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Preparation and Characterization of Porous PDMS for Printed Electronics

Eyad Khalid M. Balbaid
Wright State University

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Preparation and Characterization of Porous PDMS for Printed Electronics

A thesis submitted in partial fulfillment of the
requirements for the degree of
Master of Science in Materials Science and
Engineering

By

EYAD KHALID M. BALUBAID

Bach., Umm Al Qura University, Saudi Arabia, 2014

2019
Wright State University

WRIGHT STATE UNIVERSITY

GRADUATE SCHOOL

December 10, 2019

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Eyad Khalid M. Balubaid Entitled Preparation and Characterization of Porous PDMS for Printed Electronics BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Materials Science and Engineering.

Ahsan Mian, Ph.D. Thesis Director

Raghavan Srinivasan, Ph.D., P.E.
Interim Chair, Department of Mechanical
and Materials Engineering

Committee on Final Examination

Ahsan Mian, Ph.D.

Raghavan Srinivasan, Ph.D., P.E.

Hong Huang, Ph.D.

Barry Milligan, Ph.D.
Interim Dean of the Graduate School

ABSTRACT

Balubaid, Eyad Khalid M. MSMSE., Department of Mechanical and Materials Engineering, Wright State University, 2019. *Preparation and Characterization of Porous PDMS for Printed Electronic.*

Fabricating an elastomeric substrate with internal features could provide a novel structure with distinctive mechanical properties that allow them to stretch, bend and absorb the impact force. To date, polydimethylsiloxane (PDMS) is a great candidate as a substrate for flexible electronic applications, due to easy fabrication, high stability and low cost. In the current thesis, porous PDMS samples are fabricated and characterized based on the particle size and the fusion of salt and sugar treated micro-regions. The liquid PDMS is prepared by mixing the silicon elastomer base “Sylgard 184” and elastomer curing agent using volume ration 10:1. The salt and sugar are used as porogen to control the pore size distribution. Samples are created both by as-received porogen and moisture-treated porogen to control pore distribution. The treatment of porogen is done in a closed oven at 45˚C with moisture for two hours, and then at 60˚C without moisture for one hour to increase the fusion of particles. PDMS is then poured in molds containing treated or untreated salt or sugar. The PDMS samples are cured in the oven at 65˚C for two hours and then internal particles are removed. Porosity of samples is measured for each sample and internal pore distribution is imaged using an optical microscope. The mechanical properties including modulus of elasticity of fabricated samples were measured by performing tensile testing on these samples. From the collected data, effect of porogen type and treatment condition on porosity and modulus of elasticity is summarized and discussed. Finally, inkjet printing is used to print lines on porous PDMS substrate using nanosilver ink.

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Dedicated to my family

and to the memory of my father

CHAPTER 1: INTRODUCTION

1.1 Porous PDMS

Porous Polydimethylsiloxane (PDMS) is a three-dimensional structure of regular curable polymers that contains an internal uniform micro-pore that made at a low cost. The inner porogen can be created by using materials removable by water or by printing 3D molds with interior scaffolds shape. Porous PDMS is configurable into different shapes based on the designed molds or human organs. The reason for this kind of fabrication is to achieve the Mechanobiological goals more efficiently. Also, it is can be fabricated in triply periodic minimal surfaces structure (TPMS). The porous PDMS forms scaffolds to provide and promote a number of mechanical and transport properties, such as stiffness. It presents a light-weight structure with a solid frame while simultaneously having an open cell design.

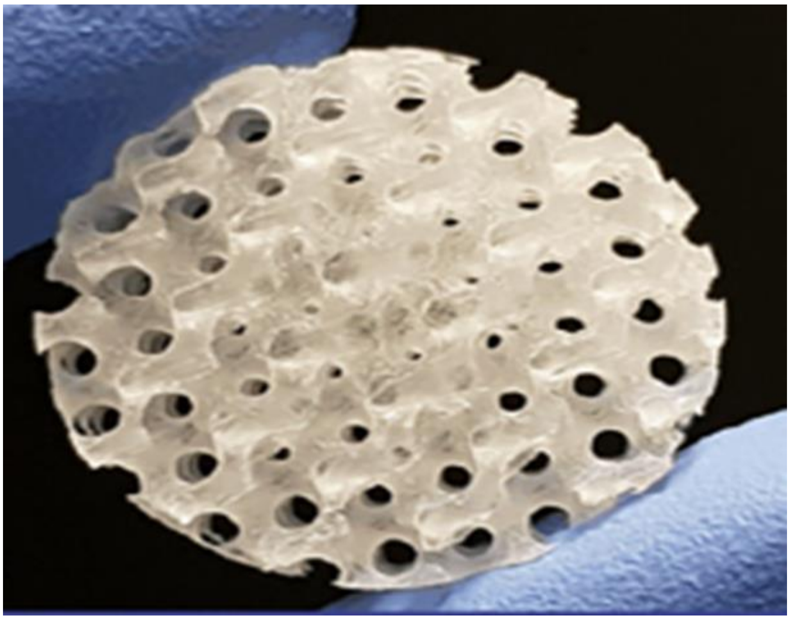


Figure 1.1 Fabricated Porous PDMS [2]

Minimal surface scaffold has the most important role in PDMS. It is made by simply mixing PDMS with the porogen particles before curing, then dissolving the samples in water to melt that particle. However, it can be fabricated separately, as done in this research to create porous section with solid backbone to help printing. Pore size can be modified in regard to the needed application and strength of structure. [1]. Scaffold design is important in porous PDMS because its extracellular matrix shape is able to work under pressure and load during use. [2].

Compared with other spongy substances, porous PDMS has its discrete advantages. For example, it has a high hydrophobicity, high compressibility and stretchability, thermal stability, and low costs [3].

Figure 1.2 Porous PDMS Shaped as a Human Organ [2]

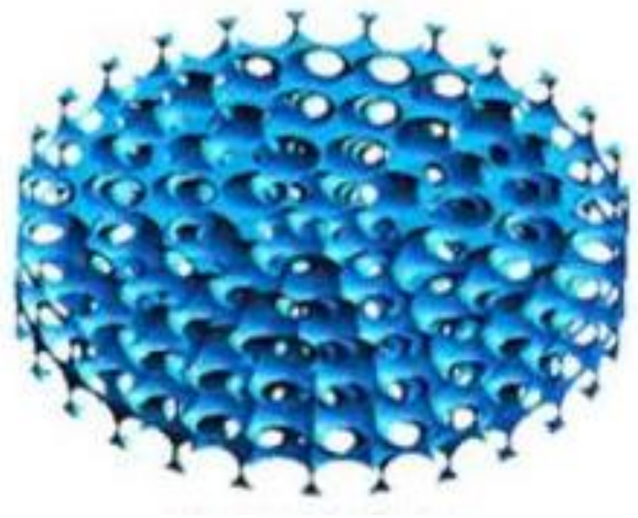


Figure 1.3 Porous PDMS in a Scaffold Shape [10]

1.2 Mechanical Properties

The Porous PDMS has many mechanical properties besides its biochemical properties. It is a compressible and expandable material, but its cells have a sensing platform. It also has a high flexibility and transparency in visible wavelengths.

1.2.1 Young's Modulus:

Young's Modulus is one of the material properties, which describe stiffness determines the relation between stress-strain by Hooke's Law:

$$E = \frac{\sigma}{\varepsilon} \qquad (1)$$

Based on Hooke's Law, the modulus of elastic E is defined as the ratio which described the stress to the strain. In the application of Hooke's Law, the modulus of elastics of any object could be obtained easily, which can be used to determine the stiffness of the object. In addition, the slope of stress-strain curve in linear elasticity region can determine the relation. Stress is defined as the physical quantity of maximum applied force on a specific cross-sectional area. The Young Modulus (E) is described as the tendency of a material or object to deform in a clear line along the axis when a force is applied to the object. It is the ratio of tensile stress to the tensile strain of any object.

On the other side, strain is not a physical quantity but is used to calculate the deformation that happens on objects when a particular force is applied to it by dividing elongation distance over the original length:

$$\varepsilon = \frac{\Delta L}{L} \qquad (2)$$

Porous PDMS is capable of large amounts of stress and strain. However, specimen thickness significantly affects true stress and true strain values.

In addition, Young's modulus and thickness have a reciprocal relationship. As thickness of sample decreases, Young's modulus increases, as shown in Figure 1.4 [4].

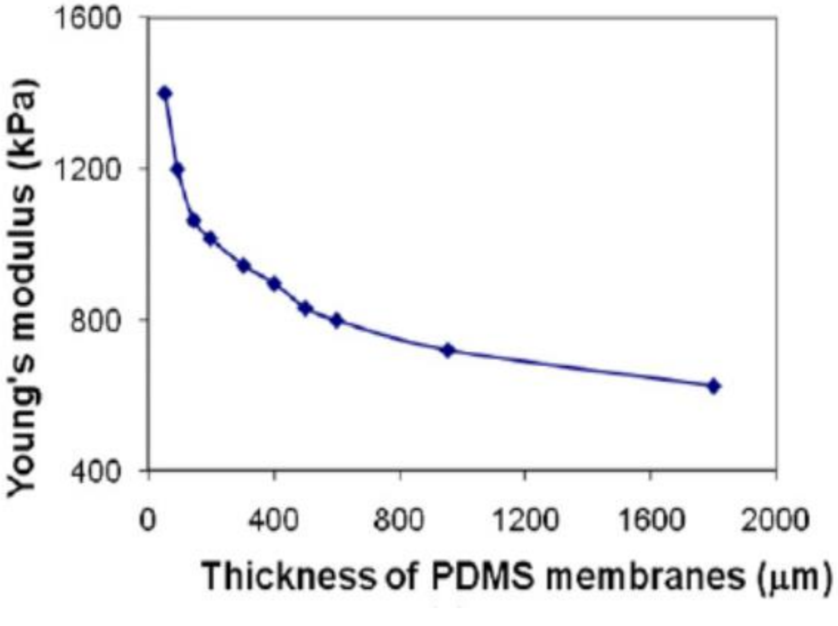


Figure 1.4 The Inverse Relation Between Young's Modulus and Thickness [4]

The relation between elastic modulus and porosity is reciprocal too, i.e. when the elastic modulus of porous PDMS decreases, porosity rises. However, PDMS is sensitive to temperature. The elastic modulus of porous PDMS changes according to the temperature. That means that as the elastic modulus of porous PDMS increases, its temperature increases.

1.3 Applications of PDMS/ Porous PDMS

Porous PDMS is the most widely used material for microfluidic equipment because of its elastomeric character and simple usage. In addition, it has a huge ability to be deformed elastically into any desired model. Since it is compressible in liquids, porous PDMS is used for absorbing oil leakages and mixing oil with water, as shown in Figure 1.5. After cleaning oil spills, this porous material swells, plugging oil leakages. [3] [5].

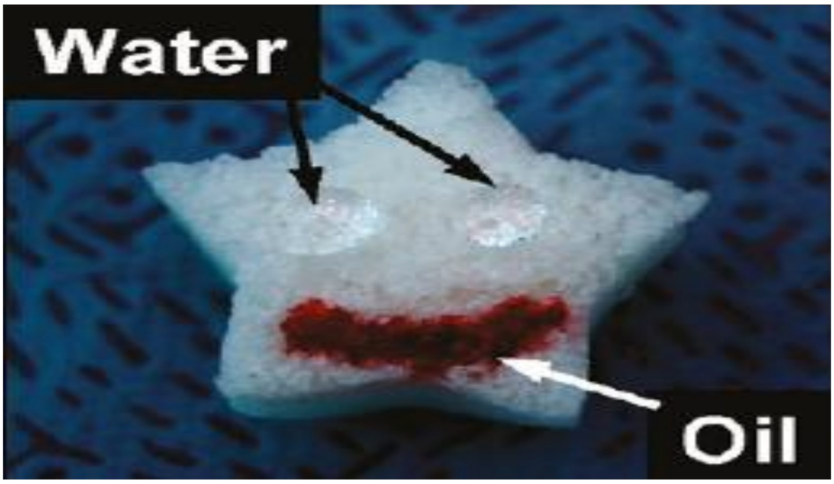


Figure 1.5 Porous PDMS (Sponge PDMS) Cleans Oil From Water Surface [5]

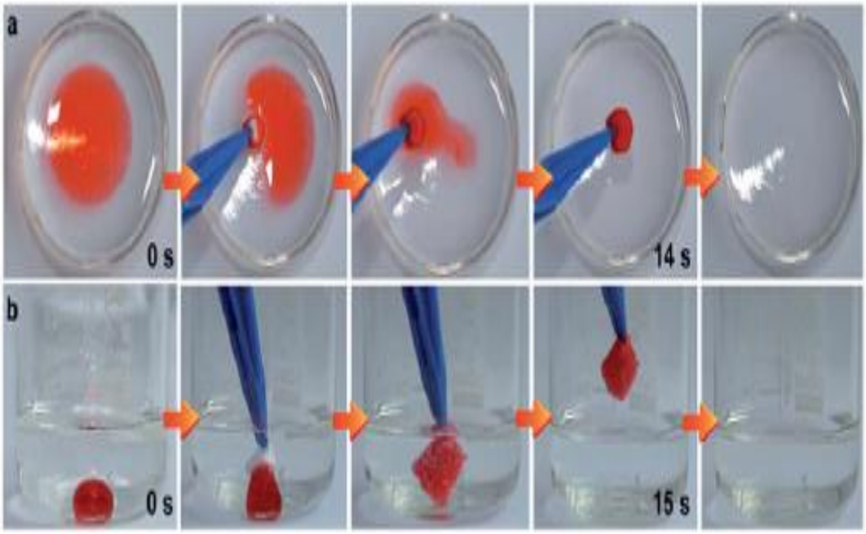


Figure 1.6 Removal of (a) n-hexane on the Surface of Water, and (b) Dichloromethane Under Water Using the PDMS Sponge [3]

Porous PDMS is highly sensitive to pressure, so it is used in flexible and stretchable electronics, biological devices, and tissue engineering. For example, long-term wearable and implantable electronics have been produced for health monitoring and controlling purposes, health care services, or communication systems. By contacting the surface of human skin or the curvatures of the brain, bio-signal reports are collected more effectively. Basically, it enhances the collection of information from monitoring vital signs, like the electrocardiogram, heart rate, blood pressure, breathing rate, and blood oxygen saturation as shown in Figure 1.8. However, this novel material cannot work independently, so besides this elastic conductive rubber (porous PDMS), other contents are attached inside electronic devices, such as nonporous gold film, nanometric cluster of platinum (Pt) salt, aligned single-walled carbon nanotube, etc. [6] [7].

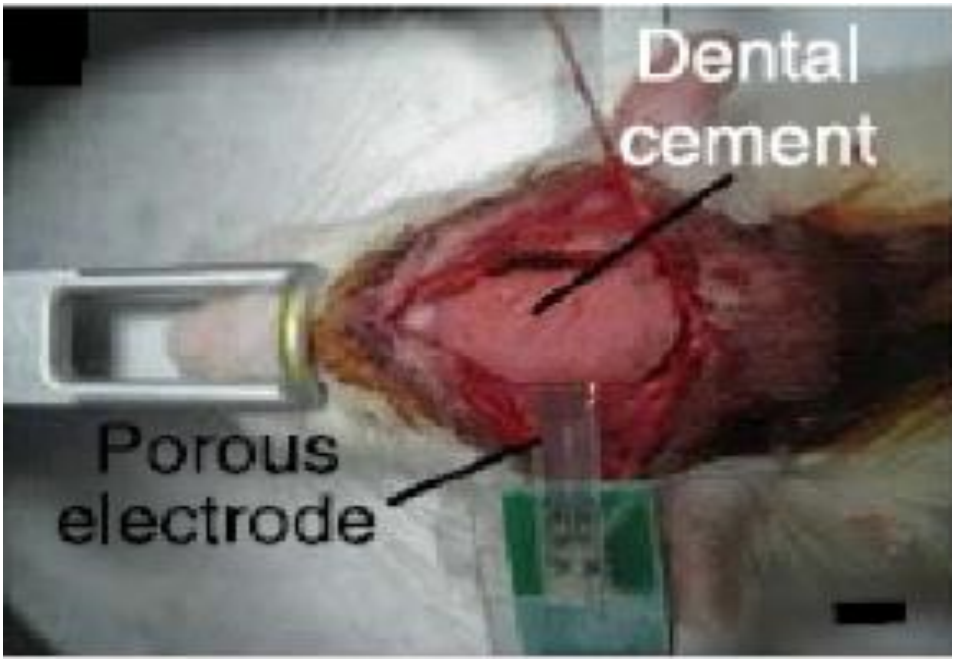


Figure 1.7 Electrode Made From Porous PDMS Works as Measuring Device for Dental Purpose [6]

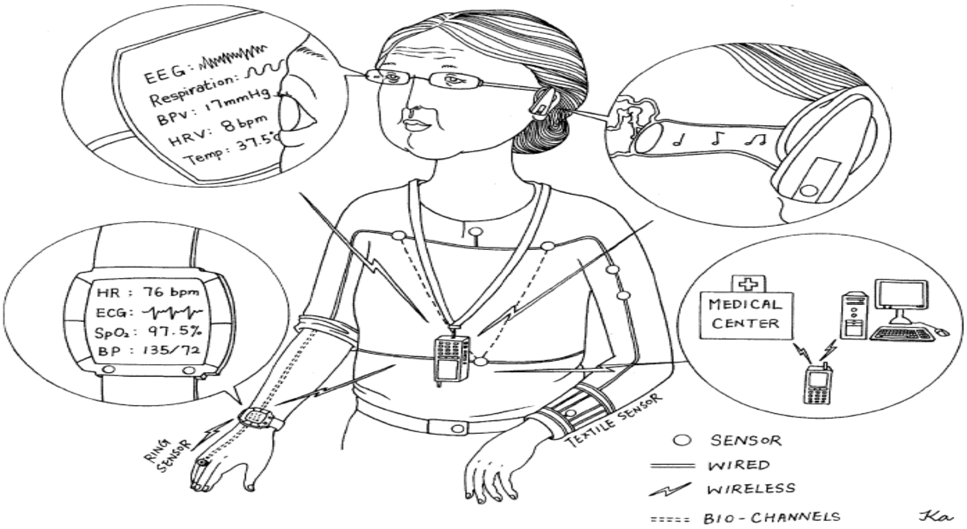


Figure 1.8 Examples of Medical Monitoring Systems Made From Porous PDMS [7]

The porous PDMS can be electrically conductive if it is filled with Carbon nanofiber composites (CNF), allowing it to be used in manufacturing circuit boards, see Figure1.10. It also protects and insulates the internal wires because it has a stable piezoresistive behavior [8].

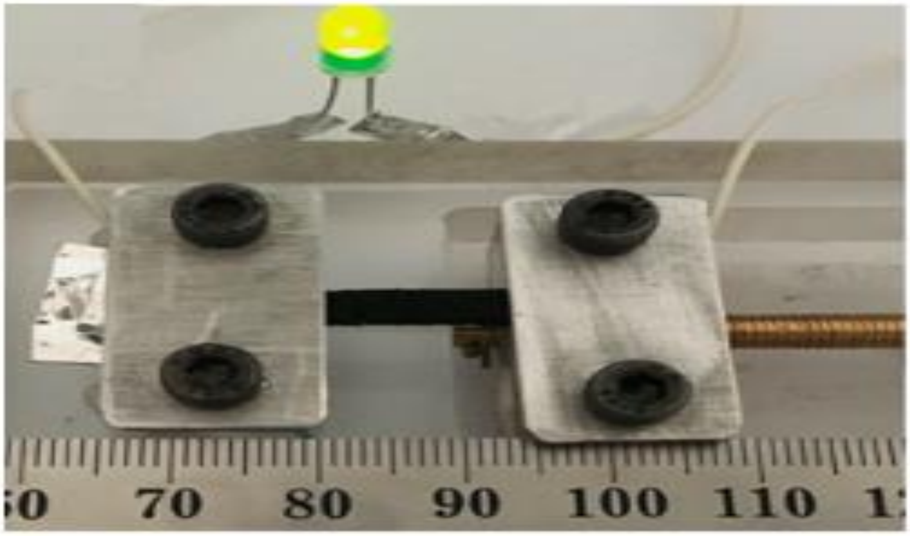


Figure 1.9 LED in a Circuit Connected by Porous PDMS [8]

1.4 Ink Jet Printing

Piezoelectrical drop on demand printer, as shown in Figure 1.11, is a micro dispensing tool that is used to eject different kinds of inks on rigid and flexible substrates. In this thesis, Jetlab 4xl produced by Microfab company is used. The printer consists of three stages X, Y and Z with printable area 210×260 mm. Stage X caries the horizontal camera and LED light that used to observe the generated droplet and estimate its velocity while stage Z handles the jetting device and the vertical camera that used to select the desired spot for printing [9].

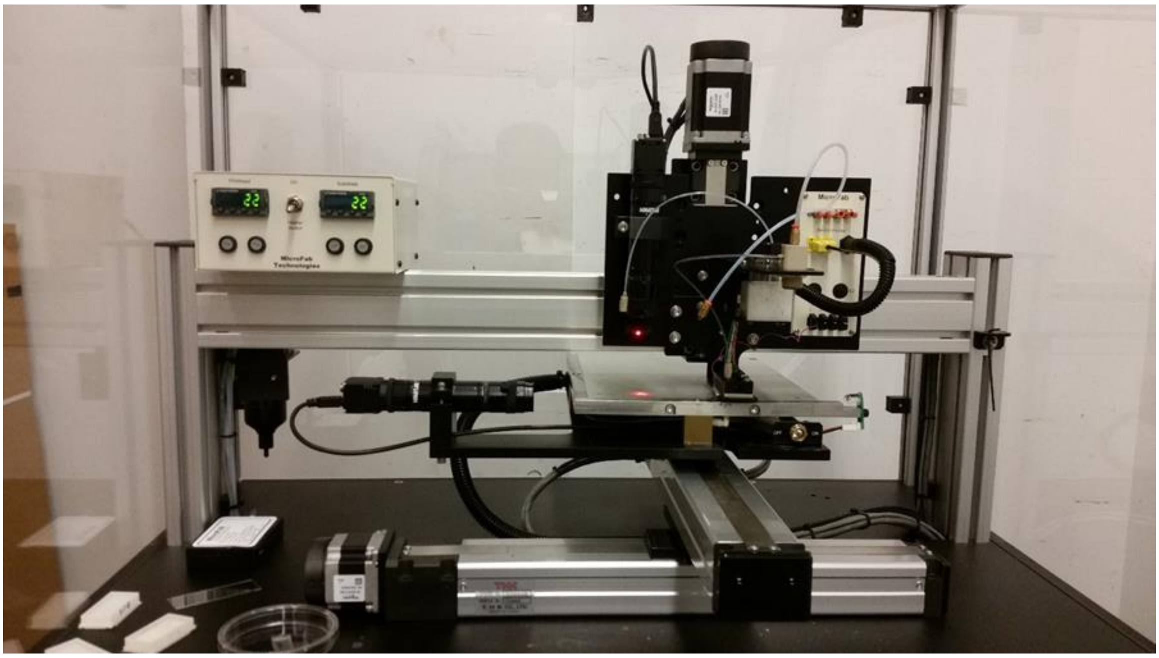


Figure 1.10 Ink Jet Printer

1.5 Porous PDMS as Substrate for Inkjet Printing

Since the inkjet printing process uses inks in liquid form, it is not easy to print devices or conductors directly on porous substrates. Because, the liquid ink will be readily absorbed by the porous substrate during printing before the printed devices are solidified. Thus, it is necessary develop a gradient PDMS substrate having both the porous and solid sections so that the solid side can be used as printing surface. The present work demonstrates the fabrication and mechanical testing of gradient PDMS substrate using three porogens, salt, sea salt, and sugar.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this chapter, the previous published research is discussed briefly. The topics discussed are fabricating porous PDMS, mechanical tests, and ink jet printing on PDMS.

2.2 Fabricating Porous PDMS

Many researchers have fabricated porous PDMS and analyzed its properties. However, it is important to have a review of designing this material and its characteristics, too. Q. Li et al. [10] reported a novel method for porous PDMS fabrication. They combined the structured molding, the micro-region fusion, and the vacuum-assisted infiltration using commercial salt cubes as porogen inside the liquid PDMS prepolymer. Li cured PDMS in oven at 65℃ for two hours, then removed salt particles by using dissolution process in water, in purpose for creating a porous PDMS. Then, they removed salt particles by dissolution in water, see Figure 2.1. Creating a well-connected network of salt/sugar cubes was one of Li et al.'s objectives. A heat source was used in combination with a water bath so that particles obtained a good adhesion, better pureness, and less particle residue. At the same time, PDMS's structure does not lose its properties. This research determined a well-controlled pore size distribution and significant improvement in processing speed with low cost. O. Dufaud et al. [11] also fabricated another different method of porous PDMS. Based on the combination of chemical cross-linking of water in PDMS emulsion droplets in a stirred thermostatic water vessel, a porous PDMS was created. This PDMS has good porosity beads and an open structure with operating parameters. Similar research was done by M. Juchniewicz et al. [12] by using water as a porogen and pumping the emulsion inside the microchannel. To evaporate the porogen and get a cross-link inside emulsion, the structure was cured at 120˚C. Moreover, G. Jeong et al. [6] explored a simple new method, too. He used a pressurized steam into liquid PDMS mixture surface with Ti (~500 Å thick) and Au (~2,000 Å thick) to find internal pores. Since this method finds a foldable and stretchable porous PDMS, it can be applied to manufacturing electronic circuits and other medical devices. S. Miller et al. [13] studied the Breath Figures (BFs) method. This method is processed by using humid air, which condenses and creates water droplets above the polymer mixture and is cooled by the evaporating solvent. S. Duan et al [14] reported a different way to fabricate. A combination of carbon nanomaterials and graphene conductive network with PDMS is able to create a stretchable and electrically conductive 3D porous nano-structured PDMS. C. Huang et al. [15] studied another new method of porous PDMS fabrication. Distilled water was added into liquid PDMS prepolymer and mixed them with a mechanical stirrer for five minutes at a speed of 11,000 revolutions per minute. He adjusted the proportion of water to get different volumes of porosities. Huang et al. mentioned that a vacuum desiccator was used for two hours to remove air bubbles from the mixture. After that, the mixture was cured in an oven for three hours at 120˚C. Finally, an open porous PDMS open was successfully achieved.

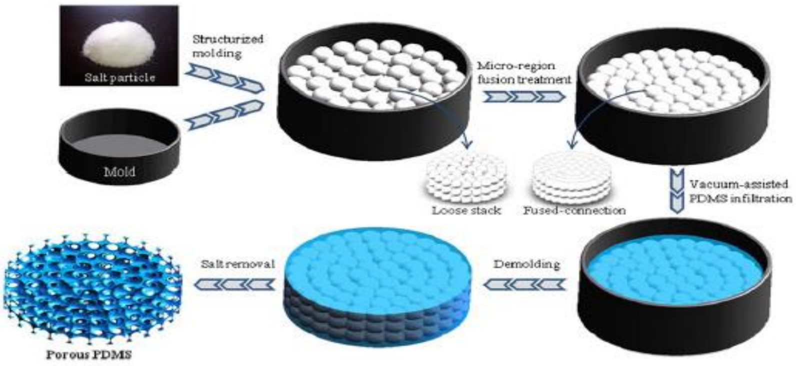
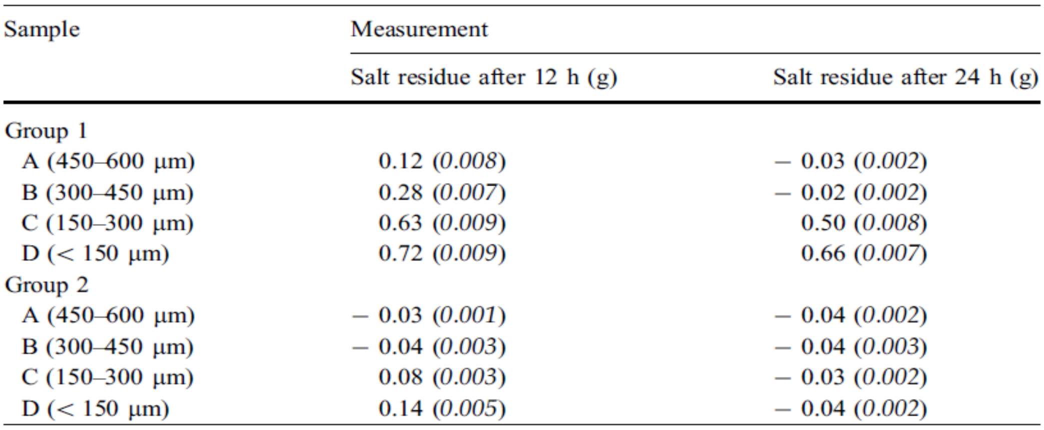


Figure 2.1 Schematic of Qi Li Fabrication Process [10]

2.3 PDMS Testing:

2.3.1 Porosity Test:

Q. Li et al. [10] tested the porosity of PDMS. His method depends on the time needed for the particle's dissolution process inside the dissolving solution. Firstly, samples were divided into two groups. Each group had four samples, two with large salt cubes, and two with small salt particles. Then, each specimen was weighed individually and immersed in deionized water for 24 hours. After 12 hours in water, Li et al. mentions that all salt particles in group I were not removed completely; even after another 12 hours, two samples still contained salt residue. On the other hand, in Group II, Li et al. found that the specimens with bigger salt particles dissolved during the first 12 hours, and no salt residue was found after 24 hours in water. See Table 2.1 below. Finally, Li et al. used microscopic images to confirm his results, and concluded that the micro-region fusion treatment improved, reducing the salt residue.



Sample	Measurement	
	Salt residue after 12 h (g)	Salt residue after 24 h (g)
Group 1		
A (450–600 μm)	0.12 (*0.008*)	– 0.03 (*0.002*)
B (300–450 μm)	0.28 (*0.007*)	– 0.02 (*0.002*)
C (150–300 μm)	0.63 (*0.009*)	0.50 (*0.008*)
D (< 150 μm)	0.72 (*0.009*)	0.66 (*0.007*)
Group 2		
A (450–600 μm)	– 0.03 (*0.001*)	– 0.04 (*0.002*)
B (300–450 μm)	– 0.04 (*0.003*)	– 0.04 (*0.003*)
C (150–300 μm)	0.08 (*0.003*)	– 0.03 (*0.002*)
D (< 150 μm)	0.14 (*0.005*)	– 0.04 (*0.002*)

Table 2.1 Weights of Salt Residue in Porous PDMS Samples After 12 h and 24 h [10]

Moreover, C. Huang et al. [16] found the mechanical properties of porous PDMS had various volumes of porosity. He reported that porogen inside PDMS can be found by dissolving particles inside water or Ethanol solution.

2.3.2 Mechanical Tests:

M. King et al. [17] performed a compression test for a porous matrix of PDMS specimens filled with carbon black, then calculated stress-strain values for loading and non-loading cycles, and measured its resistance, as shown in Figure 2.2. His examination was processed by using a rig (Wykeham Farrance Tritech 50 KN Digital), resistance measurement device (Multimeter), displacement and mass calculating software (Triax Version 5.1.5), and a recording device (Penny and Giles DS131 LVDT). King et al. reported that Young's modulus, E, increases with strain. Also, changes occurred in resistance values from 20KΩ to 100 Ω for about a 95% of compressive strain because of the filled carbon.

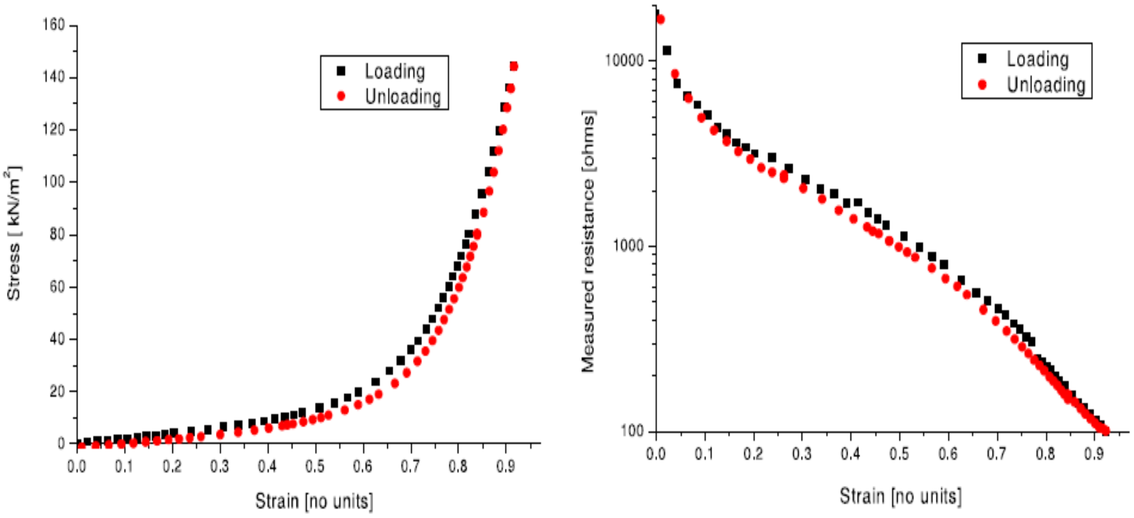


Figure 2.2 Stress-Strain Measurements (Left) Resistance Strain (Right) [17]

X. Zhao et al. [3] reported that PDMS has excellent tensile properties because of its interconnected porous structure. The stress-strain curve increased constantly until about 3 MPa then dropped sharply at 97% as shown in Figure 2.3. Zhao et al. mentioned that porous PDMS has a perfect compressibility and stretchability. The tested samples recovered their original shapes after fifty cycles of 90% strain, and their elongation at breaking was 97%.

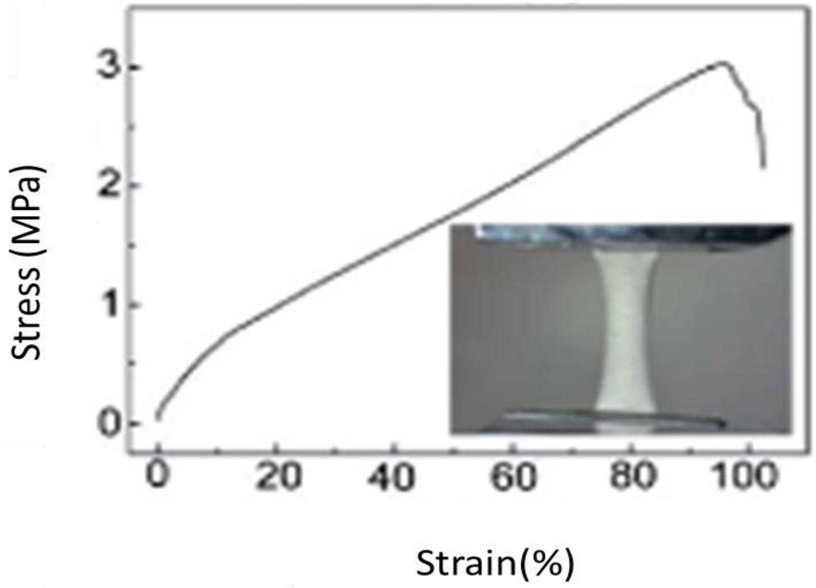


Figure 2.3 Stress-Strain Curve for Porous PDMS [3]

2.4 Ink Jet Printing on PDMS:

J. Wu et al. [18] studied Inkjet printing for Silver nanoparticles on PDMS, which simulates metal patterning on PDMS by bearing liquid inks. He wrote that PDMS prevents the existence of ink patterns on its surface with its hydrophobic properties and the weak adhesion connection of silver. Wu used a silver nanoparticle ink (ANP DGP 40LT-15C) for the drop spacing 50 and 60µm. However, two kinds of performed treatments helped in creating ink pattern on PDMS and improved its wettability, which are O_2 Plasma treatment and Silane adhesion treatment. The plasma treatment processed by using a one-step Plasma system (PDC-002, Harrick Plasma) at 29.6 Watts for 30 seconds, whereas (3-Mercaptopropyl)-trimethoxy-silane (MPTMS) modification occurred via multiple steps, starting by immersing PDMS samples into a solution of 0.5 mL MPTMS with 100 mL ethanol for one hour at room temperature, rinsing with ethanol, drying with clean air, immersing again into 0.1M HCl formula for another one hour, washing with deionized water, and drying with compressed clean air. Wu et al. also studied the sizes of ink droplets on substrate, and reported that they are different depending on the substrates' sorts and characters. Moreover, Wu et al. achieved another type of examination on his treated and untreated samples, which are the soak test, blow test, and sonication test. He concluded that a silver pattern was still able to exist on untreated PDMS after the soaking and blowing test, but the sonication test removed it partially, as seen in Figure 2.4.

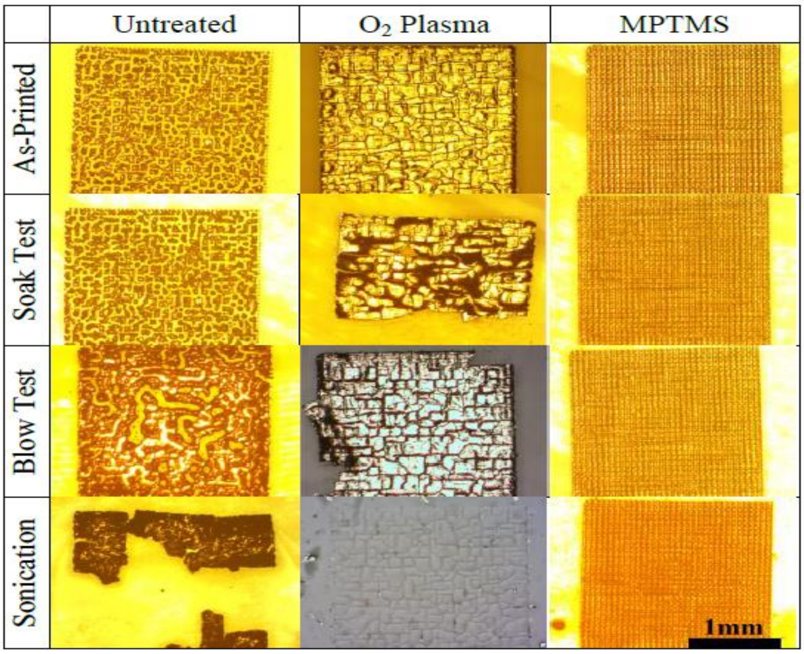


Figure 2.4 Adhesion Tests for Silver Patterns with Different Treatments and Exams [18]

Y. Kim et al. [19] studied similar work for direct ink jet printing by fabricating silver microelectrodes on treated PDMS. Kim et al. printed quadruple and castellated electrodes and conducted dielectrophoretic manipulation. a silver nanoparticle-based ink called (DGP 40LT-15C) was used with drop spacing 5, 10, 20 and 30 μm. The study also focused on the effects of mechanical bending and temperatures changes on the printed silver microelectrodes, and concluded that direct ink jet printing of silver ink on PDMS can be applied on to many applications in future. In addition, E. Starke et al. [20] printed a flexible humidity sensor by using an ink jet printer (DIMATIX DMP-2830), silver neodecanoate-based ink, and a polymer particle-based ink for the humidity sensitive part.

CHAPTER 3: PDMS FABRICATION

3.1 Overview:

In this chapter, designing the molds and fabricating the porous PDMS specimens is discussed. The molds are designed in specific dimensions, so they can be used in the required experiments and tests as well. The treated salt and sugar particles have been used as porogen inside PDMS structures. These particles were later dissolved by water and left a network of holes behind them.

3.2 Mold Design:

At the beginning, the molds are made from 3D printed acrylonitrile butadiene styrene (ABS) molds that are designed by using a blueprint of molds in SolidWorks© Software. We used four different dimensions for samples, and they were shaped in rectangular specimens, and dogbone specimens for tensile testing. Nine rectangular molds (Figures 3.1 and 3.2) and another seven dogbone shaped molds were printed. However, one of the dog bone-shaped molds was used to create solid PDMS samples. These samples were divided into 4 groups, as shown in Table 3.1 and 3.2, and the molds' dimensions were as follows:

1. Design (1): 70mm*20mm*3.5mm (Dogbone)

2. Design (2): 30mm*20mm* 5mm (Rectangular)

3. Design (3): 30mm*18mm* 5mm (Rectangular)

4. Design (4): 30mm*16mm* 5mm (Rectangular)

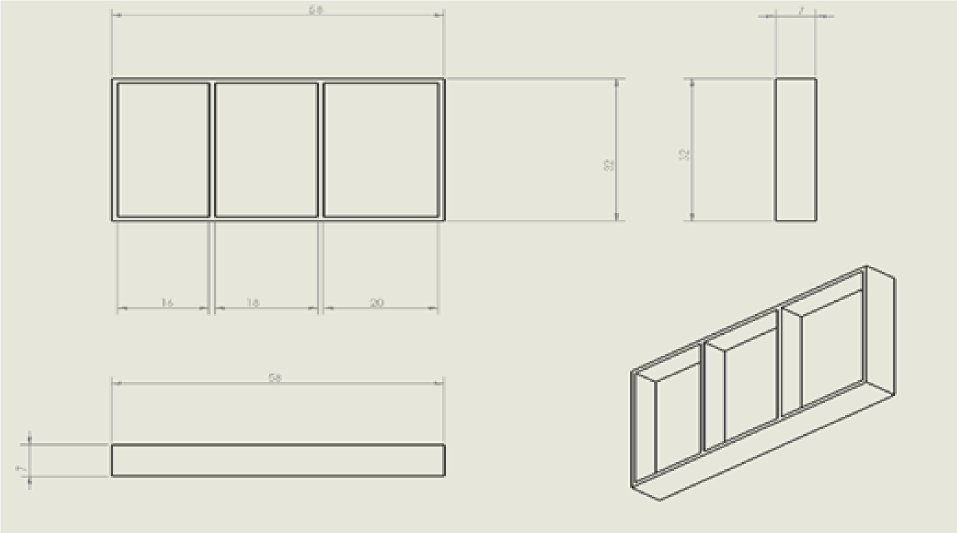


Figure 3.1 Drawing of Rectangular Molds

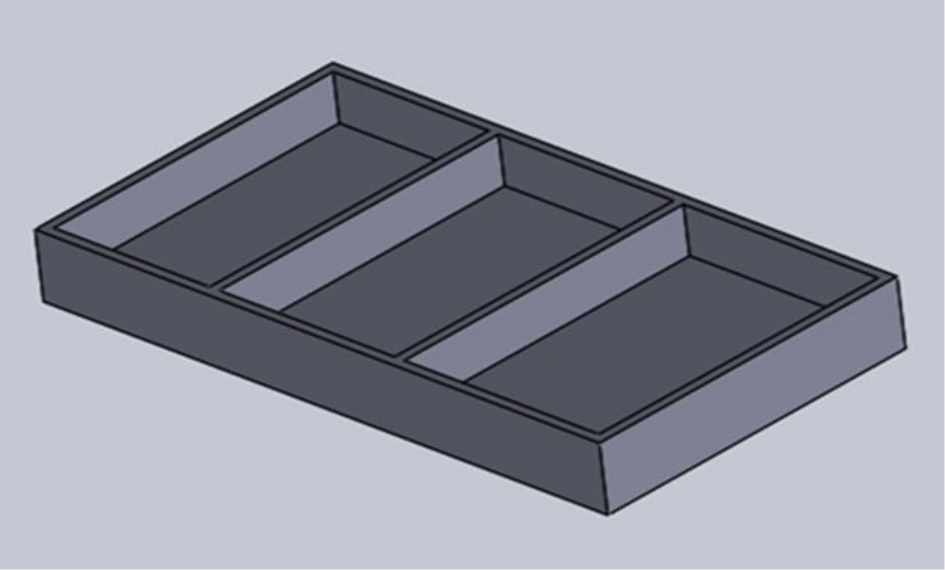


Figure 3.2 The Designed Molds

3.3 Printing the Molds:

Once the dimensions were adjusted and the molds' design was completed in SolidWorks© Software, A 3D printer was used for the next step. A Stratasys Uprint ES Printer, which accepts processing a Stereo Lithography (STL) file was used for this task. The imported file was then cut into multiple slices, making it ready for printing layer by layer. The printer, shown in Figure 3.3, uses acrylonitrile butadiene styrene

(ABS) as a printing material. Acrylonitrile butadiene styrene (ABS) is a thermo-plastic polymer that is used like an additional material to improve the toughness of plastics. Its biggest applications exist due to its mechanical properties, such as impact strength, Young's modulus, impact strength, and temperature stability. In addition, it has superior chemical resistance and recyclability. ABS materials have been applied in construction, 3D printing, computers, automotive bumpers, and toys. However, ABS polymers must be applied with a flame retardant (superior mechanical).

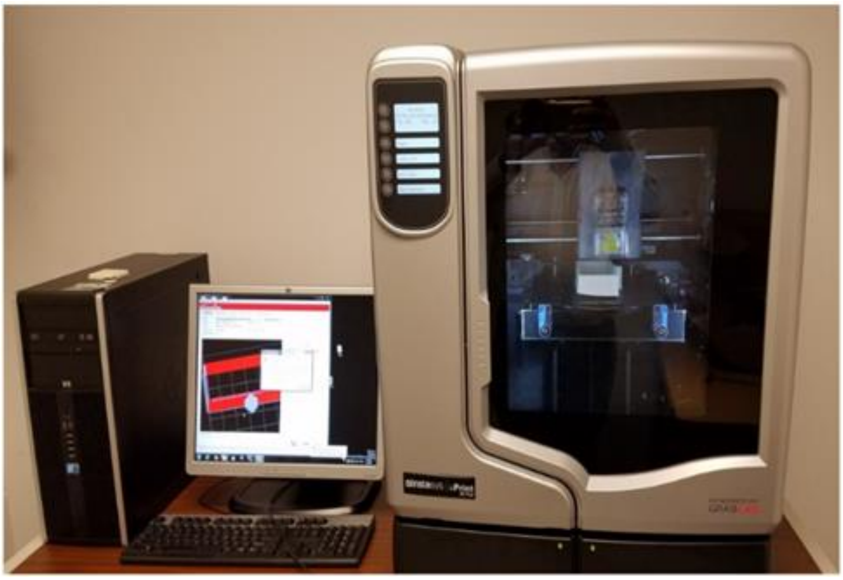


Figure 3.3   A Stratasys Uprint ES Printer

3.4 Materials as a Porogen:

In this research, Salt and sugar grains sizes were varied between normal salt grain, big sea salt grain, and sugar grain as porogen to create porous PDMS. Three different grain sizes were used, which are sugar (350-450 micro meter) with density about 1.59 g/cm^3, seal salt (900-1000 micro meter), and normal salt (250-350 micro meter) with density around 2.17 g/cm^3 [21] [22]. Particle sizes play an important role in its pores' volumes. Then, particles were divided in four main groups, as shown in Figure 3.5, and weighted as 1.0 g for Group 1 and 1.5 g for Group 2 and 3. Group 4 (dogbone samples) was divided into 3 sections A, B and C, and weighted as 1.5 g, 2.5 g, and solid sample, respectively. Sample identifications are also described in Table 3.1. A solid portion of PDMS was formed in the upper side of porous samples, see Figure 3.4. The thickness (ts) of solid section depends on the amount of porogen as the overall thickness is almost fixe, i.e. the porous part thickness (tp) also depends on the amount porogen.

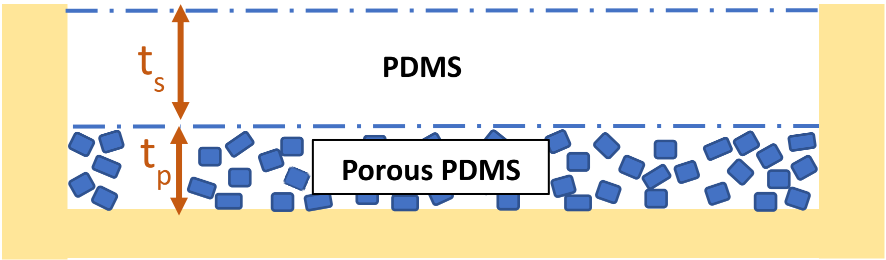


Figure 3.4 Illustrated Diagram of Porous PDMS molds

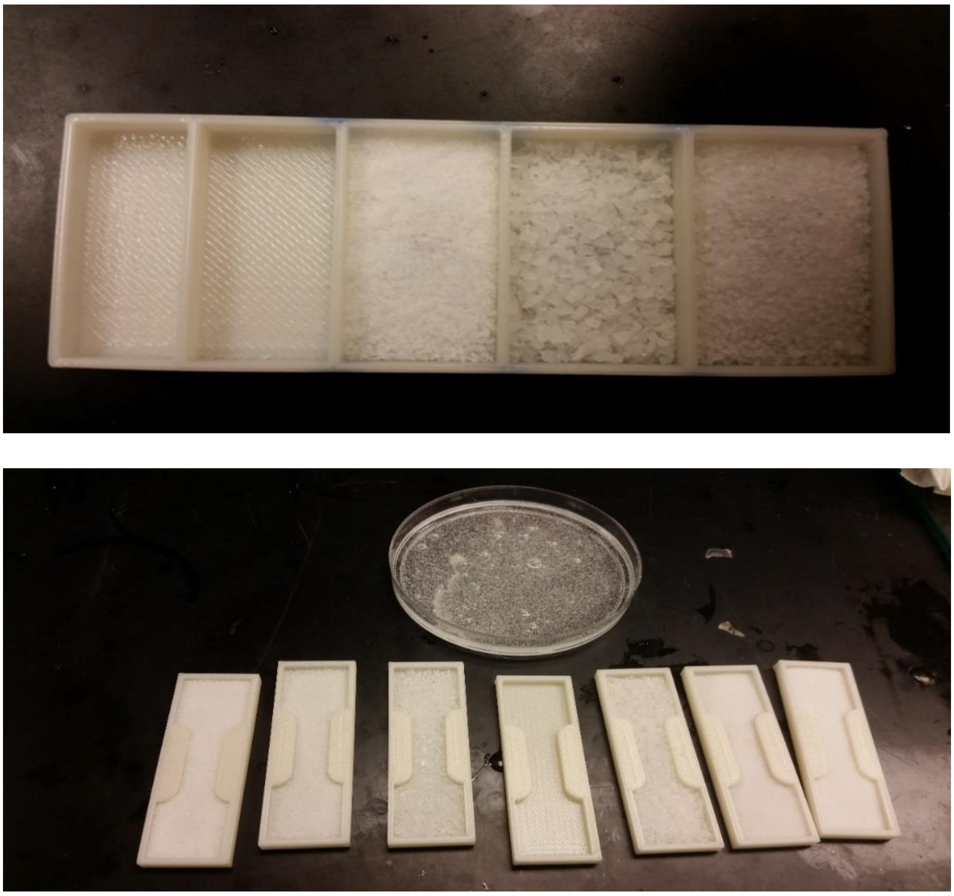


Figure 3.5 Salt and Sugar Particles in ABS Molds Before Pouring PDMS

3.5 Porous PDMS Fabrication

The first step is to partially fill the molds with carefully measured porogen particles so that the fabricated PDMS has a solid backbone on which 2D structures can be printed. After filling the mold with porogen particles and before poring the PDMS prepolymer mixture, a micro-region fusion treatment was done for Groups 2 and 4 only. It needed a closed oven (Thermolyne) for two hours at 45˚C with a water bath, as shown in Figure 3.6. Upon exposure to the generated water, the particles melted and adhered to the neighboring ones. Occasionally, particles might melt together into a single particle, which influences the sample's properties as well.

Figure 3.6 A Closed Oven with Water Vapor Source

The next data, Table 3.1, summarizes the details of each sample including its particle's status, sample number, group number, and shape, as well.

Group Number	Sample Number	Particles' Status	Description	Shape
1	1	Non-treated	1.0 g Sugar (Porous)	Rectangular
	2	Non-treated	1.0 g Big grain salt (Porous)	Rectangular
	3	Non-treated	1.0 g Small grain salt (Porous)	Rectangular
2	4	Treated	1.5 g Sugar (Porous)	Rectangular
	5	Treated	1.5 g Big grain salt (Porous)	Rectangular

	6	Treated	1.5 g small grain salt (Porous)	Rectangular
3	7	Non-treated	1.5 g Sugar (Porous)	Rectangular
	8	Non-treated	1.5 g Big grain salt (Porous)	Rectangular
	9	Non-treated	.5 g small grain salt (Porous)	Rectangular
4	10	Treated	1.5 g Small grain salt (Porous)	Dogbone
	11	Treated	1.5 g Big grain Salt (Porous)	Dogbone
	12	Treated	1.5 g Sugar (Porous)	Dogbone
	13	Treated	2.5 g Small grain salt (Porous)	Dogbone
	14	Treated	2.5 g Big grain salt (Porous)	Dogbone
	15	Treated	2.5g Sugar (Porous)	Dogbone
	16	None	Solid (Not Porous)	Dogbone

Table 3.1 The Details of PDMS Samples

Next, the molds were put into a convection oven again at 60˚C for one hour for air-drying and to processing the micro-region fusion treatment. Salt/sugar particles melted together strongly creating a well-connected network that used as the template for the following molding process. PDMS mixture contained a combination of PDMS (The Base) and its agent (SYLGRAD 184 SILICONE ELASTOMER KIT) with ratio of volume 10:1, respectively. The volume for the base was 20 mL, whereas the agent was 2 mL. Then, they mixed together in one container, as shown in Figure 3.7.

Figure 3.7: PDMS Prepolymer Mixture

A vacuum-assisted infiltration (desiccator) was used for removing any air bubbles from the PDMS mixture [10]. It was used twice before and after poring process. Specifically, it was not used for suctioning any air bubbles inside the mixture, instead it was used to suction air between particles. The desiccator device is shown in Figure 3.8. The air originally resides in the gaps between the particles and PDMS mixture as well, but by operating desiccator device, air bubbles will be evacuated and squeezed into these empty spaces instead, under the effect of vacuum-assisted capillary filling.

Figure 3.8 Desiccator Device

Once air bubbles no longer appeared, the filled molds were taken out from the desiccator and placed into the oven at 65˚C for two hours for drying and curing. Then, molds and cured mixture were taken out for cooling in room temperature. The PDMS specimens were created successfully and displayed in Figures 3.9 and 3.10.

3.6 Removal of Porogen

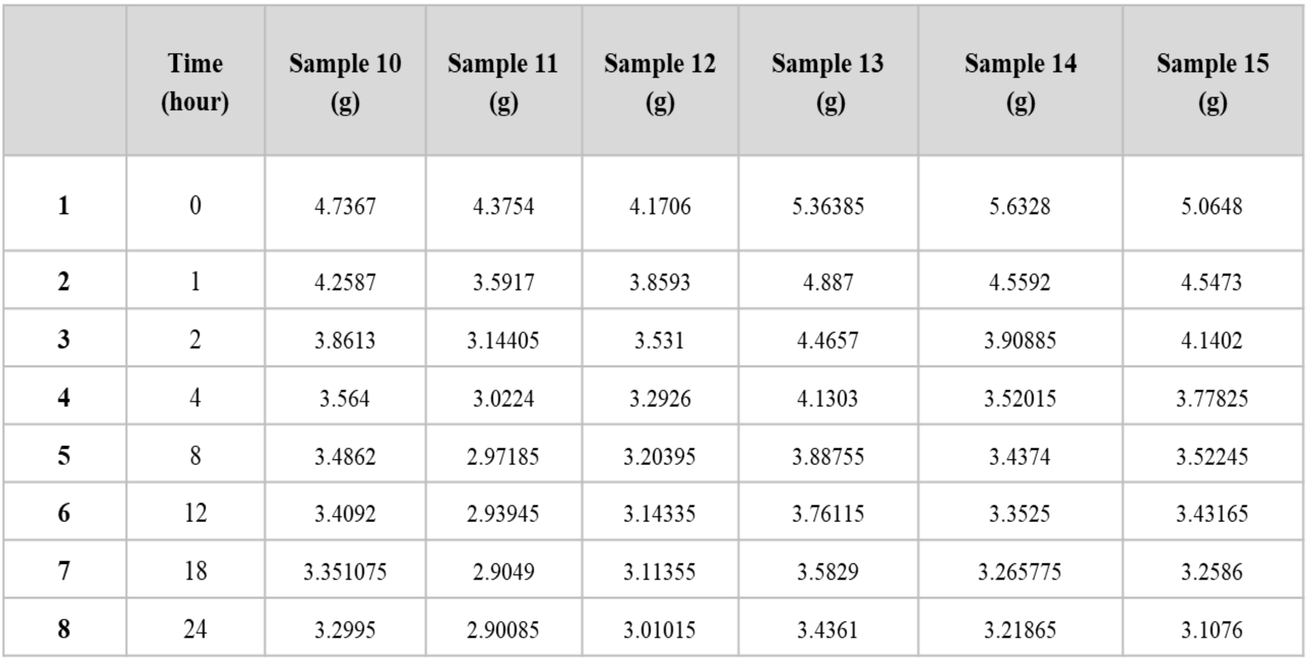
The next step focuses on removing the internal porogen particles from PDMS structure. This process involved immersing porous PDMS samples into dissolving solution (distilled water) intentionally to remove internal salt and sugar cubes from the specimens. To dissolve the particles faster, the dissolving solution was placed on a stirring device. The Specimens were submerged in warm distilled water (55℃) and stirred in a special stirring device called (Coring- PC420D) at 600-1150 RPM, Figure 3.12 depicts the stirring device. First, the weight of all the samples were measured before they were placed in stirred water. Then, they were submerged in warm water for at least 24 hours. To make sure that the porogens are removed leaving behind the pores, the samples were taken out of the solute, dried with hot air, and weighted several times after a specific period. The water that was used in the test was changed multiple times during this period to increase dissolution rate in order to keep a high concentration gradient between cubes and water [17]. Each sample has its different pore size and different quantity based on the internal particles. The data shown in Tables 3.2, 3.3 and 3.4 indicate total weight of samples 1 to 15, while Tables 3.5 indicates weights of particles' residues in porous PDMS samples 10 to 15 after specific periods of time. The amount of residual particles was calculated by subtracting the sample weight after immersing in water from the original sample weight. Since they were dried and weighted after 1, 2, 4, 8, 12, 18 and 24 hours of immersion in water, their weights decreased over time. Figure 3.11 shows the side view of a rectangular sample after removing the porogen. The sample shows a porous section with solid PDMS backbone.

	Time (hour)	Sample 1 (g)	Sample 2 (g)	Sample 3 (g)	Sample 4 (g)	Sample 5 (g)	Sample 6 (g)
1	0	2.9722	3.438	2.773	3.4504	3.9354	3.3476
2	1	2.9152	3.2475	2.6825	3.3511	3.714	3.158
3	2	2.8906	3.2004	2.6374	3.3216	3.6828	3.089
4	4	2.759	3.1404	2.5545	3.2498	3.6084	2.949
5	8	2.5458	3.067	2.4811	3.045	3.3962	2.8026
6	12	2.3326	2.8815	2.3352	2.8423	3.1267	2.5302
7	18	2.0128	2.6033	2.1163	2.5383	2.7223	2.1215
8	24	2	2.5	1.8974	2.2343	2.50	1.90

Table 3.2 Total Weights of Samples 1 -6 as a Function of Dissolution Time

	Time (hour)	Sample 7 (g)	Sample 8 (g)	Sample 9 (g)
1	0	3.7164	3.93175	3.26895
2	1	3.4267	3.77435	3.00925
3	2	3.3292	3.676	2.76265
4	4	2.71125	3.1562	2.4953
5	8	2.4743	2.57925	2.30765
6	12	2.4327	2.54505	2.17455
7	18	2.34135	2.4646	2.09395
8	24	2.250	2.38415	2.01335

Table 3.3 Total Weights of Samples 7-9 as a Function of Dissolution Time



	Time (hour)	Sample 10 (g)	Sample 11 (g)	Sample 12 (g)	Sample 13 (g)	Sample 14 (g)	Sample 15 (g)
1	0	4.7367	4.3754	4.1706	5.36385	5.6328	5.0648
2	1	4.2587	3.5917	3.8593	4.887	4.5592	4.5473
3	2	3.8613	3.14405	3.531	4.4657	3.90885	4.1402
4	4	3.564	3.0224	3.2926	4.1303	3.52015	3.77825
5	8	3.4862	2.97185	3.20395	3.88755	3.4374	3.52245
6	12	3.4092	2.93945	3.14335	3.76115	3.3525	3.43165
7	18	3.351075	2.9049	3.11355	3.5829	3.265775	3.2586
8	24	3.2995	2.90085	3.01015	3.4361	3.21865	3.1076

Table 3.4 Total Weights of Dogbone Samples 10-15 as a Function of Dissolution Time

	Time (hour)	Sample10 (g)	Sample 11 (g)	Sample 12 (g)	Sample 13 (g)	Sample 14 (g)	Sample 15 (g)
1	0	1.5	1.5	1.5	2.5	2.5	2.5
2	1	1.1389	0.8641	1.3303	2.0535	1.4538	2.2327
3	3	0.7289	0.4858	0.9883	1.6466	1.0124	1.9326
4	6	0.4391	0.3055	0.5521	1.4208	0.373	1.3931
5	9	0.4007	0.2125	0.4553	1.2449	0.286	1.1574
6	12	0.3426	0.1558	0.3974	1.0263	0.1634	1.0651
7	18	0.2703	0.0948	0.3839	0.8379	0.0771	0.8816
8	24	0.2111	0.0948	0.2062	0.7124	0.07	0.6789

Table 3.5 Particle Concentration for Dogbone Samples 10-15 as a Function of Dissolution Time

Figure 3.9: Solid PDMS Samples in Dogbone Shape

Figure 3.10: Porous PDMS Samples in Rectangular Shape

Figure 3.11: Side View of a Porous PDMS Samples with the Solid Section Backbone

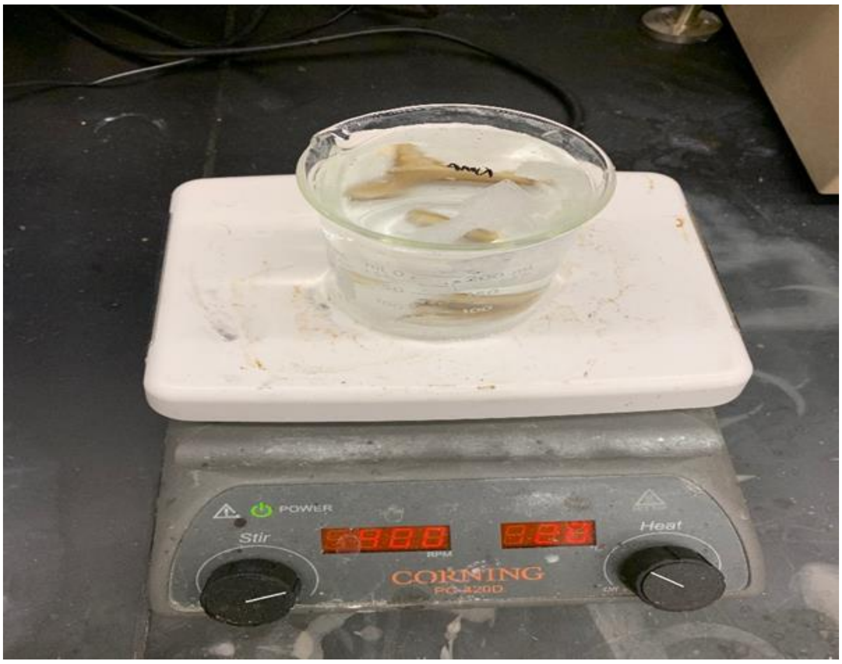


Figure 3.12: Stirring Device

CHAPTER 4: EXPERIMENTAL WORK

4.1 Overview

In this chapter, the physical and mechanical testing of fabricated PDMS are discussed. The utilized tests are porosity testing, optical testing, tensile testing, and Inkjet printing.

4.2 Porosity Test

In this research, the porosity was measured by immersing the porous PDMS samples into water for 24 hours, for the second time. The samples were weighted before placing them water. After that, they were weighted again after being in water for 24 hours. Table 4.1, 4.2 and Table 4.3 indicate weights before and after submerging the samples in water for 24 hours. The Porosity (P) of porous sections of all the samples in percentage, without the solid part, was calculated based on the following equation:

$$P = \frac{(\text{weight of sample after filling by water} - \text{weight of sample before filling})/1000000}{(\text{Volume of porous portion of sample})} * 100 \quad (3)$$

The volume of the porous section of each PDMS sample was calculated by multiplying the thickness of the porous section with the sample surface area. The thickness of the porous sections (t_p) of all the specimens were measured from microscopy images. Before that, specimens were submerged in warm distilled water (55°C) and stirred in a special stirring device called (Coring- PC420D) at 600-1150 RPM to remove any porogen from PDMS structure. Tables 3.2 to 3.4 depicted the weights measured and registered periodically after 1, 3, 6, 9, 12, 18 and 24 hours for all samples. The shown Table 4.1 indicates weights changes of PDMS before and after filling by water in 24 hours for samples 1 to 6, and weights increased after 24 hours in water. Next Table 4.2

indicates changes in weights for samples 7 to 9. Also, Table 4.3 explains the weights of Dogbone samples 10 to 16 after keeping in water for 24 hours, also.

	Time (hour)	**Sample 1 (g)**	**Sample 2 (g)**	**Sample 3 (g)**	**Sample 4 (g)**	**Sample 5 (g)**	**Sample 6 (g)**
1	0	2.54	1.59	1.66	2.12	2.22	2.16
2	24	2.82	1.96	1.90	2.50	2.62	2.51

Table 4.1 Weights of Samples 1-6 Before and After Filling by Water

	Time (hour)	**Sample 7 (g)**	**Sample 8 (g)**	**Sample 9 (g)**
1	0	2.33	2.05	1.93
2	24	2.69	2.43	2.26

Table 4.2 Weights of Non-Treated Samples 7-9 Before and After Filling by Water

	Time (hour)	**Sample 10 (g)**	**Sample 11 (g)**	**Sample 12 (g)**	**Sample 13 (g)**	**Sample 14 (g)**	**Sample 15 (g)**
1	0	3.08	2.88	3.12	3.81	3.20	3.16
2	24	3.57	3.44	3.62	4.39	4.10	3.89

Table 4.3 Weights of Samples 10-15 Before and After Filling by Water

4.3 Optical Microscopic Imaging:

This testing was done on the first six porous samples 1 through 6 only. The objective for this mic was to distinguish, characterize and analyze morphologies of fabricated porous PDMS closely.The fabricated PDMS samples were intentionally cut along in two layers and scanned from near point of view by using a Wild M400 Photomicroscope with a software called ImageJ and is shown in Figure 4.1. The microscopic images samples 1 through 6 are shown in Figures 4.2 to 4.7, respectively.

Figure 4.1 Wild M400 Photomicroscope

Figure 4.2 Microscopic Images of Porous PDMS Fabricated by Not-Treated Sugar

Figure 4.3 Microscopic Images of Porous PDMS Made by Not-Treated Sea Salt Particles

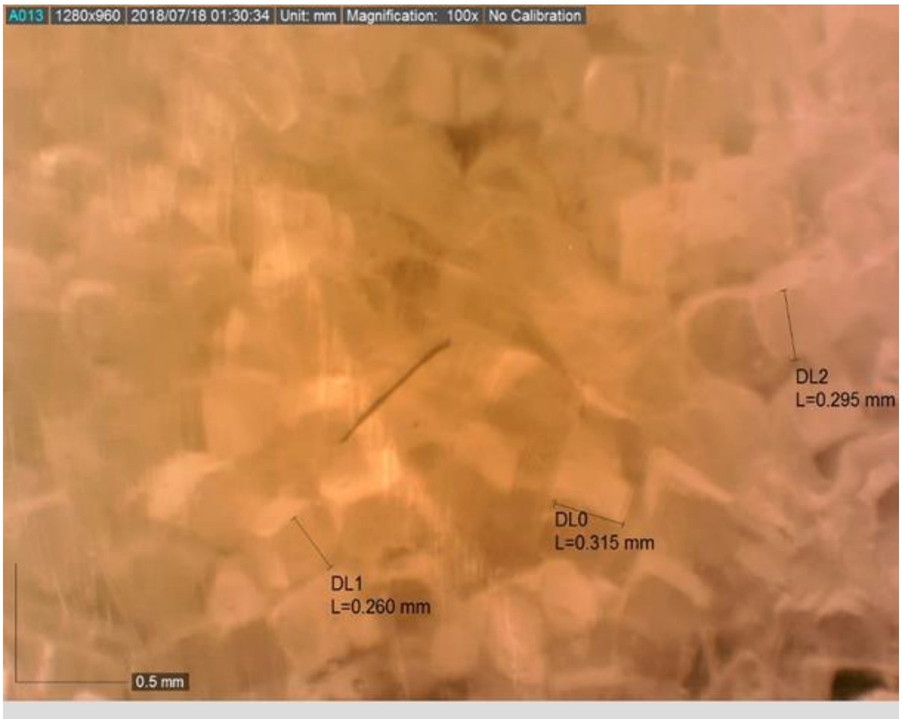


Figure 4.4 Microscopic Images of Porous PDMS Made by Not-Treated Salt Particles

Figure 4.5 Microscopic Images of Porous PDMS Samples Made by Treated Sugar Cubes

Figure 4.6 Microscopic Images of Porous PDMS Samples Made by Treated Sea Salt Cubes

Figure 4.7 Microscopic Images of Porous PDMS Samples Made by Treated Small Salt Cubes

4.4 Tensile Testing

Tensile testing of materials determines their behaviors such as elongations, strengths, and other mechanical properties, such as ductile or brittle property. For this research, tensile mechanical test was performed on the six samples in Group 4 and one solid sample to understand the effect of porosity on mechanical behavior of fabricated PDMS. The tensile tests were performed by using a table-top tensile instrument called Nidec Hand-wheel Test Stand FGS-250W with capacity of 250 lb, see Figure 4.8. By processing this tension test data, stress (σ) was calculated as:

$$\sigma = \frac{P}{A} \qquad (4)$$

which is the applied load P (N) over the cross-sectional area A (mm), and strain (ε) by using:

$$\varepsilon = \frac{\Delta L}{L} \qquad (5)$$

Here is the displacement and L is the gage length of the sample. This stress-strain curve represents the relation between them, and numbers of mechanical properties and behaviors can be concluded from it. Also, the modulus of elasticity can be calculated by using Hooke's Law, which is the ratio of stress values over strain values in the first linear zone of the stress-strain plots. This testing was applied on seven dogbone samples 10 to 16, with dimensions of 70*20*3.5 (mm), six porous and one solid sample. All tested samples were loaded untailed failed. As a result, the modulus of elasticity (E) was evaluated as the slope of elastic region of stress-strain curve.

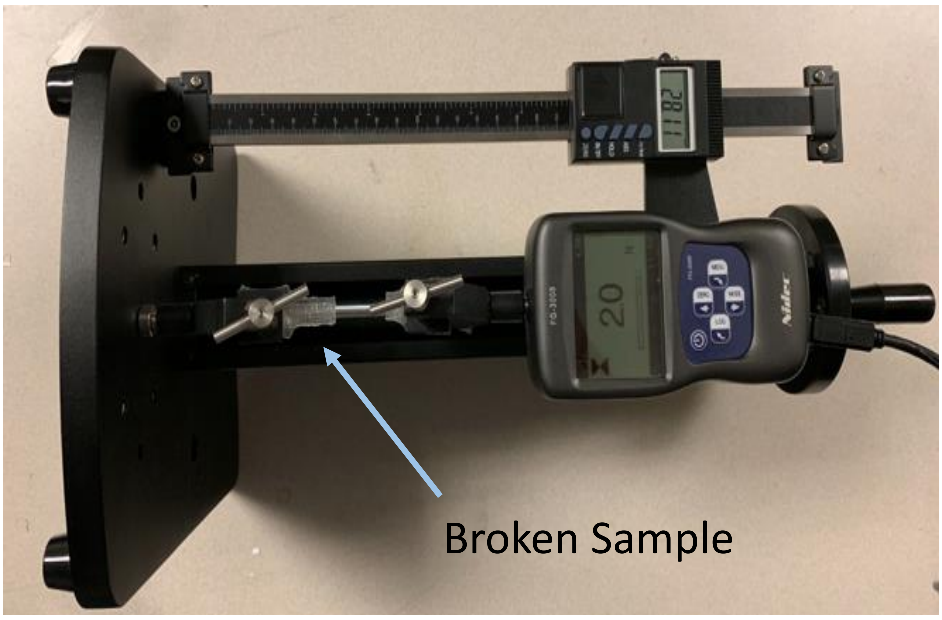


Figure 4.8 Tensile Device

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Overview

This chapter represents the results of the experimental work achieved in this research. Sixteen specimens were examined for three types of testing, which were a porosity test, a microscopy test and a tensile test. In addition, an ink-jet printing on a PDMS surface by two types of ink was achieved successfully. All specimens were fabricated as porous PDMS except one solid specimen, as previously mentioned. The comparison of the results and curves were derived from the collected data in the experiment.

5.2 Removal of Porogen

The porosity test was completed for fifteen specimens of porous PDMS. Since the pores of each sample were different in either the particles' type or quantity, their results were significantly different as well. The porosity test focused on salt/sugar particle residue in the PDMS body, and the dissolution rate. Figures 5.1 to 5.3 indicate the difference in weights between the samples, depending on changes in particles weight with respect of time. ΔW is defined as the difference between the original weight and the current weight after a certain period in water, including the solid part of PDMS. Illustrated diagram in Figure 3.4 explained a solid portion of PDMS was formed in the upper side of porous samples. Moreover, the thickness (t_s) of solid section depends on the amount of porogen as the overall thickness is almost fixed. In other words, the porous part thickness (t_p) also depends on the amount porogen. As shown in Figure 5.1, the performed test that formed Samples 1, 2, and 3 indicated the diminishing of salt/ sugar particles of the PDMS structure over time and the difference in original weights and current weights increased by time. All three samples had one gram (1.0 g) of particles. Overall, Sample 1, which contained sugar particles, had the least concentration after 24 hours in water, whereas Sample 3 had the highest concentration. The sugar and sea salt particles in Samples 1 and 2 almost dissolved after 18 hours in water but Sample 3 did not. They had about 0.968 and 0.962 grams, respectively, even after passing 24 hours in water, see Figure 5.1. Also, the porosity testing explained dropping in weights of salt/ sugar particles over time. Samples 4, 5, and 6 had a treated one and a half grams (1.5 g) of cubes. Generally, all samples had insignificant numbers of particles inside even after passing 24 hours. Their differences in weights were 1.22, 1.47, and 1.44 grams, respectively. However, Samples 5 and 6 that contained sea salt and normal salt had the lowest concentration after 24 hours in water, about 0.20, 0.48 grams, respectively. However, Sample 4 had the highest concentration, about 0.84 grams. Salt particles in Sample 5 and 6 almost have more ability to melt in water but Sample 4 did not. See Figure 5.2.

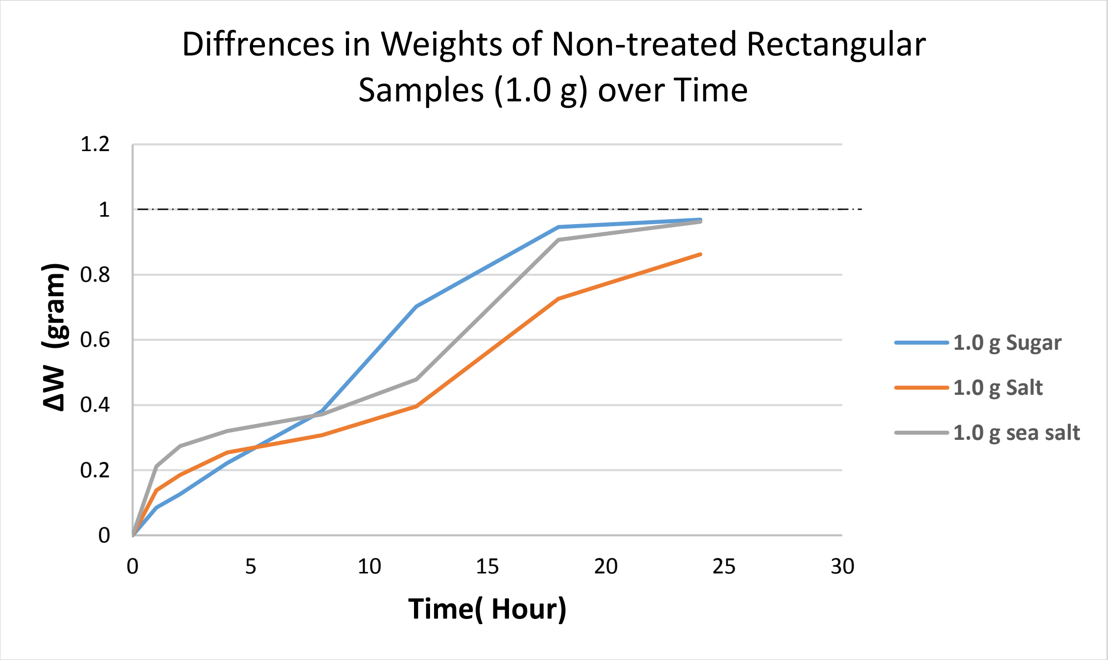


Figure 5.1 The Differences in Weights for Samples 1, 2 & 3 Over Time

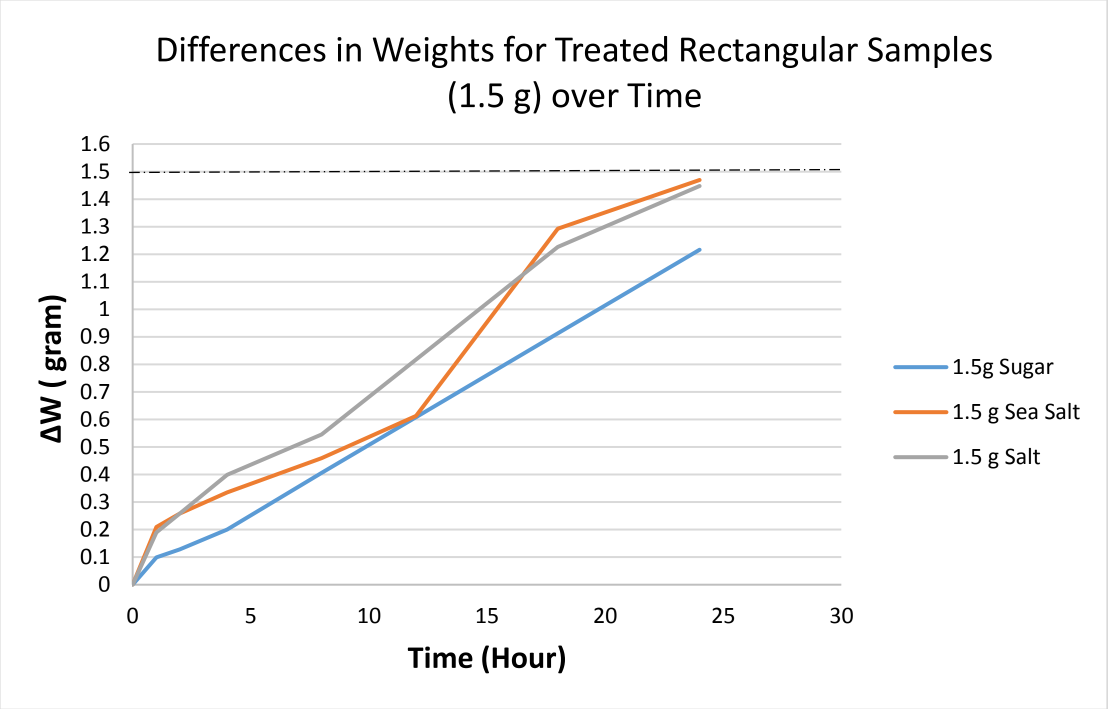


Figure 5.2 The Differences in Weights for Samples 4, 5 & 6 Over Time

On the other hand, weights for sample 7, 8, and 9 that contained 1.5 g of non-treated particles were different over the 24 hours, their weights decreased randomly. The differences in weights (ΔW) for sample 8 that contained 1.5 g of sea salt was higher than 1.5 g due to an inaccurate measurement, and potential peeling of the PDMS during the dissolution process [10], as shown in Figure 5.3.

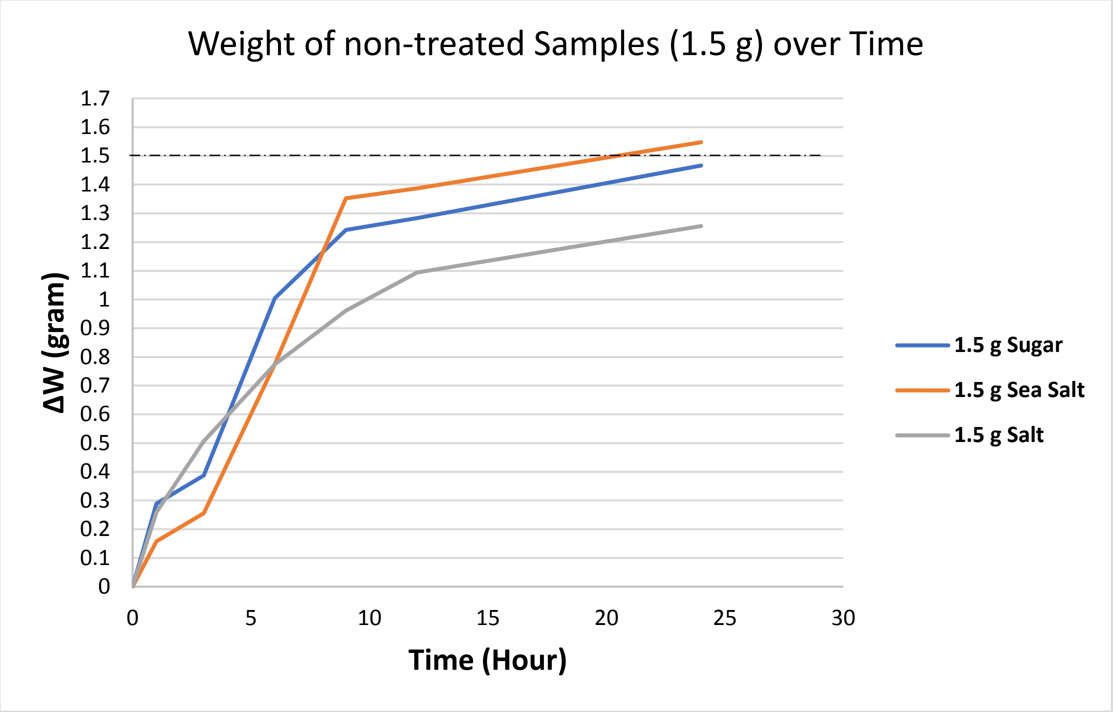


Figure 5.3 The Differences in Weights for Samples 7, 8 & 9 Over Time

All nine samples still contained particle residue after passing 24 hours in solvent. Even though they had the same material, Sample 4, which contains 1.5 g of sugar, had the highest concentration after these hours, whereas Sample 1 had the lowest concentration. Samples containing different sizes of salt particles were found between samples 1 and 4. Tables 5.1-5.3 indicates weights for samples, without the solid portions, filled by sugar/salt particles, they were 1.0 g of non-treated particles, 1.5 g of treated particles and 1.5g of non-treated. The relation between porosity and particles concentration is proportional, as concentration increases, the porosity will increase, as well, Figure 5.4. The calculated porosity was close in value from each other, they were in range from 18.11 to 24.85 %. However, the porosity value for sample contained 1.0 g of Sea Salt was cancelled from the plot.

Sugar	**Non-treated**		**Treated**
	1.0 g	1.5 g	1.5 g
Concentration (mg/mm^3)	0.33	0.5	0.5
Porosity (%) **(S.D)**	18.11 (1.55)	21.94 (2.68)	22.94 (4.15)

Table 5.1: Porosity and Concentration of Samples Made by Sugar

Sea Salt	**Non-treated**		**Treated**
	1.0 g	1.5 g	1.5 g
Concentration (mg/mm^3)	0.37	0.56	0.56
Porosity (%) **(S.D)**	69.00 (1.46)	23.57 (5.25)	24.85(5.44)

Table 5.2: Porosity and Concentration of Samples Made by Sea Salt

Salt	**Non-treated**		**Treated**
	1.0 g	1.5 g	1.5 g
Concentration (mg/mm^3)	0.42	0.63	0.63
Porosity (%) **(S.D)**	20.62 (0.68)	22.11(5.47)	24.19 (3.18)

Table 5.3: Porosity and Concentration of Samples Made by Salt

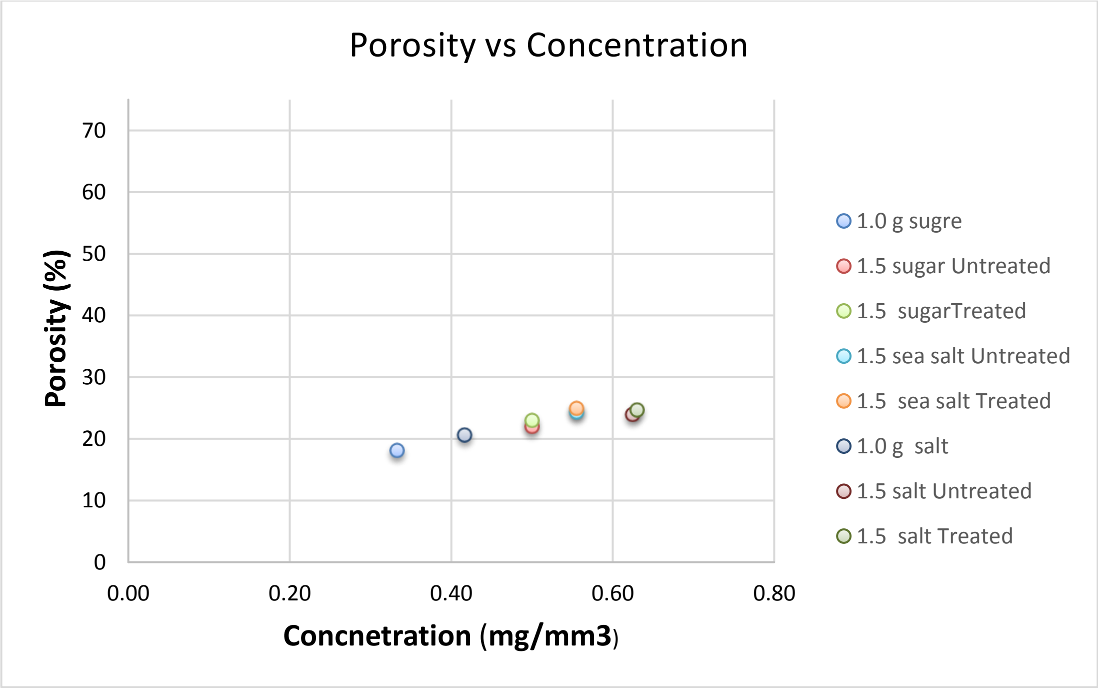


Figure 5.4 The Relation Between Porosity and Concentration

Figure 5.5 presents, normalized results, of differences in weights (ΔW) via time rate for Group 4 which were Samples 10,11 and 12. All three samples contained 1.5 gram of treated particles. Since the bigger particles in size with lowest density is dissolving faster than others materials, sea salt particles dissolved faster than sugar and normal salt. Figure 5.6 shows differences in weights of sample that had 2.5 of particles, and again sea salt dissolved faster than the other.

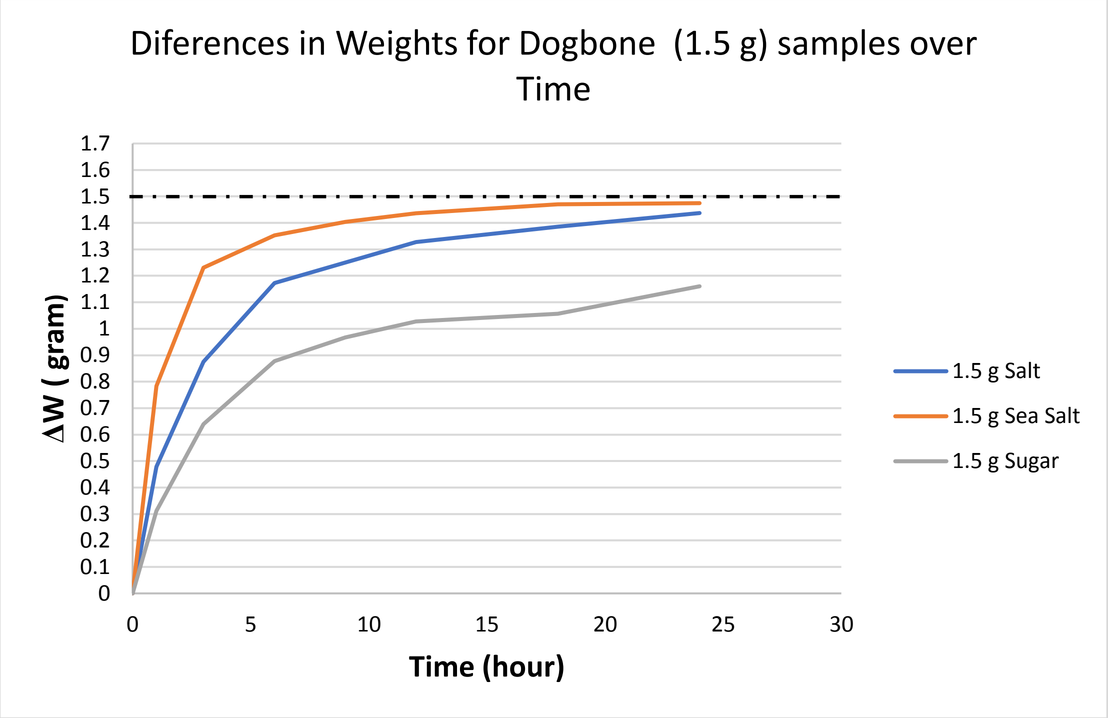


Figure 5.5 The Differences in Weights for Samples 10, 11 & 12 Over Time

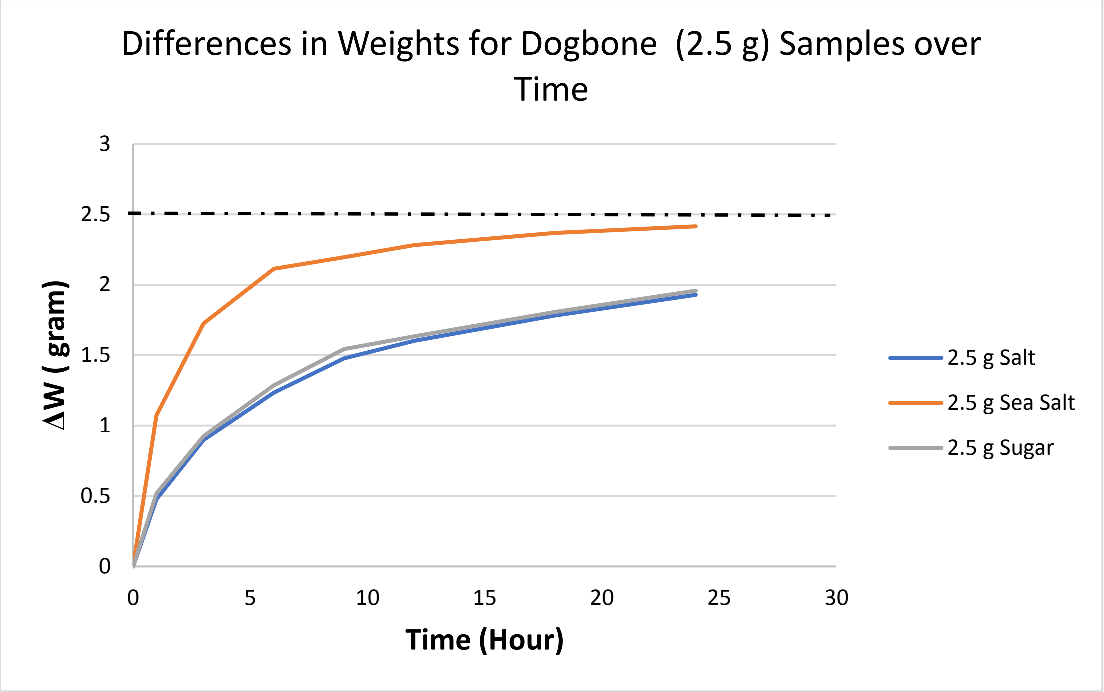


Figure 5.6 Weights of Samples13, 14 &15 During 24 Hours

Porosity testing for porous parts in Group 4 indicated that samples had close values of porosity from each other, i.e. they were in range from 23.74% to 31.45 %. Sample 14, which contained 2.5 g of sea salt particles, got the highest porosity (31.45 %) while Sample 10 had the lowest porosity (23.74%). Sample 15, 2.5 g of sugar, had the second rank of porosity (26.32%), then Sample 13, 2.5 g salt (25.0%), Sample 11 (24.6%), and Sample 12 (24.05%) respectively. In addition, insignificant number of residues existed in PDMS structures even after 24 hours in water. See Table 3.5.

Particle Type	**Particles weight (g)**	**Shape**	**Porosity (%)**
Sugar	1.5	Dogbone	24.05
	2.5	Dogbone	26.32
Sea salt	1.5	Dogbone	24.6

	2.5	Dogbone	31.45
Small salt	1.5	Dogbone	23.74
	2.5	Dogbone	25.0

Table 5.4 Porosity for Group 4 Dogbone Samples

It is mentioned before that the fabricated PDMS samples had a porous section with a solid section backbone creating a gradient structure. A schematic representation of a sample viewed from thickness direction is shown in Figure 3.4, where thickness of the porous and solid sections are indicated by t_p and t_s, respectively. All data were collected and summarized together in table to compare with each other and can be seen in Table 5.6. Porosity testing indicates thickness of solid section, porous section and porous volume.

sample config	Sample Number	Description	Solid Thickness t_s (mm)	Porous Thickness t_p (mm)	Porous Volume (%) $= \frac{tp}{tp+ts}$
Rectangular samples	1	1.0 g Sugar (Porous)	2.32	2.68	53.6
	2	1.0 g Big grain salt (Porous)	2.04	2.96	59.2
	3	1.0 g Small grain salt (Porous)	3.05	1.95	39.0
	4	1.5 g Sugar (Porous)	2.25	2.75	55.0
	5	1.5 g Big grain salt (Porous)	1.99	3.01	60.2
	6	1.5 g small grain salt (Porous)	1.74	3.26	65.2
	7	1.5 g Sugar (Porous)	2.29	2.71	54.2
	8	1.5 g Big grain salt (Porous)	1.62	3.38	67.6
	9	.5 g small grain salt (Porous)	1.89	3.2	64.0

Dogbone samples	10	1.5 g Small grain salt (Porous)	1.71	1.81	51.42
	11	1.5 g Big grain Salt (Porous)	1.58	2.02	56.11
	12	1.5 g Sugar (Porous)	1.62	1.9	53.98
	13	2.5 g Small grain salt (Porous)	1.40	2.12	60.23
	14	2.5 g Big grain salt (Porous)	0.96	2.56	72.73
	15	2.5g Sugar (Porous)	1.36	2.51	64.86

Table 5.5: Solid and Porous Thickness of PDMS Samples

5.3 Optical Microscopic

Under microscopy, it was determined that residual particles mainly concentrated within the central region as expected. This is due to the relatively large dissolution distance from the surface and the poor interconnectivity to dissolution paths. After 12 hours in water, non-treated samples had more porogen crystals inside PDMS than treated samples, which means the treated particles melted faster than the non-treated ones. Also, this testing indicated that the salt and sugar particles did not dissolve completely in both groups, see Figure 5.7 in next page. After the immersion for 24 hours in water, insignificant number of residues will still be observed, while negligible residue could be found in Sample 3. Obviously, dissolution speed greatly improved with micro-region fusion treatment compared with the non-treated ones due to the connectivity between particles.

Figure 5.7 Microscopic Images of Porous PDMS After 12 Hours in Water

5.4 Tensile Test

The results for tensile tests were classified into three groups (A, B, and C). The first group (A) was for samples 10, 11, and 12, and they had a maximum longitudinal deformation between 12.0 and 14.0 mm, with about 11.5 to 15.8 N were maximum applied load to achieve these deformations, see Figures 5.8, A-1, and A-3. The corresponding failure stress occurred in a range between 0.3 and 0.40 N/mm^2 (MPa) over a strain in between 0.40 and 0.45 in all three samples. See Figures 5.9, A-2, and A-4. Samples 13, 14, and 15 created the second group (B). Overall, they had a maximum deflection between 10.0 and 13.0 mm, with applied maximum load from 5.5 to 8.5 N. Their relationship was graphed as straight line, see Figures A-3, A-5, and A-7. The failure stress for Samples 14 and 15 were close to each other, about 0.15 N/mm^2 (MPa) but Sample 13, about 0.23 N/mm^2, had the lowest value in Group B. Strain values in the three samples were various in each one, 0.35, 0.37 and 0.38 respectively. Last group (C) was Sample 16 was the solid specimen and got the highest values in all results in comparison with the two previous groups, see Figures A-11 and A-12.

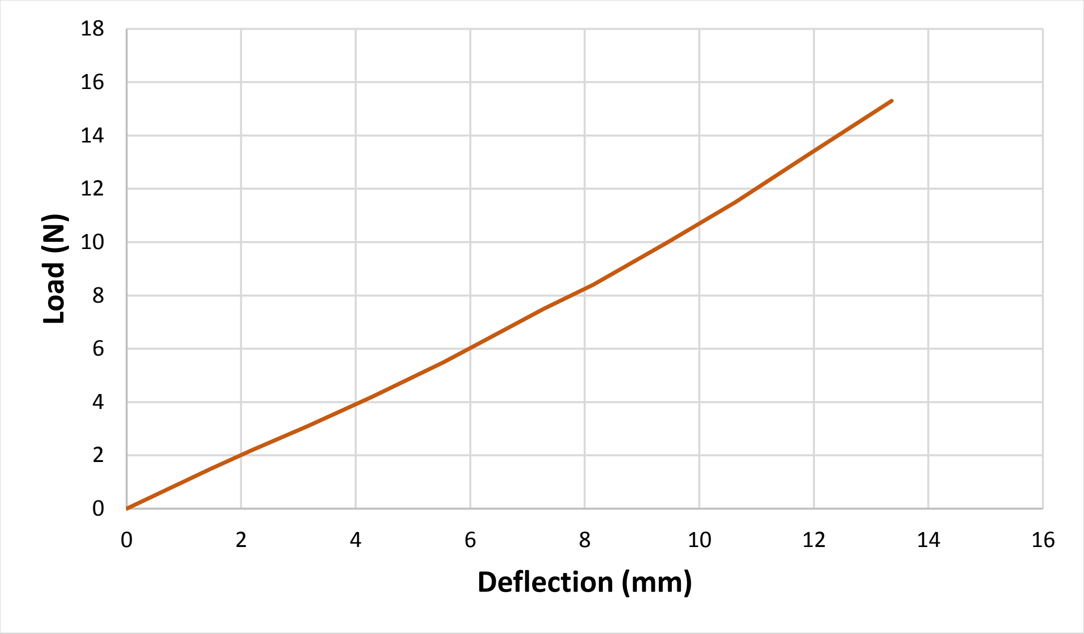


Figure 5.8 Load deflection Curve for Sample 10 (1.5 g Salt)

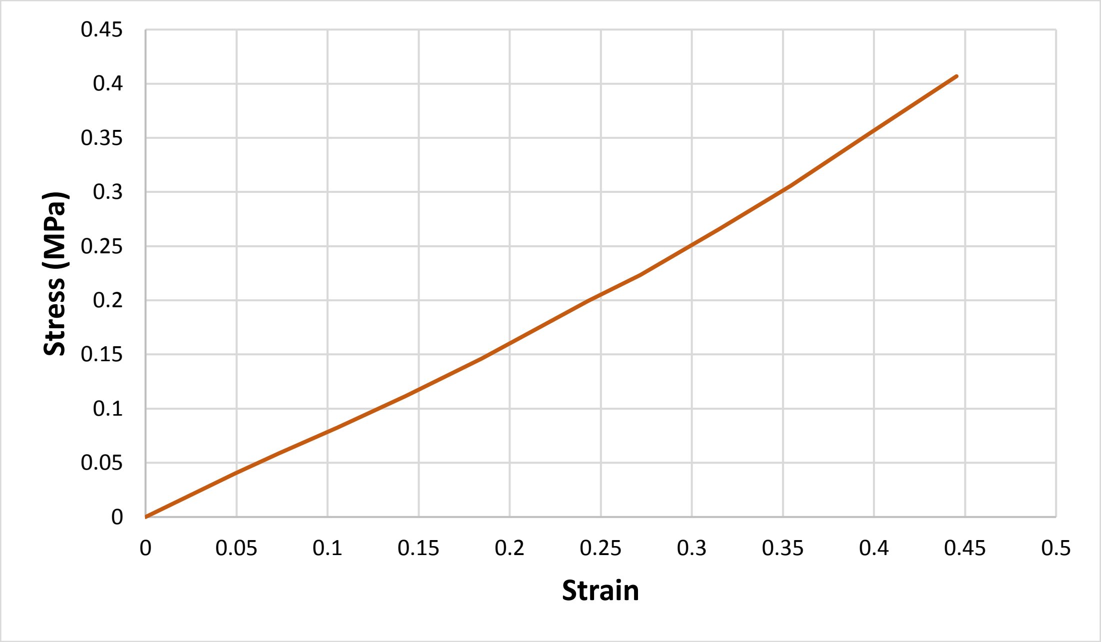


Figure 5.9 Stress Strain Curve for Sample 10 (1.5 g Salt)

The calculated modulus of elasticity (E) for Samples 11 to 16 from elastic region in stress strain curves in Figures 5.9, and Figures A-1 to A-12 in the Appendix as following:

- Sample 10, E $= \frac{\Delta\sigma}{\Delta\,\varepsilon} =$ 0.9 MPa
- In Sample 11, E = $\frac{\Delta\sigma}{\Delta\,\varepsilon} =$ 0.7 MPa
- In Sample 12, E = $\frac{\Delta\sigma}{\Delta\,\varepsilon} =$ 0.79 MPa
- In Sample 13, E = $\frac{\Delta\sigma}{\Delta\,\varepsilon} =$ 0.66 MPa
- In Sample 14, E = $\frac{\Delta\sigma}{\Delta\,\varepsilon} =$ 0.36 MPa
- In Sample 15, E = $\frac{\Delta\sigma}{\Delta\,\varepsilon} =$ 0.42 MPa
- In Sample 16, E = $\frac{\Delta\sigma}{\Delta\,\varepsilon} =$ 1.1 MPa

In short, values of modulus of elasticity are related to porosity and volume fraction of porous section, as shown in Table 5.6. The data in Table 5.6 are plotted in Figures 5.10 through 5.13. It is clear that the relationships between failure stress and porosity, and failure stress and porous section volume fraction are inverse. In other words, as porosity and porous section volume fraction increases, failure stress decreases, see Figures 5.10 and 5.11. The same behaviors between modulus of elasticity E, and porosity and volume fraction of porous section exist, see Figures 5.12 and 5.13. That means, as the porosity and porous section volume fraction increase, modulus of elasticity decreases. These relationships are intuitively correct.

Porogen Particle Type	Particles weight (g)	Porosity (%)	Volume fraction of porous section	Failure Stress (MPa)	Modulus of Elasticity (MPa)
Sugar	1.5	24.05	53.98	0.36	0.79
	2.5	26.32	64.86	0.15	0.42

Sea salt	1.5	24.6	56.11	0.31	0.70
	2.5	31.45	72.73	0.14	0.36
Small salt	1.5	23.74	51.42	0.42	0.90
	2.5	25.0	60.23	0.24	0.66
Solid	0	0	0	1.05	1.1

Table 5.6 Comparison of Tensile Test Results of PDMS

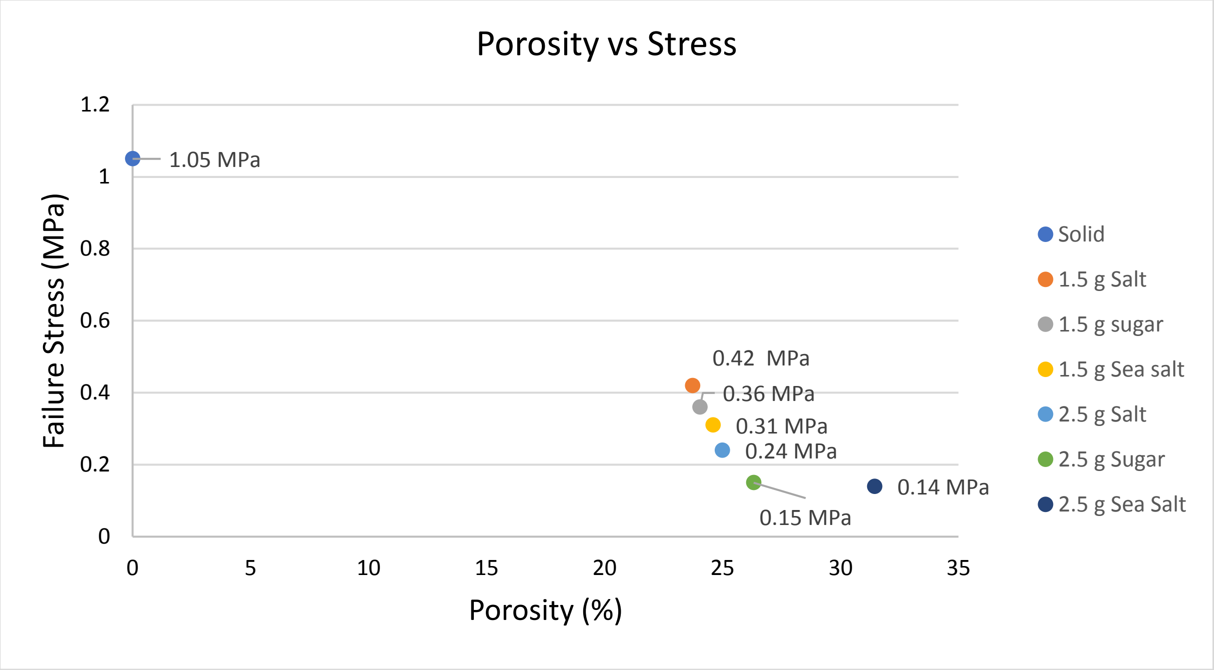


Figure 5.10 Porosity vs Failure Stress Curve

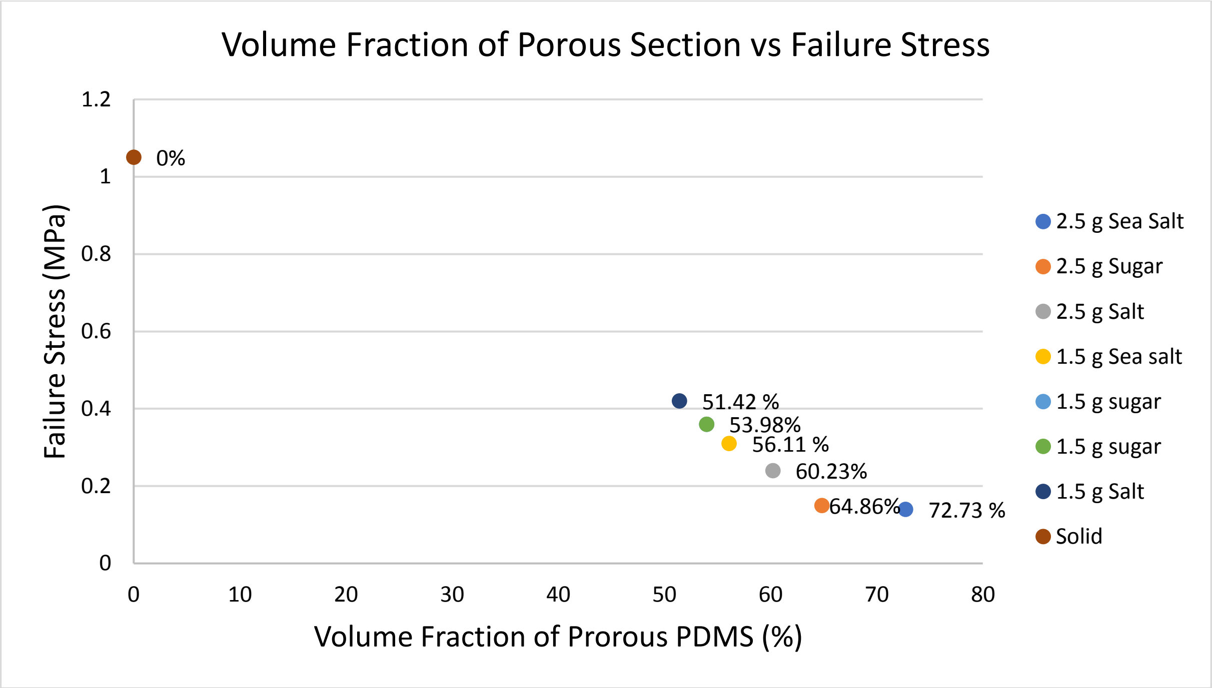


Figure 5.11 Volume Fraction of Porous Section vs Failure Stress Curve

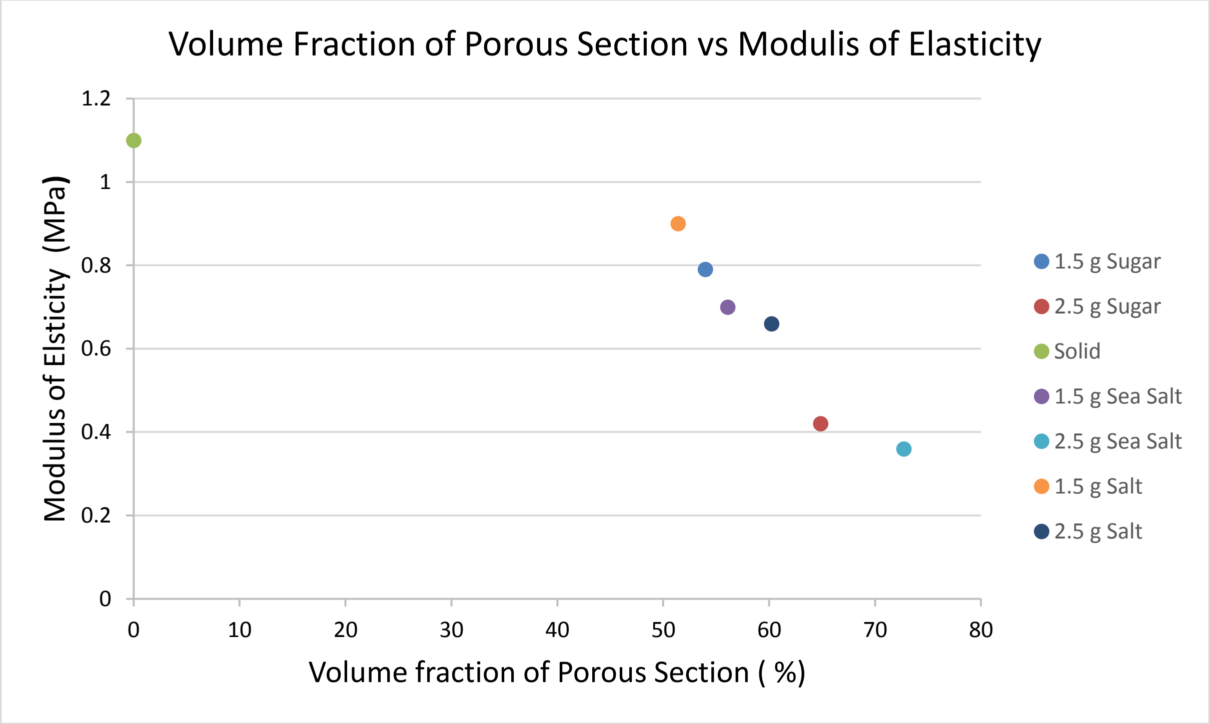


Figure 5.12 Volume Fraction of Porous Section vs Modulus of Elasticity Curve

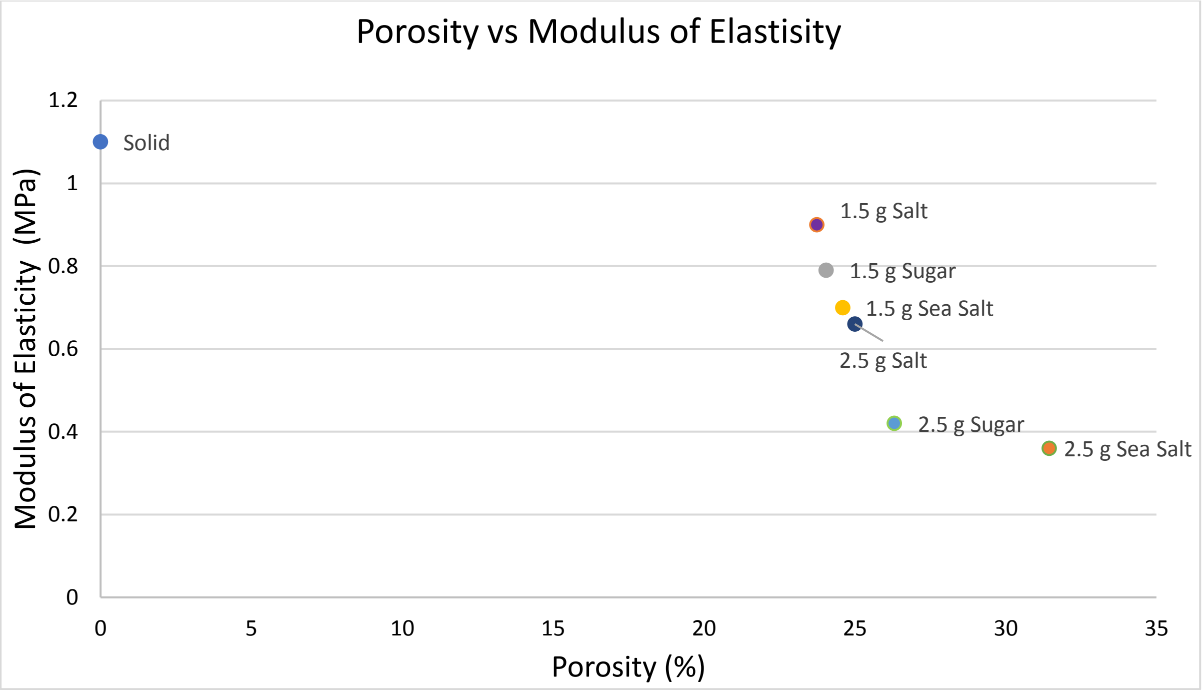


Figure 5.13 Porosity vs Modulus of Elasticity Curve

CHAPTER 6: SUMMARY, CONCLUSION, AND RECOMMENTATIONS

6.1 Summary

In summary, a porous PDMS has been prepared and characterized in three different groups under three types of testing, porosity test, optical testing, and tensile test. The properties of porous PDMS were analyzed by performing these tests. A printed mold was designed, which was needed for our fabrication process, by using SolidWorks© Software and a 3D printer. A comparison of 3 different kinds of porogens, salt, sea salt, and sugar, was completed. Also, a comparison between sixteen (16) specimens was done on the differences in the pores' character. The specimens were fabricated in multiple dimensions with salt and sugar particles. The difference between those specimens was based on pores quantities, particles dimensions, and the method of fabrication. Porous PDMS samples with different pore size distributions and different structure contours had been intentionally cut and examined under a microscope. The optical test was carried out by Photomicroscope. The dissolution of particles processed by using a stir device (Corning PC-420D), and the tensile test was performed by using a Nidec FGS-250W testing machine, with a capacity of 250 Ib. The porosity, load-displacement, and stress-strain curves were plotted via an Excel worksheet. The collected data were compared with other specimens' data. The modulus of elasticity (E), was calculated based on experimental data and the drawn stress-strain curves as well.

6.2 Conclusions

The results were obtained, studied, and compared to conclude that the solid specimen, without pores, had the highest force, and highest deformation before failure point. Also, it is concluded that the same solid specimen had the highest failure strength and modulus of elasticity values, whereas specimens containing higher porosity had the lowest mechanical properties. The stress and strain values were similar for all samples in the same group, i.e. Group A that consisted of Samples 10, 11, and 13 had close stress-strain values. The concept of the group, in this research, was basically the weight of salt/sugar particles inside PDMS specimens. In addition, the calculated modulus of elasticity values were also close in Group A and C, but Group B was different. Dissolution rate of salt/sugar particles didn’t depend on the weight of the particles, volume and the density, as well. The porogen dissolution testing indicated that even after passing 24 hours in water, most tested samples still contained insignificant number of internal particles. However, the optical microscopy and the porogen dissolution testings confirmed that the treated particles inside PDMS melted faster than non-treated one. Both the strength, and the modulus of elasticity E have an inverse relationship with porosity and porous section volume fraction, i.e. when porosity and porous section volume fraction increase, E and failure stress decrease.

6.3 Recommendations for Future Work

The present work is mainly dedicated to developing porous PDMS substrates with solid backbone and testing their physical and mechanical characteristics. Since, the intended application of the substrates is in the area of printed electronics, ink-jet printing on PDMS surface is recommended. We have done some preliminary work, as discussed below in section 6.3.1, however further work in the area is needed. The prelimery work can be used as a foundation for future work.

6.3.1 Preliminary Work Performed

A chemical treatment was required to perform printing processes. The goal of the treatment procedure was to decrease hydrophobic properties in PDMS, improving its wettability, and thus be able to print on its surface. See Figure 6.1. The PDMS treatment procedure was carried out by two chemicals steps. The first step was performed by mixing 0.5 ML of (3-Mercaptopropyl) trimethoxy-silane (MPTMS) 95.9% Purity with 100 mL of ethanol with ratio of volume 1:200 (v/v) solution. Next, PDMS samples were immersed inside this mixture at room temperature for one hour. The second step began by rinsing PDMS substrate with ethanol (99% purity), then drying it with clean compression air. After that, PDMS samples were immersed into 4.22 mL of hydrochloric acid (HCL) for one hour followed by deionized water and dried, see Figure 6.2.

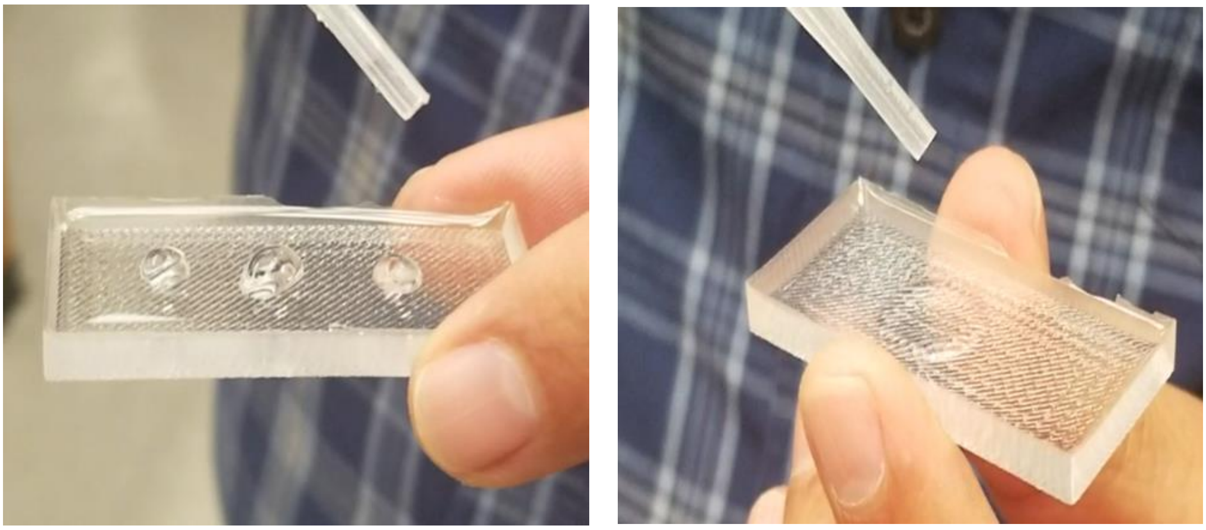


Figure 6.1 Hydrophobic Property of PDMS Surface Before Treatment (Left) & After Treatment (Right)

In this preliminary work, printing on solid and porous sides were achieved. Two types of ink were used for ink-jet printing, Smart-ink and UT Dots ink. Both inks are conductive inks based on silver nanoparticles, and they were printed on the solid face as straight lines. However, a black ink marker was printed on the porous side. UT Dots ink has general usages in ink-jet printers, and it is a printable ink on a set of substrates such as metals, paper, silicon, etc. Its particle size is around 8 to 20 nm, and curing temperature is between 120 to 300°C. Its silver concentration is about 40wt%, 60%w/v. The solvent is hydrocarbon and proprietary, and it has viscosity around 11 cP. However, its lifetime is about three months in room temperature. The viscosity for Smart ink around 13 mPa. The used printer was (Jetlab 4) Micro-Fab Technologies, shown in Figure 6.3. Straight lines were printed with speed of 10 mm/s for smart ink with a drop spacing equal to 30 µm while the printing speed for UT DOT ink was 20 mm/s with a drop spacing 50 µm. Finally, printed samples had two adhesion tests: 1) Soak test in water for 2 hours at room temperature, and 2) an ultrasonic test by using an ultrasonic cleaner device (Baxter) for 30 minutes then inspected closely under the

Wild M400 Photomicroscope. Two adhesion testing indicated that chemical treatments for one hour long was not enough to improve the hydrophilicity of the PDMS surface and were not able to increase the connection between silver particles and the PDMS surface completely.

Figure 6.2: PDMS Samples Inside Mixture of MPTMS & Ethanol

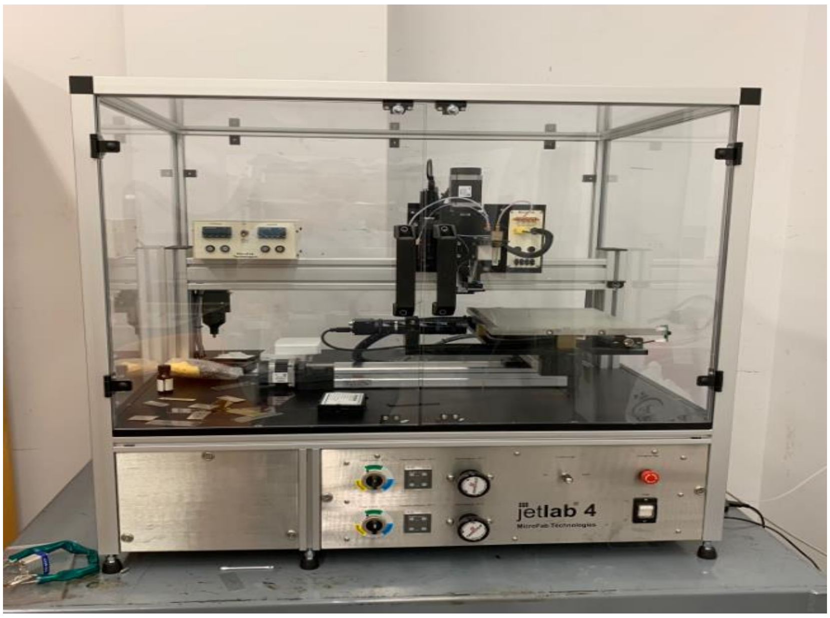


Figure 6.3: Inkjet Printer (Jetlab 4)

The results of adhesion tests were different than previous research. In non-treated samples, Smart-ink appeared darker and more concentrated on a PDMS surface than a treated one. In addition, Ultrasonic tests removed parts of smart ink, whereas soak testing could not, i.e. it was like a new printed sample. However, UT DOT ink was cracked and not coherent. In contrast, non-treated UT DOT ink was coherent. The treated samples got the same results under a microscope. Ultrasonic testing made small scratches on printed ink, and removed parts of it. Overall, the two tests indicated that chemical treatment did not show a good hydrophilicity on PDMS samples and could not increase the connection between silver and PDMS surface as well. See Table 6.1 in next page.

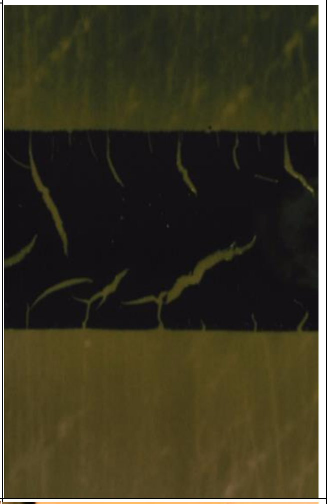
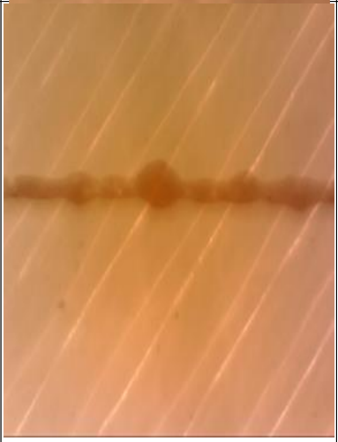
Status of Sample	**Smart ink**			**UT Dot ink**
	As printed	**Soak test**	**Ultrasonic test**	
Non-Treated				
Treated				

Table 6.1 Comparison of Printed PDMS Samples at Different Situations

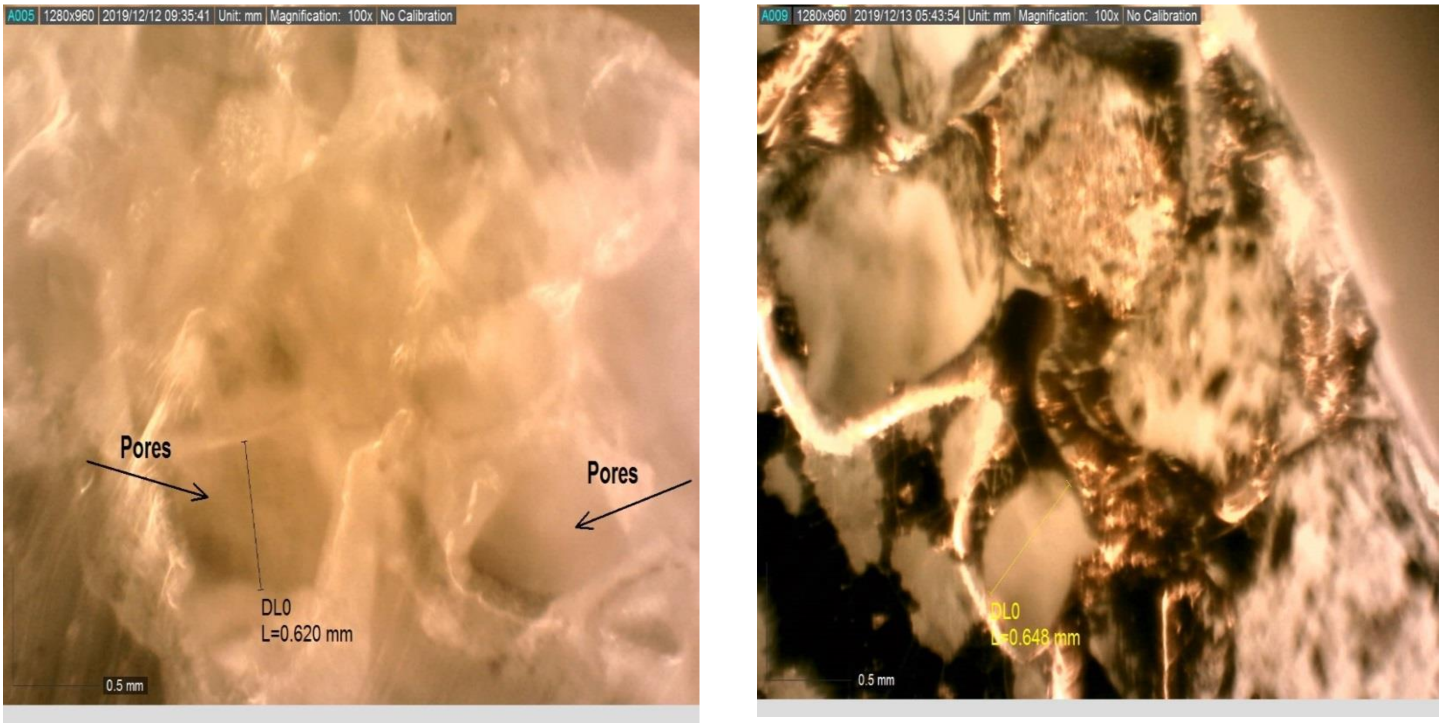


Figure 6.4 Microscopic Images of Porous PDMS Before Using a Black Marker Ink (Left) and After (Right)

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APPENDIX A

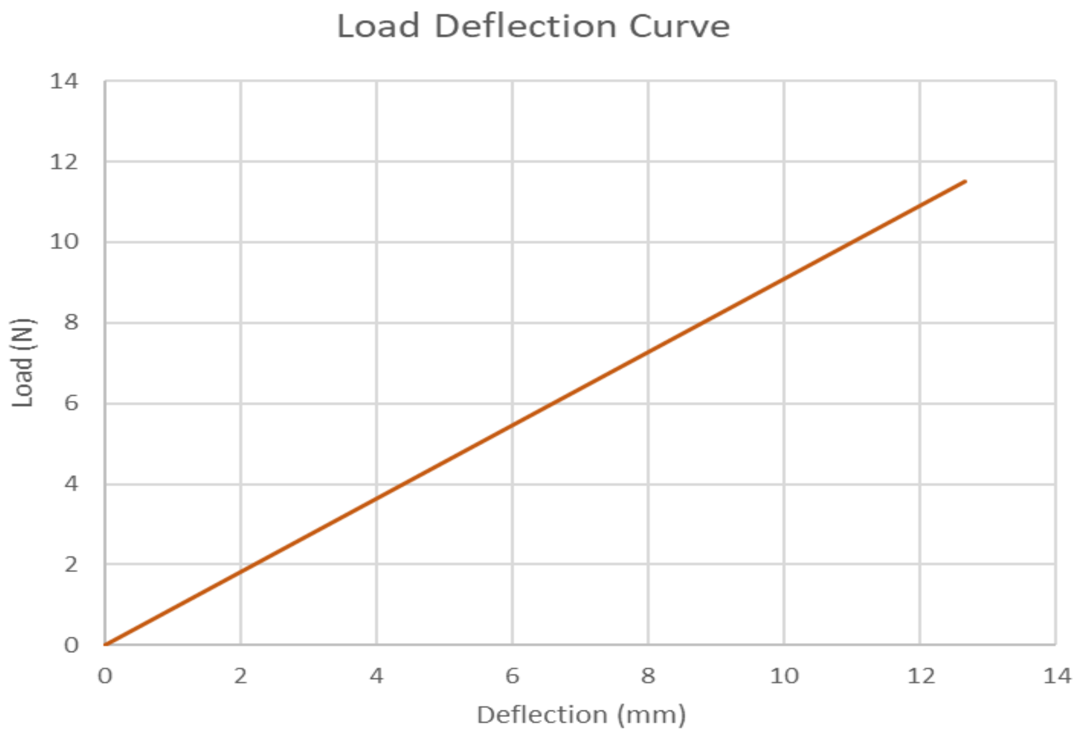

Figure A-1 Load Deflection Curve for Sample 11 (1.5 g Big Salt)

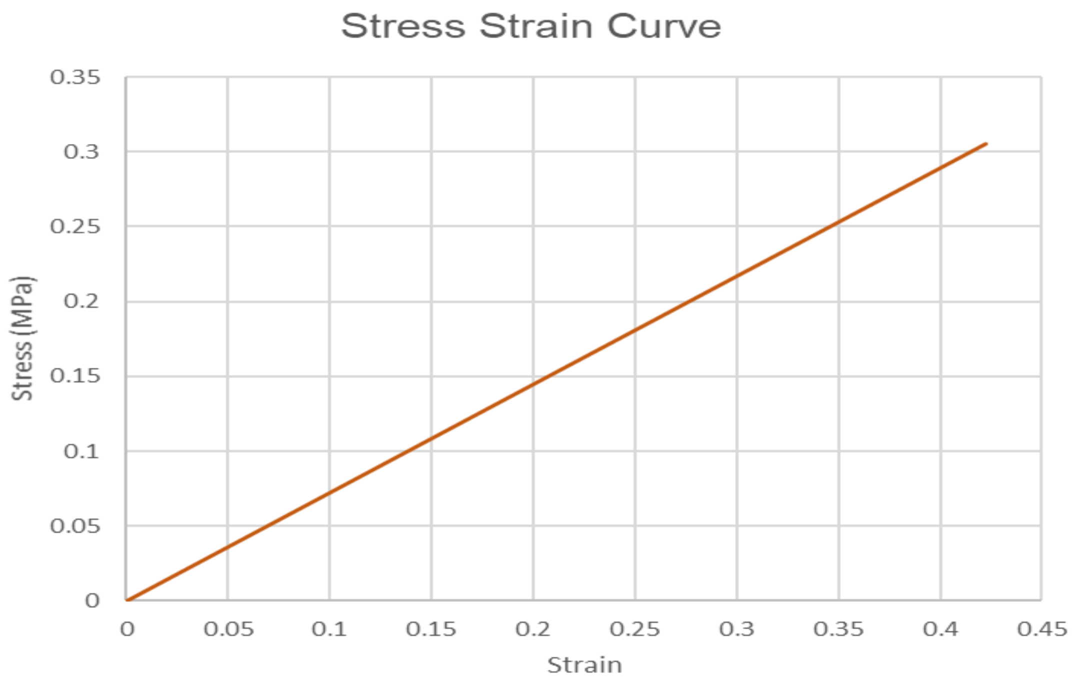

Figure A-2 Stress Strain Curve for Sample 11 (1.5 g Big Salt)

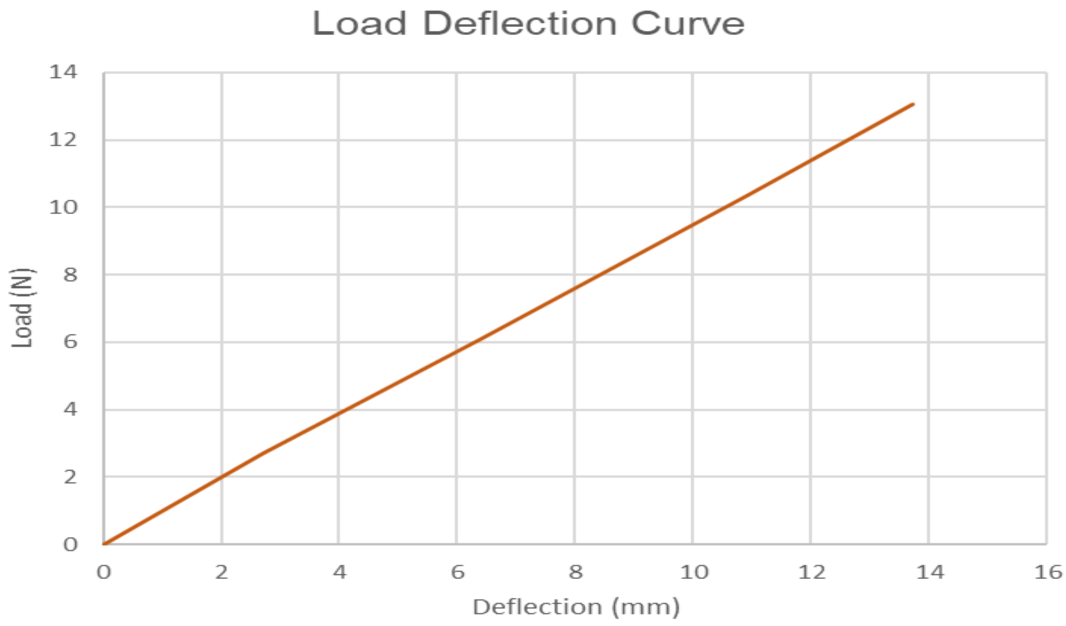

Figure A-3 Load Deflection Curve for Sample 12 (1.5 g Sugar)

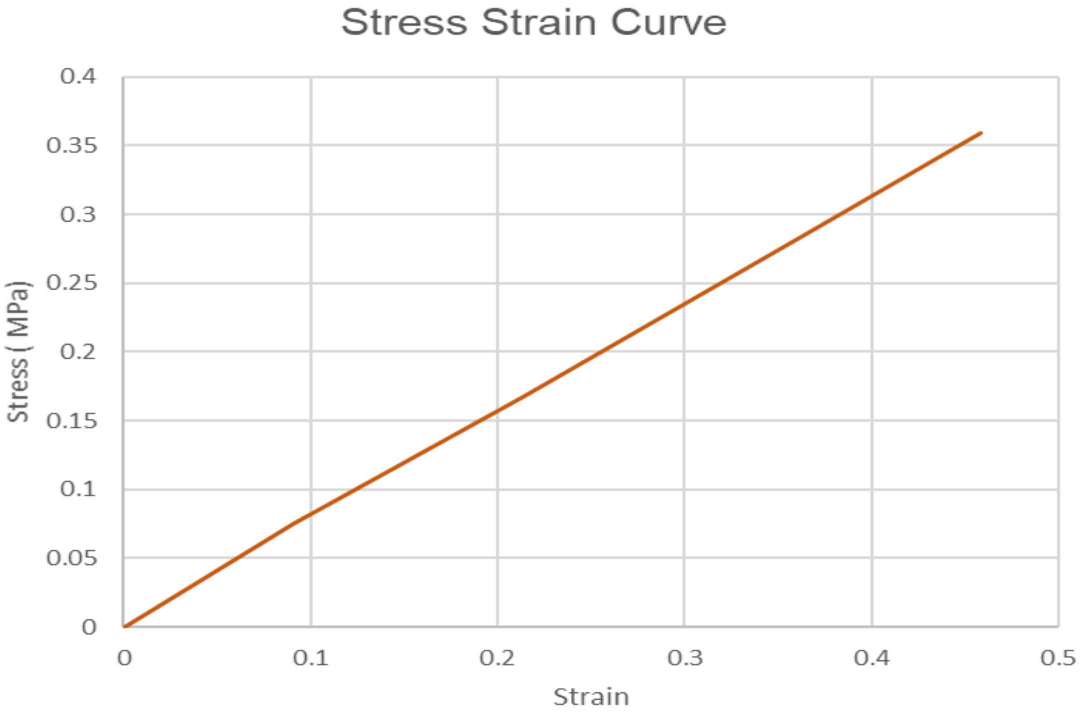

Figure A-4 Stress Strain Curve for Sample 12 (1.5 g Sugar)

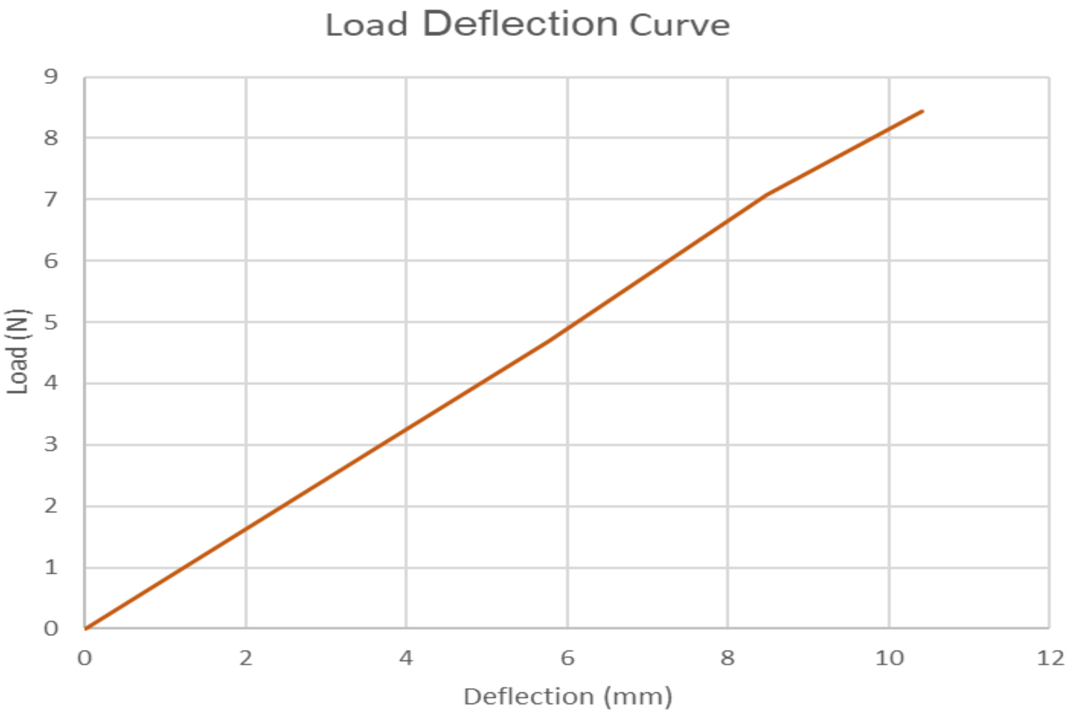

Figure A-5 Load Deflection Curve for Sample 13 (2.5 g Salt)

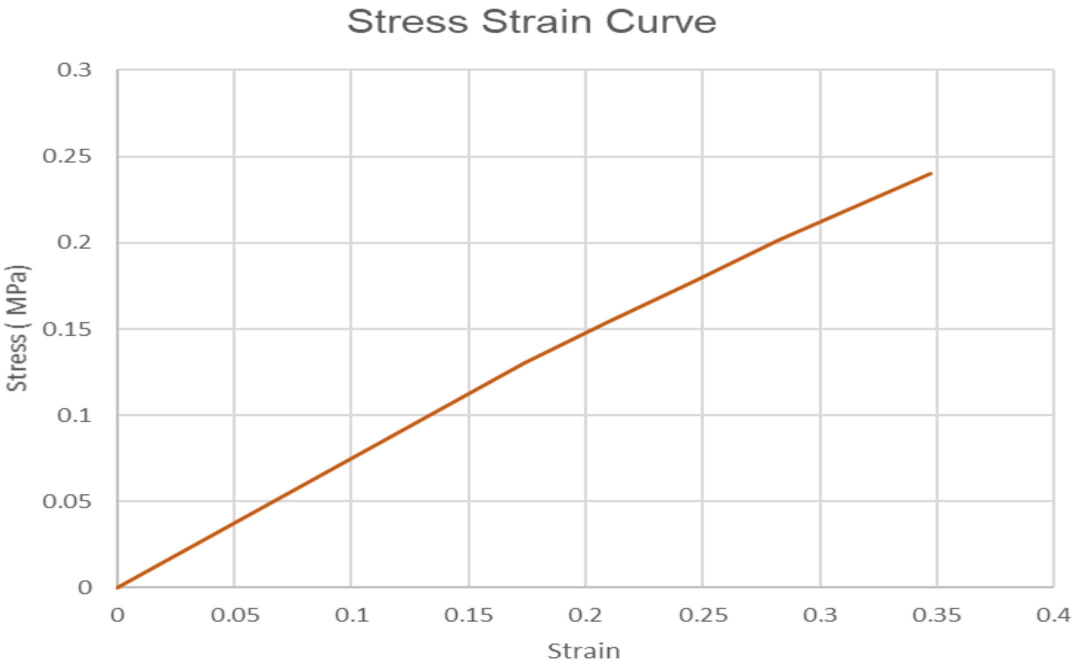

Figure A-6 Stress Strain Curve for Sample 13 (2.5 g Salt)

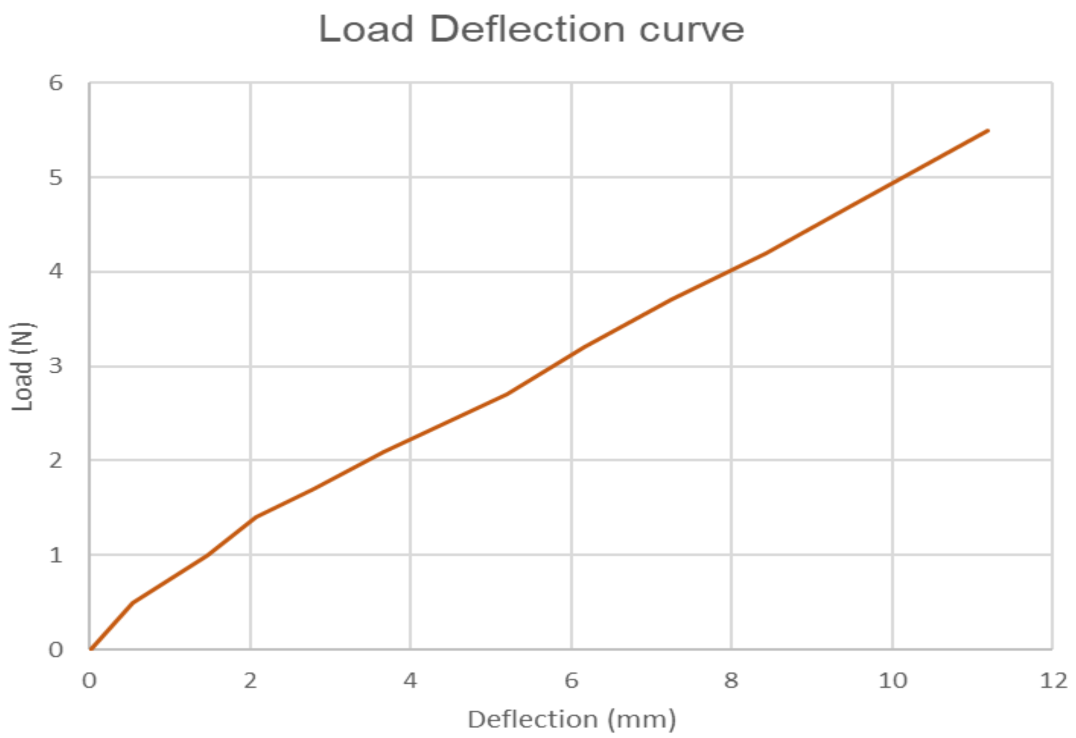

Figure A-7 Load Deflection Curve for Sample 14 (2.5 g Big Salt)

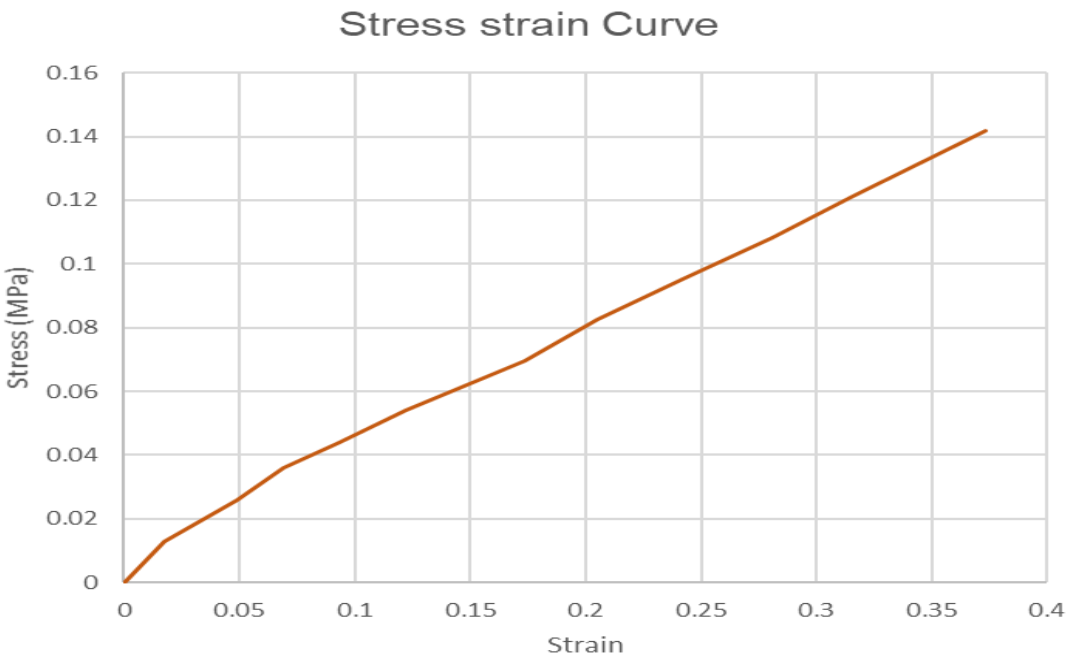

Figure A-8 Stress Strain Curve for Sample 14 (2.5 g Big Salt)

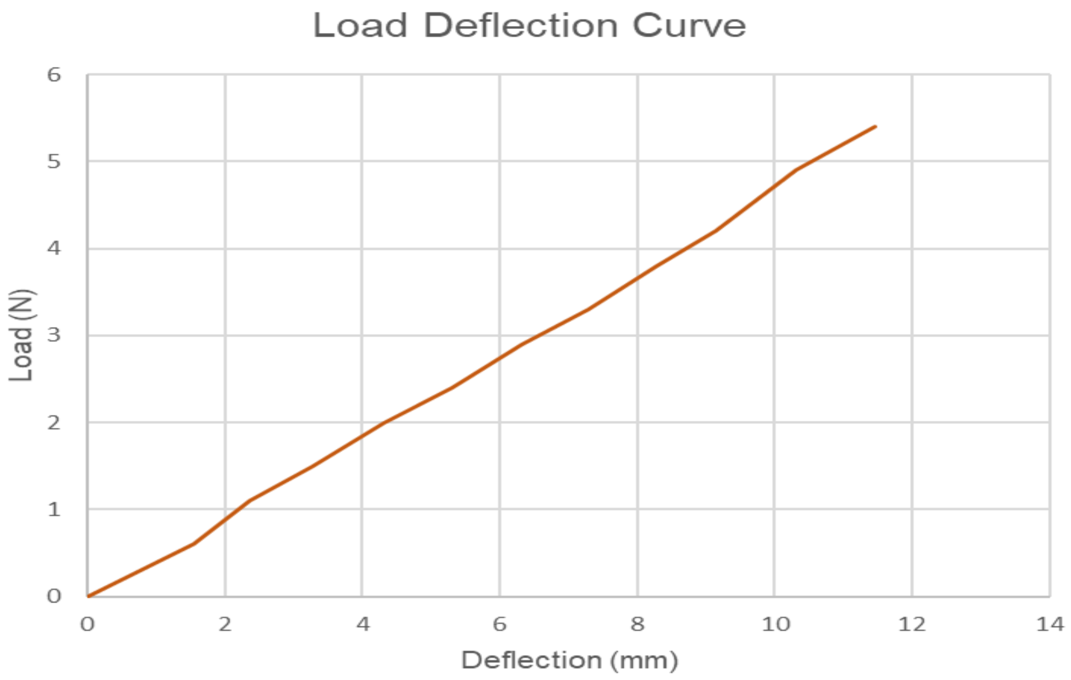

Figure A-9 Load Deflection Curve for Sample 15 (2.5 g Sugar)

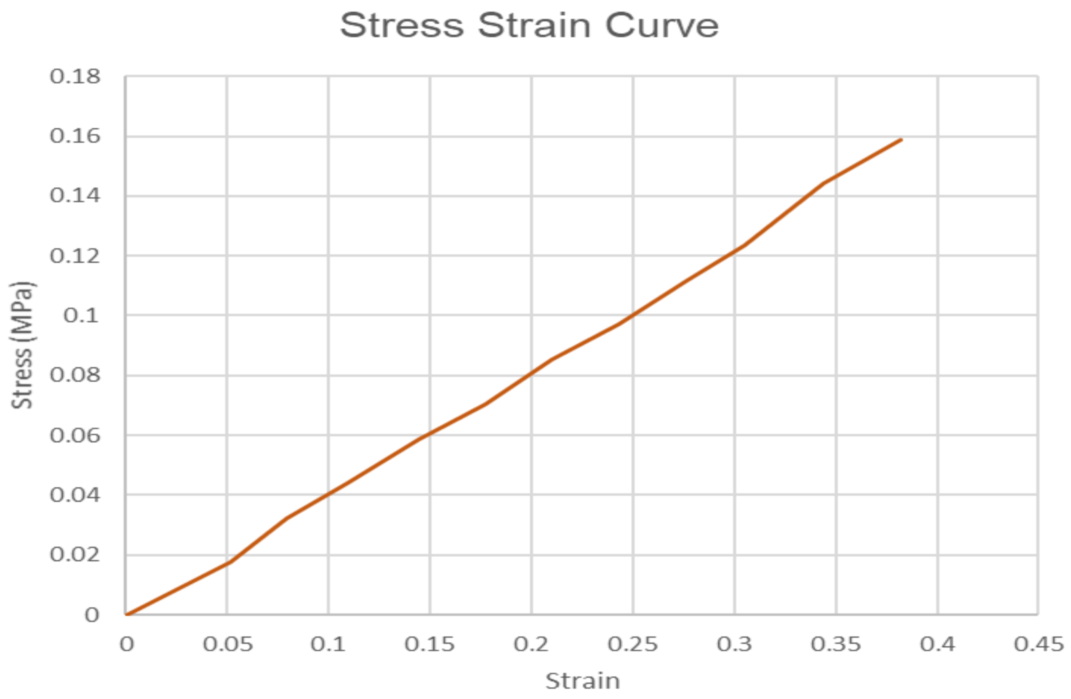

Figure A-10 Stress Strain Curve for Sample 15 (2.5 g Sugar)

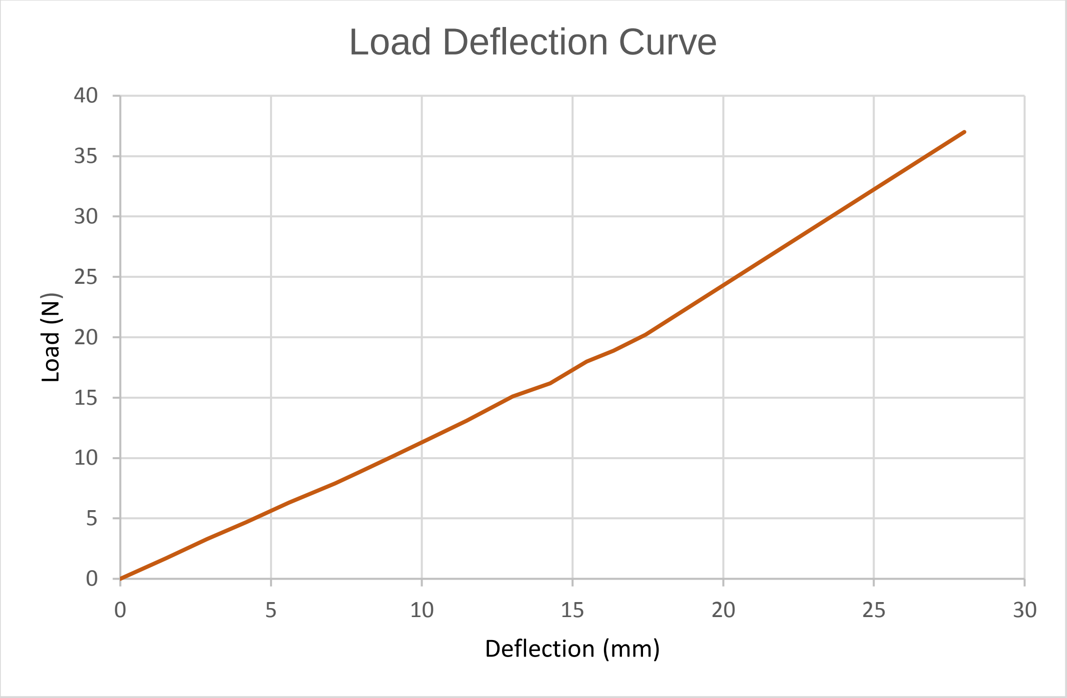

Figure A-11 Load Deflection Curve for the Solid Sample

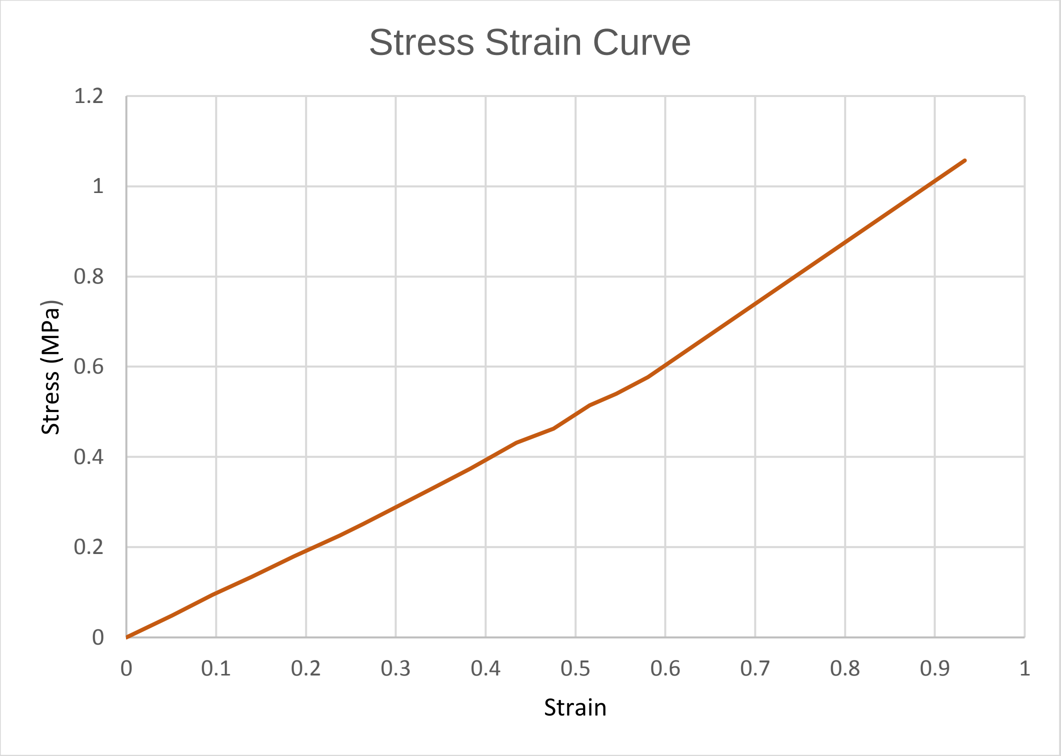

Figure A-12 Stress Strain Curve for the Solid Sample