EXPERIMENTAL STUDY ON SHEAR AND DAMPING PROPERTIES OF RUBBER MATERIALS FOR SEISMIC ISOLATION DEVICE

ESTUDIO EXPERIMENTAL DE LAS PROPIEDADES DE CORTE Y AMORTIGUAMIENTO EN MATERIALES DE CAUCHO PARA UN DISPOSITIVO DE AISLAMIENTO SISMICO

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ABSTRACT

In recent decades, seismic elastomeric isolation systems have become an effective solution to mitigate seismic hazard in civil structures. The elastomeric component resists shear forces at the base of the superstructure by decoupling it from ground motion during an earthquake. Thus, the shear modulus is a critical parameter for ensuring the seismic performance of the isolation system. This research presents an experimental study of shear properties of three types of rubber: natural rubber, recycled rubber, and neoprene to determine their feasibility as elastomeric materials in seismic isolation systems. To achieve this, nine tests (three for each type of rubber) were carried out following the ASTM D4014 standard to estimate their shear modulus at twenty-five percent shear strain. Moreover, the deterioration and hardening of each rubber material were investigated under large deformation cycles. Consequently, a correlation equation between strain and shear modulus for each rubber material was proposed. The results showed neoprene shear modulus exhibit better performance compared to natural and recycled rubber.

Keywords: Elastomeric isolator, shear properties, neoprene, natural rubber, recycled rubber.

RESUMEN

En las últimas décadas, los sistemas de aislamiento sísmico elastoméricos se han convertido en una solución efectiva para mitigar el riesgo sísmico en estructuras civiles. El componente elastomérico resiste las fuerzas cortantes en la base de la superestructura desacoplándola del movimiento del suelo durante un terremoto. Por lo tanto, el módulo de corte es un parámetro crítico para garantizar el desempeño sísmico del sistema de aislamiento. Esta investigación presenta un estudio experimental de las propiedades de corte de tres tipos de caucho: caucho natural, caucho reciclado y neopreno, para determinar su viabilidad como materiales elastoméricos en sistemas de aislamiento sísmico. Para ello, se realizaron nueve ensayos (tres para cada tipo de caucho) siguiendo la norma ASTM D4014, con el objetivo de estimar su módulo de corte al veinticinco por ciento de deformación cortante. Además, se investigó el deterioro y endurecimiento de cada material bajo ciclos de grandes deformaciones. Como resultado, se propuso una ecuación de correlación entre la deformación y el módulo de corte para cada material de caucho. Los resultados mostraron que el módulo de corte del neopreno presenta un mejor desempeño en comparación con el caucho natural y el caucho reciclado.

Palabras Clave: aislador elastomérico, propiedades de corte, neopreno, caucho natural, caucho reciclado.

1. INTRODUCTION

Since the early 20th century, various seismic protection systems have been developed and improved to enhance structural safety. These systems aim to protect human life, prevent serious damage to structural and non-structural elements, and ensure that buildings remain operational after an earthquake. One of these solutions includes passive seismic isolation systems using rubber as a primary material [1], [2].

Peru, located in a region of high seismic hazard, has implemented seismic design requirements and isolation standards to protect essential infrastructure such as hospitals [3], [4]. In this context, the use of elastomeric seismic isolation systems have gained attention, particularly due to their effectiveness in

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reducing structural damage and ensuring post-earthquake functionality. These systems are capable of resist large shear deformations while providing adequate energy dissipation, making the characterization of such materials a key aspect in the design process.

In this context, the present research focuses on the experimental evaluation of the shear modulus and equivalent damping of three commercially available rubber types: natural rubber, recycled rubber, and neoprene. The effect of deformation cycles on the shear modulus and equivalent damping ratio was investigated, which are relevant for assessing the suitability of each material for seismic isolation applications.

2. BACKGROUND

Rubber-based materials have been widely studied due to their importance in the development of seismic isolation devices such as laminated rubber bearings, high-damping rubber bearings, and natural rubber bearings. These materials are designed to provide flexibility and energy dissipation capacity, which are essential to reduce seismic forces transmitted to the structure [1].

Several experimental and analytical studies have been conducted to characterize the mechanical properties of rubber materials used in isolation devices. These works have focused on aspects such as the tensile, compressive, rotational, and shear stiffness of rubber bearings [5] - [7]. Other studies have examined the influence of strain amplitude dependency, frequency, and fatigue on the shear modulus and damping properties, especially under dynamic conditions [8] - [10]. Additionally, the effects of stress softening, and material formulation have been reported, contributing to a better understanding of the nonlinear behavior of elastomeric materials under seismic loading [11].

Consequently, special attention has been paid to the use of alternative materials such as recycled rubber and neoprene in the design of seismic isolators. These materials have been experimentally evaluated to determine their feasibility as cost-effective and sustainable options for base isolation prototype [12] - [14]. Likewise, studies have shown that recycled rubber sheets or composite materials can provide reasonable damping and deformation capacity, although their mechanical performance may vary depending on fabrication methods and loading conditions [15], [16].

3. METHODOLOGY

3.1. Shear Modulus Overview

The shear modulus, G, is an elastic characteristic that quantifies the deformation of a material subject to shear loading, as illustrated in Fig. 1. According to Hooke's law, when both stress and strain are small and within the proportional limit, the material exhibits linear and elastic behavior, as described in Eq. (1).

$$G = \frac{\tau_m}{\gamma} \approx \frac{F/A}{\Delta x/L} = \frac{FL}{\Delta x A} \quad (1)$$

where τ_m is the average shear stress, γ is the shear strain, F is the lateral force, A is the shear cross-sectional area, Δx is the lateral deformation, and L is the material thickness.

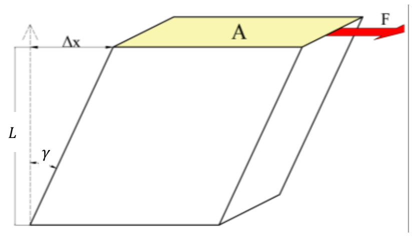


Fig. 1. Shear deformation scheme

In this study, the shear modulus of rubber materials is calculated using the methodology proposed by the ASTM D4014 standard [17]. Additionally, a complementary approach, based on this standard, is used to extend the shear modulus characterization to different levels of shear strain. This extended method is referred to as the "Other Cycles" methodology. Both approaches are described below.

3.2. Shear Modulus (ASTM D-4014):

The shear modulus is determined based on the sixth load cycle, as stated the standard ASTM D-1014 and as illustrated in the force-deformation loop in Fig. 2. For this loop, the maximum force, F_{max}, is measured at the target deformation during the sixth cycle, denoted as X_{max}. Additionally, the forces F_1 and F_2, corresponding to the deformations X_1 and X_2, respectively, are defined to calculate the shear modulus. The force F_1, referred to as the origin force, is derived as two percent of the maximum force. Similarly, the force F_2 is the force measured at the deformation X_2, expressed as:

$$X_2 = X_1 + 0.5T \quad (2)$$

where, T is the thickness of the elastomeric bearing.

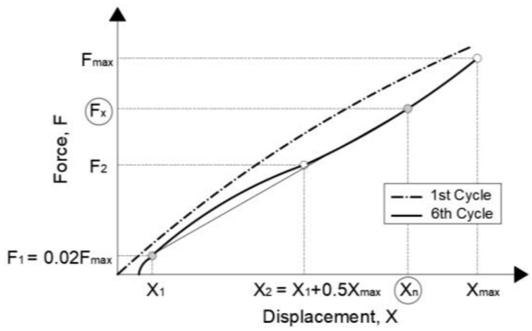


Fig. 2. Force-Deformation Curve

According to this standard, the shear modulus, G, is derived from a strain of 25% based on the target deformation of 50%. Therefore, the shear modulus is calculated using the force F_2 relative to the origin force F_1, defined as follows:

$$G = \frac{\tau}{\gamma} = \frac{\frac{F_2 - F_1}{2A}}{\frac{X_2 - X_1}{2X_{max}}} = \frac{(F_2 - F_1)X_{max}}{(X_2 - X_1)A} \quad (3)$$

where A is the area of the rubber bearing. Replacing Eq. (2) into Eq. (3), we have the following:

$$G = \frac{(F_2 - F_1)X_{max}}{(X_1 + 0.5X_{max} - X_1)A} = \frac{(F_2 - F_1)X_{max}}{(0.5X_{max})A} \quad (4)$$

and then

$$G = \frac{2(F_2 - F_1)}{A} \quad (5)$$

Eq. (5) is proposed by the standard and expresses the shear modulus from a strain of 25% for a target deformation of 50%. Likewise, this methodology can be extended for other target deformations, for which the shear modulus is defined below:

$$G_{\gamma\%} = \frac{\sigma}{\gamma} = \frac{\frac{F_2 - F_1}{2A}}{\gamma} = \frac{F_2 - F_1}{2A\gamma} \quad (6)$$

3.3. Shear Modulus (Other cycles):

In accordance with the methodology specified in the ASTM D4014 standard, the approach referred to as the "other cycles" methodology also estimates the shear modulus using the force–deformation loop from the sixth load cycle. However, unlike the standard methodology described before, this methodology allows for the shear modulus calculation to be performed using the force and deformation measured at any specific position along the loop, depending on the desired level of shear strain. This is expressed as shown in Eq. (7) [8].

$$G_{\gamma\%} = \frac{F_x - F_1}{2A(X_n - X_1)} \quad (7)$$

4. EXPERIMENTAL STUDY

4.1. Test Specimen

Commercial rubber is manufactured for use in a wide range of applications, including car carpets, bumpers, artificial turf, among others. In this study, three types of commercially available rubber materials: polychloroprene (usually called neoprene), natural rubber, and recycled rubber, were chosen as potential candidates for seismic isolation elastomer applications.

The specimen consists of four rubber bearings bonded to steel plates by a vulcanization process, as depicted in Fig. 3. Each bearing features a 50 mm square cross-section and a thickness of 10 mm. The dimensions of the side steel plates, and the central steel plates are 70 mm × 200 mm and 70 mm × 150 mm, respectively. Both plates include bolt holes positioned at their centers and ends, allowing proper connection of the specimen to the LVDTs (Linear Variable Differential Transformers) and the testing apparatus, as illustrated in Fig. 4.

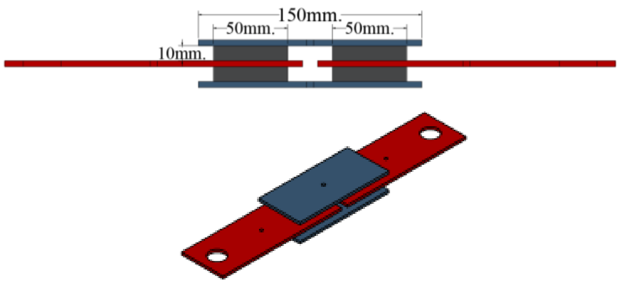


Fig. 3. ASTM D-4014 Specimen for Shear Modulus test.

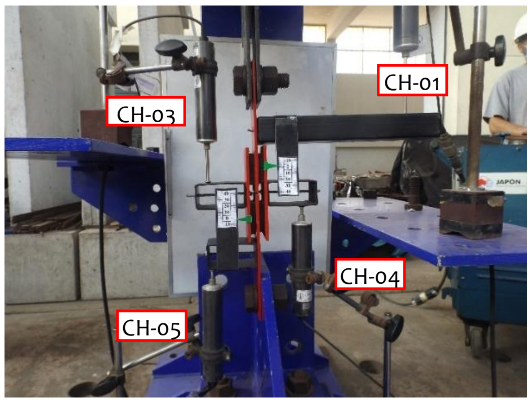


Fig. 4. Shear Modulus Test Setup.

Three specimens were fabricated for each rubber type, resulting in a total of nine specimens. The specimens were labeled as follows: Polychloroprene rubber (MCC), Natural rubber (MCN), and Recycled rubber (MCR).

4.2. Test Deformation History and Setup

According to the requirements of ASTM D4014 for calculating the shear modulus of rubber materials, the specimen must be subjected to six loading cycles for a target shear strain of 50%, each loop lasting between 30 and 60 seconds. In addition, for "other cycles" methodology, the target deformations correspond to 25%, 50%, 75%, 100%, 150%, 200%, 250%, and 300% of the rubber bearing's thickness. The deformation history for both approaches is illustrated in Fig. 5.

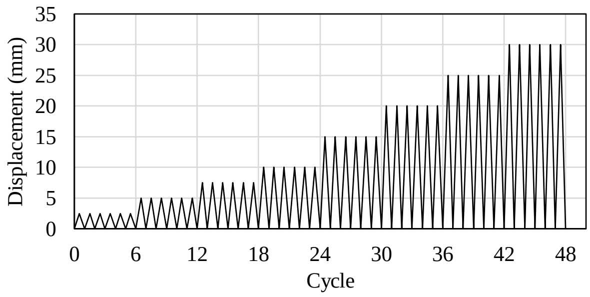


Fig. 5. Deformation History

The setup of the measuring system is shown in Fig. 7. The main function of this test mechanism is to provide optimal load and displacement directional conditions in a safe way. Fig. 6 shows the test setup used in this study, which ensures proper and safe application of the load in the vertical direction. Displacement sensors (LVDTs) and the load sensor (load cell) are assigned to six data acquisition channels, numbered from CH-00 to CH-05. Channel CH-00 corresponds to the load cell of the hydraulic jack, while channels CH-01 to CH-05 record the deformations of the specimen, with their positions indicated in Fig. 6. Additionally, Table 1 summarizes the measurement characteristics of the channels used during the test.

TABLE 1

Data acquisition Sensors

Channel	Sensor	Range
CH-00	Load Cell	25 tonf
CH-01	LVDT	100 mm
CH-02	LVDT	100 mm
CH-03	LVDT	50 mm
CH-04	LVDT	50 mm
CH-05	LVDT	25 mm

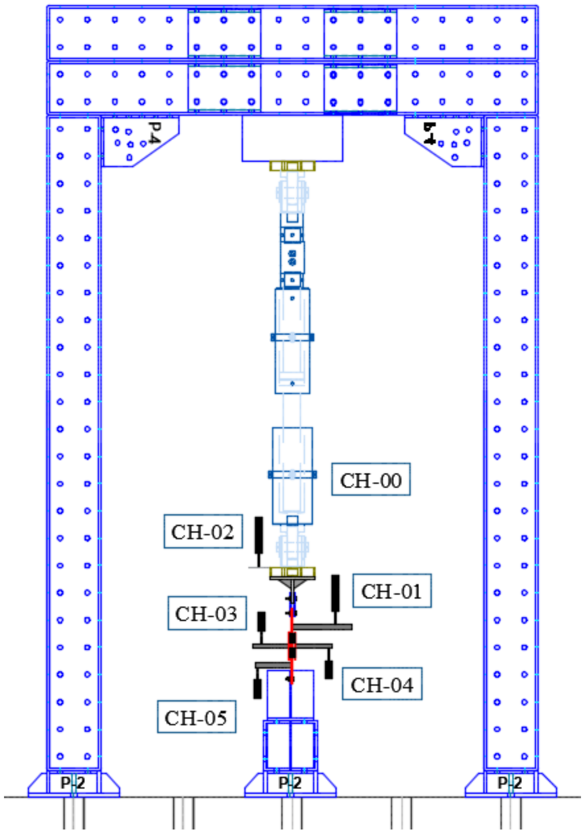


Fig. 6. Test Setup

5. Experimental Results

Fig. 7, 8, and 9 show the hysteresis loops obtained from the tests for Polychloroprene (labeled as MCC), Natural (MCN), and Recycled (MCR) rubber specimens, respectively. The force–displacement graphs display the displacements recorded by channels CH-01, CH-02, CH-03, and CH-04 for each type of rubber specimen. It should be noted that channel CH-05 was intended to measure any potential displacement or slip at the fixed base or specimen. Since no such displacement was observed during the tests, the measurements recorded by CH-05 are not presented in this study. Moreover, data acquisition was carried out using a sampling frequency of 1 Hz.

Table 2 shows the peaks of deformations and loads for the nine specimens. The number indicated on the label (e.g. MCC-#) refers to the specimen number tested. It is observed that MCC specimens have greater resistance than the MCN or MCR specimens. However, maximum displacements are achieved with natural rubber specimens.

TABLE 2

Maximum Deformations and loads

Specimen	Max. Deformation (mm)	Max. Force (tonf)
MCC-1	31.67	2.33
MCC-2	26.51	1.88
MCC-3	20.66	1.53
MCN-1	40.13	2.16
MCN-2	31.64	1.39
MCN-3	30.00	1.33
MCR-1	35.29	1.46
MCR-2	32.31	1.20
MCR-3	30.52	1.28

The action of the hydraulic jack was manually controlled throughout the test. All specimens were tested following the deformation history shown in Fig. 5. However, the first specimen of each rubber type was intended to be tested beyond this deformation history until failure. Additionally, it was observed that specimens MCC-2 and MCC-3 failed before completing the full deformation sequence. The first failed at 200% shear strain, and the second at 250%.

Channels CH-01 and CH-02 record the target deformations of the specimen which consists of a system of four rubber bearings. On the other hand, channels CH-03 and CH-04 measure the deformations corresponding to a single rubber bearing. This means that the target deformations recorded by CH-01 and CH-02 are approximately twice the values measured by CH-03 and CH-04 due to configuration of bearing on the specimen. The deformation sign indicates the directional position of the displacement sensors.

Based on the experimental results, a progressive reduction in strength is observed from the first to the sixth load cycle, accompanied by a hardening behavior associated with increasing deformation of the specimen. In addition, hysteretic energy dissipation is evident and should be taken into account in experimental analysis.

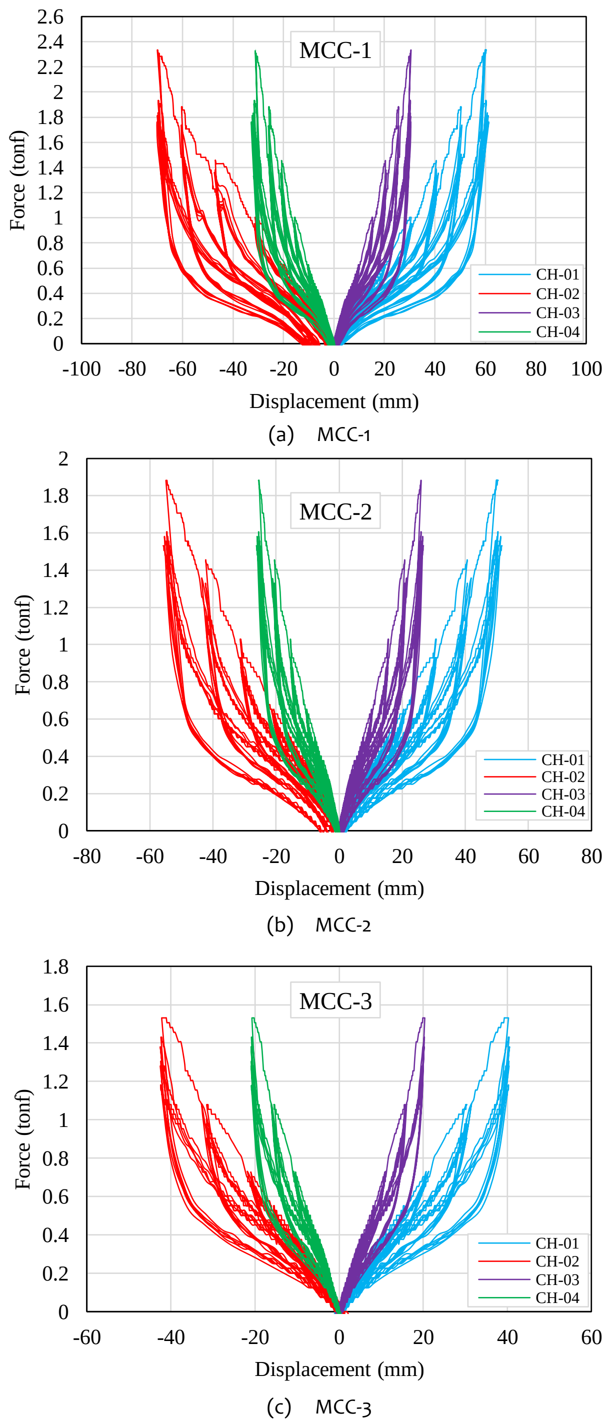
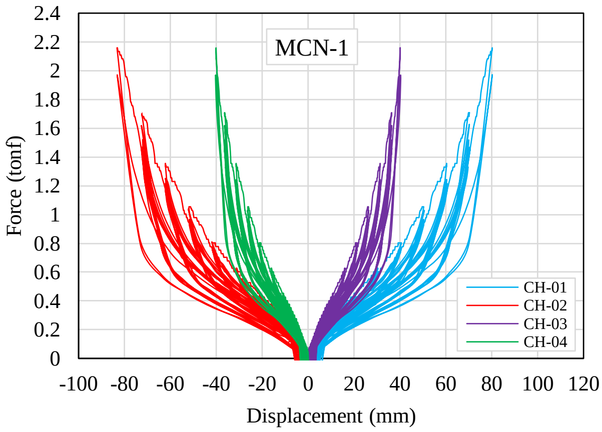
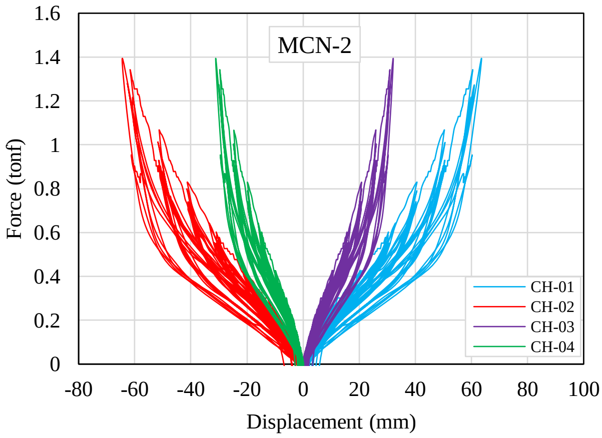


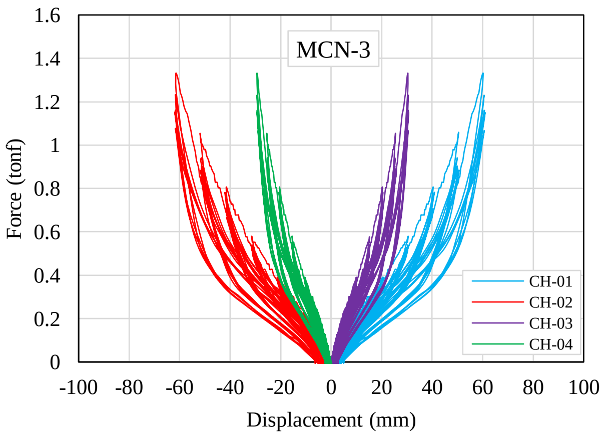
Fig. 7. Hysteretic Curves of Neoprene Rubber Specimens.



(a) MCN-1

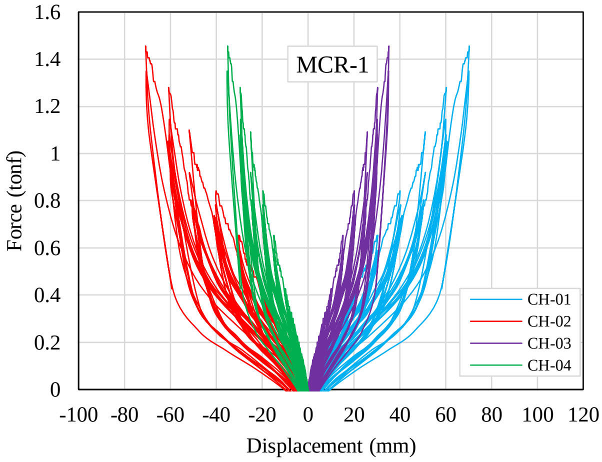


(b) MCN-2

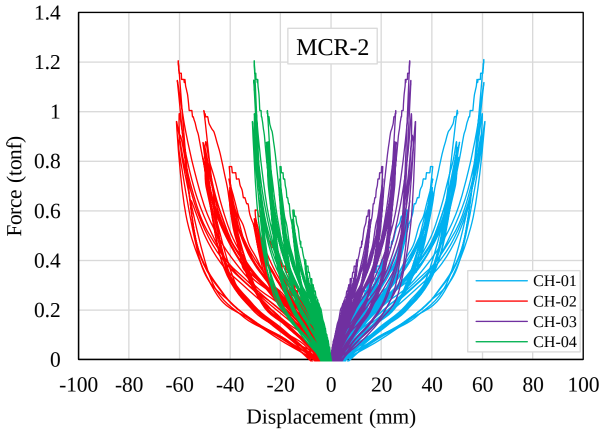


(c) MCN-3

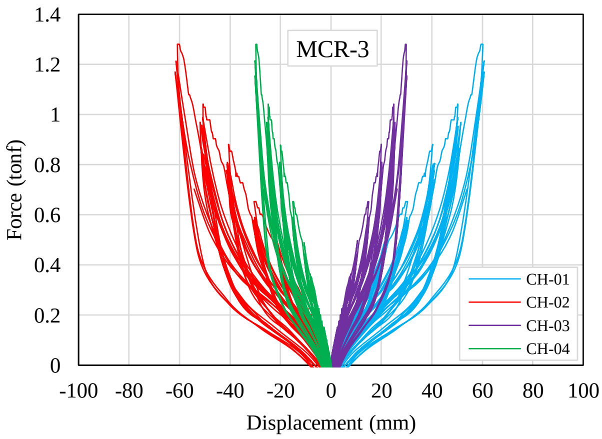
Fig. 8. Hysteretic Curves of Natural Rubber Specimens.



(a) MCR-1



(a) MCR-2



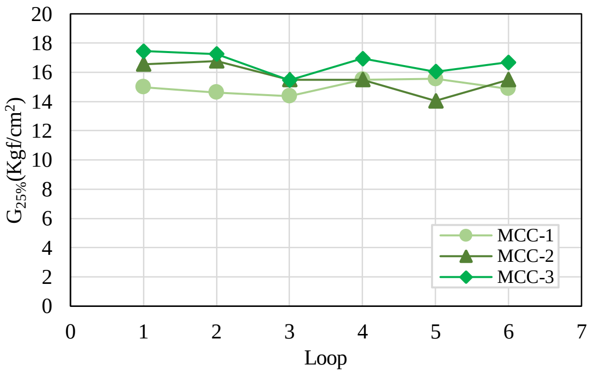
(a) MCR-3

Fig. 9. Hysteretic Curves of Recycled Rubber Specimens.

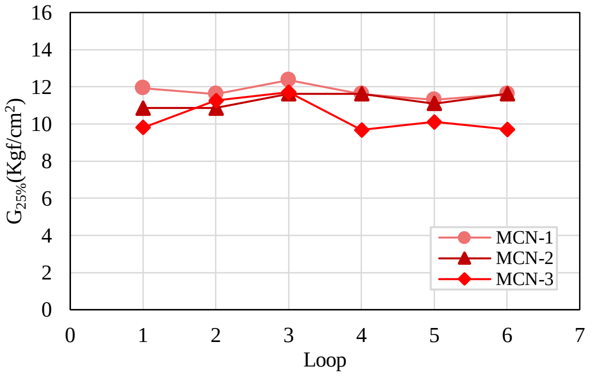
6. Experimental Analysis

According to the ASTM D-4014 methodology, a target deformation of 5 mm—equivalent to 50% of the rubber bearing thickness—is required to calculate the shear modulus at a shear strain of 25% for each bearing composing the specimen. Based on this procedure, the average shear modulus values obtained were 15.69 kgf/cm² for MCC, 10.98 kgf/cm² for MCN, and 9.95 kgf/cm² for MCR.

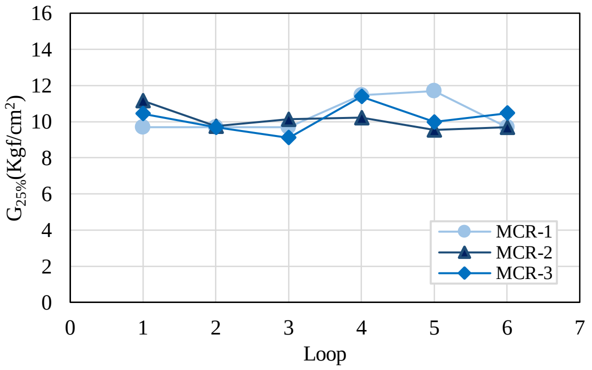
Fig. 10 illustrates the variation of the shear modulus at 25% shear strain throughout the six loading cycles. A slight dispersion in the results is observed, with average values of 15.76 kgf/cm², 11.13 kgf/cm², and 10.19 kgf/cm² for the MCC, MCN, and MCR specimens, respectively.



(a) MCC

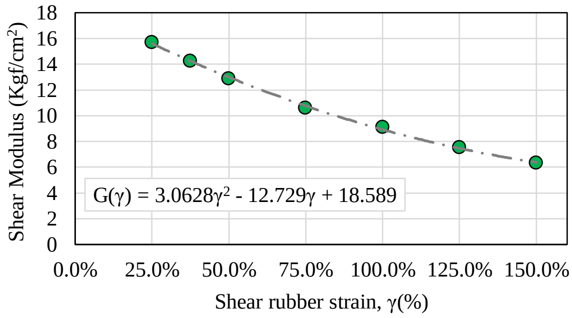


(b) MCN

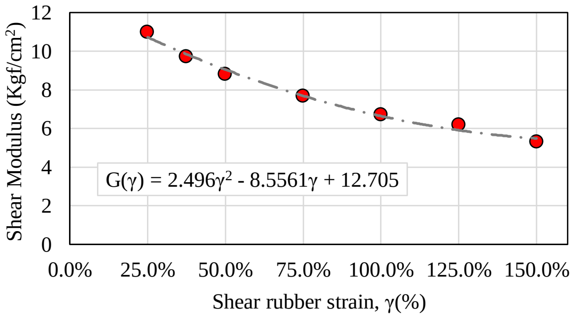


(c) MCR

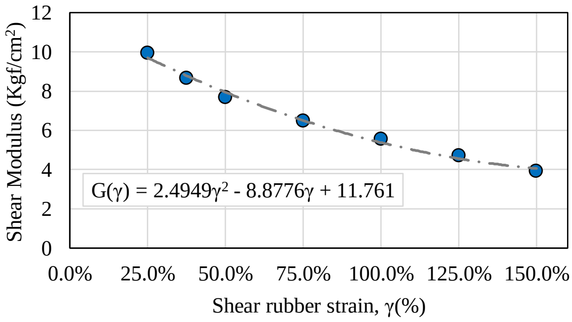
Fig. 10. Shear Modulus at 25% of strain (ASTM D-4014)



(a) MCC – ASTM D-4014



(b) MCN – ASTM D-4014



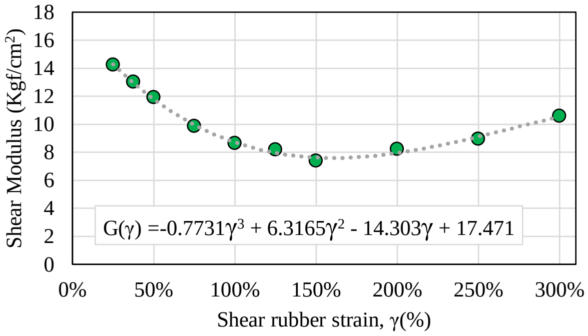
(c) MCR – ASTM D-4014

Fig. 11. Deterioration of shear modulus – ASTM D-4014

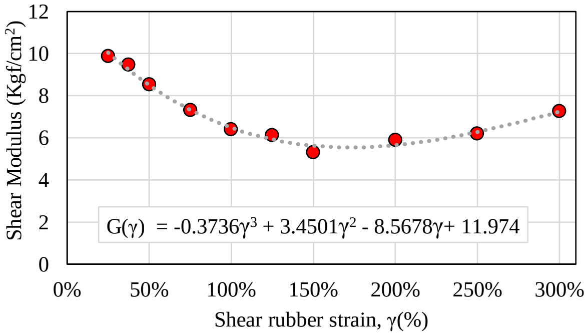
It is noted that the average shear modulus values calculated over all six cycles are slightly higher than those obtained following the standard procedure specified for the sixth cycle as expected.

On the other hand, using the ASTM D4014 methodology, the shear modulus at different levels of shear strain can be derived, as described in Eq. (7). In this way, the degradation of the shear modulus can be represented through a fitted function. Accordingly, a mathematical relationship between shear modulus and shear strain, for each type of rubber material, was obtained by fitting the experimental results using the least squares method, as shown in Fig. 11.

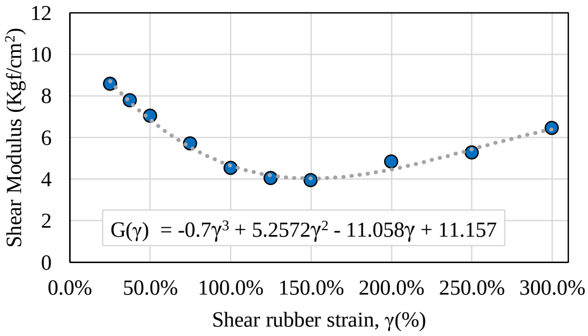
Similarly, using the "Other Cycles" methodology, a curve relating the shear modulus to shear strain was obtained, as shown in Fig. 12. A degradation of the shear modulus is observed up to a strain level of 150%, consistent with the trend identified using the ASTM D4014 approach. However, beyond 150% strain, hardening behavior is also observed. This behavior suggests that the stiffening effect should be considered in the shear modulus estimation, especially for large strains. These equations provide a continuous representation of this variation, facilitating its application in analytical models or the design of seismic isolation devices.



(a) MCC – Other cycles



(b) MCN – Other Cycles



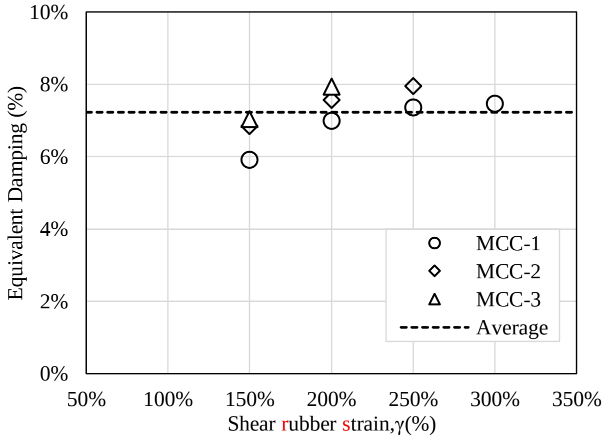
(c) MCR – Other Cycles

Fig. 12. Deterioration of shear modulus – Other Cycles

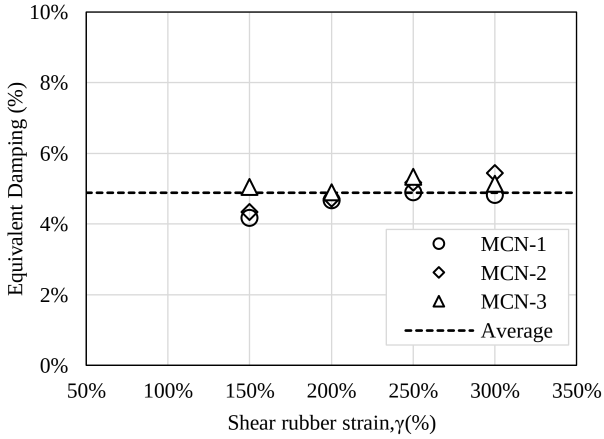
Additionally, the equivalent damping, β_{eq}, was calculated based on the hysteretic loops of a bilinear model following the Eq. (8):

$$\beta_{eq} = \frac{A_h}{2\pi K_{eq} D_{max}^2} \qquad (8)$$

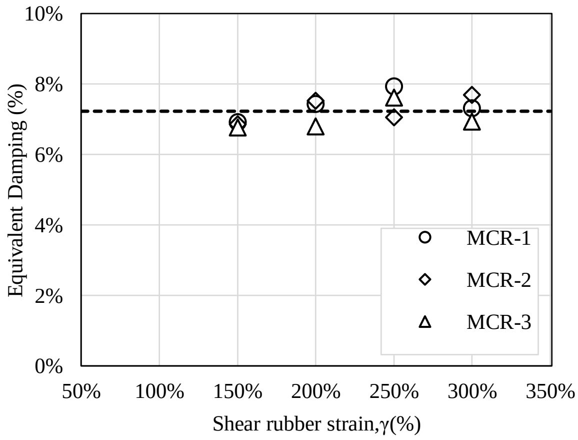
where, A_h is the hysteresis loop area per cycle, K_{eq} is the equivalent stiffness, and D_{max} is the maximum displacement for each cycle. The variation of the experimental equivalent damping through the deformations of the specimen is obtained from the processed hysteretic loops. Fig. 13 summarizes this calculation by estimating average values of the equivalent damping of 7.23%, 4.88%, and 7.20% for MCC, MCN, and MCR specimens, relatively.



(a) MCC



(b) MCN



(c) MCR

Fig. 13. Experimental equivalent damping ratio

7. CONCLUSIONS

In this study, an experimental study of shear and damping properties of three types of rubber: polychloroprene, natural rubber, and recycled rubber, was carried out to determine their feasibility as elastomeric materials in seismic isolation devices. To estimate the shear modulus, nine tests (three for each type of rubber) were conducted following the ASTM D4014 standard and the “Other Cycles” methodology. Additionally, the deterioration and hardening of each rubber material were explored under large deformation cycles, resulting in a correlation equation between strain and shear modulus for each type of rubber material. Thus, the findings of this study lead to the following conclusions:

- In the shear modulus tests, good performance was observed in the MCN and MCR specimens. However, two MCC specimens failed to complete the full deformation cycle, likely due to inadequate vulcanization or misaligned load application relative to the central axis of the specimen.
- Based on the shear modulus test results, an experimental mechanical behavior curve was developed relating shear modulus to shear strain. These relationships were fitted using a second-degree polynomial in the first methodology and a third-degree polynomial in the second, both with coefficients of determination (R^2) exceeding 95%. Therefore, these fitted curves are considered accurate and suitable for use in further research.
- In the "Other Cycles" methodology, the results were generally consistent with those of the standard methodology. Additionally, hardening behavior was observed in all rubber types beyond approximately 150% strain. This observation aligns with the approach proposed by Kelly [2] for seismic isolation design, in which a factor of 1.2 is applied to the shear modulus for isolators subjected to 200% maximum strain. In this study, the corresponding factors obtained for the MCC, MCN, and MCR specimens were 1.11, 1.11, and 1.22, respectively.
- From the processed hysteresis loops, the equivalent damping ratios at 150%, 200%, 250%, and 300% strain were calculated. The average damping values obtained were 7.23% for MCC, 4.88% for MCN, and 7.20% for MCR specimens.

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