A COMPARATIVE STUDY OF RTV-225 SILICONE ELASTOMER AND NATURAL RUBBER BASED THERMO-ELASTOMER FOR SOFT ROBOTIC APPLICATIONS

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ABSTRACT: Leveraging on material compliance, soft robots of today are mostly fabricated using silicone elastomers with reported long curing times. Hence, this opens possibilities to explore new materials for fabrication. In this paper, a recently patented natural rubber thermo-plastic elastomer (NRTE) is presented in comparison to RTV-225 silicone elastomer. NRTE inherits a mix of elasto-plastic behavior with ability to be easily formed by heating. Under normal operating conditions, it shows a unique self-healing-like behavior that allows multiple times of reuse. The post processing takes less than 2 minutes to cure. This reduces time to fabricate CiSS and CbSS soft structures. Mechanical properties of both elastomers are reported and compared by performing a tensile strength test. Additionally, this study presents design, fabrication, and testing of CiSS and CbSS simple soft structures which are made of NRTE and RTV-225 elastomers. The results reveal that NRTE has a potential to be used in prototyping of soft robotic structures.

KEYWORDS: *Bio-Inspired; Elastomers; Flexible Materials; Mechanical Properties; Soft Robotics*

1.0 INTRODUCTION

Usually robots are made of rigid links which require certain level of care during operation, particularly, in environments where humans and machines co-exist such as industrial sites, medical facilities and houses. However, recent works [1–20] show that flexible materials can be used to develop soft robotic structures for many applications. This provides possibility to aim for the future of having safe and environment-compliant robots. Most of the previously reported soft robots rely on flexible materials to achieve the desired adaptive behaviors. To mimic a continuum behavior, soft robots need to have self-deformable bodies with minimal force exertion. For that, one possibility is to use low modulus elastic materials such as elastomers [1]. Among material choices to develop a soft robotic structure, roboticists usually look for criteria that may help them to achieve the design objective. Figure 1 illustrates various types of materials based on comparison of their density and young's modulus [21].

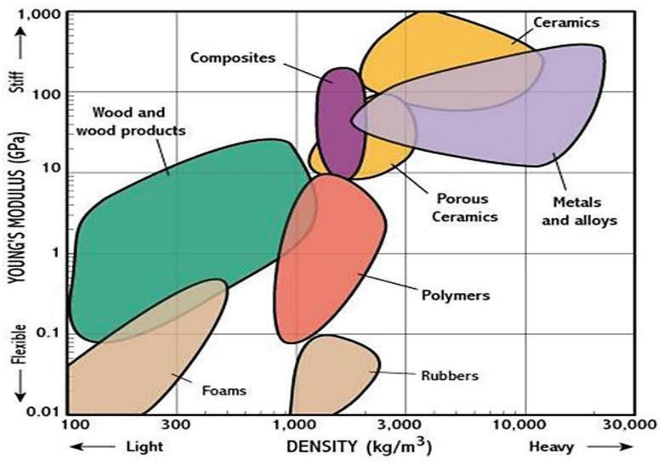

Figure 1: Material selection chart illustrating choice of materials based on density and Young's modulus [21]

Materials with low elastic modulus and fairly low density such as rubber elastomers are widely adopted due to their intrinsically flexible behavior and fairly established material processing methods. They can be used to fabricate durable, flexible, and light-weight soft structures e.g. an octopus inspired silicone elastomer made robot that has wire-based tendons controlling the movement [12]; a pneumatically controlled structure made of silicone elastomer that has multiple chambers performing ballistic rolling motion [13]; a caterpillar inspired soft robot that uses SMA wires embedded within the silicone elastomeric body, allowing it to perform rolling motion when the SMA wires contract [1]; a modular silicone membranes based worm-bot which is actuated by voice coils [14].

For most of these works, silicone elastomer is processed through a common molding/curing method in order to fabricate soft structure parts. The curing usually takes many hours. In cases that a soft structure requires fabrication of sub-assemblies, the traditional molding/curing process takes longer time for the curing stage. It also has material handling issues such as the requirement of extra care handling during the fabrication process or limitation of forming complex shapes due to limitation of the mold design. Furthermore, for some applications where a certain level of stiffness is required, silicone elastomer, which is highly elastic, cannot fulfill the high stiffness design specification. Thus, this research gap leads us to explore other choices for material selection that show fairly similar material properties with the easier material handling, shorter processing time, and tolerable level of stiffness to be considered as a soft material.

This study presents a newly patented natural rubber based thermo-elastomer (NRTE) [22] that shows interesting properties in comparison to silicone elastomer. It can be used to develop soft structures. NRTE could compete with silicone elastomer (RTV-225) in some soft robotic applications, in terms of short curing time and easy assembling during fabrication process. This paper is divided into four main sections. First, materials and methods of development and testing both material samples using tensile strength test (TST) are discussed in order to compare their mechanical properties. This section includes details of fabrication process of two soft structures – a cylindrical balloon like soft structure (CbSS) that is pneumatically actuated, and a caterpillar inspired soft structure (CiSS) that uses end-to-end connected plastic strap-like tendons to perform unidirectional locomotion on a flat surface. These structures are fabricated using NRTE as well as RTV-225 in order to investigate soft robot structural responses for two identical applications. Then, the properties and performance comparison of RTV-225 silicone elastomer with NRTE elastomer is reported in result section. The prototype designs and basic implementation scenarios of both soft structures are presented. In discussion section, the results are further analyzed and explained. Finally, conclusion section summarizes overall work and mentions potential examples of the NRTE soft robots.

2.0 METHODOLOGY

The RTV-225 and NRTE elastomer samples are prepared and tested in order to compare their tensile strength. Later, both materials are formed to be soft elastomeric structures – CbSS and CiSS. The details are presented as follows.

2.1 Preparation and Testing of the RTV-225 Silicone Elastomer

The silicone elastomer has unique mechanical properties. It has good strength and durability. It shows high elastic behavior under given stretch conditions which makes it suitable for applications that need to achieve compliance under high deformations [2, 5–8, 18–20]. Ecoflex (Smooth-On, PA, USA) elastomer products are popular in soft robotics community. Hence, various reported soft structures are fabricated using these silicone elastomers with different compositions depending on designs and applications. In this study, RTV-225 silicone elastomer (GGC, Taiwan) is used due to its availability and comparative properties to those elastomers that are reported in the previous works.

RTV-225 is a room temperature curing material (part 'a') supplied in the form of liquid resin and curing agent (part 'b') with manufacturer specified properties as shown in Table 1. The tensile strength test (ASTM D412) is performed to analyze and compare mechanical properties. Paraffinic oil is used to control concentration level of part 'a'. A mixing ratio of 95:5 (% weight) was used for part 'a' and paraffinic oil, respectively. This mixture is thoroughly stirred for 2-3 minutes by an electric mixer (stand mixer EMS-52, distributor: TCE Co., Ltd., Thailand). After that, the 3-5% of part 'b' was poured into the mixture and further stirred for 30-40 seconds.

Table 1: Properties and specifications of commercial silicone elastomers [28]

Type of elastomer	Tensile strength (MPa)	100% modulus (MPa)	Elongation at break (%)	Cure time (hours)	Shore hardness (A^0)	Mixed viscosity (cps)
RTV-225	≥ 3.4	NR	≥ 420	2-4	28 to 39	15,000-17,000
Ecoflex 00-10	0.83	0.05	800	4	00-10	14,000
Ecoflex 00-20	1.1	0.05	845	4	00-20	3,000
Ecoflex 00-30	1.37	0.06	900	4	00-30	3,000
Ecoflex 00-50	2.17	0.08	980	3	00-50	8,000

Then, it was quickly poured into a square acrylic cavity mold to obtain a sheet of RTV-225 for material testing. Direct pouring of elastomer into a mold may cause air bubbles on the elastomer surface. In general, number of air bubbles in silicone depends on ratio between silicone and paraffinic oil which influences the leftover air molecules inside the silicone mixture. This can either be eliminated by degassing the mixture using a vacuum chamber or manually bursting them with a sharp edge object such as a needle. In this study, small number of bubbles were observed after pouring the mixture into the mold, thus the bursting technique was implemented.

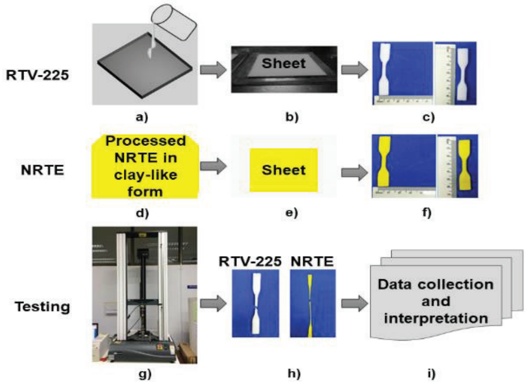

Figure 2: Steps of material preparation and testing for RTV-225 and NRTE elastomers

Material preparation and testing for RTV-225 and NRTE elastomers are shown in Figure 2. Firstly, the prepared RTV-225 liquid mixture was poured into the acrylic mold (Figure 2(a)). Then, an elastomeric sheet was obtained 4 hours after curing at room temperature. Subsequently, the obtained elastomer sheets were die cut to be three dumbbell shaped specimens (Type: Die D), each having gauge length of 1 mm and gauge width of 3 mm. A UTM - universal testing machine (H10KS, Hounsfield Test Equipment Ltd., UK) was used to evaluate mechanical properties of RTV-225 by tensile strength test. Each specimen was clamped between pneumatic force grips. Uniaxial tensile strength test was performed with a 1,000 N load cell and speed rate of 500 mm/min. The test results of all specimens were averaged for reliability. Post tensile strength test specimens are shown in Figure 2(h), in which the left is RTV-225, while the right is NRTE. Finally, testing results were calculated to determine the mechanical properties. To evaluate the material performance on soft robotic applications, two structures are fabricated by using RTV-225 as discussed next.

2.1.1 Fabrication Process of the RTV-225 Soft Structures

Currently, a number of soft robot are either actuated by pneumatic or electric/wire based control strategies. A purpose of this work is to benchmark a general silicone elastomer with the NRTE elastomer in terms of soft robotic fabrication, implementation, and working performance. Thus, two basic soft structures are developed.

Figure 3 illustrates the NRTE and RTV-225 fabrication processes to develop CbSS and CiSS soft structures. For pneumatically actuated cylindrical balloon-like soft structure (CbSS), RTV-225 silicone elastomer is poured into a cylindrical acrylic mold. A cylindrical inner mold made of paraffin wax was inserted and centrally positioned immediately into the cylindrical acrylic mold to later create 3 air chambers (Figure 3(a) bottom)). After curing for 3-4 hours, the soft structure was removed from the mold. The paraffin wax was manually removed from the body of the soft structure. To obtain a 2D (bending) motion of this soft structure, an external air compressor connected with a plastic tube supplies air pressure to the soft structure at the inlet. The inlet was punched and tightly clamped with a fixed support using plastic tightening straps at one end. During the test, the air pressure and resultant bending angle were recorded according to the pressure gauge of the supplied air and visual analysis of 2D motion.

To investigate the soft structure response when tendons or electric motors drive the system, a caterpillar inspired soft structure (CiSS) is designed to perform crawling on a flat surface by its material compliance. From Figure 3(a) (top), the liquid silicone was poured into a plastic CiSS cavity mold. After 3-4 hours of curing at room temperature, the resultant soft structure was taken out. Using a utility knife, minor rough edges the CiSS were evenly cropped to match final design. A 10 cm-long thin plastic strap was attached on both ends of the CiSS. These straps act as side-to-side tendons that support pulling and releasing in unidirectional motion. An externally fixed servo motor attached through tendon provides pulse like crawling motion.

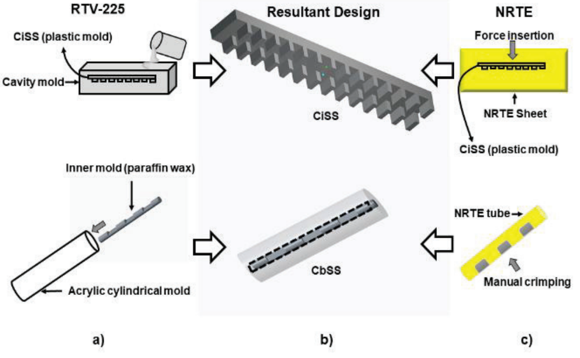

Figure 3: Fabrication processes to develop soft structures using RTV-225 and NRTE-35: (a) Top: Pouring RTV-225 liquid into a cavity mold, Bottom: Inserting an inner mold made of paraffin wax into a cylindrical acrylic mold, (b) CAD view of desired structures of CiSS and CbSS and (c) Top: Pressing manually the CiSS plastic mold on the NRTE sheet, Bottom: Manually crimping the cylindrical wall of the tube made of NRTE

2.2 Testing of Natural Rubber Based Thermo-Elastomer

Natural rubber based thermo-elastomer is reported here for the first time in context of soft robotic applications. It is prepared by blending of Standard Thai Rubber (STR5L) and thermoplastic along with other material compositions [22]. In this study, the shore A hardness test is performed to determine the material hardness. There are two different hardness levels of NRTE: F35 and F45. Each has different hardness regarding the proportion of rubber and thermoplastic. Their tensile strength, hardness and mechanical properties are revealed through the result section.

NRTE material is easy to fabricate and process. It can be formed and reformed by any controlled heating equipment in temperature range of 70°C to 90°C. A simple method is to put it in the water, and then heat up the water to allow a slow heat transfer to NRTE. During the heating, chemical bonding of NRTE is soften. This allows the material to be pressed against any cavity mold. On the other hand, a heat gun can be used to heat up the NRTE material by blowing hot air on the surface. This can reshape it to a desired geometry. The curing takes only 2-3 minutes which is a major benefit when it is used to develop soft robotic structures. Both F35 and F45 NRTE are tested to determine tensile strength. However, only the F35 is chosen for further fabrication of soft structures. This is because F35 has the lesser hardness while other mechanical properties are slightly different. After obtaining NRTE sheets, the tensile strength testing is performed on 3 identical NRTE specimens of F35 and F45 by replicating the test as previously reported in Section 2.1. To investigate this material on soft robotic applications, the similar soft structures are fabricated as reported in Section 2.1.1. However, NRTE and RTV-225 elastomers differ in material handling, hence explanation of NRTE fabrication method is presented next.

2.2.1 Preparation of Soft Robotic Structures using NRTE-35

Since the NRTE cannot be poured into a mold like silicone elastomer, it relies on heat-based material processing methods. To prepare an inflatable CbSS structure, freshly prepared thermo-elastomer sheets were fed through an industrial scale extruder (Hong Yow Thai Co. Ltd., Thailand) with a tube-like nozzle to prepare a flexible elastomeric tube of 15mm in diameter and 3mm wall thickness. The extruder deforms the raw NRTE and performs pressure-based extrusion, yielding the heated soft NRTE tube. By keeping it cool down in a water tank for about 2 minutes, it was completely cured. To make air chambers inside the tube, a heat gun (RYOBI AG-180; 220V, 1800W, 50 Hz; P.R.C) is utilized by operating on mode 1 that provides temperature up to 440°C of hot air as output through its 35.5 mm nozzle (kept at 5 cm distance facing NRTE surface for 10-15 seconds). After heating up tube surface, marked points on the outer surface of the tube are crimped to the inner side using an iron rod edge (Figure 3(c) bottom). This imprints the air chambers inside the tube. Leaving it for 2 minutes of curing, a CbSS structure made of NRTE, similar to RTV-225, is obtained.

To fabricate CiSS using NRTE, a NRTE sheet of 5mm thickness was heated by a compression molding machine (LLC-140, Tang-Master Co. Ltd., Thailand). The CiSS plastic mold was pressed on the sheet (Figure 3(c) top). After 2 minutes, removing the plastic mold result in NRTE CiSS structure. After that, uneven sides of this soft structure were manually cropped using a utility knife. Then, NRTE made CiSS and CbSS soft structures are tested. Their working performance is evaluated by the same experimental setup as explained in Section 2.1.1.

3.0 RESULTS

Tensile strength test of RTV-225 and NRTE provides useful information in terms of mechanical properties. For RTV-225, results include: 3.24 MPa of tensile strength and fracture strength, 477.06 (%) of elongation at break, 0.35 MPa of 100% modulus and 100% elongation, and shore A hardness of 20. For the F35 and F45 NRTE, results respectively include: 4.52 and 5.81 MPa of tensile and fracture strengths, 1195.30 and 1224.49 (%) elongation at break, 1.38 and 1.36 MPa of 100% modulus and 100% elongation, and shore A hardness of 38 and 45. Figure 4 provides comparative overview of tensile strength test results that are further discussed in the next section.

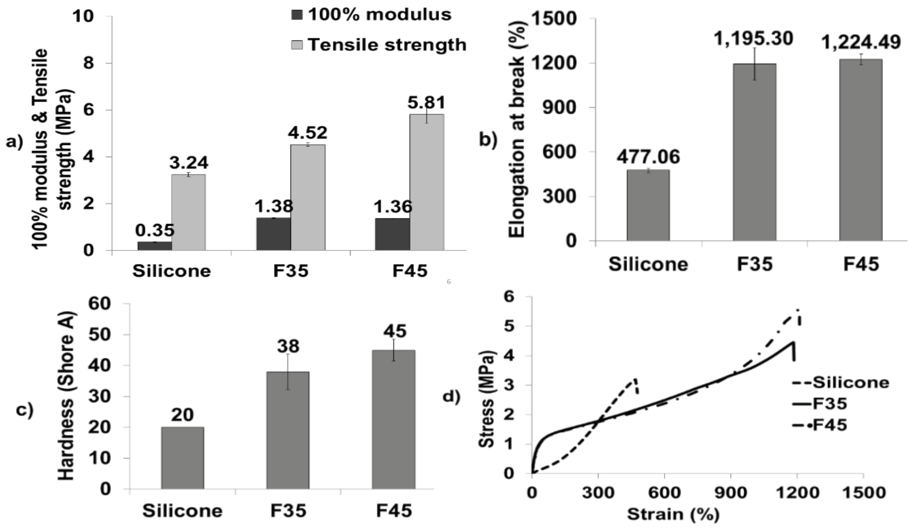

Figure 4: Tensile strength test results of RTV-225, NRTE-F35 and NRTE-F45: (a) Tensile strength and 100% modulus/elongation, (b) % elongation at break, (c) Shore A hardness and (d) Stress and strain relationship

Later, RTV-225 and NRTE-F35 materials are fabricated to be the two soft structures as discussed previously. Two experimental setups are used to test CbSS and CiSS soft structures (Figure 5). The CbSS structures are pressurized by the air compressor, resulting in a bending profile as illustrated in Figure 6. The CiSS structures are used to mimic an open loop point-to-point locomotion pattern. Figure 7 shows a set of photographs taken at run time with marked instances. They indicate the caterpillar-like locomotion of the soft structures moving from the left to right hand side. The discussion section provides some noted performance and comparison issues of CbSS and CiSS.

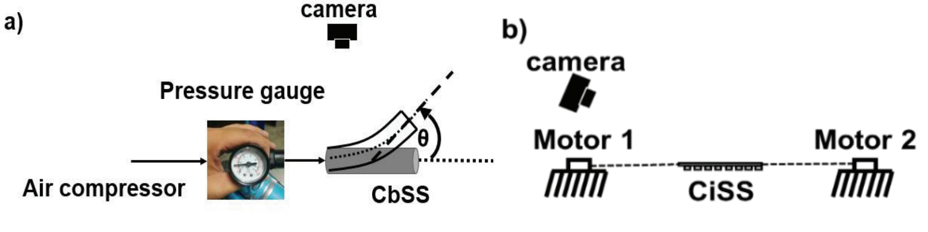

Figure 5: Experimental setups to test soft robotic structures: (a) CbSS deformation and (b) CiSS locomotion: two servo motors

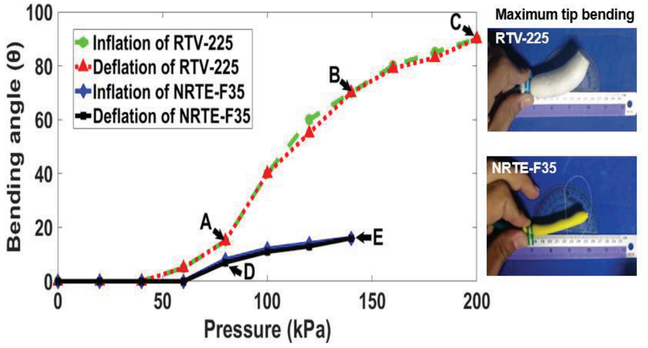

Figure 6: Relationship between the actuated air pressure and deflection angle of RTV-225 and NRTE-F35 CbSS structures with Points (A, B, C, D, E) for the comparison of the performance while photographs on the right show the maximum bending profile of CbSS structures

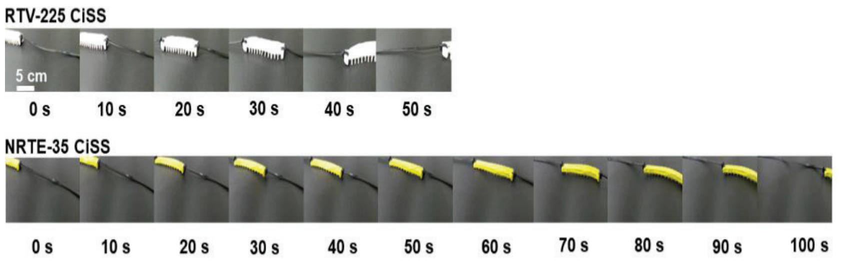

Figure 7: The experimental locomotion of RTV-225 (top) and NRTE-F35 (bottom) CiSS structures

4.0 DISCUSSION

In post processing, NRTE takes 2-3 minutes to completely cure. It also has self-healing behavior. The self-healing is observed when the material is left at the room temperature after processing. The chemical composition allows the NRTE to be reformed multiple times without losing the material properties. This reduces curing time significantly compared with silicone elastomers such as RTV-225 that usually takes a couple of hours. There are three methods to process NRTE: (i) using hot water to perform equally distributed heating. (ii) using a compression machine to heat and roll NRTE sheets. (iii) using an air heating gun to blow at a specific surface area. All these methods support simple processing and fabrication of different structures, but they lack of repeatability as observed during fabrication of CbSS. For example, it took a few tries to make the tube walls stick together during heating process. The fabrication processes can be further developed for process reliability and quality control.

The tensile strength test data indicates that NRTE has higher tensile strength than RTV-225. However, RTV-225 and general silicone elastomers still have the better elasticity than NRTE. Figure 2(h) and Figure 4(d) show that NRTE has a plastic-dominant behavior because it shows elongation with permanent deformation. This was further confirmed when the NRTE CbSS robot was tested. That is, the CbSS robot undergoes complete deformation unless it is kept under 50% of recoverable elastic elongation limit.

On the other hand, the RTV-225 CbSS robot showed consistent performance and returned to the original position after deflation because the silicone elastomer is a highly elastic material. Hence, it is suitable for pneumatically actuated soft robots. Figure 6 shows the bending angle of the CbSS structures during inflation and deflation. The plot implies that the NRTE CbSS required higher pressure to deform yet yielded smaller deflection than the RTV-225 CbSS. By comparing the marked A, B, C, D, and E points, it can be further explained as follows. In the early state of deflection at the same actuated pressure (Points A and D), the RTV-225 CbSS gives 2 times larger bending angle than the NRTE CbSS does. To have the same bending angle (Points A and E), the NRTE CbSS requires 1.75 times higher pressure than the RTV-225 CbSS does. The pressure that makes the NRTE CbSS to reach the maximum deflection (Point E) causes the RTV-225 CbSS to have only 75% of deflection (Point B). At the peak input pressure (Points C and E), the RTV-225 CbSS yields the maximum bending angle 4 times larger than the maximum bending angle of NRTE CbSS.

The higher stiffness of NRTE contributes to bending limitation and permanent deformation when it is inflated beyond the 50% recoverable elongation limit. This implies that NRTE has a limitation if it is used for pneumatically actuated soft structures. The range of flexibility depends on the robot structural design and applications.

However, the permanent deformation could be prevented by having a mechanical stretch constraint such as a hard shell or lock. The shell protects the soft structure not to stretch over the recoverable limit. Besides this initial development, more reliable prototyping equipment to process NRTE would bring a good expected performance of pneumatically actuated soft structures.

In contrast, CiSS made of RTV-225 and NRTE elastomers reasonably well performed as expected. The RTV-225 CiSS was able to perform a simple unidirectional locomotion according to a specific actuation

cycle. Being more elastic, it is able to complete a point-to-point locomotion earlier than the NRTE CiSS does for the same distance. However, in comparison, the tendon pulling-and-releasing duration are identical (0.5 cm/s) for both structures. When the tendon pulls, the NRTE CiSS body is stretched out shorter than the RTV-225 CiSS body which resulted in different crawling speed. The time to complete locomotion is not considered as criteria of evaluation, rather this study investigates ability of the NRTE CiSS to complete a basic level of the crawling locomotion based on the material compliance.
The presented designs of the soft robotic structures have shown that they are capable of fulfilling design goals at basic implementation level. This implies that they could be implemented and further developed to be complicated soft structures as previously reported in [1, 13, 16-17, 23]. Silicone elastomers are widely used to make soft structures due to their easiness to process and conformity to soft mechanism design [24–26].

In contrast, plastic materials are not suitable to develop soft robotic structures as they tend to undergo complete non-reversible deformation. For soft robotic applications, the material should be flexible and able to recover after deformation. However, the presented natural rubber based thermo-elastomer demonstrates a mix of elasto-plastic properties that has potential to be used in soft robotics such as development of cartilage-like parts (with acceptable stiffness) within the soft body of a manta robot [27] that provides acceptable level of material compliance, or using it to design soft prosthetic devices such as a tendon actuated soft robotic glove for hand rehabilitation with firm grasping of objects.

5.0 CONCLUSION

This paper has presented a comparative study between RTV-225 silicone elastomer and natural rubber based thermo-elastomer (NRTE). By the tensile strength test, it has found that NRTE has twice tensile strength and thrice 100% modulus/elongation in comparison with RTV-225. The NRTE has plastic dominance elongation behavior with the higher stiffness. Advantages of NRTE over silicone elastomers are its post processing curing with 2 minutes, multiple times of reuse, and simple heating methods for forming.

Using both elastomeric materials, custom design and fabrication of two soft structures are described with application perspective. The CbSS soft structure made of NRTE was pneumatically actuated and compared with the similar structure made of RTV-225. It has found that the NRTE CbSS is permanently deformed if operated over 50% elongation due to its plastic dominant composition. However, the CiSS soft structures made of NRTE and RTV-225 have performed point-to-point locomotion pattern successfully.

In this work, three heating-based processing methods were adopted in fabrication of NRTE soft structures. Despite the observed plastic behavior of NRTE, it is capable to provide necessary material compliance to the soft robot structures. This work introduces the new material type to the soft robotic material selection category. However, tools and reliable fabrication processes are needed to be developed in order to compliment the unique properties of NRTE with applications on the soft robotic structures

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