 2016). Among these areas, the applications for beeswax were diverse, such as food packaging (Bucio et al., 2021), (Cosate et al., 2019), burns, medicines, conservation of statues (Čížová et al., 2019), and waterproofing (Omar-Aziz et al., 2020). polydimethylsiloxane is also broadly followed by filtration membranes (Adrees et al., 2019; Gouyon et al., 2020), microfluidic devices (Gouyon et al., 2020), (dos Santos et al., 2018), blood analogues (Pinho et al., 2019), lubricants (Ressel et al., 2020) and optical devices (Hu et al., 2020). This wide range of applications is justified by the admirable properties exhibited by these materials. PDMS is a biocompatible silicone (Montazerian et al., 2019), (Rao et al., 2013), viscoelastic, chemically and thermally stable, highly flexible (An et al., 2016), corrosion and abrasion resistance (Bolvardi et al., 2018), (Zhang et al., 2021) and optically transparent (Park et al., 2018). However, beeswax has some similar characteristics such as being biocompatible (Manivannan et al., 2021), extremely ductile, biodegradable (Pavon et al., 2020), antibacterial (Mazur et al., 2018), (Bahrami et al., 2019), and humidity resistant (Sun et al., 2021).

PDMS and beeswax exhibit hydrophobic characteristics and are widely applied in coatings, resulting in a decrease in surface energy (Lee et al., 2016a; He et al., 2018; Oliveira et al., 2017). The improved properties that can stand out are water repellent (Syafiq et al., 2019), anti-fogging (Tarmizi et al., 2019), self-cleaning (Zhang et al., 2020), oxygen permeability (Haq et al., 2016), and water vapour permeance (Bucio et al., 2021). Syafiq et al. presented a study to develop a transparent hydrophobic hybrid coating by adding PDMS to 3-aminopropyltriethoxyslane (APTES). The hydrophobic coating showed improvement in self-cleaning, anti-fogging, and transparency properties due to the presence of PDMS. After prolonged outdoor exposure at a 20° angle, the coating exhibited 84% transparency indicating excellent self-cleaning properties, the hybrid coating also exhibited anti-fogging behaviour after prolonged exposure to mist, and small water droplets disappeared after 6 min, consequently these properties, the hybrid coating has high relevance for application on external surfaces of photovoltaic panels (Syafiq et al., 2019).

Smart materials are classified in this way, as they can react to an external stimulus and have adaptive behaviours. Recently, studies of the use of this type of materials for application in smart windows have been reported, La et al. reported a smart thermosensitive window based on polyampholyte hydrogel (PAH) and PDMS. The smart window works with temperature-stimulated transparency and opacity, ie during the day at high-temperature PAH is transparent to visible light and at night at low temperature, it blocks visible light. The smart window fabrication attached a PDMS film to a citron plate as a substrate for PAH, after irradiation with a UV lamp for 4h the precursor solution was crosslinked in PAH. A layer of PAH/PDMS was removed from the glass plates and dialyzed in a deionized water bath for 12 h. The window obtains 80% transmittance of opalescence at low temperature and transparency at high temperature. Its application is aimed at building windows with fast switching (La et al., 2017).

The objective of this study is evidenced by the development of a PDMS composite containing different proportions by weight of beeswax, with a focus on improving the hydrophobic properties of PDMS. So far there are no reports of studies mixing only PDMS and beeswax in various weight ratios, but the work contains a high amount of mechanical, optical, and wettability tests followed by analysis and evaluation of mechanical, chemical, optical, and wettability. This compound has great potential for application in many everyday products such as food packaging, controllable transparent films, and transparent protective films.

2. Materials and methods

2.1. Materials

PDMS used to manufacture the samples were silicon-based silicone (Dow Corning Sylgard 184), consisting of a 2-component kit, part A being the polydimethylsiloxane prepolymer and part B being the crosslinking agent, both offered by the Polytechnic Institute of Bragança. The beeswax used was purchased from a local beekeeper (Portugal, Bragança). Specification of the PDMS in Table 1.

2.2. Preparation of the specimens

The samples were manufactured using specially designed equipment, a Multifunctional Vacuum Chamber that controls some important parameters to improve process efficiencies, such as temperature, agitation speed, and internal pressure (Ariati et al., 2022). The complete fabrication of samples consists of 3 steps. Firstly, 1% beeswax was added to the PDMS (5.5 g). The mixture was blended in a mechanical stirrer with a speed controller for 3 min at 23% of the maximum engine power until the mixture was homogeneous, controlling the temperature at approximately 65 °C. In the second step, the curing agent was added with the 10:1 ratio, recommended by the manufacturer, followed by the stirring in the chamber at a multifunctional vacuum at a rotational speed of 150 RPM, carrying out the process of simultaneous degassing for approximately 3 min and poured into metallic moulds. The last step of the manufacturing process is to remove the few bubbles from the previous step by placing the mixture in multifunctional vacuum chamber, for 5 min. Samples were left for 48h at room temperature of 25 °C to complete the curing process. The samples were enumerated according to the

Table 1
Properties of the beeswax and PDMS.

Properties	PDMS	Beeswax	References
melting temperature (°C)	−49	60–65	(Panou et al., 2013), (Amin et al., 2017), (Su et al., 2015)
		65–70	(Bucio et al., 2021), (Tulloch and Hoffman, 1972)
Density 25 °C (g/cm^3)	0.98	0.95	(Bucio et al., 2021), (Smitha Alex et al., 2017)
Kinematic Viscosity (mPa.s) 100 °C	–	0.47	Bucio et al. (2021)
Viscosity	5100 cP	0.1 cP ratio	(Amin et al., 2017), (T. Dow Chemical Company, 2017)
Work time (pot life)	1.5 h	–	T. Dow Chemical Company (2017)
Cure time (25 °C)	48 h	–	T. Dow Chemical Company (2017)
Thermal conductivity (W/m°K)	0.27–0.30	0.24–0.32	(Amin et al., 2017), (T. Dow Chemical Company, 2017), (Xiao et al., 2013)

amount by weight of beeswax. The sample identification was 1st and 2nd characters (BW) indicate beeswax and the last characters refer to the amount of wax in the group. For instance, BW0% means that the sample is made with pure PDMS, and BW1%, indicates 1% of wax. In this work, tests were done at BW0%, BW1%, BW2%, BW4% e BW8%.

2.3. *Dynamic mechanical analysis (DMA)*

Dynamic mechanical measurements were performed using the DMA Q800 V21.2 (TA Instruments). Two samples were made for each proportion of beeswax according to ASTM D7028 (By and Mechanical, 2012), with the length, width, and thickness equivalent to 27 x 6 × 2 mm, respectively. The elastic (storage modulus) and viscous (loss modulus) components were measured while heating the samples at a rate of 3 °C/min in the temperature range between room temperature and 130 °C. The oscillation frequency was fixed at 1 Hz and the applied strain was 0.5%.

2.4. *Thermogravimetric analysis (TGA)*

Measurements were performed using the Q5000 IR instrument (TA Instruments) under inert material argon and air, heating the samples from room temperature to 400 °C. Four samples were used, including 2 samples of 100% PDMS (without beeswax) and 2 samples with 8% beeswax (10 mg) to perform the test and heated under the temperature program of 20 °C/min. The respective sample weights are listed in Table 2.

2.5. *Wettability test*

The wettability test was performed in a Contact Angle System OCA equipment from DataPhysics and the test was processed by the static sessile drop method, using distilled water as solvent (see Fig. 1). Two samples from tensile samples were used and carried out at a room temperature of approximately 25 °C. The samples were placed on the surface of the equipment and the parameters of focus, luminosity, and droplet deposition were adjusted for each sample. The drop of distilled water (with controlled volume) was placed on the surface of the sample, as shown in Fig. 2, being intercalated every 5 mm and the measurement was performed 5 times.

2.6. *Spectrophotometry test*

To perform the test, a spectrophotometer, model Shimadzu UV-2600 brand was used. One sample of each beeswax proportion group was used, samples from the traction samples. The wavelength range created for the equipment was between 200 nm and 800 nm. Transmittance measurements were performed with the samples heated due to beeswax in the composition. To warm up the samples, a baby bottle heater was used in a bain-marie with the samples immersed in the water, raising the temperature to 80 °C. After a few minutes of heating, the samples were removed from the water, dried, and placed on the spectrophotometer.

2.7. *Tensile test*

Uniaxial tensile tests were performed for 5 specimens of each sample in a universal testing machine, brand SHIMADZU, software version 1.5.1. The test was performed according to ASTM D412 (American Society for Testing and Materials. ASTM, 2018). To perform the test, a pre-test was set up on the machine, with a speed of 5 mm/min being adjusted until it reached a preload of 1 N, and from this point, the test was set up for a speed of 500 mm/min until the sample breaks. To minimize the slip effect of samples during the test, fine sandpaper was placed on the ends of the samples.

Table 2
Mass of samples used in the TGA.

Specimen	Mass (mg)
BW0% - Air	10.203
BW0% - Argon	11.523
BW8% - Air	10.985
BW8% - Argon	12.984

2.8. *Hardness test*

The test was performed in a portable Shore A analogue hardness tester according to ASTM D2240 (American Society for Testing and Materials. ASTM Rubber Property—Durometer et al., 2017). To measure hardness, two samples of each proportion of beeswax were placed on a flat surface with the flatter side of the samples being chosen for testing. Five-point measurements were taken at room temperature of approximately 25 °C.

2.8.1. *Scanning electron microscope (MEV)*

For a more detailed study of the microstructure of the samples, a Scanning Electron Microscope - NanoSEM - FEI Nova 200 (FEG/SEM) system was used. The working principle of the test consists of using an electron beam to explore the surface of the sample. Before the analyses, the samples were prepared (4% and 8% beeswax). It consisted of a cross-section and then a metallic coating of the surface to be analyzed, to make them conductive and generate images with good resolution in the SEM. The formation of images in SEM was given through secondary electron (SE) signals, which is the most used method to obtain topographical information.

3. Results and discussion

3.1. *Dynamic mechanical analysis test*

The DMA test was used to explore the mechanical characteristics of composites and analyze their behaviour with increasing temperature. Fig. 3 represents the behaviour and the results are shown in Table 3. Fig. 3a shows the superposition of the storage modulus variation with temperature for pure PDMS (BW0%) and compounds with different beeswax content (1, 2, 4, and 8%; in weight percentage). The storage modulus of Polydimethylsiloxane (PDMS) initially increases with the addition of beeswax, demonstrating mechanical reinforcement at room temperature and in the temperature ranges tested. However, when adding higher concentrations of beeswax, specifically 4%–8%, a decrease in Storage Modulus is observed. This inverse behavior can be attributed to the less homogeneous distribution of wax particles in the PDMS matrix, resulting in non-uniform interactions that negatively affect the mechanical properties of the composite. Therefore, homogeneity in the distribution of beeswax particles is crucial to maintain or increase the stiffness of the material. Before the glass transition, the BW8% had a maximum storage module of 3.3 MPa. The glass transition occurred around 76 °C, while the elastic state started around 87 °C, followed by a storage modulus of 1.3 MPa.

The presence of crystalline domains in beeswax causes a decrease in storage modulus at the glass transition zone. These domains appear to be modestly cross-linked, minimizing storage module drop (Osman et al., 2001). This is followed by a sharp decline marked by a unique modulus value for each sample, indicating the crystalline phase melting phenomena (Roy and Bhowmick, 2010). The glass transition temperature of the composites produced is between 75 and 77 °C, as shown in Fig. 3a. At 30 °C, the highest storage modulus comparable to 3.7 MPa was found for the BW4% compound. When beeswax exceeds its melting temperature, the particles evenly change from solid to liquid, limiting contact with the PDMS and supporting the drop into the storage module.

The Loss Modulus of pure PDMS and composites including beeswax is shown in Fig. 3b. When compared to the other composites, pure PDMS

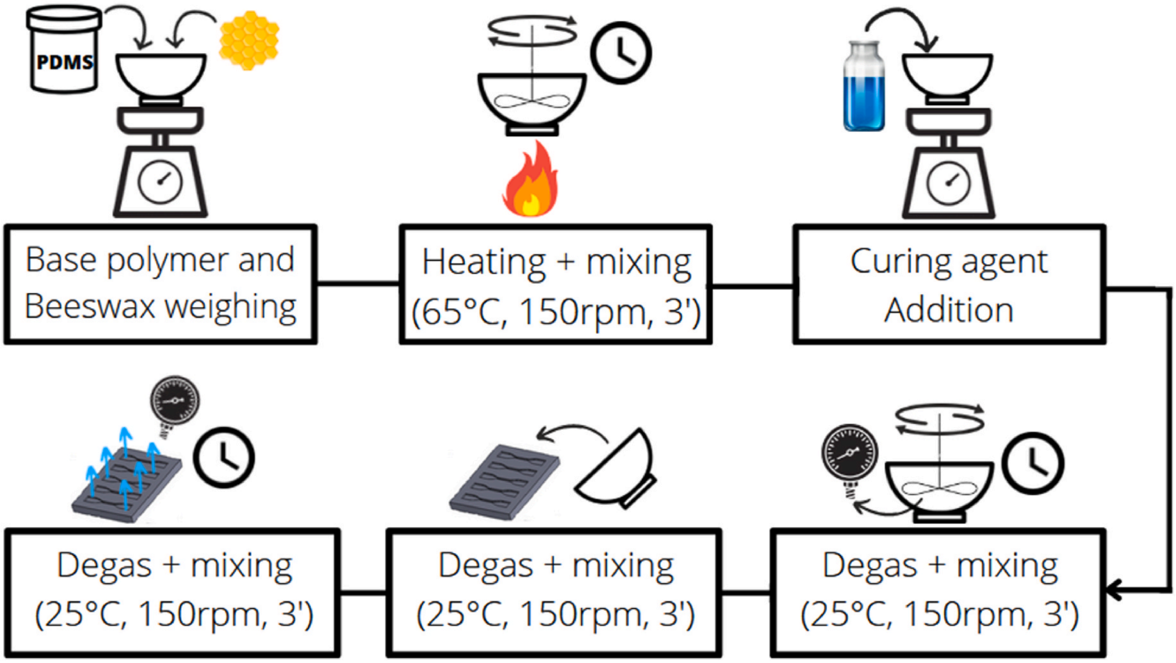


Fig. 1. Specimens manufacturing process using a multifunctional vacuum chamber.

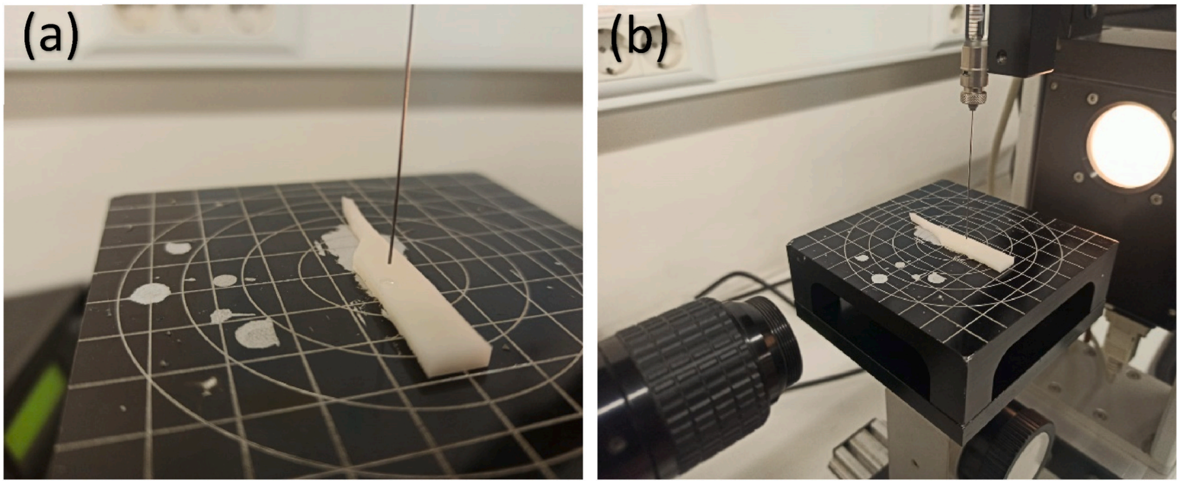


Fig. 2. Wettability test: (a) positioning for dripping and (b) performing the test.

has the lowest Loss Modulus; however, as the amount of beeswax grows, the Loss Modulus at ~30 °C increases due to the greater amount of mass of the beeswax in the PDMS. The Loss Modulus evolution with the temperature follows a similar trend for all the tested compositions. After ~90 °C the Loss Modulus of the PDMS and PDMS + beewax have similar values, indicating that the addition has a negligible effect. The BW8% composite has the highest loss modulus before the glass transition and the lowest Tg compared to the BW4% composite. The loss modulus of sample BW8% was 0.23 MPa, which was greater for the sample with the greatest percentage of beeswax.

It is worth noting that melting the crystalline phase of beeswax resulted in a higher decline in the temperature range of 75–80 °C. Another noteworthy aspect of beeswax is that the BW8% sample had the lowest loss modulus of 0.018 MPa after the test. The same phenomenon happens again after 90 °C due to the action of solely PDMS after the melting point of beeswax.

3.2. *Thermogravimetric analysis test*

Thermogravimetric analysis is a critical technique for analyzing and identifying thermal stability. The samples of pure PDMS and PDMS containing 8% beeswax were tested in an inert argon atmosphere, and the results are displayed in Fig. 4.

The DSC thermogram presented in Fig. 4 was obtained using the TA Instruments DSC Q2000. The samples, with 10 mg of mass, were heated at a rate of 10 °C/min from −50 °C to 300 °C under a nitrogen atmosphere.

Fig. 4a indicates that neither sample loses weight until roughly 200 °C, validating the thermal durability of the composite BW0% and BW8% up to this temperature in an inert environment. This conclusion is consistent with prior research findings (Dinker et al., 2017), (Cheng et al., 2018). The weight of the two materials falls after 200 °C; nevertheless, at 390 °C, a weight loss of 4% and 7% is reported for BW0% and BW8%, respectively. Because beeswax is included in the makeup of the BW8% sample, a 40% bigger decrease was predicted. This large weight reduction is beneficial to thermal stability studies (Abdelwahab et al., 2012). A study in the literature shows that the weight loss of beeswax is 100% when subjected to 443 °C (Dinker et al., 2017), which can be an explanation to justify why at approximately 390 °C the BW8% sample is close to 8% loss.

The peak melting temperatures in Fig. 4b are fairly comparable because of the variation in one inert material; in this figure, one can see the accurate heat flow of the BW8% sample in two inert substances. The melting temperature of the sample BW8% in argon is 67.93 °C, which might vary according to the origin and location of the beeswax, and this is consistent with the findings given in the literature (Bucio et al., 2021),

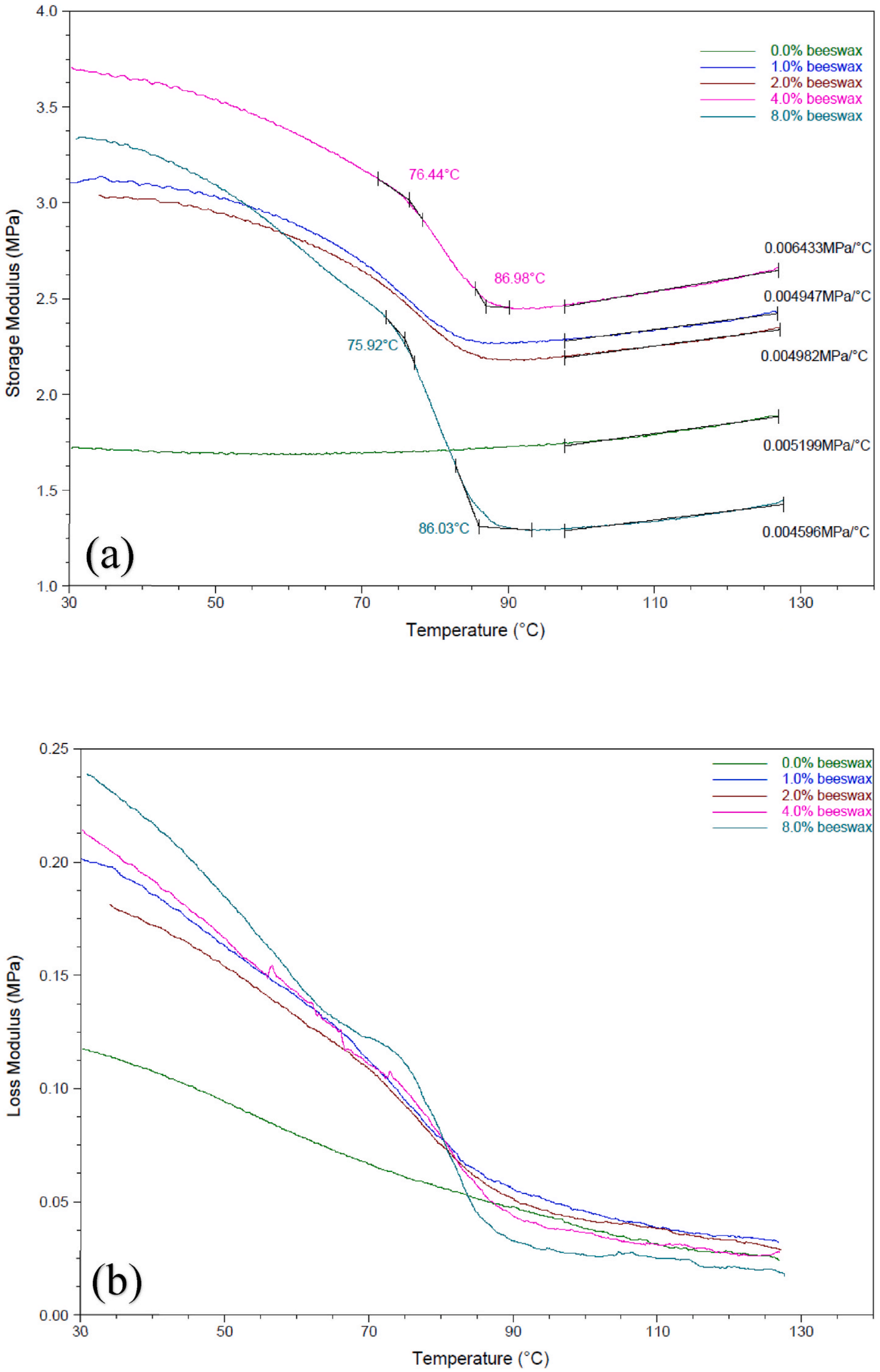


Fig. 3. Dynamic mechanical analysis. (a) Storage modulus and (b) loss modulus.

Table 3
Dynamic mechanical analysis (DMA) test result (at 35 °C).

Composites (wt.% beeswax)	(Storage modulus)$_{\text{máx}}$ (MPa)	(Loss modulus)$_{\text{máx}}$ (MPa)	Tan delta
0.0	1.70	0.11	0.065
1.0	3.04	0.19	0.062
2.0	2.93	0.18	0.059
4.0	3.72	0.21	0.068
8.0	3.34	0.23	0.055

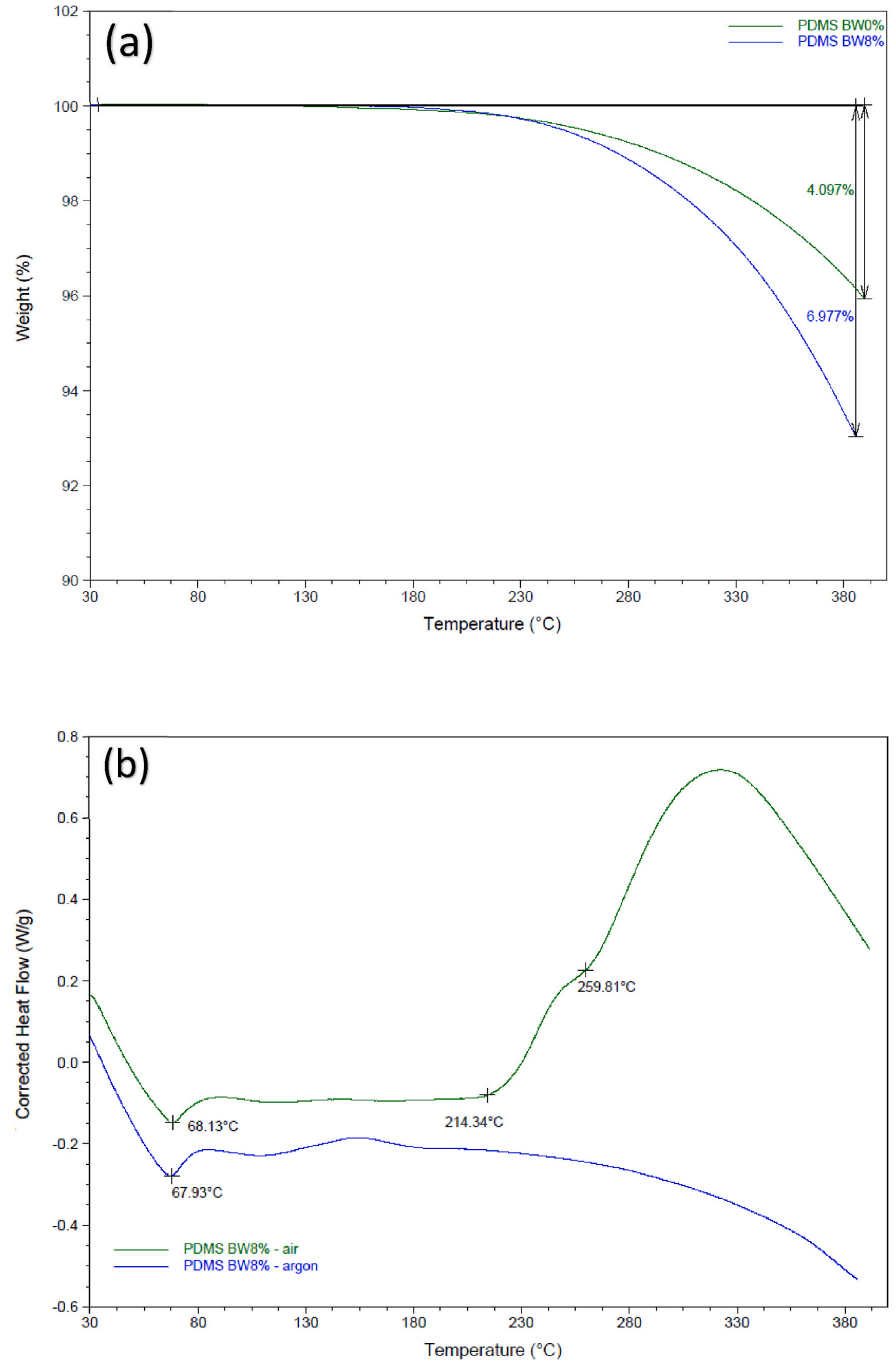


Fig. 4. (a) Thermal gravimetric analysis of the pure PDMS and BW8% and (b) Correct heat flow BW8% sample in two inert substances.

(Buchwald et al., 2005), (Masae et al., 2014).

Table 4
Contact angle values (n = 4) and S.D. obtained for pure PDMS and composite PDMS/beeswax.

Sample	BW0%	BW1%	BW2%	BW4%	BW8%
Contact Angle ±S.D.	123.8 ± 2.4	126.1 ± 1.8	128.9 ± 0.8	134.2 ± 2.5	144.9 ± 4.3

3.3. *Wettability test*

The determination of the water contact angle (WCA) to measure the hydrophobic nature of the samples as well as the wettability of their surface. Table 4 shows the findings for the various measurements of each % of beeswax.

The hydrophobic behaviour of the examined materials is representative of all composite compositions. Table 4 depicts a pure PDMS sample (BW0%) with contact angle with water of 124°, which is consistent with the approximate values reported in the literature (Zhang et al., 2020), (Sales et al., 2021), (Gokaltun et al., 2017). Furthermore, the hydrophobicity of PDMS is connected to the presence of

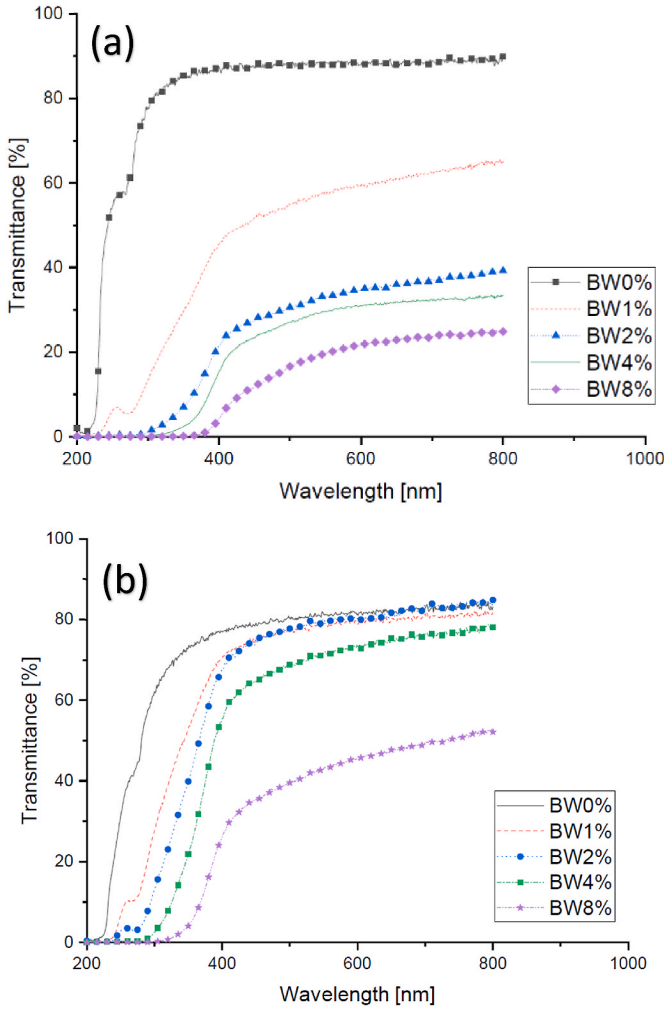


Fig. 5. Wavelength versus transmittance for different percentages of beeswax: (a) at 25 °C and (b) at 80 °C.

methyl/siloxane groups in the material's chemical structure (Akther et al., 2020), (Tanardi et al., 2014). A sample with a surface that has a contact angle with water that is less than 90° is considered a hydrophilic surface, a surface that has a contact angle with water that is less than 150° is considered a hydrophobic surface, and a surface that has a WCA greater than or equal to 150° is considered a superhydrophobic surface (Alzahid et al., 2018).

Furthermore, adding beeswax to PDMS would make the surface more hydrophobic due to the creation of beeswax-rich domains inside the sample, which might enhance surface roughness produced by the lotus leaf effect (Muscat et al., 2014), (Zhang et al., 2019). However, while some readings of the composite containing 8% beeswax surpassed 150°, the arithmetic mean was lower. These changes might be related to a reduction in roughness and surface energy, which are the major criteria for lowering a material's wettability (Pakzad et al., 2020).

The performance of beeswax in the composites was directly related to the percentage of beeswax applied to the samples. The contact angle with water rises as the proportion of beeswax increases. The BW8% sample, on the other hand, had the greatest contact angle with water, measuring 144.85°. When BW1% and BW8% were compared to pure PDMS, there was a 15% and 18% improvement, respectively.

3.4. *Spectrophotometry test*

PDMS is a very transparent polymer that provides for good light propagation. Small quantities of chemicals are applied to improve their mechanical qualities. Pure PDMS demonstrated 88.9% transparency in the visible region, which is consistent with previous research (Hu et al., 2020), (Chen et al., 2015). When PDMS is combined with waxes, such as paraffin wax and beeswax, it becomes opaque at room temperature (Owuor et al., 2018). When heat is applied to the material, the effect reverses; as the temperature rises, the substance becomes transparent (Sales et al., 2021), (Shi et al., 2020). Other investigations using a PDMS-wax combination are likewise encouraged to transparency by actuation stress, with a very short time from opaque to transparent (Weng et al., 2016), (Park et al., 2016).

As previously stated, the BW0% sample acquired 88.9% transmittance in the visible band, between 380 and 740 nm, as shown in Fig. 5a, at room temperature of 25 °C. The transmittance value for the BW1% sample was reduced to 64% in the visible area, as predicted since beeswax has an opaque property at room temperature, as shown in Fig. 6a, and is consistent with the research described in the literature (Sales et al., 2021). Transparency decreases as the amount of beeswax increases, demonstrating a clear inverse relationship. For samples with a greater proportion of beeswax, there was a significant increase in transmittance near the beginning of the visible zone, but Table 5 shows that the transmittance only reached 38%, 32%, and 24% for BW2%, BW4%, and BW8%, respectively. It was unexpected that the BW2% sample reduced the transmittance by almost ~58% in the same visible area range when compared with pure PDMS; nevertheless, due to this impact of the wax at room temperature, transmissibility tends to decrease when the amount of beeswax is raised added.

However, when the composites were tested at 80 °C, the transparency of the samples containing beeswax increased dramatically, as seen in Fig. 5b. As shown in Fig. 6b, samples BW1%, BW2%, and BW4% achieved values as high as pure PDMS in the range of 80% transmittance in the visible area. When compared to the same sample at 25 °C, the BW1% sample had a 21% increase in transmittance, while the BW2% sample had a 54% increase in transmittance. When compared to 25 °C, samples BW4% and BW8% showed a 50% rise. This phenomenon occurs because waxes in the solid state do not scatter light, resulting in opacity, and as the temperature increases above the wax's melting point, at 65 °C, the wax becomes liquid and molten, producing expansion of the wax beeswax into the PDMS matrix and making it transparent. There have been no reports of spectrophotometry experiments for PDMS samples with larger concentrations of beeswax for this test so far.

3.5. *Tensile test*

Mechanical characteristics of composites are commonly assessed by measuring parameters such as tensile strength (Shankar et al., 2016). Fig. 7a shows the test parameters that were used following ASTM D412. Fig. 7b depicts a graph of engineering stress vs engineering stress, and Table 6 lists the data gathered. The graphic depicts the arithmetic mean of the stress of each % of beeswax as well as pure PDMS, as well as the related standard deviation.

The standard variation for maximum tensile strength is approximately 10% of the value achieved by pure PDMS for each sample, which is consistent with the standard deviation described in the literature (Johnston et al., 2014). It was required to apply sandpapers at the ends of the samples to aid the samples not slipping during the test for samples with high standard deviation, which might be owing to the equipment's displacement speed.

Fig. 6b depicts a typical behaviour of elastic materials with high values of deformation approximately in the linear area of the samples, which can be up to 50% (Johnston et al., 2014). The BW0% curve relates to pure PDMS with the highest maximum tensile strength value of 4.4 MPa, which is consistent with the values published in the literature (Sales et al., 2021). The BW1% sample, which contained 1% by weight of beeswax, showed a 35% reduction in maximum tensile strength compared to BW0% and an increase in maximum deformation of approximately 37%, which may be due to the ductile behaviour of the

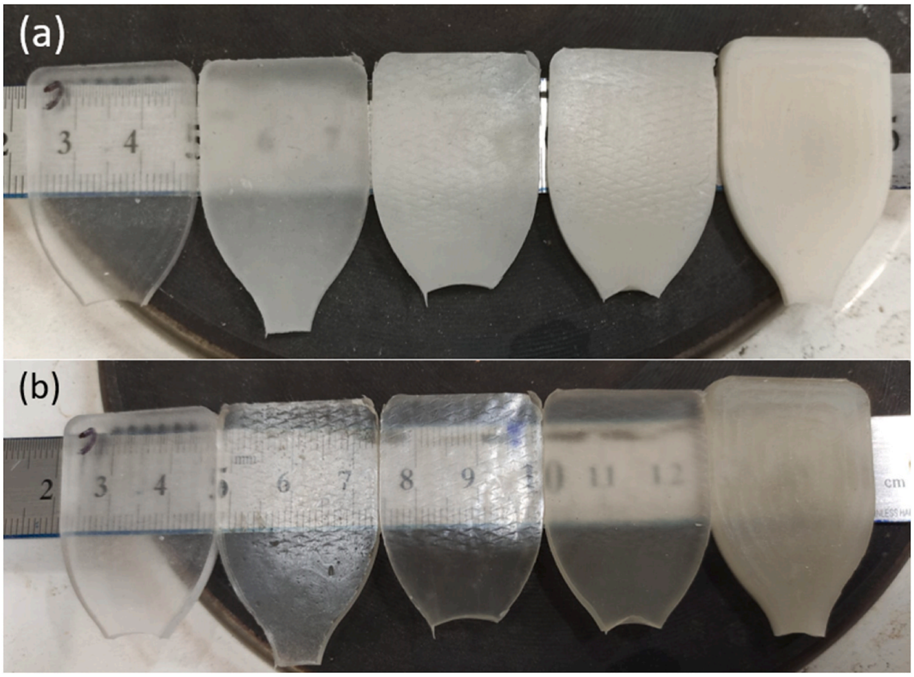


Fig. 6. Sample heating process for visible analysis: (a) at 25 °C and (b) at 80 °C.

Table 5
Comparative results of maximum transmittance in the visible region conducted at 25 °C and 80 °C.

Temperature	BW0%	BW1%	BW2%	BW4%	BW8%
25 °C - Visible region	88.9	63.6	37.8	32.4	23.9
80 °C - Visible region	82.6	82.9	81.1	76.8	50.2

wax after tension application (Bucio et al., 2021), (Pavon et al., 2020), and thus this effect may justify the reduction of the as a result, this impact may justify lowering the maximum tensile strength and increasing the maximum deformation (Wardhono et al., 2019). Another theory proposed to explain the loss in tensile strength is that adding beeswax to PDMS changes the network's cohesive forces, resulting in an elastic and brittle composite at room temperature (Oliveira et al., 2017). The BW1% composite manufactured in this work demonstrated higher maximum strength compared to our previous study, which used the same proportion by weight of beeswax; this value was 12% higher (Sales et al., 2021), which could be attributed to the manufacturing process, which allows some parameters to be controlled. When utilizing synthetic filtration membranes, increasing the polyvinyl chloride-co-vinyl acetate (PVCA)/PDMS combination also enhances tensile strength (Adrees et al., 2019). Other investigations (Brown et al., 2005), (Lee et al., 2016b) show that when PDMS is cross-linked with the curing agent, trapped tangles develop to enhance the network, hence boosting mechanical characteristics.

The BW2% curve behaves similarly to the BW1% curve, but with a 59% drop in maximum tensile strength in comparison to the BW1% and a 116% reduction in comparison to pure PDMS. This impact was predicted due to the greater concentration of beeswax particles in the PDMS matrix, which made the specimen more brittle. BW4 and BW8 samples exhibited unexpected behaviour, significantly decreased deformation, and increased tensile strength. This behaviour of the BW4% and BW8% samples might be attributed to the concentration of beeswax particles in the macromolecular area, as previously stated, although this impact should work in the other direction, as beeswax promotes increased tenacity (Pavon et al., 2020).

An experimental investigation discovered that fatty acids impart ductile qualities to beeswax since the elastic limit is reduced when fatty acids are removed from beeswax (Buchwald and Greenberg, 2005). On the other hand, the use of beeswax enhances the toughness of the composite (Pavon et al., 2020). Johnston et colleagues discovered a link between the Young modulus and the curing temperature of the samples, demonstrating that the curing temperature is directly proportional to the Young Modulus, implying that increasing the curing temperature increases the elastic modulus values (Johnston et al., 2014).

3.6. Hardness test

Fig. 8 shows a summary of all results obtained in hardness tests for pure PDMS (BW0%) and its composites with 1, 2, 4, and 8% beeswax addition. The points were positioned on the horizontal axis (abscissa) according to the amount of wax used. In addition, the standard deviation values were also plotted and presented as can be seen in Table 7.

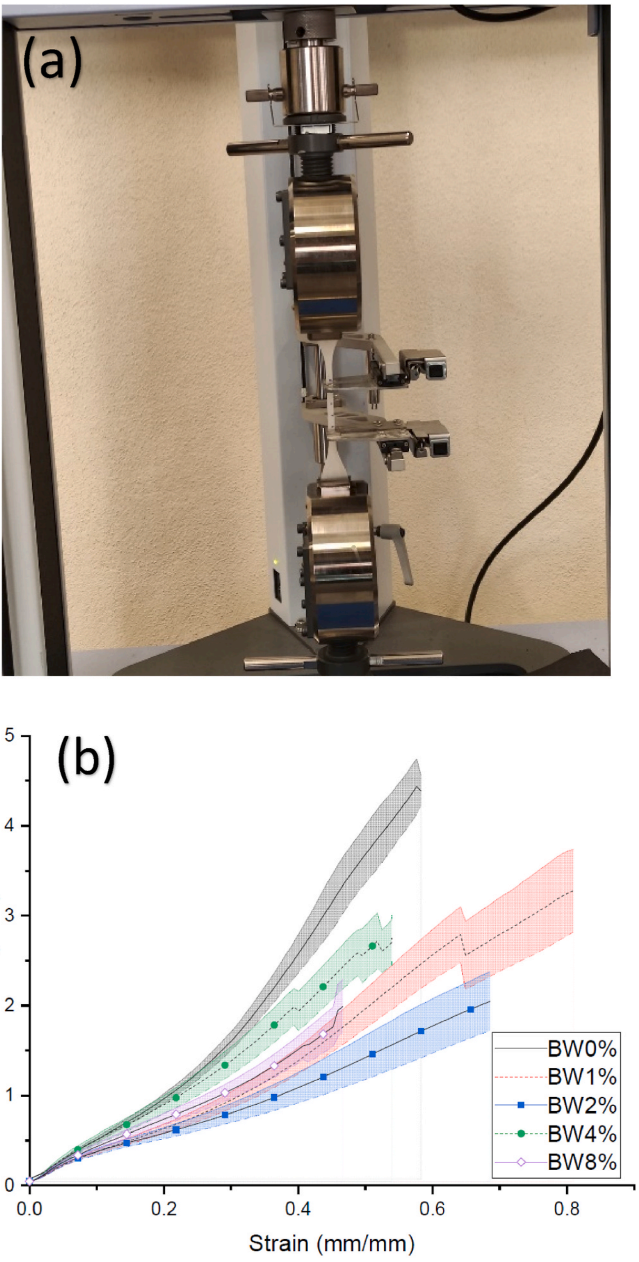
Although the hardness always increases directly proportionally to the increase in the wax amount, the results can be analyzed in two groups, the first one regarding small additions (between 0 and 2%) and the second for materials with the highest amount of wax (4 and 8%).

In the first group, pure PDMS presented results very close to those shown in the manufacturer's datasheet, which is 44 Shore A (T. Dow Chemical Company, 2017). Furthermore, as the amount of wax is increased, the increase in hardness presents a linear relationship (coefficient of determination $R^2 = 0.9877$) until reaching 4% of beeswax.

Above that value, in the second sample group, the average values were very close, which means that considering the standard deviation presented, by doubling the amount of wax, from 4 to 8%, the hardness was not visibly affected.

3.6.1. Scanning electron microscope

The material's internal structure is constituted by free disperse beeswax particles over the PDMS matrix. Some smaller beeswax particles are embedded by the matrix as shown in Fig. 9a) and 9b). For higher additions (8%) the beeswax particles show a tendency to agglomerate in elongated particles creating an internal structure with some continuity. Also, smaller particles seem to be embedded in the matrix and are distributed along the matrix with a more spherical shape.



(b)

Fig. 7. Engineering stress versus engineering strains for composites. (a) A specimen in testing and (b) Stress versus strain graph.

Table 6
Mechanical properties of PDMS from stress/strain testing.

Composites	$\sigma_{Máx}$ (MPa)	$\varepsilon_{Máx}$ (mm/mm)
BW0%	4.43 ± 1.01	0.58 ± 0.14
BW1%	3.27 ± 1.10	0.81 ± 0.17
BW2%	2.05 ± 0.83	0.68 ± 0.12
BW4%	2.74 ± 0.96	0.53 ± 0.09
BW8%	1.99 ± 0.71	0.46 ± 0.11

The significant decrease of the E′ from the sample with 4–8% of beeswax (with a lower than PDMS), above ~85 °C, might be associated with the higher percentage of beeswax and, also, with the formation of long beeswax particles, forming an internal structure with some continuity.

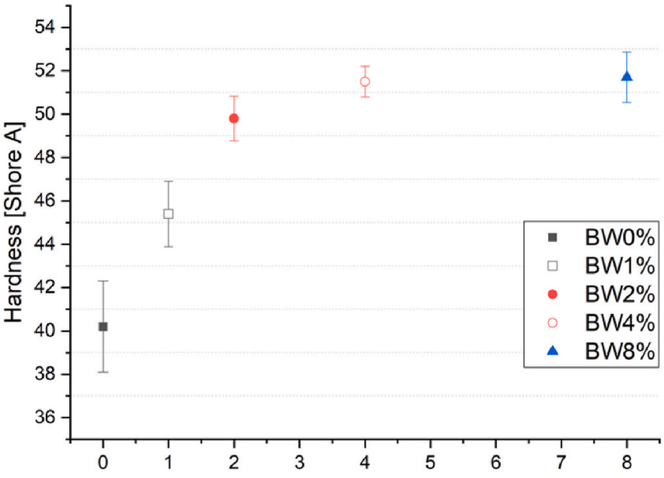


Fig. 8. Results: Hardness Shore A tests.

Table 7
Results of hardness test (Shore A).

Samples	BW0%	BW1%	BW2%	BW4%	BW8%
Hardness ±S. D.	40.2 ± 2.1	45.4 ± 1.5	49.8 ± 1.0	51.5 ± 0.7	51.7 ± 1.2

4. Conclusion

This study has demonstrated the impact of incorporating beeswax into PDMS on the mechanical, thermal, and hydrophobic properties of the composite. The results reveal that varying the concentration of beeswax significantly affects the mechanical behavior of PDMS, as evidenced by changes in tensile strength, deformation, hardness, and storage modulus. Specifically, the addition of beeswax enhances the stiffness and elastic properties while also increasing hydrophobicity, which is indicative of its potential for developing advanced biomaterials.

The thermal stability observed in the PDMS/beeswax composites up to 200 C further suggests their applicability in biomedical scenarios where materials are subjected to elevated temperatures, such as in certain medical devices and implants. The ability to tailor mechanical properties through compositional adjustments could lead to new applications in tissue engineering scaffolds, where specific mechanical cues are essential for cell growth and tissue development.

The significant improvement in hydrophobic properties with increased beeswax content, along with tunable transparency at different temperatures, positions this composite as a promising candidate for use in coatings and membranes in medical devices, where control over moisture, optical clarity, and surface interactions are critical.

Overall, this research contributes to the field of biomaterials by providing insights into how natural additives like beeswax can modify the mechanical and functional properties of synthetic polymers. These findings are particularly relevant for the development of new materials that mimic or replace biological tissues, thereby supporting the journal s focus on the mechanical deformation, damage, and failure of biomaterials under applied forces. Future work should investigate the long-term durability, biocompatibility, and specific biomedical applications of this composite, as well as explore its performance under physiological conditions to further align with the journal's interdisciplinary emphasis.

CRediT authorship contribution statement

Ronaldo Ariati: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation. **Andrews Souza:**

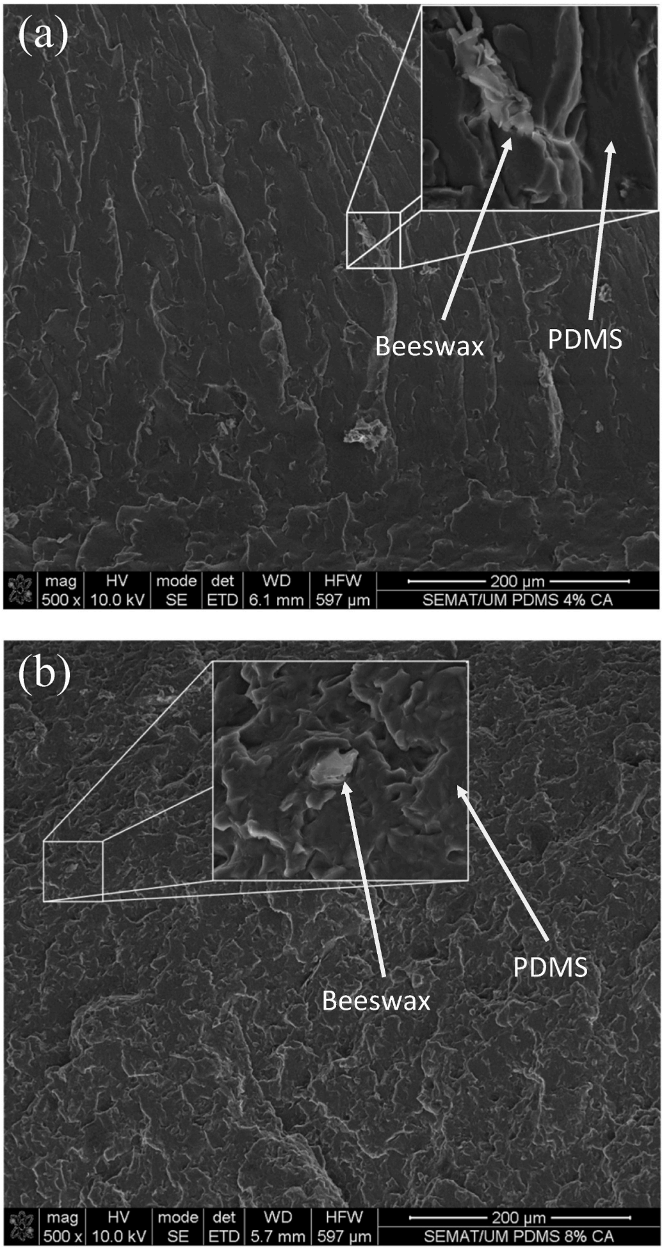


Fig. 9. Fracture surface of the sample with 4 a) and 8% b) of beeswax showing the shape of particles and their distribution, obtained by SEM analysis.

Writing – review & editing, Visualization, Validation, Methodology, Data curation. **Maria Souza:** Visualization, Validation, Data curation. **Andrea Zille:** Writing – review & editing, Resources, Formal analysis. **Delfim Soares:** Validation, Resources, Investigation, Data curation. **Rui Lima:** Writing – review & editing, Resources, Investigation, Funding acquisition, Conceptualization. **João Ribeiro:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing interest

The authors of this manuscript declare that they have not any conflict of interests.

Data availability

No data was used for the research described in the article.

Acknowledgements

Financial support was provided by Portugal's national funding FCT/MCTES (PIDDAC) to Centro de Investigação de Montanha (CIMO) (UIDB/00690/2020 and UIDP/00690/2020), 2C2T (UID/CTM/00264/2021) and SusTEC (LA/P/0007/2020). Additionally, this work was partially supported by Portuguese FCT, under the reference projects UIDB/04077/2020, UIDP/04077/2020, UIDB/00532/2020, UIDB/04436/2020 and LA/P/0045/2020 (ALiCE). This research was also partially funded by EXPL2021CIMO_01, EXPL/EMEEME/0732/2021, 2022.06207.PTDC (https://doi.org/10.54499/2022.06207.PTDC) and PTDC/EEI-EEE/2846/2021 (https://doi.org/10.54499/PTDC/EEI-EEE/2846/2021) and project ARCHKNIT (POCI-01-0247-FEDER-039733) financed by FCT, FEDER, and POCI of Portugal (2020). Andrews Souza was supported by the doctoral Grant 2021.07961.BD financed by the Portuguese Foundation for Science and Technology (FCT).

References

Abdelwahab, M.A., Flynn, A., Chiou, B.-S., Imam, S., Orts, W., Chiellini, E., 2012. Thermal, mechanical and morphological characterization of plasticized PLA–PHB blends. Polym. Degrad. Stab. 97 (9), 1822–1828.

Adiguzel, Z., Sagnic, S.A., Aroguz, A.Z., 2017. Preparation and characterization of polymers based on PDMS and PEG-DMA as potential scaffold for cell growth. Mater. Sci. Eng. C 78, 942–948.

Adrees, M., et al., 2019. Characterization of novel polydimethylsiloxane (PDMS) and copolymer polyvinyl chloride-co-vinyl acetate (PVCA) enhanced polymer blend membranes for CO2 separation. Polym. Test. 80 (March), 106163.

Akther, F., Yakob, S.B., Nguyen, N.T., Ta, H.T., 2020. Surface modification techniques for endothelial cell seeding in PDMS microfluidic devices. Biosensors 10 (11).

Alzahid, Y.A., et al., 2018. Functionalisation of polydimethylsiloxane (PDMS)-microfluidic devices coated with rock minerals. Sci. Rep. 8 (1), 1–15.

American Society for Testing and Materials. ASTM, 2018. Designation: D 412 – 06a Standard Test Method for Tensile Properties of Vulcanized Rubber and Thermoplastic Elastomers—, vol. 598. ASTM D 412-06a, pp. 143–152.

American Society for Testing and Materials. ASTM, Rubber Property—Durometer HardnesMaterials, E.I., Manufacturing, C.B., Hardness, D., Laboratories, C., 2017. Rubber property—durometer hardness 1Methods, S. T. (2008). Standard Test Methods for Rubber Property — Compression Set 1, i(Reapproved). Astm D 2240, pp. 1–6, 1–13, 2017.

Amin, M., Putra, N., Kosasih, E.A., Prawiro, E., Luanto, R.A., Mahlia, T.M.I., 2017. Thermal properties of beeswax/graphene phase change material as energy storage for building applications. Appl. Therm. Eng. 112, 273–280.

An, A.K., et al., 2016. PDMS/PVDF hybrid electrospun membrane with superhydrophobic property and drop impact dynamics for dyeing wastewater treatment using membrane distillation. J. Memb. Sci. 525, 57–67, 2017.

Ariati, R., Sales, F., Noronha, V., Lima, R., Ribeiro, J., 2022. Low-Cost multifunctional vacuum chamber for manufacturing PDMS based composites. Machines 10 (2), 92.

Bahrami, A., Rezaei Mokarram, R., Sowti Khiabani, M., Ghanbarzadeh, B., Salehi, R., 2019. Physico-mechanical and antimicrobial properties of tragacanth/hydroxypropyl methylcellulose/beeswax edible films reinforced with silver nanoparticles. Int. J. Biol. Macromol. 129, 1103–1112.

Bernal, J.L., Jiménez, J.J., Del Nozal, M.J., Toribio, L., Martín, M.T., 2005. Physico-chemical parameters for the characterization of pure beeswax and detection of adulterations. Eur. J. Lipid Sci. Technol. 107 (3), 158–166.

Bolvardi, B., Seyfi, J., Hejazi, I., Otadi, M., Khonakdar, H.A., Davachi, S.M., 2018. Towards an efficient and durable superhydrophobic mesh coated by PDMS/TiO2 nanocomposites for oil/water separation. Appl. Surf. Sci. 492, 862–870, 2019.

Brown, X.Q., Ookawa, K., Wong, J.Y., 2005. Evaluation of polydimethylsiloxane scaffolds with physiologically-relevant elastic moduli: interplay of substrate mechanics and surface chemistry effects on vascular smooth muscle cell response. Biomaterials 26 (16), 3123–3129.

Buchwald, R., Greenberg, A.R., 2005. Beeswax properties, 51 (1), 39–41.

Buchwald, R., Greenberg, A.R., Breed, M.D., 2005. A biomechanical perspective on beeswax. Am. Entomol. 51 (1), 39–41.

Bucio, A., Moreno-Tovar, R., Bucio, L., Espinosa-Dávila, J., Anguebes-Franceschi, F., 2021. Characterization of beeswax, candelilla wax and paraffin wax for coating cheeses. Coatings 11 (3), 261.

By, T., Mechanical, D., 2012. Standard test method for glass transition temperature (DMA Tg) of polymer matrix composites by dynamic mechanical analysis (DMA), 1 (C), 1–14.

Cavallaro, G., Lazzara, G., Milioto, S., Parisi, F., Sparacino, V., 2015. Thermal and dynamic mechanical properties of beeswax-halloysite nanocomposites for consolidating waterlogged archaeological woods. Polym. Degrad. Stab. 120, 220–225.

Chen, D., Chen, F., Hu, X., Zhang, H., Yin, X., Zhou, Y., 2015. Thermal stability, mechanical and optical properties of novel addition cured PDMS composites with nano-silica sol and MQ silicone resin. Compos. Sci. Technol. 117, 307–314.

Cheng, F., et al., 2018. Synthesis and characterization of beeswax-tetradecanol-carbon fiber/expanded perlite form-stable composite phase change material for solar energy storage. Compos. Part A Appl. Sci. Manuf. 107, 180–188.

Čížová, K., Vizárová, K., Ház, A., Vykydalová, A., Cibulková, Z., Šimon, P., 2019. Study of the degradation of beeswax taken from a real artefact. J. Cult. Herit. 37, 103–112.

Cosate de Andrade, M.F., Strauss, M., Morales, A.R., 2019. Toward greener polymeric blends: study of PBAT/thermoplastic whey protein isolate/beeswax blends. J. Polym. Environ. 27 (10), 2131–2143.

Dinker, A., Agarwal, M., Agarwal, G.D., 2017. Experimental assessment on thermal storage performance of beeswax in a helical tube embedded storage unit. Appl. Therm. Eng. 111, 358–368.

dos Santos, E.C., Ładosz, A., Maggioni, G.M., Rudolf von Rohr, P., Mazzotti, M., 2018. Characterization of shapes and volumes of droplets generated in PDMS T-junctions to study nucleation. Chem. Eng. Res. Des. 138, 444–457.

Farias, B.V., Khan, S.A., 2021. Probing gels and emulsions using large-amplitude oscillatory shear and frictional studies with soft substrate skin surrogates. Colloids Surfaces B Biointerfaces 201 (October 2020), 111595.

Felicioli, A., et al., 2017. In vitro antibacterial activity and volatile characterisation of organic Apis mellifera ligustica (Spinola, 1906) beeswax ethanol extracts. Food Biosci. 29, 102–109, 2019.

Fratini, F., Cilia, G., Turchi, B., Felicioli, A., 2016. Beeswax: a minireview of its antimicrobial activity and its application in medicine. Asian Pac. J. Trop. Med. 9 (9), 839–843.

Gokaltun, A., Yarmush, M.L., Asatekin, A., Usta, O.B., 2017. Recent advances in nonbiofouling PDMS surface modification strategies applicable to microfluidic technology. Technology 5 (1), 1–12.

Gouyon, J., d'Orlyé, F., Griveau, S., Bedioui, F., Varenne, A., 2020. Characterization of home-made graphite/PDMS microband electrodes for amperometric detection in an original reusable glass-NOA®-PDMS electrophoretic microdevice. Electrochim. Acta 329.

Haq, M.A., Hasnain, A., Jafri, F.A., Akbar, M.F., Khan, A., 2016. Characterization of edible gum cordia film: effects of beeswax. LWT - Food Sci. Technol. 68, 674–680.

He, X., Wang, T., Li, Y., Chen, J., Li, J., 2018. Fabrication and characterization of micro-patterned PDMS composite membranes for enhanced ethanol recovery. J. Memb. Sci. 563 (April), 447–459.

Heo, B., Fiola, M., Yang, J.H., Koh, A., 2020. A low-cost, composite collagen-PDMS material for extended fluid retention in the skin-interfaced microfluidic devices. Colloids Interface Sci. Commun. 38, 100301.Higazy et al., 2022 Higazy, S.A., Hao, Z., Jing Mo, P., 2022. A comparative study between two novel silicone/graphene-based nanostructured surfaces for maritime antifouling. J. Colloid Interface Sci. 606, 367–383.

Hu, H., et al., 2020. Hydrophilic PDMS with a sandwich-like structure and no loss of mechanical properties and optical transparency. Appl. Surf. Sci. 503 (September 2019), 144126.

Johnston, I.D., McCluskey, D.K., Tan, C.K.L., Tracey, M.C., 2014. Mechanical characterization of bulk Sylgard 184 for microfluidics and microengineering. J. Micromechanics Microengineering 24 (3).

Khanzadi, M., Jafari, S.M., Mirzaei, H., Chegini, F.K., Maghsoudlou, Y., Dehnad, D., 2015. Physical and mechanical properties in biodegradable films of whey protein concentrate-pullulan by application of beeswax. Carbohydr. Polym. 118, 24–29.

La, T.G., Li, X., Kumar, A., Fu, Y., Yang, S., Chung, H.J., 2017. Highly flexible, multipixelated thermosensitive smart windows made of Tough hydrogels. ACS Appl. Mater. Interfaces 9 (38), 33100–33106.

Lee, J.H., et al., 2016a. Fabrication of superhydrophobic fibre and its application to selective oil spill removal. Chem. Eng. J. 289, 1–6.

Lee, W.S., Yeo, K.S., Andriyana, A., Shee, Y.G., Mahamd Adikan, F.R., 2016b. Effect of cyclic compression and curing agent concentration on the stabilization of mechanical properties of PDMS elastomer. Mater. Des. 96, 470–475.

Liu, H., et al., 2021. Triboelectric-optical responsive cholesteric liquid crystals for self-powered smart window, E-paper display and optical switch. Sci. Bull. 66 (19), 1986–1993.

Luo, J., et al., 2021. Durable and flexible Ag-nanowire-embedded PDMS films for the recyclable swabbing detection of malachite green residue in fruits and fingerprints. Sensors Actuators B Chem. 347 (April), 130602.

Manivannan, K., Jaganathan, G., Sithique, M.A., 2021. Novel beeswax-chitosan/Zinc-hydroxyapatite biocomposite porous scaffolds: preparation and biological evaluation. J. Sci. Adv. Mater. Devices 6 (2), 197–201.

Masae, M., Pitsuwan, P., Sikong, L., Kongsong, P., Kooptarnond, K., Phoempoon, P., 2014. Thermo- physical characterization of paraffin and beeswax on cotton fabric. Thammasat Int. J. Sci. Technol. 19 (2), 69–77.

Mazur, K.L., et al., 2018. Diethyldithiocarbamate loaded in beeswax-copaiba oil nanoparticles obtained by solventless double emulsion technique promote promastigote death in vitro. Colloids Surfaces B Biointerfaces 176, 507–512, 2019.

Montazerian, H., et al., 2019. Permeability and mechanical properties of gradient porous PDMS scaffolds fabricated by 3D-printed sacrificial templates designed with minimal surfaces. Acta Biomater. 96, 149–160.

Muscat, D., Tobin, M.J., Guo, Q., Adhikari, B., 2014. Understanding the distribution of natural wax in starch–wax films using synchrotron-based FTIR (S-FTIR). Carbohydr. Polym. 102, 125–135.

Nazari, A.M., Miri, A.K., Shinozaki, D.M., 2016. Mechanical characterization of nanoclay-filled PDMS thin films. Polym. Test. 52, 85–88.

Oh, J.H., Woo, J.Y., Jo, S., Yang, H.M., Han, C.S., 2021. Surface morphology and transparency control of a metal/PDMS layered substrate by stretching. Surface. Interfac. 29, 101732, 2022.

Oliveira, V.R.L., Santos, F.K.G., Leite, R.H.L., Aroucha, E.M.M., Silva, K.N.O., 2017. Use of biopolymeric coating hydrophobized with beeswax in post-harvest conservation of guavas. Food Chem. 259, 55–64, 2018.

Omar-Aziz, M., et al., 2020. Combined effects of octenylsuccination and beeswax on pullulan films: water-resistant and mechanical properties. Carbohydr. Polym. 255, 117471, 2021.

Osman, M.A., Atallah, A., Müller, M., Suter, U.W., 2001. Reinforcement of poly (dimethylsiloxane) networks by mica flakes. Polymer (Guildf). 42 (15), 6545–6556.

Owuor, P.S., et al., 2018. High stiffness polymer composite with tunable transparency. Mater. Today 21 (5), 475–482.

Pakzad, H., Liravi, M., Moosavi, A., Nouri-Borujerdi, A., Najafkhani, H., 2020. Fabrication of durable superhydrophobic surfaces using PDMS and beeswax for drag reduction of internal turbulent flow. Appl. Surf. Sci. 513 (November 2019), 145754.

Panou, A.I., Papadokostaki, K.G., Tarantili, P.A., Sanopoulou, M., 2013. Effect of hydrophilic inclusions on PDMS crosslinking reaction and its interrelation with mechanical and water sorption properties of cured films. Eur. Polym. J. 49 (7), 1803–1810.

Park, J.Y., et al., 2016. PDMS-paraffin/graphene laminated films with electrothermally switchable haze. Carbon N. Y. 96, 805–811.

Park, J.S., Cabosky, R., Ye, Z., Isaac Kim, I., 2018. Investigating the mechanical and optical properties of thin PDMS film by flat-punched indentation. Opt. Mater. 85 (August), 153–161.

Pavon, C., Aldas, M., López-Martínez, J., Ferrándiz, S., 2020. New materials for 3D-printing based on polycaprolactone with gum rosin and beeswax as additives. Polymers 12 (2).

Pinho, D., Muñoz-Sánchez, B.N., Anes, C.F., Vega, E.J., Lima, R., 2019. Flexible PDMS microparticles to mimic RBCs in blood particulate analogue fluids. Mech. Res. Commun. 100, 18–20.

Ploy Klangmuang, R.S., 2016. Combination of beeswax and nanoclay on barriers, sorption isotherm and mechanical properties of hydroxypropyl methylcellulose-based composite films. LWT - Food Sci. Technol. 65, 222–227.

Qian, W., et al., 2018. Polydimethylsiloxane incorporated with reduced graphene oxide (rGO) sheets for wound dressing application: preparation and characterization. Colloids Surfaces B Biointerfaces 166, 61–71.

Rao, H., Zhang, Z., Liu, F., 2013. Enhanced mechanical properties and blood compatibility of PDMS/liquid crystal cross-linked membrane materials. J. Mech. Behav. Biomed. Mater. 20, 347–353.

Reis, M.O., Olivato, J.B., Bilck, A.P., Zanela, J., Grossmann, M.V.E., Yamashita, F., 2017. Biodegradable trays of thermoplastic starch/poly (lactic acid) coated with beeswax. Ind. Crops Prod. 112, 481–487, 2018.

Ren, L.F., Liu, C., Xu, Y., Zhang, X., Shao, J., He, Y., 2020. High-performance electrospinning-phase inversion composite PDMS membrane for extractive membrane bioreactor: fabrication, characterization, optimization and application. J. Memb. Sci. 597 (September 2019), 117624.

Ressel, J., Seewald, O., Bremser, W., Reicher, H.P., Strube, O.I., 2020. Self-lubricating coatings via PDMS micro-gel dispersions. Prog. Org. Coatings 146 (April), 105705.

Roy, N., Bhowmick, A.K., 2010. Novel in situ polydimethylsiloxane-sepiolite nanocomposites: structure-property relationship. Polymer (Guildf). 51 (22), 5172–5185.

Sales, F., et al., 2021. Composite material of PDMS with Interchangeable transmittance: study of optical, mechanical properties and wettability. J. Compos. Sci. 5 (4), 110.

Shankar, S., Wang, L.F., Rhim, J.W., 2016. Preparations and characterization of alginate/silver composite films: effect of types of silver particles. Carbohydr. Polym. 146, 208–216.

Shi, Y., Hu, M., Xing, Y., Li, Y., 2020. Temperature-dependent thermal and mechanical properties of flexible functional PDMS/paraffin composites. Mater. Des. 185.

Smith, J.A., Li, S., Mele, E., Goulas, A., Engstrøm, D., Silberschmidt, V.V., 2021. Printability and mechanical performance of biomedical PDMS-PEEK composites developed for material extrusion. J. Mech. Behav. Biomed. Mater. 115 (January).

Smitha Alex, A., et al., 2017. Thermal protection characteristics of polydimethylsiloxane-organoclay nanocomposite. Polym. Degrad. Stab. 144, 281–291.

Soleimanian, Y., Goli, S.A.H., Varshosaz, J., Sahafi, S.M., 2017. Formulation and characterization of novel nanostructured lipid carriers made from beeswax, propolis wax and pomegranate seed oil. Food Chem. 244, 83–92, 2018.

Su, W., Darkwa, J., Kokogiannakis, G., 2015. Review of solid–liquid phase change materials and their encapsulation technologies. Renew. Sustain. Energy Rev. 48, 373–391.

Sun, R., et al., 2021. Effect of basil essential oil and beeswax incorporation on the physical, structural, and antibacterial properties of chitosan emulsion based coating for eggs preservation. Lwt 150 (February), 112020.

Syafiq, A., et al., 2019. Transparent self-cleaning coating of modified polydimethylsiloxane (PDMS) for real outdoor application. Prog. Org. Coatings 131 (December 2018), 232–239.

Szulc, J., et al., 2020. Beeswax-modified textiles: method of preparation and assessment of antimicrobial properties. Polymers 12 (2), 4–7.

T. Dow Chemical Company, 2017. SYLGARDTM 184 Silicone Elastomer FEATURES & BENEFITS.

Tan, Y., et al., 2021. Temperature-responsive 'cloud' with controllable self-assembled particle size for smart window application. Appl. Mater. Today 25.

Tanardi, C.R., Pinheiro, A.F.M., Nijmeijer, A., Winnubst, L., 2014. PDMS grafting of mesoporous γ-alumina membranes for nanofiltration of organic solvents. J. Memb. Sci. 469, 471–477.

Tarmizi, Z.I., et al., 2019. Fabrication of Hydrophilic Silica Coating Varnish on Pineapple Peel Fiber Based Biocomposite, vol. 7, pp. 77–82.

Tulloch, A.P., Hoffman, L.L., 1972. Canadian beeswax: Analytical values and composition of hydrocarbons, free acids and long chain esters. J. Am. Oil Chem. Soc. 49 (12), 696–699.

Wang, F., Lei, S., Ou, J., Li, W., 2020. Effect of PDMS on the waterproofing performance and corrosion resistance of cement mortar. Appl. Surf. Sci. 507 (December 2019).

Wang, S., Zhou, Y., Jiang, T., Yang, R., Tan, G., Long, Y., 2021. Thermochromic smart windows with highly regulated radiative cooling and solar transmission. Nano Energy 89 (PB), 106440.

Wardhono, E.Y., et al., 2019. Cellulose nanocrystals to improve stability and functional properties of emulsified film based on chitosan nanoparticles and beeswax. Nanomaterials 9 (12), 1–17.

Weng, M., Chen, L., Zhou, P., Li, J., Huang, Z., Zhang, W., 2016. Low-voltage-driven, flexible and durable paraffin-polydimethylsiloxane-based composite film with switchable transparency. Chem. Eng. J. 295, 295–300.

Xiao, X., Zhang, P., Li, M., 2013. Preparation and thermal characterization of paraffin/metal foam composite phase change material. Appl. Energy 112, 1357–1366.

Xu, C., Huang, C., Huang, H., 2021. Recent advances in structural color display of cellulose nanocrystal materials. Appl. Mater. Today 22.

Yamamoto, Y., et al., 2016. Printed multifunctional flexible device with an integrated motion sensor for health care monitoring. Sci. Adv. 2 (11).

Yi, D., Huo, Z., Geng, Y., Li, X., Hong, X., 2020. PDMS-coated no-core fiber interferometer with enhanced sensitivity for temperature monitoring applications. Opt. Fiber Technol. 57 (January), 102185.

Yun, S., Lee, J., Ryu, T., Park, J., 2022. Stretchable translucent nanocomposite membranes with 3D heterogeneous interfaces derived from sugar templates for mechano-responsive optical applications. Compos. Part B Eng. 237, 109852. February.

Zeng, Z. wei S., Taylor, S.E., 2020. Facile preparation of superhydrophobic melamine sponge for efficient underwater oil-water separation. Sep. Purif. Technol. 247 (February), 116996.

Zhai, G., et al., 2021. Durable super-hydrophobic PDMS@SiO2@WS2 sponge for efficient oil/water separation in complex marine environment. Environ. Pollut. 269, 116118.

Zhang, W., et al., 2017. Transparency-switchable actuator based on aligned carbon nanotube and paraffin-polydimethylsiloxane composite. Carbon N. Y. 116, 625–632.

Zhang, Y., et al., 2019. Functional food packaging for reducing residual liquid food: Thermo-resistant edible super-hydrophobic coating from coffee and beeswax. J. Colloid Interface Sci. 533, 742–749.

Zhang, W., Jiang, S., Lv, D., 2020. Fabrication and characterization of a PDMS modified polyurethane/Al composite coating with super-hydrophobicity and low infrared emissivity. Prog. Org. Coatings 143 (February), 105622.

Zhang, B., Duan, J., Huang, Y., Hou, B., 2021. Double layered superhydrophobic PDMS-Candle soot coating with durable corrosion resistance and thermal-mechanical robustness. J. Mater. Sci. Technol. 71, 1–11.