Evaluation of Mechanical Properties of Natural and Synthetic Rubber Material

Chang-Su Woo and Hyun-Sung Park

Abstract It is critical to investigate the mechanical properties of rubber materials to secure the reliability of rubber components. In this study, we performed mechanical tests of natural and synthetic rubber in various environmental conditions. The hardness, elongation, stress-strain relation, dynamic properties, and the nonlinear material constants that are necessary for a finite element analysis were determined through uniaxial tension, equi-biaxial tension and pure shear tests. The hardness of thermally aged rubber increased in proportion to aging time and temperature while that of elongation decreased. The storage modulus increased in proportion to aging time in dynamic property tests while the loss factor decreased. In mechanical tests according to change in strain, we determined the second Mooney-Rivlin and the third Ogden terms that are necessary for the finite element analysis of rubber components.

Keywords Rubber material · Mechanical test · Aging · Strain energy function

1 Introduction

Most rubber products are composites in which various additives including fillers are mixed with rubber that is selected according to the characteristics of the products. The most important thing in selecting materials is that they meet the standards for mechanical properties that are required for applications and the usage conditions of products [1, 2]. Mechanical properties or dynamical behaviors of rubber differ significantly depending on the kind of vulcanizing agents, the kind and quantity of

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antiozonants or the quantity of modifiers or tenderizers. Data on the mechanical properties of rubber can be determined only through experiments because the components and mechanical properties of rubber compounds demanded by clients vary greatly. To improve the mechanical test methods and estimation skills of rubber material, we obtained data on the mechanical properties for selected natural and synthetic rubbers in this study, through mechanical tests under various conditions such as room temperature, high and low temperatures, and aging in the uniaxial and equi-biaxial tension and pure shear states. Owing to various advantages of rubber, it has been widely used in the following applications: anti-vibration rubber mounts for vehicles and trains, rubber rollers for printing and paper-making, and components in semiconductors, IT, and aerospace [3]. Establishing mechanical test methods and estimation skills in this study can result in savings in both time and cost required to develop rubber components and achieve advances in related technology by promoting localization and strengthening global competitiveness by securing reliability and stability.

2 Experiment

2.1 Rubber Material

Six kinds of rubber materials were selected for material tests: natural rubber (NR), copolymers of acrylonitrile and butadiene (NBR), polychloroprene rubber with chloroprene as a repetitive unit (CR), polymers of ethylene, propylene, and diene (EPDM), chloroethylsulfonyl polyethylene (CSM), and silicon rubber (Si).

2.2 Mechanical Test

The viscoelasticity of rubber has an impact on its strain velocity. The faster the strain velocity is, the greater the stress on material is, and vice versa. The suitable range of the strain velocity to obtain static mechanical properties is 0.007–0.17 m/s. Because there was no remarkable difference in the stress-strain curves of rubber in this range, we conducted tests at the same strain velocity of 0.01 m/s [4]. Mechanical properties of the rubber materials were investigated in environmental tests at room temperature (23 °C), low temperature (−40 °C), and high temperature (85, 100, and 125 °C), through uniaxial tension tests, and obtained hardness, elongation, stress-strain relation, and dynamic properties after aging for 1000 h at 70, 85, 100, and 200 °C to construct databases on mechanical properties. Uniaxial tension tests were conducted as shown in Fig. 1a by mounting load cells of 500 N on material testers, in which laser extensometers were used to measure the strain of specimens. A pure compressive stress-strain relation is difficult to obtain in uniaxial

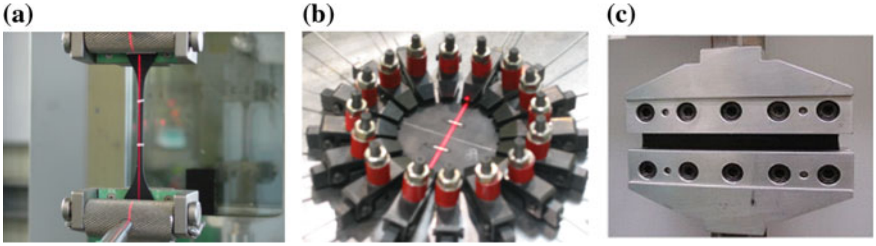

Fig. 1 Mechanical test of rubber materials. **a** Uniaxial tension. **b** Equi-biaxial tension. **c** Pure shear

tests due to friction generated on contact surfaces between rubber specimens and compression plates. To overcome this problem, equi-biaxial tension tests [5] with the same strain mode as in the compression tests were conducted as shown in Fig. 1b to determine the nonlinear material constants according to the range of the strain. Shear strain state is a more important mode of deformation for engineering applications than tension. If the material is incompressible and the width of the specimen is longer than the height, a pure shear state exists in the specimen at 45° angle to the stretching direction. The aspect ratio of the specimen is most significant in pure shear tests because the specimen is perfectly constrained in the horizontal direction. Figure 1c shows the pure shear test by using a non-contacting strain measurement with laser extensometer.

3 Result and Discussions

3.1 Environmental Test

Environmental tests were conducted at various temperatures including room temperature (23 °C), low temperature (−40 °C), and high temperature (85, 100, and 125 °C) to investigate the mechanical properties of the rubber materials depending on temperature conditions. As a result (Fig. 2), the higher the temperature, the lower the strength: changes in strength were significant at low temperature. The strength of rubber including NBR and CR was much greater than the strain below the glass transition temperature (Tg).

3.2 Thermal Aging Test

For most rubber products, the degradation of mechanical properties by environmental effects has impacts on the characteristics and life expectancy of the rubber. In this study, we investigated changes in the mechanical properties of rubber with

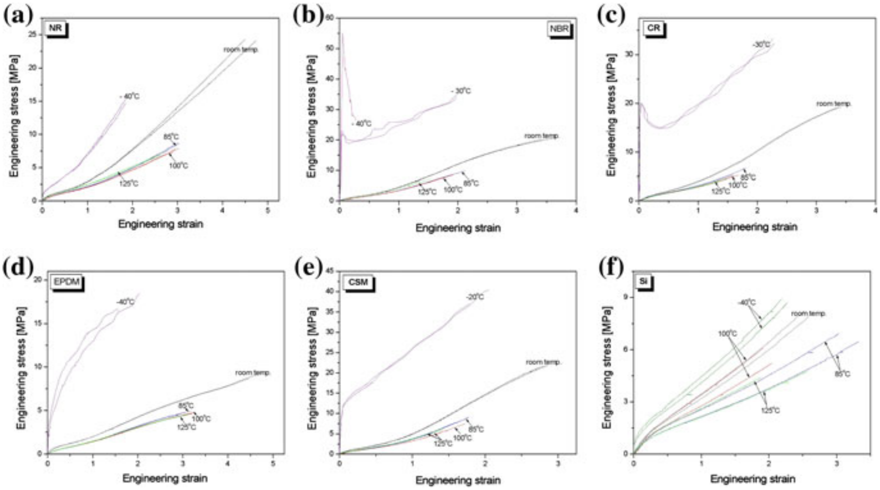

Fig. 2 Stress-strain curves at various temperatures. **a** NR, **b** NBR, **c** CR, **d** EPDM, **e** CSM, **f** Si

accelerated test in which rubber was aged at a higher temperature than rubber parts which are actually used, considering temperature as the most important factor among several degradation factors [6, 7]. Specimens of rubber were aged in the oven for 1000 h at 70, 85, and 100 °C conforming to ASTM D412, and then kept at room temperature for 24 h before measuring hardness, elongation, and stress-strain relations. Figures 3 and 4 show the changes in hardness and elongation depending on the aging temperature: the hardness is proportion to temperatures and aging period and drastically increases at 100 °C; elongation is inversely proportional to

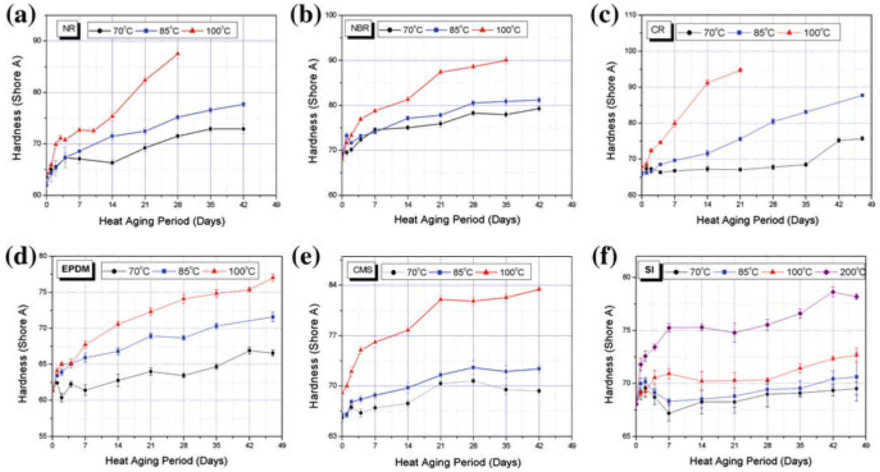

Fig. 3 Change of hardness at thermal aging conditions. **a** NR, **b** NBR, **c** CR, **d** EPDM, **e** CSM, **f** Si

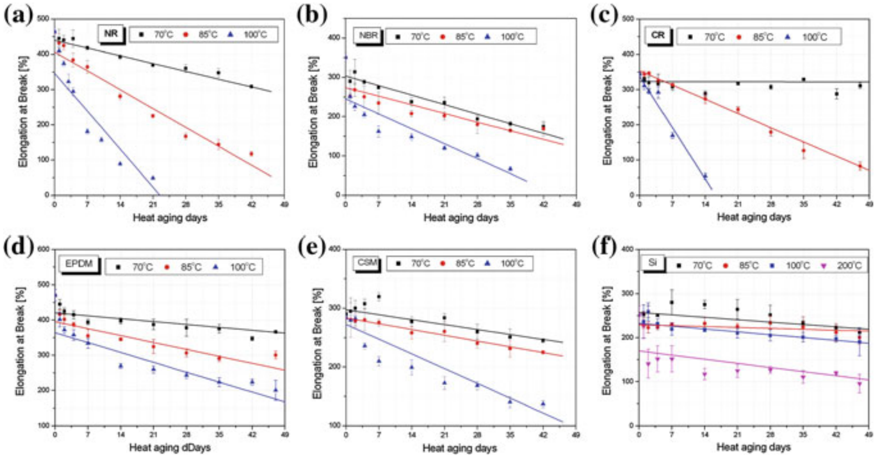

Fig. 4 Change of elongation at thermal aging conditions. **a** NR, **b** NBR, **c** CR, **d** EPDM, **e** CSM, **f** Si

temperature and the aging period decreases drastically at high temperatures. Figure 5 shows the stress-strain relation through tensile strength tests: a remarkable change in strength from the aging property of each rubber material can be seen at 100 °C while changes in properties are not remarkable at 70 °C.

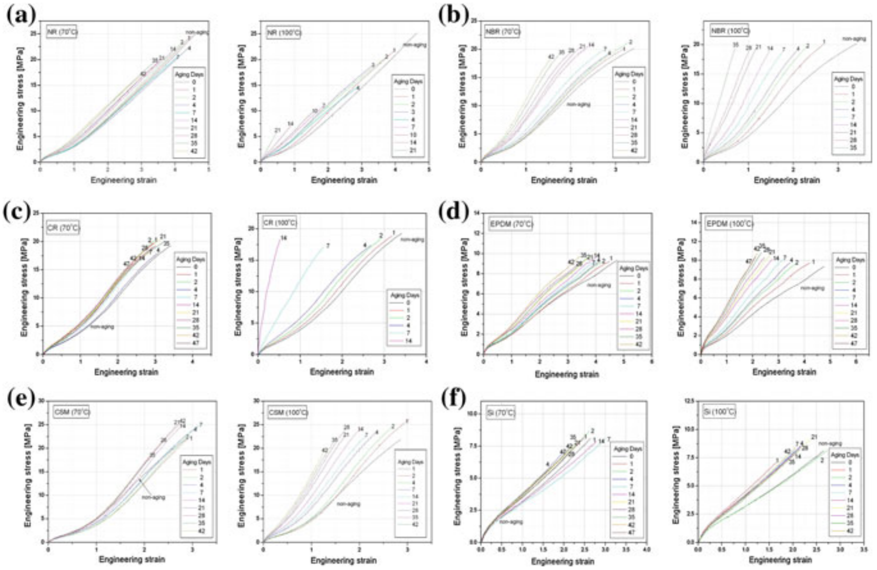

Fig. 5 Stress-strain curves at thermal aging conditions. **a** NR (70 and 100 °C), **b** NBR (70 and 100 °C), **c** CR (70 and 100 °C), **d** EPDM (70 and 100 °C), **e** CSM (70 and 100 °C), **f** Si (70 and 100 °C)

3.3 Dynamic Test

The conditions of the dynamic test to investigate dynamic properties of rubber materials such as storage modulus, loss factor, and glass transition temperatures were as follows: static and dynamic strain were 10 and 1.0 %, respectively, the frequency range was 1–100 Hz, and the temperature range was −80 to 100 °C. Figures 6 and 7 show the changes in the storage modulus and the loss factor of rubber materials that were aged for 1000 h at 85 °C. It shows a similar tendency with the frequency property of the general rubber material in that the storage modulus is proportional to the aging period while the loss factor is inversely proportional to it. Figure 8 shows the glass transition temperature of each rubber material. The transition temperature of natural rubber and EPDM was −45 °C at which the storage modulus and loss factor drastically changed; that of NBR and CR was −20 °C; and that of Si was −80 °C. We, therefore, can see that the physical properties of Si at low temperatures were excellent.

3.4 Stain Energy Function

The material of the rubber component is taken to be an incompressible rubberlike material modeled as a hyper-elastic material. The constitutive behavior of a hyper-elastic material is defined as a total stress–total strain relationship [8, 9]. Hyper-elastic materials are described in terms of their strain energy potential, which defines the strain energy stored in the material per unit of reference volume as a function of the strain at that point in the material. The strain energy functions have

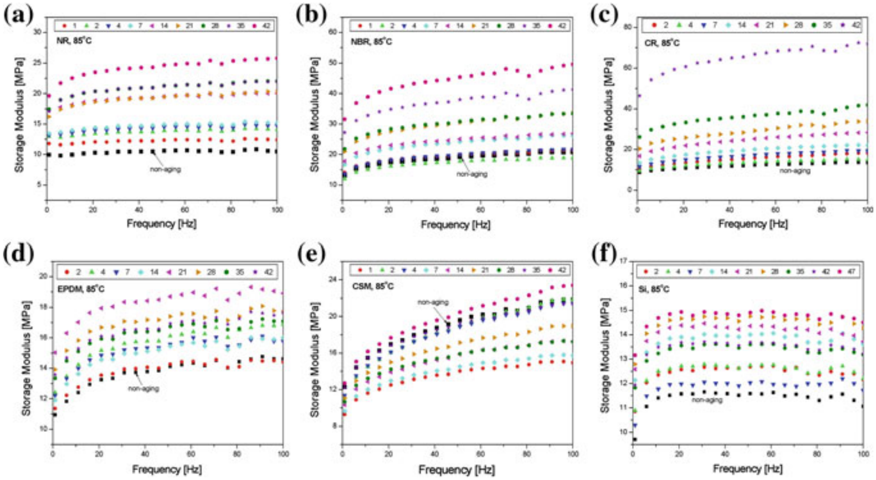

Fig. 6 Storage modulus at thermal aging conditions. **a** NR, **b** NBR, **c** CR, **d** EPDM, **e** CSM, **f** Si

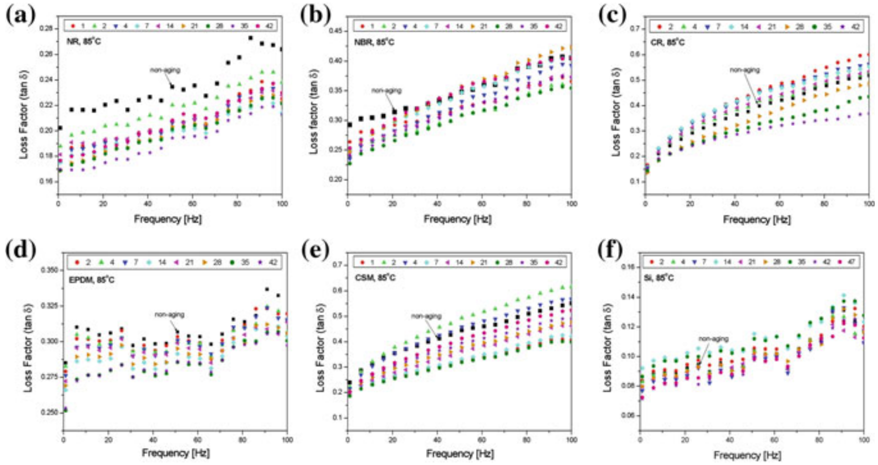

Fig. 7 Loss factor at thermal aging conditions. **a** NR, **b** NBR, **c** CR, **d** EPDM, **e** CSM, **f** Si

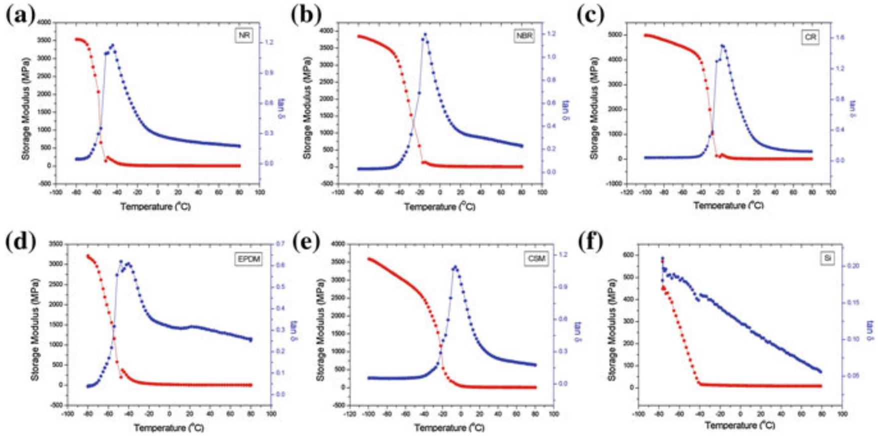

Fig. 8 Glass transition temperatures of rubber materials. **a** NR, **b** NBR, **c** CR, **d** EPDM, **e** CSM, **f** Si

been represented either in term of the strain invariants that are functions of the stretch ratios, or directly in terms of the principal stretch. Successful modeling and design of rubber components relies on both the selection of an appropriate strain energy function and an accurate determination of the material coefficient in the function. Material coefficients in the strain energy functions can be determined from the curve fitting of experimental stress-strain data. There are several different types of experiments, including simple tension, equi-biaxial tension and pure shear tests. In general, a combination of simple tension, equi-biaxial tension and pure shear tests are used to determine the material coefficient. The classical Mooney-Rivlin and Ogden models are an example of a hyper-elastic model that is implemented in the FEA. In order to explain the deformation of the rubber materials, it is assumed that the material has elastic behavior and is isotropic. Then, strain energy function (W) can be written as Eq. (1), with strain invariant functions (I_1, I_2, I_3) and principal stretch functions $(\lambda_1, \lambda_2, \lambda_3)$.

$$W = W(I_1, I_2, I_3), \quad W = W(\lambda_1, \lambda_2, \lambda_3) \tag{1}$$

When the material is isotropic, I_1, I_2, I_3 can be expressed as follows;

$$I_1 = {\lambda_1}^2 + {\lambda_2}^2 + {\lambda_3}^2, \quad I_2 = {\lambda_1}^2{\lambda_2}^2 + {\lambda_2}^2{\lambda_3}^2 + {\lambda_3}^2{\lambda_1}^2, \quad I_3 = {\lambda_1}^2{\lambda_2}^2{\lambda_3}^2 \tag{2}$$

Most rubber materials are incompressible and their bulk modulus is much greater than their shear modulus. Thus, it is widely accepted to presume the materials to be incompressible when they are under less restriction. When the materials are incompressible in Eq. (2), $\lambda_1, \lambda_2, \lambda_3 = 1$ and $I_3 = 1$. Since, Eq. (1) can be rewritten as follows,

$$W = W(I_1, I_2) \tag{3}$$

The strain energy function, which is widely used to analyze deformations of incompressible materials, can be described with Mooney-Rivlin's function and Ogden's function.

Mooney-Rivlin's function:

$$W = \sum_{n=1}^{N} C_{ij}(I_1 - 3)^i (I_2 - 3)^j \tag{4}$$

Ogden's function:

$$W = \sum_{n=1}^{N} \frac{\mu_n}{\alpha_n}\left(\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3\right) \tag{5}$$

where C_{ij}, μ_n, α_n are the material constants determined experimentally from the stress-strain relationship.

3.5 Material Constant

When rubber is strained, its strength decreases and its damping properties change due to a modification and redistribution of the molecular structure in the initial state. These stress-strain relaxation phenomena are called the Mullins effect [10] that frequently occur in rubber filled with carbon black. That is, the strength of rubber is history dependent. Due to this, the stress-strain curves of rubber are different on loading and unloading. Figure 8 shows the stress-strain curves obtained from the uniaxial tension, equi-biaxial tension and pure shear test in which we applied five repetitive loads in each of the vertical and horizontal direction with 25, 50 and 100 % of the strain range for rubber material. According to Fig. 8, the stress-strain curves during the second repetition showed a greater decline than in the first repetition. The stress-strain curve gradually decreased as the number of repetitions increased, and ultimately stabilized to a fixed stress-strain value.

In order to predict the behavior of the rubber components using the finite element analysis, the rubber material constants must be determined from the stabilized cyclic stress-strain curve. The stress-strain curve varies significantly depending on the cyclic strain levels. A 5th loading cycle was selected as the stabilized stress-strain relationship in this study. But this stabilized relation should be shifted to pass through the origin of the curve, to satisfy the hyper-elastic nature of rubber. Figure 9 shows the stress-strain relation of rubber material. The shift of curve meant that the gage length and initial cross sectional area were changed as shown in Eq. (6).

$$\varepsilon = \frac{\varepsilon' - \varepsilon_p}{1 + \varepsilon_p}, \sigma = \sigma'(1 + \varepsilon_p) \tag{6}$$

Using the stress-strain relation obtained from the strain energy function, the nonlinear material constants of the second Mooney-Rivlin and the third Ogden terms [11, 12] were determined from the results of the stress-strain through uniaxial tension, equi-biaxial tension and pure shear tests, as shown in Fig. 10. The material constants obtained as in Table 1 was be used as material data necessary for finite element analysis of rubber components. It is possible to exactly estimate the properties of rubber components when material tests are conducted in the same level of strain as when components are actually used. We investigated the mechanical properties of selected natural and synthetic rubber through material tests in uniaxial tension, equi-biaxial tension and pure shear states, under various conditions including room temperature, low and high temperature, and aging. Because the mechanical behaviors and dynamic properties of rubber materials even with the

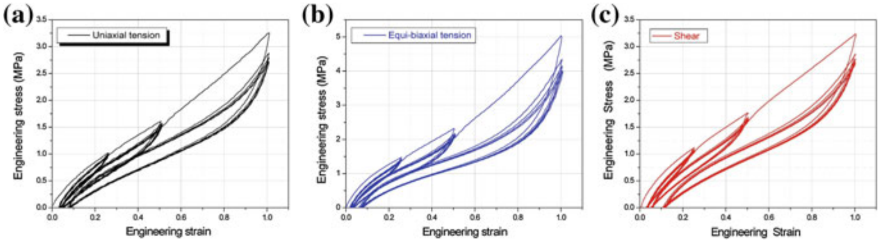

Fig. 9 Stress-strain curves at various loading and strain range. **a** Uniaxial tension, **b** Equi-biaxial tension, **c** Pure shear

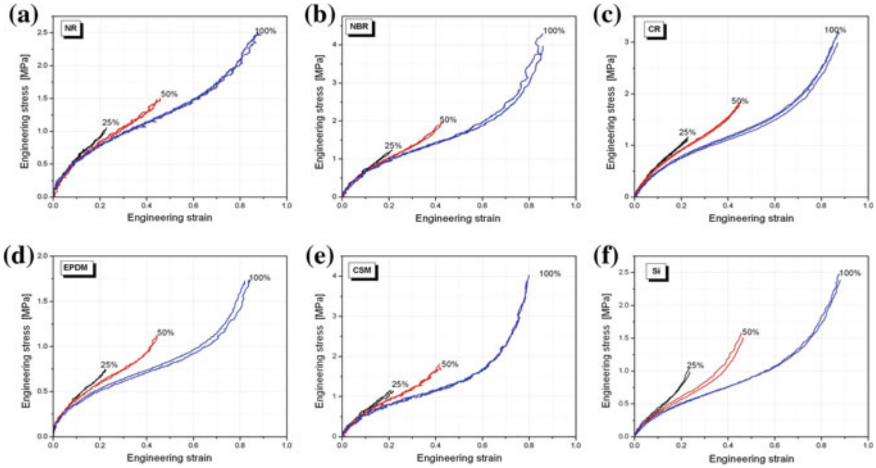

Fig. 10 Stress-strain curves after stabilized. **a** NR, **b** NBR, **c** CR, **d** EPDM, **e** CSM, **f** Si

Table 1 Mooney-Rivlin and Ogden function of rubber materials

Material	Mooney-Rivlin			Ogden						
	C_{10}	C_{01}	G_{mooney}	μ_1	α_1	μ_2	α_2	μ_3	α_3	G_{ogden}
NR	0.587	0.0	1.174	0.53	2.876	0.054	4.473	0.079	2.854	0.995
NBR	0.656	0.0	1.312	0.001	1.012	0.731	3.390	0.001	2.305	1.235
CR	0.170	0.806	1.952	219.2	0.012	129.1	0.012	0.001	34.16	2.106
EPDM	0.369	0.103	0.944	0.004	1.305	0.799	1.214	0.624	1.603	0.987
CSM	0.598	0.317	1.830	0.010	7.550	0.001	13.73	2.340	1.370	1.980
Si	0.257	0.337	1.188	0.001	22.18	0.001	16.97	508.2	0.005	1.290

same raw rubber depend on the kind or quantity of vulcanized agents or antioxidants, the quantity of modifiers or tenderizers, material tests and estimation should be conducted to exactly investigate their mechanical properties.

4 Conclusion

An estimation of the mechanical properties under various environmental conditions and loads is required in order to exactly investigate the mechanical properties of rubber material. Through material tests on six kinds of rubber materials in this study, we concluded that: (1) We obtained data on the mechanical properties of rubber materials under various conditions including room temperature, high and low temperatures, and aging in the uniaxial tension, equi-biaxial tension and pure shear states. (2) As a result of material tests at various temperatures, the strength lowered as temperature increased and its change was remarkable at low temperatures. (3) The hardness of thermally aged rubber materials increased in proportion to temperature and time while the elongation decreased. We found the aging properties of rubber materials that changes in its mechanical properties were not significant over time at 70 °C while a change in the strength was remarkable at 100 °C. (4) The glass transition temperature of rubber materials was obtained through dynamic property tests: the storage modulus increased over aging period while the loss factor decreased. (5) The nonlinear material constants of the second Mooney-Rivlin and the third Ogden terms for the finite element analysis of rubber components were determined through material tests according to changes in the strain. (6) In this study, we constructed databases of the mechanical properties of rubber materials under various environment conditions and by utilizing this, it is expected to greatly contribute to the development of rubber materials and to enhance the quality of components.

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