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Development of soft pneumatic actuators using high-strain elastic materials with stress anisotropy of short fibers

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Abstract: In recent years, soft robots, such as those with high human affinity and those that excellently imitate the movements of natural creatures, have gained considerable attention. In soft robots, structurally flexible soft actuators need to be used, not conventional motors or hydraulic/pneumatic cylinders. Various types of soft actuators have been developed depending on the driving principle. A pneumatic rubber artificial muscle is a kind of soft actuator that acquires power through injection of a working fluid, such as air, into an elastic structure, such as rubber. In this study, the authors developed an actuator, namely, the straight-fiber-type artificial muscle, which exhibits excellent contraction characteristics. This artificial muscle consists of a rubber tube that contains reinforcing fibers arranged in the axial direction. When air pressure is applied to the rubber tube the artificial muscle expands only in the radial direction and contracts in the axial direction due to the restraining effect of the reinforcing fiber. While this artificial muscle exhibits excellent contraction properties, it has some drawbacks. One is the difficulty in enclosing the reinforced fibers that have accumulated in the rubber tube, making this artificial muscle difficult to manufacture. In this study, we investigated short-fiber-reinforced artificial muscles that can be easily manufactured. First, a short-fiber-reinforced rubber was prepared, and anisotropy was evaluated *via* a tensile test. Then, the short-fiber-reinforced artificial muscles were prepared, and their contractions rates were evaluated. The results confirmed that a short-fiber-reinforced rubber can be useful for the manufacture of artificial muscles.

Keywords: Straight-fiber-type artificial muscle; Short fiber; Artificial muscle; Stress anisotropy; Latex; Solid rubber

1. Introduction

A pneumatic artificial muscle is a rubber actuator that is activated by air pressure. It is lightweight and exhibits higher power density than the other actuators, such as conventional motors and hydraulic cylinders. Moreover, it is highly compatible with humans owing to its flexibility[1]. Currently, the McKibben-type artificial muscle (hereinafter referred to as the McKibben type) has been widely used. It consists of a rubber tube covered with a fiber cord [2]. When this fiber cord expands in the radial direction, the McKibben type artificial muscle contracts in the axial direction. The restraining effect of the fiber cord converts the expansion force into the axial contraction force.

The McKibben type has a maximum contraction rate of approximately 28%, which is smaller than that of the human muscles, which is about 30%. Such an amount of contraction is insufficient when manufacturing a human imitation system. To solve this problem, the authors have developed the straight-fiber-type pneumatic rubber artificial muscle (hereinafter referred to as SF-ARM) [3]. The SF-ARM consists of reinforcing fibers aligned only in the axial direction and are enclosed in a rubber tube. When air pressure is applied, the SF-ARM expands only in the radial direction and contracts in the axial direction due to the restraining effect of the reinforcing fibers. The SF-ARM has a contraction rate of up to 38% or more at low pressure. It is capable of generating the same contraction ratio as the living muscles. Moreover, it has been confirmed by both experiments and theory that its output is more than three times that of the McKibben type as the total air pressure applied to the inner cylinder contributes to the contraction force [4]. Furthermore, since the reinforcing fibers accumulate in the rubber tube, no rubbing between the rubber tube and reinforcing fibers occurs; thus, a longer life can be expected.

With regard to the short-fiber-reinforced rubber, the types of rubber and fibers, fiber lengths, etc., have been investigated [5]. However, the short-fiber-reinforced rubber as a material for the manufacture of the SF-ARM has not been studied. If this material can be used for the manufacture of artificial muscles, a continuous, easy, and efficient production by extrusion will be possible. Therefore, in this study, we fabricated an SF-ARM using a rubber material whose short fibers are oriented in one direction. Moreover, we investigated the potential of the short-fiber-reinforced rubber as a material that can be used to manufacture axial fiber-reinforced artificial muscles. First, anisotropy was evaluated by conducting a tensile test on the short-fiber-reinforced rubber fabricated using three methods. Next, artificial muscles were prepared using three types of short-fiber-reinforced rubber, and their contraction rates were evaluated.

2. Methods

2.1. Pneumatic Rubber Artificial Muscle

2.1.1. Straight-fiber-type artificial muscle

As presented in Figure 1, the SF-ARM consists of reinforced fibers aligned only in the axial direction and are enclosed in a rubber tube. When air pressure is applied, it expands only in the radial direction and contracts in the axial direction due to the restraining effect of the reinforcing fibers.

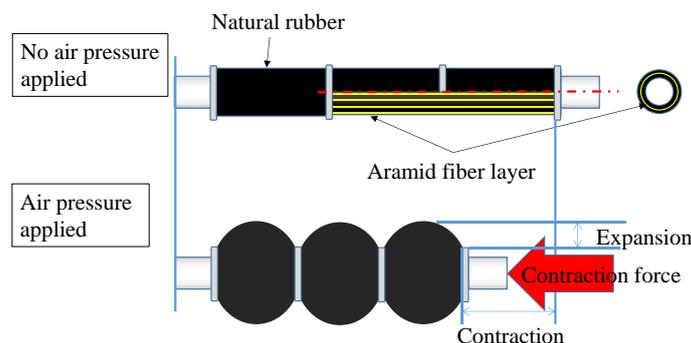


Figure 1. Straight-fiber-type artificial muscle.

2.1.2. Short-Fiber-Reinforced Artificial Muscle

Figure 2 presents the outline of the short-fiber-reinforced artificial muscle. By enclosing the short fibers oriented in the axial direction in the rubber tube, the rubber develops anisotropy and expands in the radial direction and contracts in the axial direction, similar to a normal SF-ARM.

Since the short-fiber-reinforced artificial muscle can be manufactured through extrusion of the short-fiber-reinforced rubber, a continuous manufacturing process can be achieved.

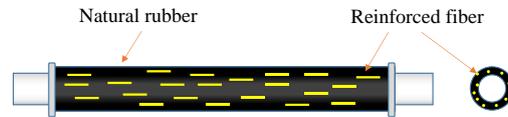
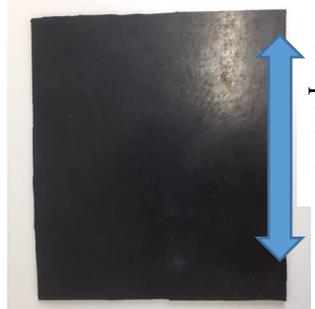


Figure 2. Short-fiber-reinforced artificial muscle.

Table 1. Short-fiber-reinforced rubber manufacturing methods

Sample	A	B	C
Rubber	NR latex	NR solid	NR solid
Fiber	Aramid	CB	Aramid
Fiber length [mm]	30	3	1-2
Fiber content [phr]	5	2	12
Rubber sheet manufacturing method	1. Arrange the fibers in latex 2. Dry to make a sheet	1. Dissolve NR in toluene 2. Mix CB fibers 3. Align by shaking 4. Dry to make a sheet 5. Heat (140°C × 30 min)	1. Mix MB with NR 2. Sheet using open roll 3. Heat (150°C × 20 min)
Appearance of short-fiber-reinforced rubber sheet			 Fiber parallel
Artificial muscle manufacturing method	1. Apply latex to a core with an inner diameter of 10 mm and dry to make an inner rubber tube 2. Arrange the aramid fibers in the inner rubber tube 3. Apply latex to the outer layer of the fiber layer and dry to make an outer-layer rubber tube	1. Wrap a rubber sheet around the core and vulcanize 2. Wrap a fiber-reinforced-rubber sheet and vulcanize 3. Wrap a rubber sheet and vulcanize	1. Wrap a fiber-reinforced rubber sheet around the core 2. Vulcanize
Appearance of short-fiber-reinforced artificial muscle			 Fiber parallel

2.2. Fabrication of Short-Fiber-Reinforced Rubber and Short-Fiber-Reinforced Artificial Muscle

In this study, three methods for producing short-fiber-reinforced rubber and short-fiber-reinforced artificial muscle were investigated. In Table 1, the manufacturing methods are presented.

3. Experiment

3.1. Anisotropy Evaluation for Short-Fiber-Reinforced Rubber Sheet

To evaluate the anisotropy of the three types of short-fiber-reinforced rubber sheets prepared in Section 2.2, we conducted tensile tests in the directions perpendicular and parallel to the aligned reinforcing fibers (Figure 3.). In the tensile test, Autograph AG-1 (SHIMADZU Corp. Japan), with a test speed of 50 mm/min (JIS K6253-compliant) was used, and the test piece was of strip shape with a width, thickness, and length of 10, 2, and 30 mm, respectively.

3.2. Evaluation of Contraction Ratio of Short-Fiber-Reinforced Artificial Muscle

The end of the artificial muscle prepared in Section 2.2 was sealed with a terminal, and air pressure was applied in 0.01 MPa increments. Moreover, the contraction rate ($(\text{natural length} - \text{length when air pressure was applied}) / \text{natural length}$) was measured (Figure 4).

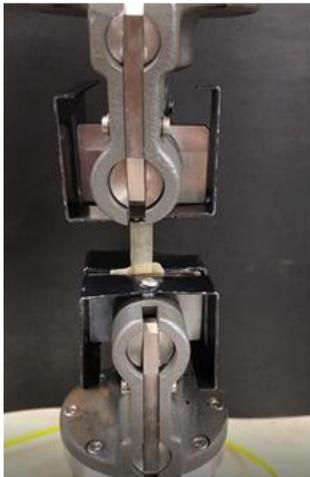


Figure 3. Outline of the tensile test.

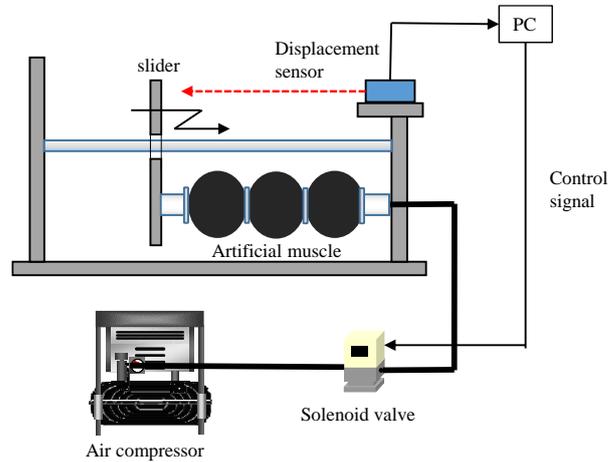


Figure 4. Outline of the contraction test.

4. Results and Discussion

4.1. Anisotropy Evaluation Result of Short-Fiber-Reinforced Rubber Sheet

The results of the tensile test conducted on the rubber sheet using each of the three manufacturing methods are presented in Figure 7 (a)–(c). Table 2 presents the calculation results of elastic modulus. From Figure 7, it can be seen that all the rubber sheets exhibited anisotropy with different stress–strain characteristics in the directions perpendicular and parallel to the fiber orientation direction. In Figure 7 (a) and (c), the stress in the parallel direction is about 1.5 times that in the vertical direction, and the strain at break is approximately 0.2 times. This is possibly due to the increase in stress caused by the reinforcing effect of the fiber and decrease in the strain at break caused by the decrease in the rubber content in the stretching direction. This finding is supported by the comparison presented in Table 2. Furthermore, from Figure 7 (b), it can be inferred that such a result was obtained because the amount of mixed fibers was small, and their physical properties were not hindered by the fibers in the vertical direction.

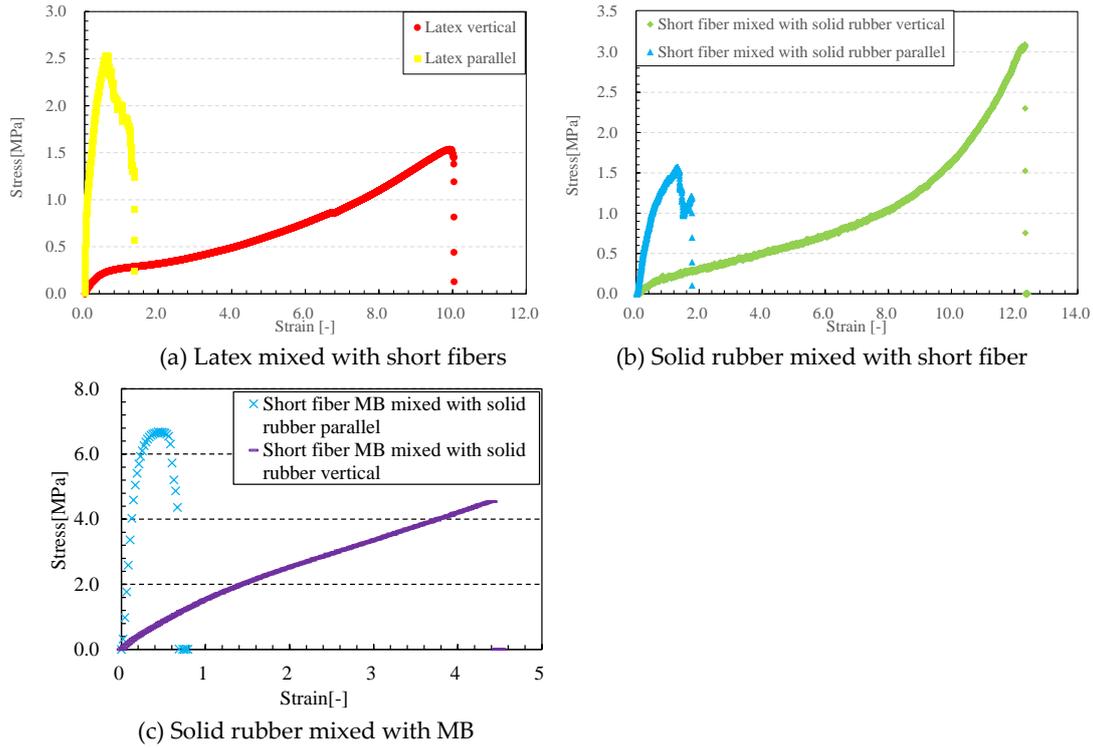


Figure 7. Stress–strain curve of the rubber sheet.

Table 2. Elastic modulus calculation result

Sample	A	B	C	Without fiber
Vertical [MPa]	0.2	0.2	1.1	0.75
Parallel [MPa]	3.1	1.3	14	0.75

4.2. Evaluation Result of the Contraction Rate of Short-Fiber-Reinforced Artificial Muscle

Figure 8 presents the measurement results of the contraction rate of the artificial muscle using each of the three manufacturing methods. From Figure 8, it can be seen that the contraction ratio is about 5% for latex mixed with short fibers, about 6% for solid rubber mixed with short fibers, and about 17% for solid rubber mixed with MB. This is possibly due to the influence of the amount of mixed fibers, degree of fiber orientation, and ratio of fiber diameter to length. In this sample, it is considered that the mixture of latex and solid rubber with short fibers has resulted in inadequate reinforcement and inferior shrinkage due to the small amount of mixed fibers.

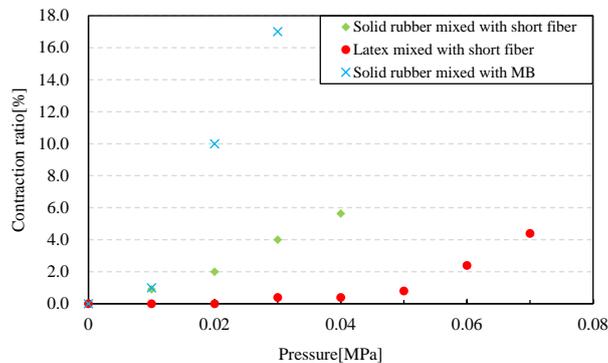


Figure 8. Contraction ratio of short-fiber-reinforced artificial muscle.

5. Conclusions

In this study, we investigated the possibility of manufacturing an artificial muscle using a rubber sheet mixed with short fibers to achieve an easy and efficient production of an axial fiber-reinforced artificial muscle, which exhibits excellent contraction characteristics but is generally difficult to fabricate. From the results, the following conclusions were obtained:

- A short-fiber-reinforced rubber can be used as a material for the manufacture of axial fiber-reinforced artificial muscle.
- By orienting the short fibers on the rubber sheet, anisotropy can be expressed in the stress–strain characteristics.
- By fabricating an artificial muscle using short-fiber-reinforced rubber, it is possible to obtain contraction in the same way as the SF-ARM.
- The characteristics of the short-fiber-reinforced rubber sheet and artificial muscle depend on the mixing amount of short fibers, degree of orientation, and ratio of fiber diameter to length.

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Author Contributions:

Taro Nakamura conceived the experiments; Akihiro Kojima and Manabu Okui designed the experiments; Akihiro Kojima performed the experiments; Akihiro Kojima and Manabu Okui wrote the paper.

Conflicts of Interest:

The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NR: Natural rubber

SF-ARM: Straight-fiber-type artificial muscle

MB: Master batch

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