DESIGN AND TESTING OF HYDROGEL BASED ACTUATOR FOR BIOMEDICAL APPLICATIONS

Fatima Darakhshan

NUST201463171MSMME62414F

Supervisor: **Dr. Murtaza Najabat Ali**

Department of Biomedical Sciences and Engineering
School of Mechanical and Manufacturing Engineering
National University of Sciences and Technology
H-12 Islamabad, Pakistan
January, 2017

DESIGN AND TESTING OF HYDROGEL BASED ACTUATOR FOR BIOMEDICAL APPLICATIONS

A thesis submitted in partial fulfillment of the requirement for the degree of Masters of Science

In
Biomedical Sciences and Engineering

By

FATIMA DARAKHSHAN
NUST201463171MSMME62414F

Supervised by: **Dr. Murtaza Najabat Ali**

Thesis Supervisor's Signature: _____

Department of Biomedical Sciences and Engineering
School of Mechanical and Manufacturing Engineering
National University of Sciences and Technology
H-12 Islamabad, Pakistan
January, 2017

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil Thesis written by Mr/Ms FATIMA DARAKHSHAN, (Registration No. NUST201463171MSMME62414F), of MS Biomedical Sciences SMME (School/College/ Institute) has been vetted by undersigned, found complete in all respects as per NUST Statutes /Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil Degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature: _____

Name of Supervisor: Dr. Murtaza Najabat Ali

Date: 14/02/2017

Signature (HOD): _____

Date: 14/02/2017

Signature (Principal): _____

Date: 14/02/17

FORM TH-4

National University of Sciences & Technology

MASTER THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by: **Ms Fatima Darakhshan** Regn no. **NUST201463171MSMME62414F** Titled: **"Design and Testing of Hydrogel based Actuator for Biomedical Applications"** be accepted in partial fulfillment of the requirements for the award of **MS Biomedical Sciences** degree. (Grade A)

Examination Committee Members

1. Name: **Dr. Umar Ansari** Signature: _____

2. Name: **Dr. Nabeel Anwar** Signature: _____

3. Name: **Dr. Adeeb Shahzad** Signature: _____

Supervisor's name: Dr. Murtaza Najabat Ali Signature: _____

31/01/2017
Date

_____
Head of Department

14/02/2017
Date

COUNTERSIGNED

Date: 14/02/17

_____
Principal

DECLARATION

I certify that this research work titled ***"Design and testing of hydrogel based actuator for biomedical applications"*** is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Fatima Darakhshan
NUST201463171MSMME62414F

PLAGIARISM CERTIFICATE

(Turnitin Report)

This thesis has been checked for Plagiarism.Turnitin report endorsed by Supervisor is attached.

Fatima Darakhshan

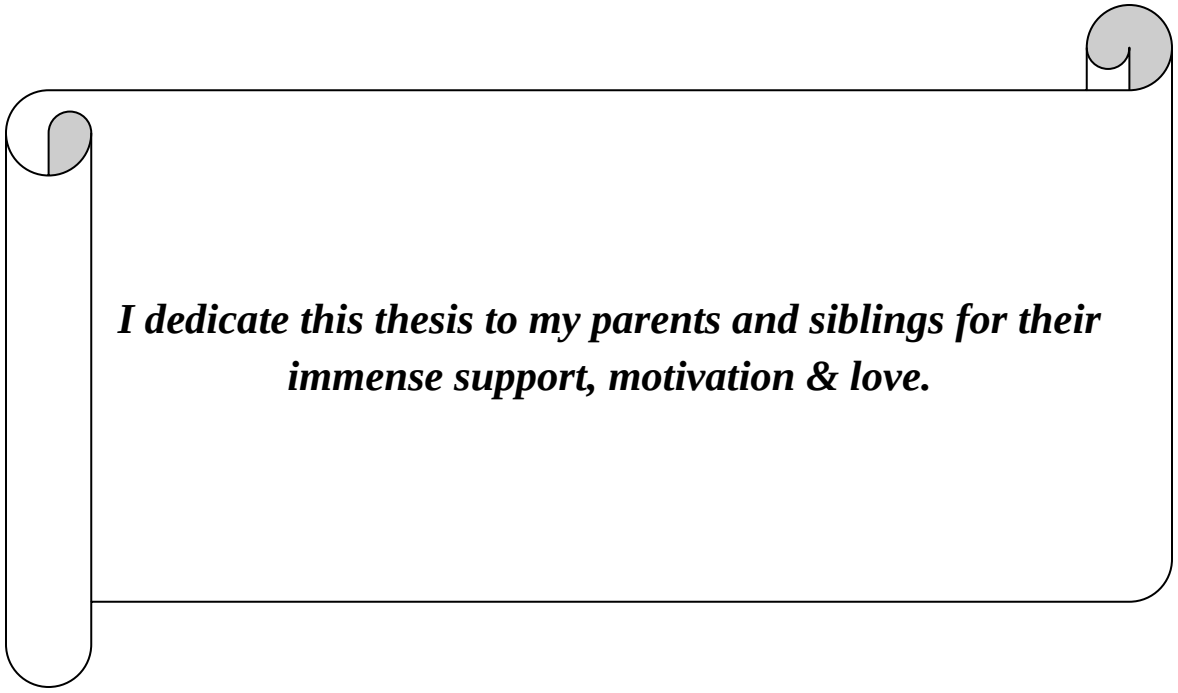
NUST201463171MSMME62414F

Dr. Murtaza Najabat Ali

Signature: _____

COPYRIGHT STATEMENT

- Copyright in text of this thesis rests with the student author. Copies (by any process) either in full, or of extracts, may be made only in accordance with instructions given by the author and lodged in the Library of NUST School of Mechanical & Manufacturing Engineering (SMME). Details may be obtained by the Librarian. This page must form part of any such copies made. Further copies (by any process) may not be made without the permission (in writing) of the author.
- The ownership of any intellectual property rights which may be described in this thesis is vested in NUST School of Mechanical & Manufacturing Engineering, subject to any prior agreement to the contrary, and may not be made available for use by third parties without the written permission of the SMME, which will prescribe the terms and conditions of any such agreement.
- Further information on the conditions under which disclosures and exploitation may take place is available from the Library of NUST School of Mechanical & Manufacturing Engineering, Islamabad.


I dedicate this thesis to my parents and siblings for their immense support, motivation & love.

ACKNOWLEDGEMENTS

All praise to Allah Almighty for bestowing me with the courage, knowledge and health to carry out this project.

I would like to express my sincere gratitude to my supervisor, Dr. Murtaza Najabat Ali and Dr. Umar Ansari for their guidance, continuous support and providing me with the resources that came in handy throughout my project. I am obliged to Dr. Nabeel, HoD BMES for his valuable advices and administrative support.

I would like to express my sincerest thanks to Rector NUST and Principal SMME, Dr. Abdul Ghafoor for providing us with an excellent research environment in SMME, NUST.

I am highly gratified to my friends Misha Mazhar and Amnah Mahroo for being with me in every thick and thin throughout my Masters. I would like to say special thanks to Mariam Mir and Bakhtawar Ghafoor for their assistance, motivation and scientific discussions.

I would like to acknowledge lab technician Prosthetics Lab, SMME and Characterization Lab, SCME for their assistance. I am also thankful to my lab fellows Aisha Tahir, Amber Zahoor, Javairia Yousuf and Hafsa Inam for creating a friendly lab environment.

I owe my gratitude to my friends Sana Javed, Sidrah Naseem, Hafsah Akhtar and Ahmed Raza for their valuable advices and bearing with me during hard times.

Finally, an honorable mention goes to my family for their support.

Fatima Darakhshan

ABSTRACT

The rapid progress of microtechnology has augmented the need for the breakthrough of medical devices that are capable to achieve mechanical output in-vivo on the micro and macroscale. Actuators are a kind of machine that can move or control a mechanism and requires a controlling signal or a stimuli. Based on the external stimuli they need, actuators can be classified into different categories, including mechanical, electro-mechanical, pneumatic and hydraulic actuators. Among all types of actuators, those supported stimuli-responsive hydrogels deserve individual consideration. Hydrogels are three-dimensional crosslinked hydrophilic polymer networks which have ability to swell and shrink in response to different stimuli such as temperature, light, pH etc. The ability of stimuli responsive hydrogels to change their volume in response to change in their physiological surroundings makes them fascinating to be used as smart materials for biomedical applications such as: carriers for drug delivery, microfluidic system, sensors as well as actuators. The aim of this project was to explore the performance of hydrogels as actuator that uses natural environment stimulus to produce microscale displacement and force that has potential in different biomedical applications e.g. controlled drug dispensation, stent expansion, wound management etc.

Keywords*:* *Hydrogels, Actuators, Mechanical characterization, biomedical applications*

TABLE OF CONTENTS

LIST OF ACRONYMS

Acetic Acid	CH3COOH
Centimeters	cm
Chitosan	CS
Fourier Transform Infrared Spectroscopy	FTIR
Hydrogel based linear actuator	HBLA
Millimeters	mm
Percent	%
Poly (vinyl alcohol)	PVA
Scanning Electron Microscopy Analysis	SEM
X-ray Diffraction Analysis	XRD

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

The recent advancement in microsystem technology has been of great interest due to its ability to produce mechanical devices with more precisely defined features in a size range similar to polymeric materials (Cao, Lai, & James Lee, 2001). The evolution of hydrogels as new smart polymeric materials offers new possibilities in microsystems; thus, for the approaching technology, microscale hydrogel devices would be of great interest.

Hydrogels are three-dimensional crosslinked polymer networks and have the ability to absorb water or biological fluids due to presence of great number of hydrophilic groups. The degree of swelling increases strikingly in response to external stimuli like temperature (Hirokawa, Tanaka, Johnson, & Sen, 1984; Shirota, Endo, & Horie, 1998), pH (Brannon-Peppas & Peppas, 1991), solvent (Ohmine & Tanaka, 1982) or electric field (Tanaka, Nishio, Sun, & Ueno-Nishio, 1982). This ability to respond to an external stimulus can be used in a variety of applications, including sensors (Bashir, Hilt, Elibol, Gupta, & Peppas, 2002), carriers in drug delivery (Langer, 1998), as well as actuators in microfluidic devices (Harmon, Tang, & Frank, 2003). Many kinds of actuators for different biomedical applications have been known, but stimuli-responsive hydrogel based actuators need individual attention.

Polyvinyl alcohol (PVA) is a hydrophilic synthetic polymer that has been extensively used in biomedical and pharmaceutical industry due to good biocompatibility and physical properties. It also comprise of enormous hydroxyl groups and can certainly form hydrogen bonds with free water molecules. (Morita, Honda, & Takahashi, 2000). Chitosan is a natural polysaccharide derived from chitin containing hydroxyl and amine groups, has the potential to form hydrogen bonds when mixed with PVA (Chuang, Young, Yao, & Chiu, 1999). Gelatin

is natural biological material derived from collagen exhibiting the water absorbing capacity about 5–10 times of their own weight (Remington, Troy, & Beringer, 2006). Gelatin has countless noteworthy properties, like; the gel and film forming property, water holding capacity, and emulsifying property (Djagny, Wang, & Xu, 2001). Thus, the hydrogel composite combining the synthetic i.e. PVA and natural polymers i.e. chitosan and gelatin can be synthesized providing the desired physical, chemical and mechanical properties.

The present work focuses to explore the performance of hydrogels as actuator that uses natural environment stimulus to produce microscale displacement and force which may have potential in diverse biomedical applications e.g. controlled drug dispensation, stent expansion, wound management etc. To investigate this, novel hydrogel composition has been synthesized and different parameters have been evaluated including the temporal submersion analysis of hydrogel and comparative volumetric analysis. Hydrogel composition has also been structurally and chemically characterized using SEM, FTIR and XRD analysis. Finally, the hydrogel has been employed in an actuator configuration and it is mechanically characterized by studying different parameters of the hydrogel as linear actuator.

CHAPTER 2 REVIEW OF LITERATURE

2.1 Introduction to Hydrogels

Hydrogels are three-dimensional (3D) crosslinked networks made of polymers that are water soluble and exhibit hydrophilic nature. Softness, smartness, and the capacity to swell and retain a substantial amount of water when exposed to an aqueous solution make hydrogels exclusive materials (Shibayama & Tanaka, 1993). The quantity of water can approach up to 99 wt% of the hydrogel mass (Kudela, 1987). In reaction to diverse stimuli such as temperature (Cai & Suo, 2011), light, pH (Brannon-Peppas & Peppas, 1991) and ionic strength, hydrogels can considerably swell and shrink due to change in total water in the polymer network. The swollen form of hydrogel is soft and rubbery, showing high biocompatibility due to great amount of water retention (Kalshetti, Rajendra, Dixit, & Parekh, 2012). Hydrogels can be produced in a range of physical forms, including films, microstructures, nanoparticles and coatings. Researchers believe that the behavior of hydrogels is similar to plants, in a way that twisting and bending is achieved by altering the amount of water in the cells and tissues. The reversible change in sizes and shape of hydrogels makes it suitable for an extensive range of biomedical applications, including the design of different optical devices, microfluidic devices (Harmon et al., 2003), sensors (Bashir et al., 2002), actuators (Guenther et al., 2007) and drug delivery systems (Dinarvand & D'Emanuele, 1995; Langer, 1998).

In order to adapt hydrogels for different biomedical applications, microsystems exhibiting the responsive behavior of smart materials need to be established. The requirements of hydrogel synthesis for this purpose include preparation of novel sensitive polymers, selection of

relevant and specified stimulus and speed of response. The most common methods to synthesize the composite hydrogels are based on the crosslinking methods including the physical, chemical and radiation crosslinking.

In recent times, Hydrogels have become useful to be used as smart material because of their ability to produce intense volume transition in reply to a range of physical and chemical stimuli. The physical stimuli consist of temperature, light, electric or magnetic field, pressure, and sound, whereas the chemical stimuli comprise pH, ionic strength, molecular species and solvent composition, as illustrated in Figure 2.1 (Ahmed, 2015).

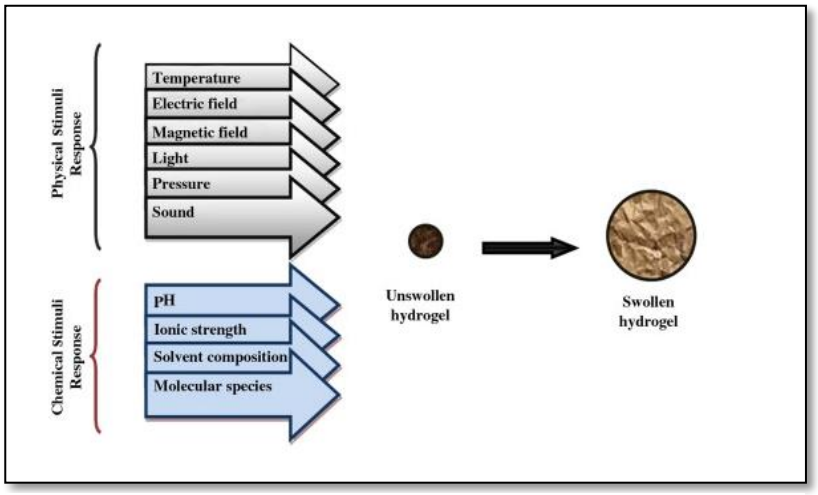


Figure 2.1 Stimuli responsive swelling properties

2.2 Characterization Parameters of Hydrogels

Hydrogels are usually characterized by variety of parameters depending on the applications they are synthesized for. The parameters that affect the properties of hydrogels includes: chemical composition/structure of hydrogel, degree to swell/deswell and the response rate etc. The volume fraction of hydrogel in the swollen state, indicating how much fluid can be absorbed and retained, is an important parameter for structural characterizations of hydrogel (Chai, Jiao, & Yu, 2017). For increased response rate of hydrogels, porous structure is the

demanding property, which can be obtained by changing the crosslinking density of the gel matrix. For the application of hydrogels in drug delivery systems, the release rate is an important parameter which depends on the diffusion coefficient through the gel network and can also be modified according to desired mechanism (Gupta, Vermani, & Garg, 2002). The size and the mechanical strength of the hydrogel also act as important parameters to establish the hydrogels for actuator applications.

For various applications, the swelling behavior of hydrogel under loaded condition need significant importance than a free swelling. Thus, pressure measuring device can be utilized for characterizing the swelling behavior of hydrogels, where an external pressure decreases the swelling pressure of hydrogels. Examples include: an active diaper absorbent must be capable of swelling when an external pressure is applied as result of baby's weight. In agricultural applications, the swelling pressure of the absorbent hydrogels be influenced by the depth and the density of the soil. (Peppas, Ottenbrite, Park, & Okano, 2010).

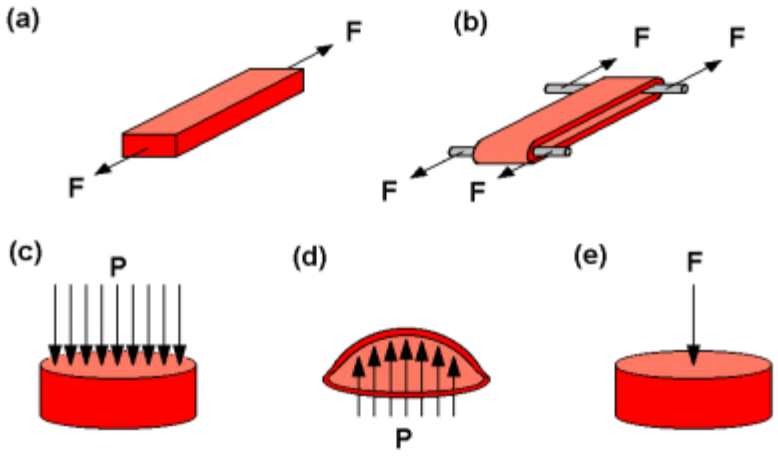


Figure 2.2 Techniques for Mechanical characterization of hydrogels: (a-b) Extensiometry; (c) Compression Test (d) Bulge Test (e) Indentation (F is force and P is pressure).

Several approaches have been considered to scrutinize the mechanical performance of hydrogels as demonstrated in Figure 2.2. The most commonly used method is by tensile testing in which sample material is held between two grips, then the change in elongation of the material is observed due to applied force. The second most common technique known as Compression testing comprises of the material between two plates and squeezing it. Other approaches include bulge testing and indentation (Ahearne, Yang, & Liu, 2008).

2.3 Hydrogels as Actuators

Actuators are a kind of machine that can move or control a mechanism and requires a controlling signal or a stimuli. Based on the external stimuli they need, actuators can be classified into different categories, including mechanical, electro-mechanical, pneumatic and hydraulic actuators. However, the use of stimuli-responsive hydrogels as actuators deserve particular consideration. Originally, it was expected that the novel kind of actuator, entitled as artificial muscle, can be offered by stimuli responsive hydrogel due to comparable properties of hydrogels to the natural muscle. Nevertheless, due to the deliberate swelling process of hydrogels, its early to use hydrogels for the robotic "artificial muscle" applications. Though, hydrogels suggest remarkable properties for low dynamic applications such as medical pumps (Andreas Richter, Klenke, & Arndt, 2004) or automatic mattresses (A Richter, Krause, Lienig, & Arndt, 2005).

The distinctive properties of a range of actuators are presented in Table 1. Although hydrogels have brilliant static actuation characteristics, like natural muscle, their actuation speed is restricted by the rate of diffusion, making them unfeasibly slow for a lot of applications. So, hydrogels are usually working in presentations on the microscale, and have had some degree of victory when practiced to devices on large scale (Dicker, Weaver, Rossiter, & Bond, 2014).

Actuator	Energy den.(kJ m^{-3})	Stroke (%)	Pressure (MPa)	Reaction time (ms)
Hydrogels	3.5	90	4	300–10^{6}[a]
Solenoids	0.25	50	0.1	5
SMA	100	8	900	300[b]
Muscle	5.9	70	1.18	0.03

[a]Actuator size in the micrometre range to centimetre range.
[b]Depending on the applied heating power.

Table 1 Actuator types and their characteristics

The physical principle of hydrogel actuators is based on their ability to experience large volume changes as a stimulus (thermal, photonic, chemical or electrical) is applied. The alteration in the properties of stimuli responsive hydrogels occurs due to application of external signal while the initial form of hydrogels can be achieved by the removal of stimuli. The interchanging property of the stimuli responsive polymeric materials permits one to study them as basic machines i.e. actuators converting the surrounding signals into a mechanical reaction (Ionov, 2010). There are numerous reports related to the design and fabrication of hydrogel as actuating layers with diverse stimuli responsive characteristics. For instance, pH-responsive structures composed of polyelectrolytes (Bassik, Abebe, Laflin, & Gracias, 2010; Guan, He, Hansford, & Lee, 2005; He, Guan, & Lee, 2006; Kelby, Wang, & Huck, 2011;

Kumar, Luchnikov, Nandan, Senkovskyy, & Stamm, 2008; Kumar et al., 2009); Polymer based thermo responsive machines with varying critical solution temperature behavior (Stoychev, Puretskiy, & Ionov, 2011; Wang et al., 2005; Xia et al., 2013); solvent sensitive systems (Guan et al., 2005; Kelby et al., 2011). As illustrated in above mentioned applications, the deformation and relaxation of a hydrogel is effected by the application and removal of stimuli, correspondingly.

An interesting method for construction of hydrogel-based actuators has been explained by Aizenber and Sidorenko. They made-up a thin hydrogel films with incorporated high-aspect ratio rods. The change of orientation of the rods is produced by breakdown or swelling of the thin hydrogel layer (Pokroy, Epstein, Persson-Gulda, & Aizenberg, 2009; Sidorenko, Krupenkin, Taylor, Fratzl, & Aizenberg, 2007). Lee et al. have utilized the ability of hydrogels to swell and deswell reversibly and fabricated pH-sensitive hydrogel actuators copying the shape and motion of octopus and sperm (Kwon et al., 2008). These kinds of aquabots are capable to yield directional motion in reaction to change of electrochemical potential and can be possibly used for variety of biomedical applications to sense and destroy certain microorganisms. It is identified that behavior of cells (differentiation, growth, apoptosis) depends on geometrical constrains. Thus, a thermoresponsive polymeric actuator has been established by Pelah, which can reversibly deform cell shape (Pelah, Seemann, & Jovin, 2007). More recently, smart bilayer hydrogels with reconfigurable shapes actuated by pH-triggered swelling difference were constructed successfully by using natural polymers. This newly established soft actuator have the ability to perform mechanical work by lifting up objects (Duan, Liang, Zhu, Guo, & Zhang, 2017).

The use of hydrogels as actuators exhibit some advantages as well as disadvantages. The main advantage of hydrogel as actuator configuration is the sensitivity to their surrounding environment such as pH, temperature, concentration, biosignals etc. Hydrogels possess good biocompatibility and an amount of flexibility akin natural tissue, thus can be utilized in numerous biomedical applications as in vivo actuator configuration. Despite of such vast benefits, the usage of hydrogel as actuator configuration is restricted to aqueous solutions as the water or biological fluid is really required for actuation mechanism. Another limitation of hydrogels is the slow response time of hydrogels which marks them inappropriate for extensive applications or in conditions where fast response is required, but the solution can be provided by using porous hydrogels (O'Grady, Kuo, & Parker, 2009).

CHAPTER 3 MATERIALS AND METHODS

3.1 Materials

Polyvinyl alcohol (PVA) 72000 BioChemica was obtained with molecular weight of approx. 72000 g/mol and 85-89% degree of hydrolysis. Chitosan (CS) was purchased from Avonchem (UK). Gelatin (4055–1405) was procured from Daejung Chemical Co. (Siheung, Korea). Glutaraldehyde (Daejung Chemical Co.) used as chemical crosslinking reagent was purchased as a 25% (wt%) aqueous solution. Acetic Acid was used as received without further purification. Doubly distilled water was used during the course of the experiment.

3.2 Synthesis of Hydrogels

Hydrogels were synthesized in the form of two compositions.

Composition 1: (Chitosan/Gelatin)

A 0.5% Chitosan (CS) solution was prepared by dissolving in 1% Acetic Acid (CH_3COOH) solution with gentle stirring for 30 minutes at 30C. The 7% Gelatin solution was made by dissolving in distilled water with gentle magnetic stirring for 1h at 50C. The CS and gelatin solution was mixed into the PVA solution. The 1:3 weight ratio of Chitosan and gelatin was used. 0.063% Glutaraldehyde was used as a crosslinking agent.

Composition 2: (PVA/Chitosan/Gelatin)

A PVA solution of 5% was ready by mixing 5g PVA powder into distilled water with gentle magnetic stirring for 2 h at 150C. A 0.5% Chitosan solution was prepared by mixing in 1% CH_3COOH solution with gentle stirring for 30 minutes at 30C. The 7% Gelatin was prepared by dissolving in distilled water with gentle magnetic stirring for 1h at 50C. The CS and

gelatin solution was mixed into the PVA solution. The weight ratio of PVA, Chitosan and gelatin were1:1:3. 0.063% Glutaraldehyde was used as a crosslinking agent.

The solutions were then poured into molds specifically design for hydrogel preparation. The gels were then air dried at room temperature. The completely dried gels were then cut into variable sizes and thicknesses.

3.3 Characterization of Hydrogels

The shortlisted composition was then characterized by performing numerous analysis:

3.3.1 Surface Morphological Analysis

The assessment of the surface morphology of the hydrogel composite was done by Scanning Electron Microscopic (SEM) using JSM-6490A Analytical scanning electron microscope (JEOL, Tokyo, Japan). The SEM images were acquired at an activation voltage of 5 kV.

3.3.2 Chemical Structure Analysis

The Fourier Transform Infrared Spectroscopy (FTIR) was performed to chemically characterize the presence of specific functional groups and types of interactions in the hydrogels. FTIR spectra were obtained in KBr mode, with wavenumber range from 4000 to 450 cm-^{s} during 256 scans, with 8 cm-1 resolution (Perkin Elmer, spectrum 100 FTIR spectrophotometer).

3.3.3 Crystallographic Analysis

The amorphous or crystalline structure of composite hydrogel was identified by X-ray diffraction (XRD) analysis. The diffraction pattern was obtained using a STOE X-ray Diffractometer, with Cu-K α radiation source (λ= 0.15418). The data was composed at 2θ between 5-60 degrees.

3.4 Parametric Analysis of Hydrogels

Different parameters including the temporal submersion analysis and comparative volumetric analysis has been studied, in which the volumetric changes of hydrogel at different time intervals has been evaluated.

3.4.1 Temporal Submersion Analysis

For temporal submersion analysis, hydrogels were immersed in aqueous medium at different levels of submersions i.e 25%, 50%, 75%, 100% as shown in **Figure 3.1.** All tests were performed at pH 7. Different sized hydrogel samples of varying height and thickness were used. Dried hydrogel samples were cut into desired size. The change in volume of submerged portion of hydrogel was measured using Vernier caliper after every 10 minutes for total time of 1 hr. Each test was repeated 3 times.

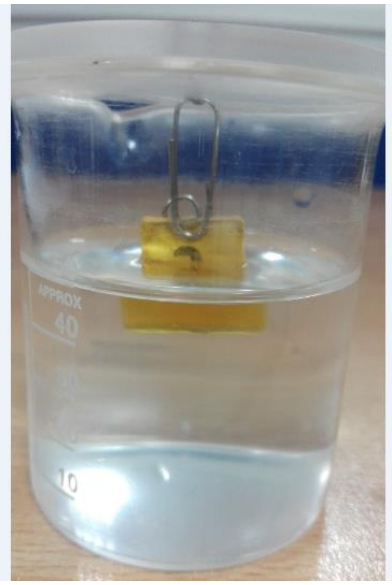


Figure 3.1 Hydrogel sample immersed in aqueous medium

3.4.2 Comparative Volumetric Analysis

The comparative analysis and selection of different compositions was done by measuring swelling/volume change kinetics of hydrogels. For this, hydrogels were characterized by their rate of change of volume, which is defined by the duration taken by hydrogels to achieve certain fraction of stable swelling measurements.

3.5 Investigation of Hydrogel as Linear Actuator

3.5.1 Design of Hydrogel based Linear Actuator (HBLA)

The initial sketch of the Hydrogel based Linear Actuator (HBLA) was made using Pro Engineer wildfire 5.0 software. The actuator consist of multiple parts which were assembled in a configuration to obtain the final device. The overall actuator consists of three parts as shown in **Figure 3.3**; one is the hollow cylindrical tube containing holes on the base for liquid exposure. Second, the hydrogel sample, which is placed inside the hollow tube. One end of the hydrogel sample is exposed to the liquid medium and the other face touches the end effector.

The working mechanism of the HBLA is described in the **Figure 3.2**. When the hydrogel sample swells by absorbing water, it creates a force when it touches the end effector, causing the end effector to move.

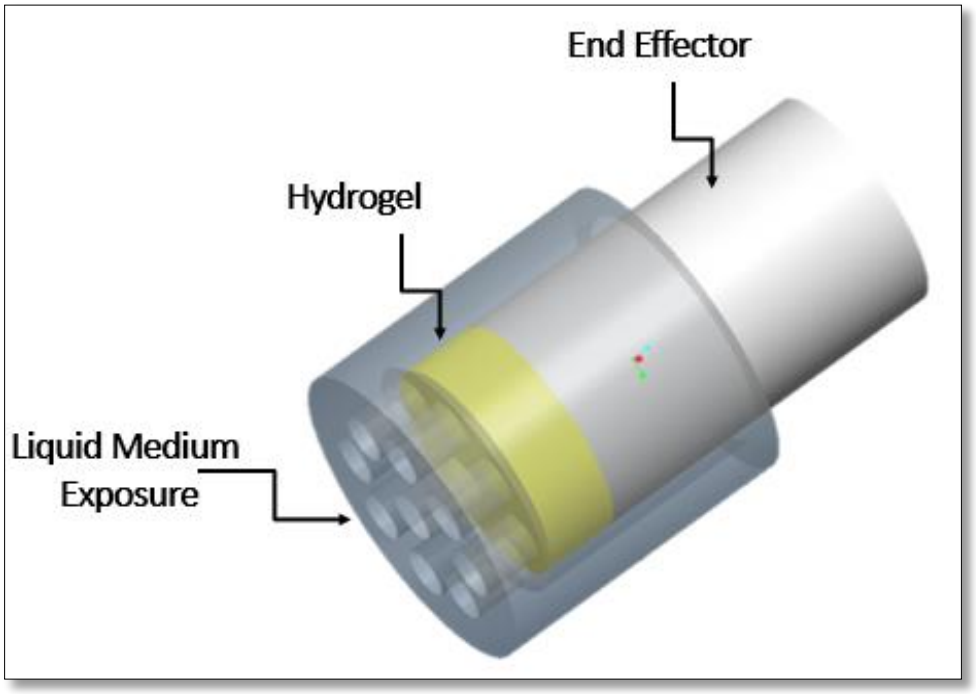


Figure 3.3 Hydrogel based Linear Actuator

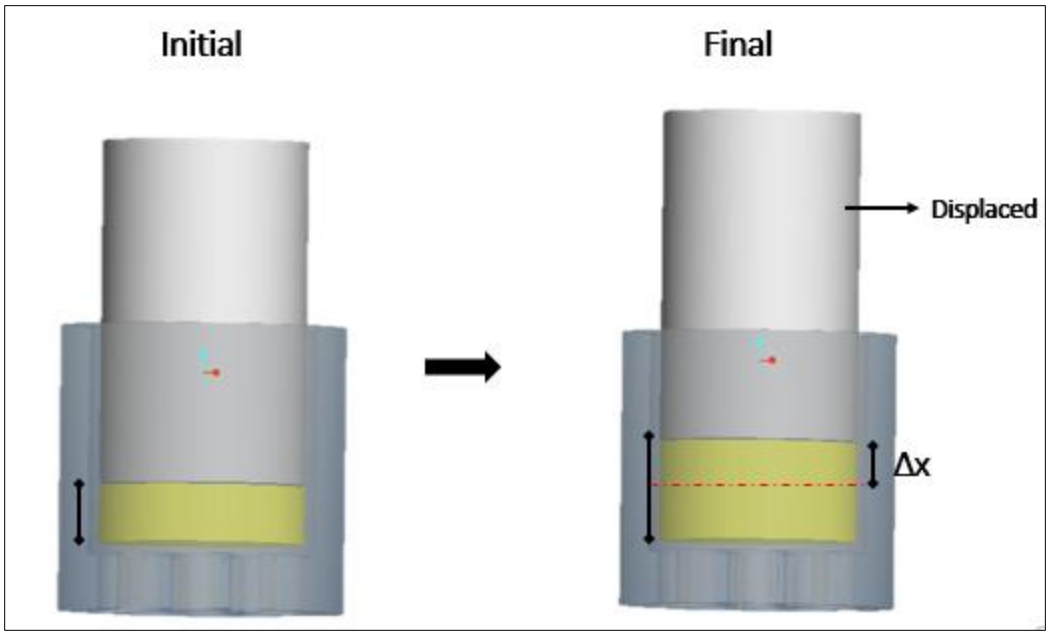


Figure 3.2 Illustration of concept behind the working mechanism of Hydrogel based linear Actuator (HBLA)

3.5.2 Characterization of Hydrogel in Actuator Configuration

In actuator configuration, Hydrogel was characterized by studying its behavior under constraint and loaded conditions. For this purpose, hydrogel was cut into disc shaped samples of about 2.5mm thickness and 8.5mm diameter. These samples were placed in hollow cylindrical tube in which the hydrogel samples were restricted from all sides, however, one face of the hydrogel was exposed to aqueous medium and the other face of the hydrogel was set free and allowed to swell.

The change in length of hydrogel in constraint environment was measured by taking images after every 10 mins for total time 2h. These images were then processed in Matlab. The change in length of hydrogel was measured using command *imtool* which scales the length in pixels. The pixels were then converted into millimeters (mm).

The behavior of hydrogel under loading condition has also been evaluated. The experiments were performed by applying different loads on the hydrogel and measuring the difference in hydrogel swelling over time.

3.5.3 Mechanical Characterization of Hydrogel Based Linear Actuator

Actuators are generally mechanically described by two main parameters: force and the displacement. The swelling behavior and change in volume of hydrogel can be utilized to generate a force (Gerlach & Arndt, 2009). Thus, to calculate the force that can be lifted by HBLA, the load was simply placed on the end effector of the HBLA and the gel was allowed to swell undergoing mechanical work. The displacement of the end effector was measured and the load lifting capacity of hydrogel was then observed, as illustrated in **Figure 3.4**.

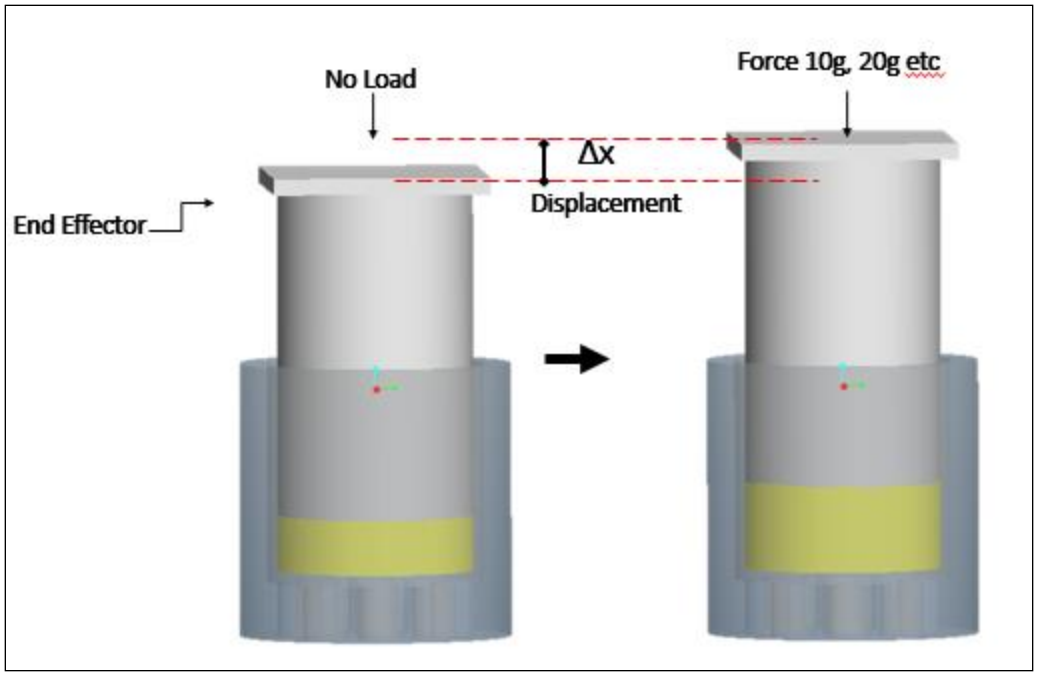


Figure 3.4 Illustration of Displacement and Weight Lifting capacity of HBLA

CHAPTER 4 RESULTS AND DISCUSSION

The high swelling and volume change properties of hydrogel can be achieved by forming a composite material with high affinity for water or aqueous medium that can be achieved by adding hydrophilic and functional groups such as carboxyl, amide, and hydroxyl. These groups can freely form hydrogen bonds (Peppas et al., 2010). Therefore, two hydrogel composites have been synthesized with the high affinity for aqueous medium.

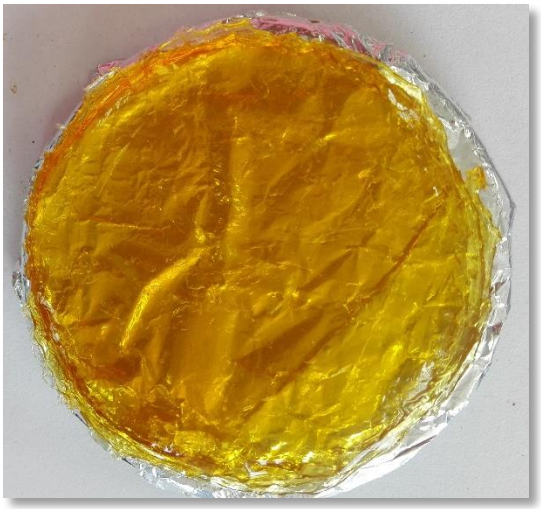


Figure 4.1 Hydrogel Composite Film (Semi-cured form)

4.1 Characterization of Hydrogels

4.1.1 Surface Morphological Analysis

The surface morphology of the PVA/Chitosan/Gelatin hydrogel composite has been evaluated using SEM analysis as shown in the **Figure 4.3**

The figure shows homogenous, not tightly woven, non-stratified structure. The little bit rough surface could be due to the reorientation of polar functional groups toward to the top surface indicating hydrophilic 3D polymeric structure (Chen, Wang, Mao, Liao, & Hsieh, 2008). The irregular surface nature suggests that the composite maybe of amorphous nature.

4.1.2 Chemical Structure Analysis

The FTIR analysis was done to identify the presence of specific functional groups and types of interactions in the hydrogel composition. The FTIR spectra of PVA/Chitosan/Gelatin hydrogel has been shown in **Figure 4.2**. The spectra shows two characteristic bands at 3422 cm^{-1} and 1638 cm^{-1} (Fan, Yang, Yang, Peng, & Hu, 2016). The 3422 cm^{-1} band indicate the presence of hydroxyl group and secondary amide thus confirming the presence of PVA in the composite material. The peak at 1638 cm^{-1} and 1542 cm^{-1} confirms the chemical crosslinking of the blend and presence of secondary amide group respectively (Costa Jr & Mansur, 2008). The peaks at 1079 cm^{-1} and 1239 cm^{-1} indicated the C-O stretching of secondary alcoholic groups and ester (Pawde & Deshmukh, 2008). The peak at 2940 cm^{-1} specifies the existence of a hydrocarbon chromophore in the esterified product. Briefly, the esterified product has an ester linkage, a secondary alcoholic group, and secondary amide groups additionally.

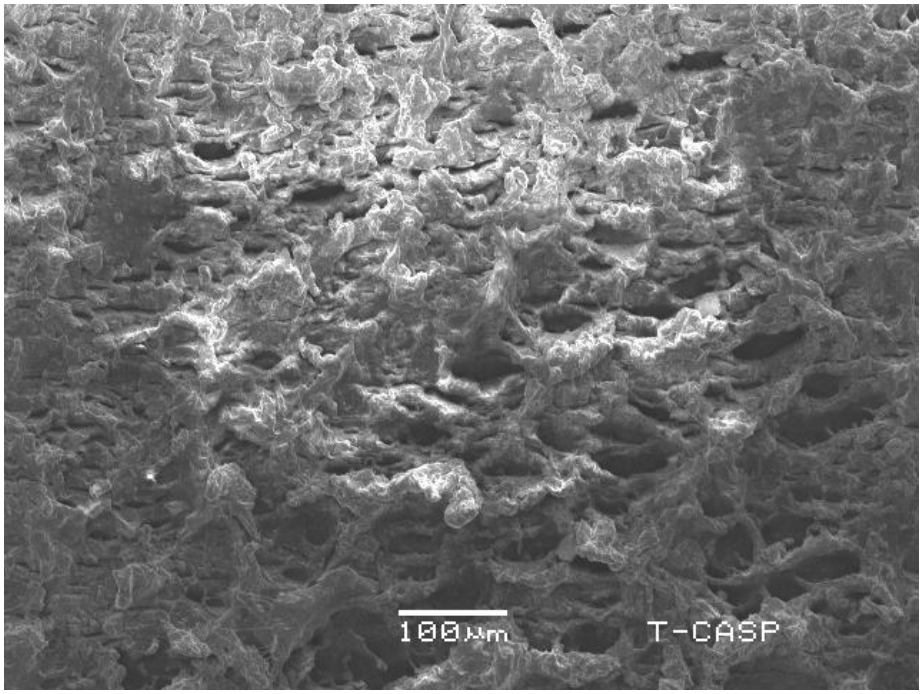


Figure 4.3 SEM image of PVA/Chitosan/Gelatin hydrogel composite at 5kV and x150 magnification

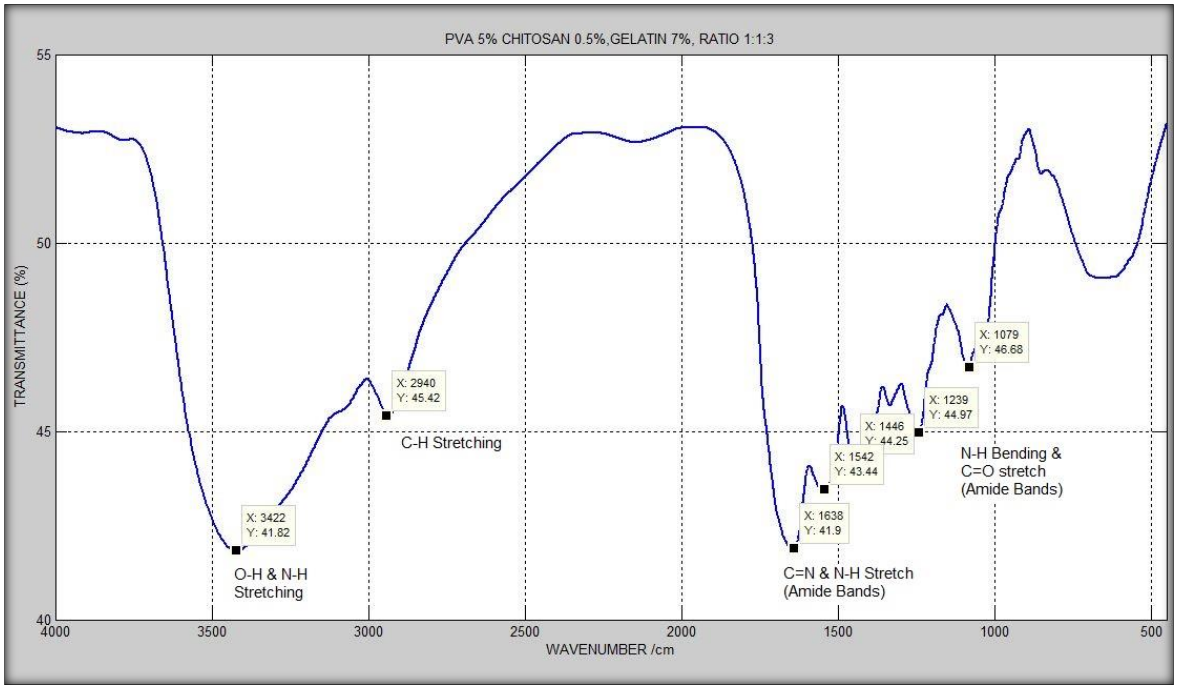


Figure 4.2 FTIR results of PVA/Chitosan/Gelatin hydrogel composite

4.1.3 Crystallographic Analysis

The XRD pattern of PVA/Chitosan/Gelatin composite hydrogel is shown in **Figure 4.4**. According to Kweon H et al; the diffraction peaks at about 19° and 22.5° represents the crystal-like peaks of PVA and the hydrated crystalline structure of chitosan, respectively (Kweon, Um, & Park, 2001). The pattern of PVA/Chitosan/Gelatin shows a flat and broad peak at 20°, illustrating that the presence of gelatin decreases the crystalline nature of PVA and chitosan. This occurrence can be explained by the noteworthy hydrogen bonding among chitosan, PVA and gelatin (Chen et al., 2008).

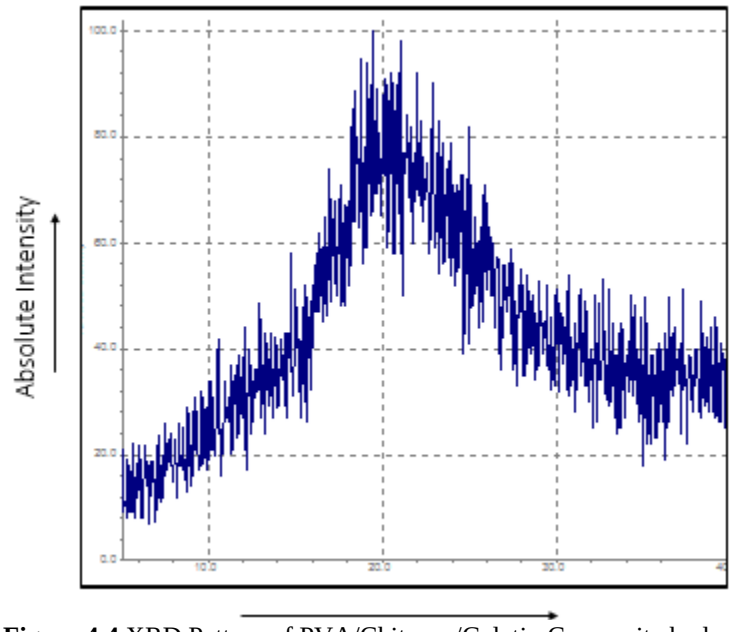


Figure 4.4 XRD Pattern of PVA/Chitosan/Gelatin Composite hydrogel

4.2 Parametric Analysis of Hydrogel

When the hydrogel is immersed in an aqueous medium, it absorbs water and swells. Since the different dimensional changes of hydrogels appear during the swelling process, these parameters can be utilize to study the behavior of hydrogel as actuators.

4.2.1 Temporal Submersion Analysis

For different biomedical applications, hydrogel is considered to be in contact with aqueous medium or biological fluid fully or partially. Therefore, the behavior of hydrogel at different immersed levels has been evaluated. The change in volume of hydrogel ($\Delta V = V_t - V_i$), where V_t= Volume of hydrogel at time t and V_i= initial hydrogel volume in dry state, has been calculated at different time intervals for different percentages of volume submersions. The x – axis of the graph shows the time in which the hydrogel swells and change in volume take place, whereas the y axis of the shows the overall ΔV of the hydrogel composites. The results reveal the constant increase in (ΔV) (**Figure 4.5**) with time for both the hydrogel compositions i.e. Chitosan/Gelatin and PVA/Chitosan/Gelatin.

The hydrogel samples with different height and thicknesses are compared.

Figure *4.6* depicts that at 50% submersion, when the height of the hydrogel is increased, the change in volume is also increased. However, when the thickness of the hydrogel samples is increased, thicker samples shows less change in volume (ΔV) initially as compared to thin samples as depicted in **Figure 4.7**. This occurs may be due to more part of the gel exposed to aqueous medium; also because minor hydrogel particles reply to external stimuli more rapidly than hydrogels in bulk form (Oh, Oh, Choi, & Bae, 1998).

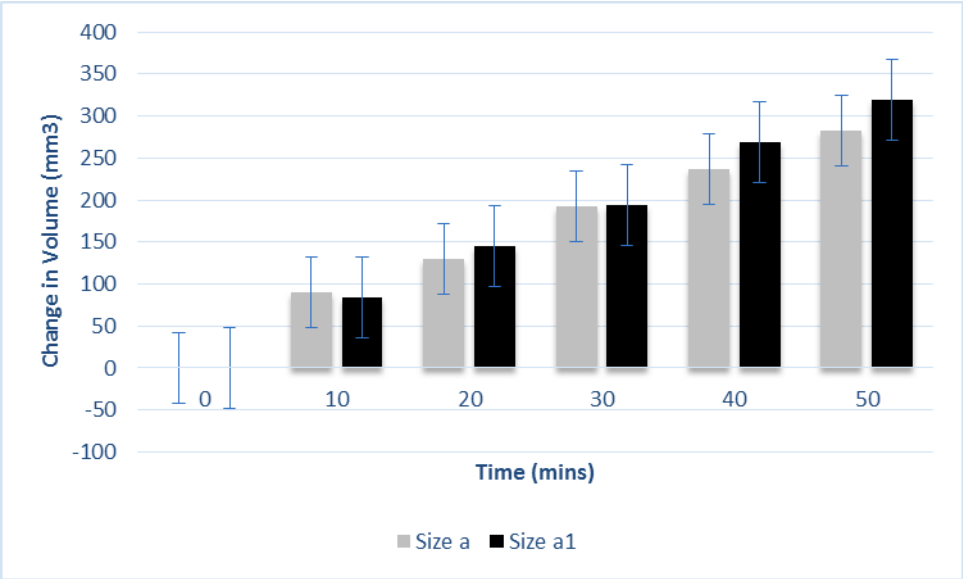


Figure 4.5 Temporal Volume Submersion of Chitosan/Gelatin at 50% volume submerged in liquid; Size a= 15x15x1.5 (mm) small and Size a1= 15x20x1.5 (mm) large

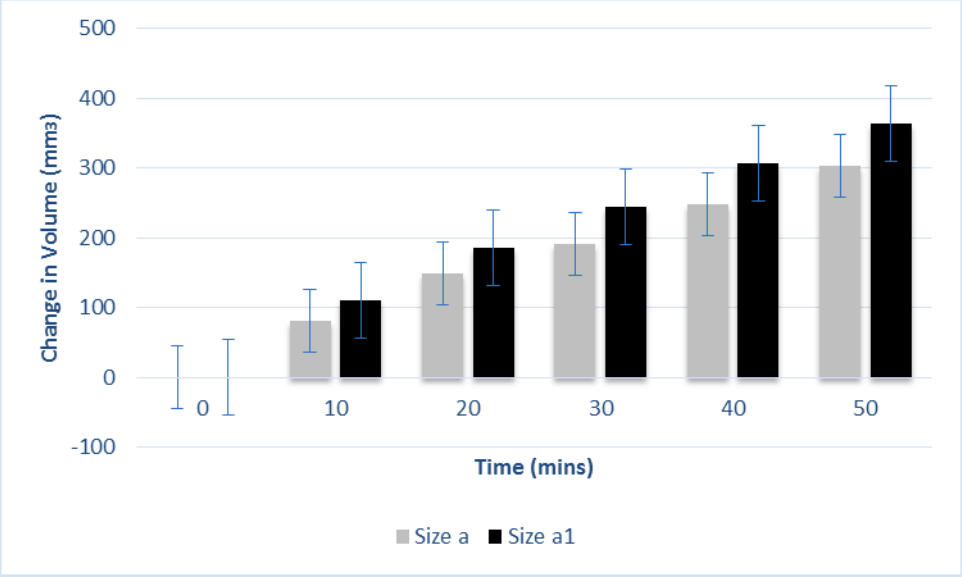


Figure 4.6 Temporal Volume Submersion of PVA/Chitosan/Gelatin at 50% volume submerged in liquid; Size a= 15x15x1.5 (mm) small and Size a1= 15x20x1.5 (mm) large

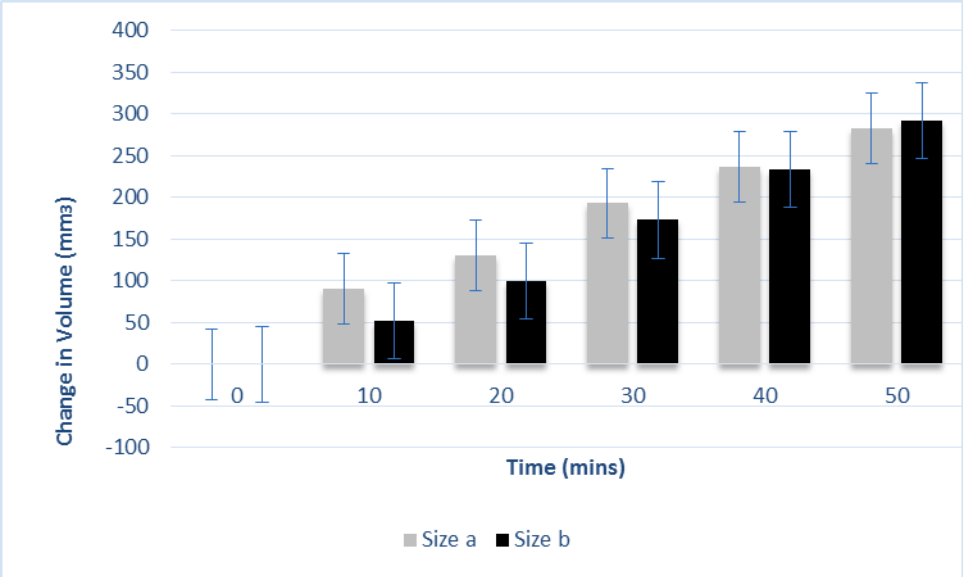


Figure 4.7 Temporal Volume Submersion of Chitosan/Gelatin at 50% volume submerged in liquid; Size a= 15x15x1.5 (mm) thin and Size b= 15x15x3(mm) thick

4.2.2 Comparative Volumetric Analysis

According to Shibayama & Tanaka, the rate of response to external stimuli has inverse relation to size of the hydrogel, thus the rate of the two hydrogel compositions i.e. Chitosan/Gelatin and PVA/Chitosan/Gelatin were compared using the smallest size (Shibayama & Tanaka, 1993). The **Figure 4.8** shows that at 100% volume submersion, PVA/Chitosan/Gelatin shows higher overall change in Volume and higher rate of Volume change as compared to Chitosan/Gelatin. The initial rate volume change of PVA/Chitosan/Gelatin composition is 5.92 whereas of Chitosan/Gelatin composition is 5.28 as illustrated by slope of the graph. Thus, the addition of PVA to the hydrogel composite has confirmed the increased rate of water absorption which is in agreement to the property of PVA according to the literature (Chuang et al., 1999).

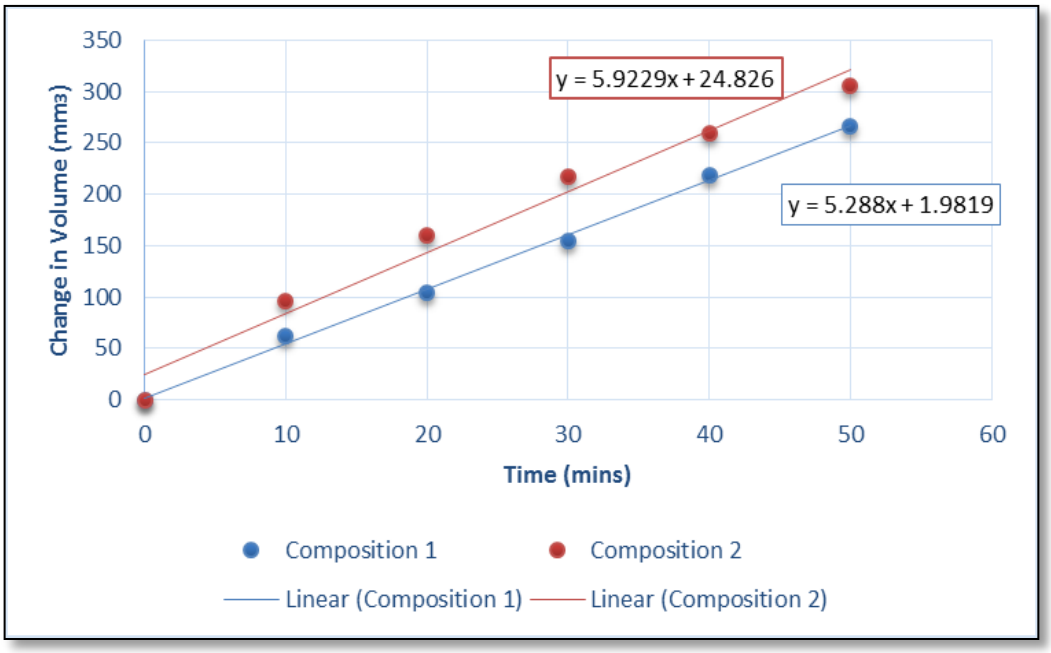


Figure 4.8 Comparative volumetric profile of hydrogel compositions. Composition 1= Chitosan/Gelatin and Composition 2= PVA/Chitosan/Gelatin

4.3 Investigation of Hydrogel as Linear Actuator

The configuration of hydrogel based polymeric structure as linear actuator has been developed and different properties have been studied.

4.3.1 Characterization of Hydrogel in Actuator Configuration

The free swelling of the hydrogel has been widely studied but little is known about swelling performance of hydrogels in constrained and loaded conditions. The change in length ($\Delta L = L_t - L_i$), where L_t= Length/thickness of hydrogel at time t and L_i= initial hydrogel length in dry state) of the hydrogel in constraint state as linear actuator has been calculated. The **Figure 4.9** demonstrates that the change in length (ΔL) of hydrogel increases with time rapidly upto 70 minutes, after 70 minutes, ΔL increases gradually and comes to equilibrium.

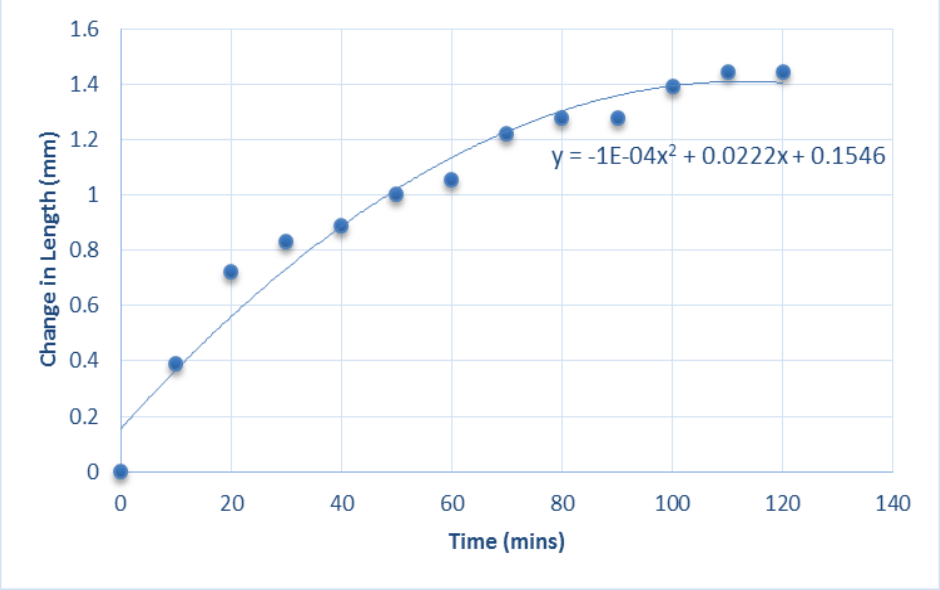


Figure 4.9 Swelling Behavior of Hydrogel under Constraint Condition

For many applications, the measurement of hydrogel under loaded conditions is significant than a free expansion behavior where no stress is present additionally. For this, the effect of pressure on the hydrogel swelling was evaluated. The **Table 1** shows that as we increase the load on the hydrogel, the pressure on the hydrogel increases, thus change in thickness of the hydrogel decreases.

Load	Final thickness	Change in thickness
5g	4.05mm	1.55mm
10g	3.9mm	1.40mm
15g	3.61mm	1.11mm
20g	3.76mm	1.26mm
25g	3.37mm	0.87mm
30g	3.40mm	0.90mm
35g	3.37mm	0.87mm
40g	3.17mm	0.67mm

Table 2 Swelling behavior of Hydrogel under loaded condition in actuator configuration. Initial thickness= 2.5mm. Change in thickness=Final hydrogel thickness - Initial hydrogel thickness

4.3.2 Mechanical Characterization of Hydrogel Based Linear Actuator

HBLA is mechanically characterized by observing the displacement of end effector and its weight lifting capacity. For this, the load displacement graph (**Figure 4.10**) has been plotted indicating an inverse relation between load and displacement. As we increase the load, the displacement of the end effector decreases. However, the initial loading does not have a significant effect on the displacement of the end effector of hydrogel actuator as depicted in the graph. The load lifting capacity of hydrogel in this particular linear actuator configuration is about 40g.

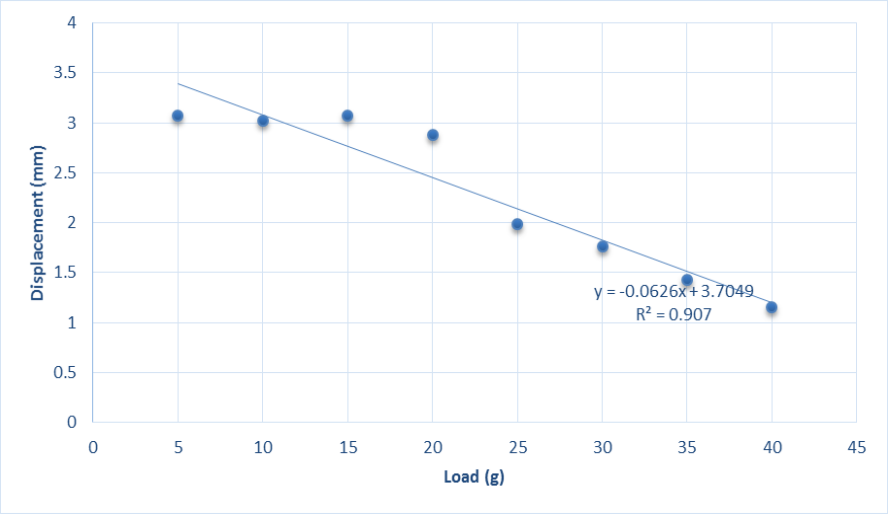


Figure 4.10 Mechanical Testing of Hydrogel Based Linear Actuator Illustrating the weight lifting capacity.

CHAPTER 5 CONCLUSION AND FUTURE PERSPECTIVES

In this project, Hydrogel based linear actuator has been developed and different properties of hydrogels as actuators has been studied, which can be utilized in variety of biomedical applications including the drug delivery systems, stent expansion etc. The PVA/Chitosan/Gelatin hydrogel composite illustrated the good results indicating its use where fast initial swelling rate is required. The hydrogel behaving as passive actuator producing microscale displacement with low lifting capacity demonstrate their use in applications where small amount of displacement is required. However, the result shows use of studied hydrogel composition in limited applications.

FUTURE PERSPECTIVES

In the fields of science and medicine, hydrogels have become realistic as sensing and actuating machines. Hence, in future, the hydrogel based actuator can be used in numerous biomedical applications like drug delivery system and auxetic film or stent expansion. The concept may include the formation of bilayer structure; active layer of hydrogel film and passive layer containing the auxetic structure as described in Figure 5.1. When the hydrogel swells and expands, the auxetic films adhered to hydrogel will also expand and thus opening the pores of the auxetic film. Therefore, in this bilayer structure, Hydrogel will be acting as the passive actuator. Secondly, hydrogel can be used as a lining material for stent expansion. Thus, studying the behavior of hydrogels as actuators and their application in biomedical devices would open possibilities for the upcoming technology.

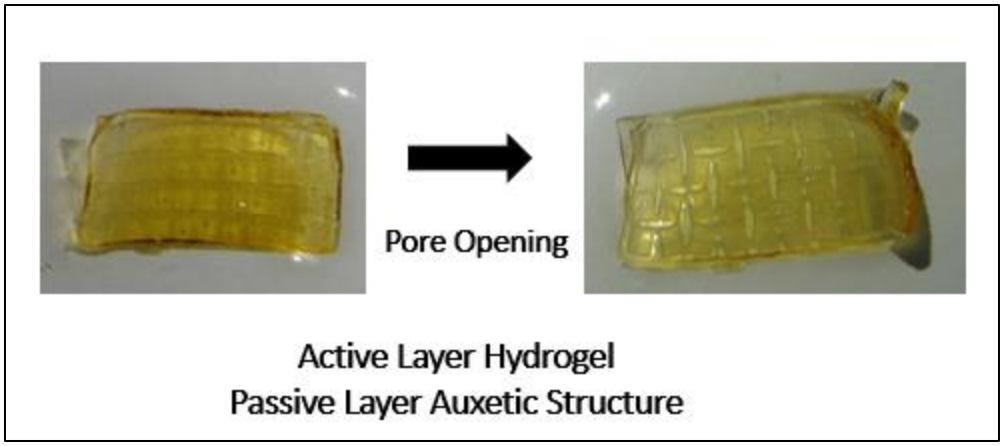


Figure 5.1 Illustration of hydrogel as actuator for auxetic structure

CHAPTER 6 REFERENCES

Ahearne, M, Yang, Y, & Liu, KK. (2008). Mechanical characterisation of hydrogels for tissue engineering applications. *Topics in tissue Engineering, 4*(12), 1-16.

Ahmed, Enas M. (2015). Hydrogel: Preparation, characterization, and applications: A review. *Journal of Advanced Research, 6*(2), 105-121.

Bashir, R, Hilt, JZ, Elibol, O, Gupta, A, & Peppas, NA. (2002). Micromechanical cantilever as an ultrasensitive pH microsensor. *Applied Physics Letters, 81*(16), 3091-3093.

Bassik, Noy, Abebe, Beza T, Laflin, Kate E, & Gracias, David H. (2010). Photolithographically patterned smart hydrogel based bilayer actuators. *Polymer, 51*(26), 6093-6098.

Brannon-Peppas, Lisa, & Peppas, Nikolaos A. (1991). Equilibrium swelling behavior of pH-sensitive hydrogels. *Chemical Engineering Science, 46*(3), 715-722.

Cai, Shengqiang, & Suo, Zhigang. (2011). Mechanics and chemical thermodynamics of phase transition in temperature-sensitive hydrogels. *Journal of the Mechanics and Physics of Solids, 59*(11), 2259-2278.

Cao, Xia, Lai, Siyi, & James Lee, L. (2001). Design of a self-regulated drug delivery device. *Biomedical Microdevices, 3*(2), 109-118.

Chai, Qinyuan, Jiao, Yang, & Yu, Xinjun. (2017). Hydrogels for Biomedical Applications: Their Characteristics and the Mechanisms behind Them. *Gels, 3*(1), 6.

Chen, Cheng-Ho, Wang, Fang-Yu, Mao, Ching-Feng, Liao, Wei-Tung, & Hsieh, Ching-Dong. (2008). Studies of chitosan: II. Preparation and characterization of chitosan/poly (vinyl alcohol)/gelatin ternary blend films. *International Journal of Biological Macromolecules, 43*(1), 37-42.

Chuang, Wen-Yuan, Young, Tai-Horng, Yao, Chun-Hsu, & Chiu, Wen-Yen. (1999). Properties of the poly (vinyl alcohol)/chitosan blend and its effect on the culture of fibroblast in vitro. *Biomaterials, 20*(16), 1479-1487.

Costa Jr, Ezequiel de Souza, & Mansur, Herman Sander. (2008). Preparation and characterization of chitosan/poly (vinyl alcohol) blend chemically crosslinked by glutaraldehyde for tissue engineering application. *Química Nova, 31*(6), 1460-1466.

Dicker, MPM, Weaver, PM, Rossiter, JM, & Bond, IP. (2014). Hydrogel core flexible matrix composite (H-FMC) actuators: theory and preliminary modelling. *Smart Materials and Structures, 23*(9), 095021.

Dinarvand, RDAE, & D'Emanuele, A. (1995). The use of thermoresponsive hydrogels for on-off release of molecules. *Journal of Controlled Release, 36*(3), 221-227.

Djagny, Kodjo Boady, Wang, Zhang, & Xu, Shiying. (2001). Gelatin: a valuable protein for food and pharmaceutical industries: review. *Critical reviews in food science and nutrition, 41*(6), 481-492.

Duan, Jiangjiang, Liang, Xichao, Zhu, Kunkun, Guo, Jinhua, & Zhang, Lina. (2017). Bilayer hydrogel actuators with tight interfacial adhesion fully constructed from natural polysaccharides. *Soft Matter, 13*(2), 345-354.

Fan, Lihong, Yang, Huan, Yang, Jing, Peng, Min, & Hu, Jin. (2016). Preparation and characterization of chitosan/gelatin/PVA hydrogel for wound dressings. *Carbohydrate polymers, 146*, 427-434.

Gerlach, Gerald, & Arndt, K-F. (2009). *Hydrogel sensors and actuators: engineering and technology* (Vol. 6): Springer Science & Business Media.

Guan, Jingjiao, He, Hongyan, Hansford, Derek J, & Lee, L James. (2005). Self-folding of three-dimensional hydrogel microstructures. *The Journal of Physical Chemistry B, 109*(49), 23134-23137.

Guenther, M, Kuckling, D, Corten, C, Gerlach, G, Sorber, J, Suchaneck, G, & Arndt, K-F. (2007). Chemical sensors based on multiresponsive block copolymer hydrogels. *Sensors and Actuators B: Chemical, 126*(1), 97-106.

Gupta, Piyush, Vermani, Kavita, & Garg, Sanjay. (2002). Hydrogels: from controlled release to pH-responsive drug delivery. *Drug discovery today, 7*(10), 569-579.

Harmon, Marianne E, Tang, Mary, & Frank, Curtis W. (2003). A microfluidic actuator based on thermoresponsive hydrogels. *Polymer, 44*(16), 4547-4556.

He, Hongyan, Guan, Jingjiao, & Lee, James L. (2006). An oral delivery device based on self-folding hydrogels. *Journal of Controlled Release, 110*(2), 339-346.

Hirokawa, Yoshitsugu, Tanaka, Toyoichi, Johnson, DL, & Sen, PN. (1984). *Volume phase transition in a non-ionic gel.* Paper presented at the AIP Conference Proceedings.

Ionov, Leonid. (2010). Actively-moving materials based on stimuli-responsive polymers. *Journal of Materials Chemistry, 20*(17), 3382-3390.

Kalshetti, Prashant P, Rajendra, Vivek B, Dixit, Deepashree N, & Parekh, Pranav P. (2012). Hydrogels as a drug delivery system and applications: a review. *International Journal of Pharmacy and Pharmaceutical Sciences, 4*(1), 1-7.

Kelby, Tim S, Wang, Ming, & Huck, Wilhelm TS. (2011). Controlled folding of 2D Au–polymer brush composites into 3D microstructures. *Advanced Functional Materials, 21*(4), 652-657.

Kudela, V. (1987). Hydrogels. *Encyclopedia of polymer science and engineering, 7*, 703-807.

Kumar, Kamlesh, Luchnikov, Valeriy, Nandan, Bhanu, Senkovskyy, Volodymyr, & Stamm, Manfred. (2008). Formation of self-rolled polymer microtubes studied by combinatorial approach. *European Polymer Journal, 44*(12), 4115-4121.

Kumar, Kamlesh, Nandan, Bhanu, Luchnikov, Valeriy, Simon, Frank, Vyalikh, Anastasia, Scheler, Ulrich, & Stamm, Manfred. (2009). A novel approach for the fabrication of silica and silica/metal hybrid microtubes. *Chemistry of Materials, 21*(18), 4282-4287.

Kweon, HaeYong, Um, In Chul, & Park, Young Hwan. (2001). Structural and thermal characteristics of Antheraea pernyi silk fibroin/chitosan blend film. *Polymer, 42*(15), 6651-6656.

Kwon, Gu Han, Park, Joong Yull, Kim, Jeong Yoon, Frisk, Megan L, Beebe, David J, & Lee, Sang-Hoon. (2008). Biomimetic soft multifunctional miniature aquabots. *Small, 4*(12), 2148-2153.

Langer, Robert. (1998). Drug delivery abd targeting. *Nature, 392*(6679), 5-10.

Morita, Ryoichi, Honda, Ritsuko, & Takahashi, Yoshiteru. (2000). Development of oral controlled release preparations, a PVA swelling controlled release system (SCRS): I. Design of SCRS and its release controlling factor. *Journal of controlled release, 63*(3), 297-304.

O'Grady, Megan L, Kuo, Po-ling, & Parker, Kevin Kit. (2009). Optimization of electroactive hydrogel actuators. *ACS applied materials & interfaces, 2*(2), 343-346.

Oh, Kwang Suk, Oh, Jeong Seok, Choi, Hyun Seok, & Bae, Young Chan. (1998). Effect of cross-linking density on swelling behavior of NIPA gel particles. *Macromolecules, 31*(21), 7328-7335.

Ohmine, Iwao, & Tanaka, Toyoichi. (1982). Salt effects on the phase transition of ionic gels. *The Journal of Chemical Physics, 77*(11), 5725-5729.

Pawde, SM, & Deshmukh, Kalim. (2008). Characterization of polyvinyl alcohol/gelatin blend hydrogel films for biomedical applications. *Journal of applied polymer science, 109*(5), 3431-3437.

Pelah, Avishay, Seemann, Ralf, & Jovin, Thomas M. (2007). Reversible cell deformation by a polymeric actuator. *Journal of the American Chemical Society, 129*(3), 468-469.

Peppas, Nicholas A, Ottenbrite, Raphael M, Park, Kinam, & Okano, Teruo. (2010). *Biomedical applications of hydrogels handbook*: Springer Science & Business Media.

Pokroy, Boaz, Epstein, Alexander K, Persson-Gulda, Maria, & Aizenberg, Joanna. (2009). Fabrication of bioinspired actuated nanostructures with arbitrary geometry and stiffness. *Advanced Materials, 21*(4), 463-469.

Remington, Joseph Price, Troy, David B, & Beringer, Paul. (2006). *Remington: The science and practice of pharmacy* (Vol. 1): Lippincott Williams & Wilkins.

Richter, A, Krause, W, Lienig, J, & Arndt, KF. (2005). Polymer networks as actuator and sensor systems to be used for automation of biomedical devices. *Biomedizinische Technik. Biomedical engineering, 50*(3), 66-68.

Richter, Andreas, Klenke, Christian, & Arndt, Karl-Friedrich. (2004). *Adjustable low dynamic pumps based on hydrogels.* Paper presented at the Macromolecular Symposia.

Shibayama, Mitsuhiro, & Tanaka, Toyoichi. (1993). Volume phase transition and related phenomena of polymer gels *Responsive gels: volume transitions I* (pp. 1-62): Springer.

Shirota, Hideaki, Endo, Noriko, & Horie, Kazuyuki. (1998). Volume phase transition of polymer gel in water and heavy water. *Chemical physics, 238*(3), 487-494.

Sidorenko, Alexander, Krupenkin, Tom, Taylor, Ashley, Fratzl, Peter, & Aizenberg, Joanna. (2007). Reversible switching of hydrogel-actuated nanostructures into complex micropatterns. *Science, 315*(5811), 487-490.

Stoychev, Georgi, Puretskiy, Nikolay, & Ionov, Leonid. (2011). Self-folding all-polymer thermoresponsive microcapsules. *Soft Matter, 7*(7), 3277-3279.

Tanaka, Toyoichi, Nishio, Izumi, Sun, Shao-Tang, & Ueno-Nishio, Shizue. (1982). Collapse of gels in an electric field. *Science, 218*(4571), 467-469.

Wang, Jing, Chen, Zongyuan, Mauk, Michael, Hong, Kuang-Sheng, Li, Mengyan, Yang, Shu, & Bau, Haim H. (2005). Self-actuated, thermo-responsive hydrogel valves for lab on a chip. *Biomedical microdevices, 7*(4), 313-322.

Xia, Lie-Wen, Xie, Rui, Ju, Xiao-Jie, Wang, Wei, Chen, Qianming, & Chu, Liang-Yin. (2013). Nano-structured smart hydrogels with rapid response and high elasticity. *Nature communications, 4*.

PUBLICATIONS

Published Articles

*"*Bakhtawar Ghafoor, Murtaza Najabat Ali, Umar Ansari, Muhammad Faraz Bhatti, Mariam Mir, Hafsah Akhtar, **Fatima Darakhshan** , (2016) "*New biofunctional loading of Natural Anti-microbial agent in biodegradable polymeric films for Biomedical Applications",* International Journal of Biomaterials. Available Online: http://www.hindawi.com/journals/ijbm/2016/6964938/

Submitted Articles

Original Articles

Fatima Darakhshan, Murtaza Najabat Ali, Umar Ansari, Mariam Mir (2017*),"Design and Testing of Hydrogel based Actuator for Biomedical Applications".*

Hafsah Akhtar, Murtaza Najabat Ali, Umar Ansari, Faiza Bukhari, **Fatima Darakhshan** *(2015), "Designing and Development of Novel Auxetic Geometry for non-vascular Oesophageal Stent Application".*

Review Articles

Fatima Darakhshan, Aisha Tahir, Javairia Sami ,Murtaza Najabat Ali , Umar Ansari, Mariam Mir ,"*PVA based Composite materials for biomedical applications: A Review".*

Hafsah Akhtar, Murtaza Najabat Ali , Umar Ansari , Javaria Sami , **Fatima Darakhshan** , "*Esophageal Intubation-A Review".*

TRP Fatima

ORIGINALITY REPORT

9%	1%	8%	2%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Ionov, Leonid. "Actively-moving materials based on stimuli-responsive polymers", Journal of Materials Chemistry, 2010. Publication	2%
2	Fan, Lihong, Huan Yang, Jing Yang, Min Peng, and Jin Hu. "Preparation and characterization of chitosan/gelatin/PVA hydrogel for wound dressings", Carbohydrate Polymers, 2016. Publication	1%
3	Biomedical Applications of Hydrogels Handbook, 2010. Publication	1%
4	Costa-Junior, E.S.. "Preparation and characterization of chitosan/poly(vinyl alcohol) chemically crosslinked blends for biomedical applications", Carbohydrate Polymers, 20090409 Publication	1%
5	V. Sugantha Kumari. "Physicochemical and morphological evaluation of chitosan/poly(vinyl	1%

	alcohol)/methylcellulose chemically cross-linked ternary blends", Polymer Bulletin, 10/04/2011 Publication	
6	Hua Li. "Introduction", Smart Hydrogel Modelling, 2009 Publication	1%
7	Submitted to CSU, San Jose State University Student Paper	1%
8	Submitted to King Saud University Student Paper	1%
9	Springer Series on Polymer and Composite Materials, 2016. Publication	1%
10	Schnelle Jr, Karl, Partha Dey, Shankha Banerji, Shivaji Sircar, Sangchul Hwang, Chung-Chiun Liu, Xuekun Xing, Lyle Albright, and James Ryan. "Detergent Enzymes", Encyclopedia of Chemical Processing (Print Version), 2005. Publication	<1%
11	www.oulu.fi Internet Source	<1%
12	S. M. Pawde. "Characterization of polyvinyl alcohol/gelatin blend hydrogel films for biomedical applications", Journal of Applied Polymer Science, 09/05/2008	<1%

	Publication	
13	Evans, Benjamin, and Rich Superfine. "Design Considerations for Magnetically Actuated Biomimetic Cilia", Biomimetic Based Applications, 2011. Publication	<1%
14	www.numo.or.jp Internet Source	<1%
15	www.omicsonline.org Internet Source	<1%
16	www.dovepress.com Internet Source	<1%

EXCLUDE QUOTES	ON	EXCLUDE MATCHES	OFF
EXCLUDE BIBLIOGRAPHY	ON		