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Experimental investigation of the effects of material and geometric characteristics on the mechanical behavior of viscoelastic dampers

Sanam Ansarighadim *[a], Alireza Manafpour [b], Negin Manafpour [c]

[a] *Ph.D. Student, Civil Engineering Department, Urmia University, 5756151818, Urmia, Iran*.*

[b] *Assistant Professor, Civil Engineering Department, Urmia University, 5756151818, Urmia, Iran.*

[c] *B.Sc. Student, Civil Engineering Department, Urmia University, 5756151818, Urmia, Iran.*

* Corresponding author e-mail: sanamansarighadim@gmail.com

Abstract

Recent earthquakes have caused widespread damage, highlighting the urgent need for the development of intelligent and sustainable cities. As a result, there is an increasing effort to prevent permanent damage or disruption to urban structures caused by earthquakes or other environmental factors. One effective solution for mitigating the damage to structures during severe earthquakes is the use of energy dissipation devices. This paper investigates the mechanical behavior of viscoelastic dampers (VEDs) used in structural engineering for seismic and vibration control. Two types of viscoelastic dampers, plate-shaped and cylindrical, were designed, fabricated, and evaluated under dynamic sinusoidal loading conditions. The study aims to compare the energy dissipation capacity of different viscoelastic materials, specifically natural rubber (NBR) and chlorobutyl rubber (CIIR), and to examine how damper geometry influences their performance. The fabricated dampers were tested under dynamic sinusoidal loading with amplitudes of 4, 8, and 12 mm, and frequencies of 0.1, 0.5, and 1 Hz. The results showed that the dampers made from chlorobutyl rubber exhibited higher damping capacity than those made from natural rubber. However, the natural rubber dampers demonstrated greater load-bearing capacity due to their higher stiffness. Additionally, due to their larger volume of material under deformation, the cylindrical dampers outperformed the plate-shaped dampers, with nearly double the damping capacity.

Keywords: dampers; viscoelastic material; natural rubber; chlorobutyl rubber.

1. Introduction

The seismic design philosophy used in most building codes around the world focuses on protecting human lives during strong earthquakes. This approach ensures that buildings are designed to endure significant structural damage without collapsing, providing safety for occupants during intense seismic events [1]. Designing structures with this approach leads to the occurrence of two phenomena after strong earthquakes: cumulative damage to primary structural elements and residual deformations in the structures. The experiences from major earthquakes in recent decades have shown that current structures can adequately protect human lives during severe earthquakes [2]. However, structures often become irreparable due to significant damage [3]. If the residual inter-story drift exceeds 0.5%, the repair of the structure is not economically justifiable [4]. The use of energy dissipation devices is one of the effective solutions for reducing damage to structures during severe earthquakes [5-6].

Structural control systems are generally categorized into four main types: active, semi-active, passive, and hybrid systems [7-8]. Among these, passive systems are more widely used because they are more cost-effective and can function without relying on any external power sources [9-10]. The use of passive dampers to reduce the demand for inelastic energy dissipation through structural framing systems has grown significantly since the mid-1990s [11]. Commonly used dampers for seismic protection of structures include viscous fluid dampers, viscoelastic solid dampers, friction dampers, and metallic dampers. Additionally, tuned mass and tuned liquid dampers, primarily used for controlling wind-induced vibrations, fall under this category [12]. Semi-active dampers, which have controllable mechanical properties, such as variable-orifice, magnetorheological, and electrorheological dampers, are also among the different types of dampers [13].

Dampers fall into two main categories: displacement-dependent and velocity-dependent [14]. Displacement-dependent devices, like metallic yielding and friction dampers, are less effective at low vibrations. In contrast, velocity-dependent dampers, such as viscous and viscoelastic (VE) dampers, efficiently dissipate energy at all displacement levels under dynamic loads [15].

VE dampers not only provide velocity-based damping but also add a displacement-dependent restoring force. They effectively reduce vibrations in both seismic and wind scenarios and increase both damping and stiffness, though the added stiffness is minimal [16]. Their performance is influenced by amplitude, frequency, and temperature [15].

The mechanical properties of viscoelastic dampers are directly dependent on the elastomer material, the polymer network within the rubber, the polymeric substances, and the rubber matrix [17-19]. Despite numerous studies exploring different viscoelastic materials for damper construction, achieving an optimal balance between damping capacity and stiffness in viscoelastic dampers continues to be a major challenge. Moreover, research has shown that the performance of viscoelastic dampers, even when made from a single type of viscoelastic material, can vary significantly depending on the damper's dimensions and geometric design [20].

In this study, the primary objective was to investigate and compare the mechanical behavior of three types of viscoelastic dampers with different geometries and materials under sinusoidal loading with varying amplitudes and frequencies. Initially, two plate dampers were designed and fabricated using two different viscoelastic materials. These samples were subjected to dynamic loading under various conditions, including different amplitudes and frequencies, and the results of the materials' behavior were compared. After evaluating the performance of the materials, the material that exhibited better energy absorption and vibration control was used to construct a cylindrical viscoelastic damper. This damper was then subjected to similar loading conditions, and its results were compared with the plate viscoelastic damper made from the same material. This comparison provided deeper insights into the impact of damper geometry and structure on performance, offering valuable information for optimizing the design of viscoelastic dampers. Two different viscoelastic materials, based on natural rubber and chlorobutyl, have been used to manufacture these dampers.

They have been produced in the "Lastik Fan" rubber manufacturing plant. The curing temperature of these dampers was 150°C for 30 minutes.

2. Viscoelastic Dampers (VEDs)

Since the 1960s, the use of viscoelastic dampers has made significant progress in civil engineering due to their low cost, simple design, and effective energy absorption performance [21-22]. These dampers dissipate the applied energy through shear deformation [23-24]. Viscoelastic dampers have played a significant role in controlling vibrations in aerospace structures and civil engineering structures since 1969 [25-26]. Viscoelastic dampers can increase the damping of a structure by 2% to 25% [27]. Fig. 1. illustrates various common types of VEDs, such as the plate, cylinder, fan-shaped, and circular type. The energy dissipation in these VED dampers occurs through shear deformation in the viscoelastic material (VEM) layers. These deformations can be divided into three types: extrusion shear, axial lateral shear, and rotational shear [28].

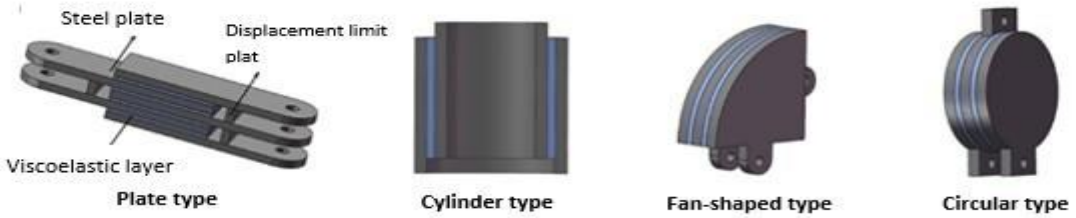


Figure 1. typical VED dampers [28].

Many studies have investigated the impact of various factors on the performance of viscoelastic dampers. Soong et al. and Tsai et al. conducted experiments that demonstrated temperature, frequency, and displacement amplitude as the main factors affecting the performance of these dampers [29-30]. Similarly, Bergman et al. found that ambient temperature and excitation frequency significantly influence the mechanical performance of viscoelastic dampers. These studies showed that as temperature increases, the energy absorption capacity and stiffness of the dampers decrease [31].

Chang et al., through experimental research on three types of dampers with different sizes, concluded that increasing ambient temperature leads to varying degrees of reduction in stiffness and energy dissipation capacity of the dampers [32]. In recent years, extensive research has been conducted on viscoelastic dampers and elastomeric materials. Zhan Shu and his colleagues carried out a comprehensive study on various types of dampers and elastomeric materials in 2022. In their research, they examined the effects of various factors such as frequency, temperature, and displacement amplitude on the performance of viscoelastic dampers [28].

2.1 Viscoelastic Materials

Rubber materials are categorized as high-polymer damping materials that exhibit both hyperelastic and viscoelastic properties [33]. When these materials are subjected to dynamic external forces, the induced strain lags behind the stress variations. The mechanical energy loss in this process is reflected through the damping effect of rubber materials. The damping performance of rubber materials is typically characterized by the damping loss factor ($\tan \delta$) (η). The larger the damping loss factor, the greater the energy dissipation of the material. The relationship is described by $\tan \delta = E'' / E'$, where δ is the phase angle representing the lag of strain behind stress; E' is the storage modulus, which represents the energy stored in the material under stress; and E'' is the loss modulus, which indicates the energy loss [34]. The hysteresis diagram in Fig. 2. illustrates the behavior of viscoelastic materials under load and displacement. (F) represents the maximum force the material can handle, while (F1) is the force at maximum displacement, and (F2) is the force sustained without displacement. Important material properties include the loss factor (η), loss shear modulus (G2), and storage shear modulus (G1). The maximum displacement is denoted by ($u0$), with (Av), (nv), and (t) representing the shear area, number of material layers, and material thickness, respectively. (Ed), indicates the amount of energy dissipated per loading cycle.

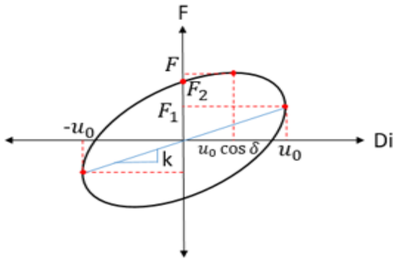


Figure 2. Typical hysteretic behavior of VED [35].

$$\eta = \frac{F_2}{F_1} = \frac{G_2}{G_1} \tag{1}$$

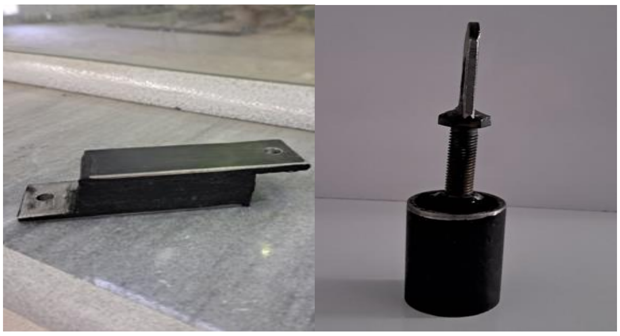
$$G_1 = \frac{F_1\, t}{n_v A_v u_0} \tag{2}$$

$$E_d = \pi\, {\gamma_0}^2 G_1 \eta V \tag{3}$$

3. Experimental study

In this study, to investigate the hysteretic behavior of chlorobutyl rubber and natural rubber , two plate type dampers were fabricated with the following dimensions: 11 cm in length, 3 cm in width, and 2 cm in thickness. As shown in Fig. 3.a., these dampers consist of two metal sheets with a thickness of 2.5 mm and a length of 8 cm, along with a layer of viscoelastic material measuring 6 cm in length, 2.5 cm in thickness, and 3 cm in width. The materials used for constructing these dampers, along with detailed specifications, are provided in Table 1.

For the composition of the viscoelastic material in the first damper with natural rubber base, the formulations presented in reference [36] were used. For the fabrication of the viscoelastic material in the second damper with chlorobutyl rubber base, 39% of the composition was derived from the formulation outlined in Reference [37], combined with 39% reclaimed rubber and 22% natural rubber compound.



(a) (b)

Figure 3. a. Plate elastoplastic dampers Prototype, b. Cylinder elastoplastic dampers Prototype.

In addition to comparing the effect of viscoelastic materials on the hysteretic behavior of viscoelastic dampers, this study also investigates the influence of damper geometry on its hysteretic performance. For this purpose, a cylindrical damper with dimensions of 6 cm in length, 4 cm in outer diameter, and an inner shaft diameter of 2 cm was fabricated, as illustrated in Fig. 3.b. The viscoelastic material used in this cylindrical damper is based on chlorobutyl rubber, identical to that used in the construction of the second plate damper. The damper consists of a cylindrical viscoelastic layer with a height of 6 cm, an outer diameter of 3 cm, and an inner diameter of 2 cm.

Table 1. The composition of the viscoelastic material for Damper 1,2 [36] [37].

The composition of Damper 1	percentage	The composition of Damper 2	percentage
Natural rubber	26	CIIR	80
synthetic rubber	13	NBR	20
antioxidant	3.9	CPE	10
liquid rubber	13	N550	30
sulfur	0.3	sulfur	2
accelerator	0.6	Paraffinic Oil	20
zinc oxide	2.6	Cumarone Resin	3.5
carbon black	40.1	Acid Stearic	1
		Zn O	5
		CBS	1.5
		ZDEC	1.5

3.1 Test setup and loading protocol

All three dampers were subjected to the same loading protocol, which involved applying sinusoidal loads with three different amplitudes of 4, 8, and 12 mm. These loads were applied at three distinct frequencies: 0.1, 0.5, and 1 Hz. All tests were conducted using a universal testing machine to ensure accuracy and consistency of the results. Fig. 4. shows the loading protocol applied at all three frequencies. Fig. 5. shows all three dampers in the loading setup of the universal testing machine.

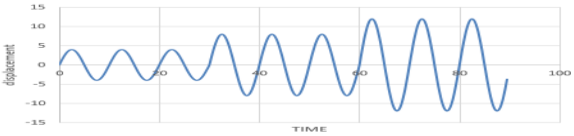


Figure 4. Loading protocol in 0.1 HZ.

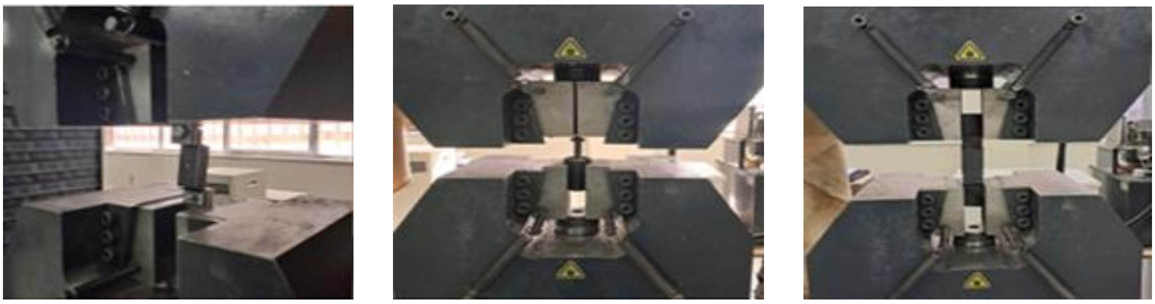


Figure 5. Test setup for dampers in universal testing machine.

3.2 Results and discussion

Fig. 6.a., 6.b., and 6.c. display the hysteresis curves for the first and second viscoelastic plate dampers and the cylindrical damper, respectively. The volume of viscoelastic material subjected to shear strain in the plate dampers is 27 cm³, while in the cylindrical damper it is 94 cm³. Furthermore, the thickness of the viscoelastic layer under shear strain is 1.5 cm for the

plate dampers and 0.5 cm for the cylindrical damper. Based on the obtained hysteresis curves, the loss factor (η) for dampers 1, 2, and 3 at different frequency ranges were found to be 0.35, 0.4, and 0.4, respectively. Additionally, the storage shear modulus for dampers 1, 2, and 3 at 0.1, 0.5 and 1 frequencies were measured as follows: (0.88, 1.06, 1.34), (0.7, 0.83, 1.25), (0.76, 1, 1.38) Likewise, for the loss shear modulus, we have the following values:(0.22, 0.27, 0.55), (0.28, 0.33, 0.5), (0.3, 0.4, 0.5).

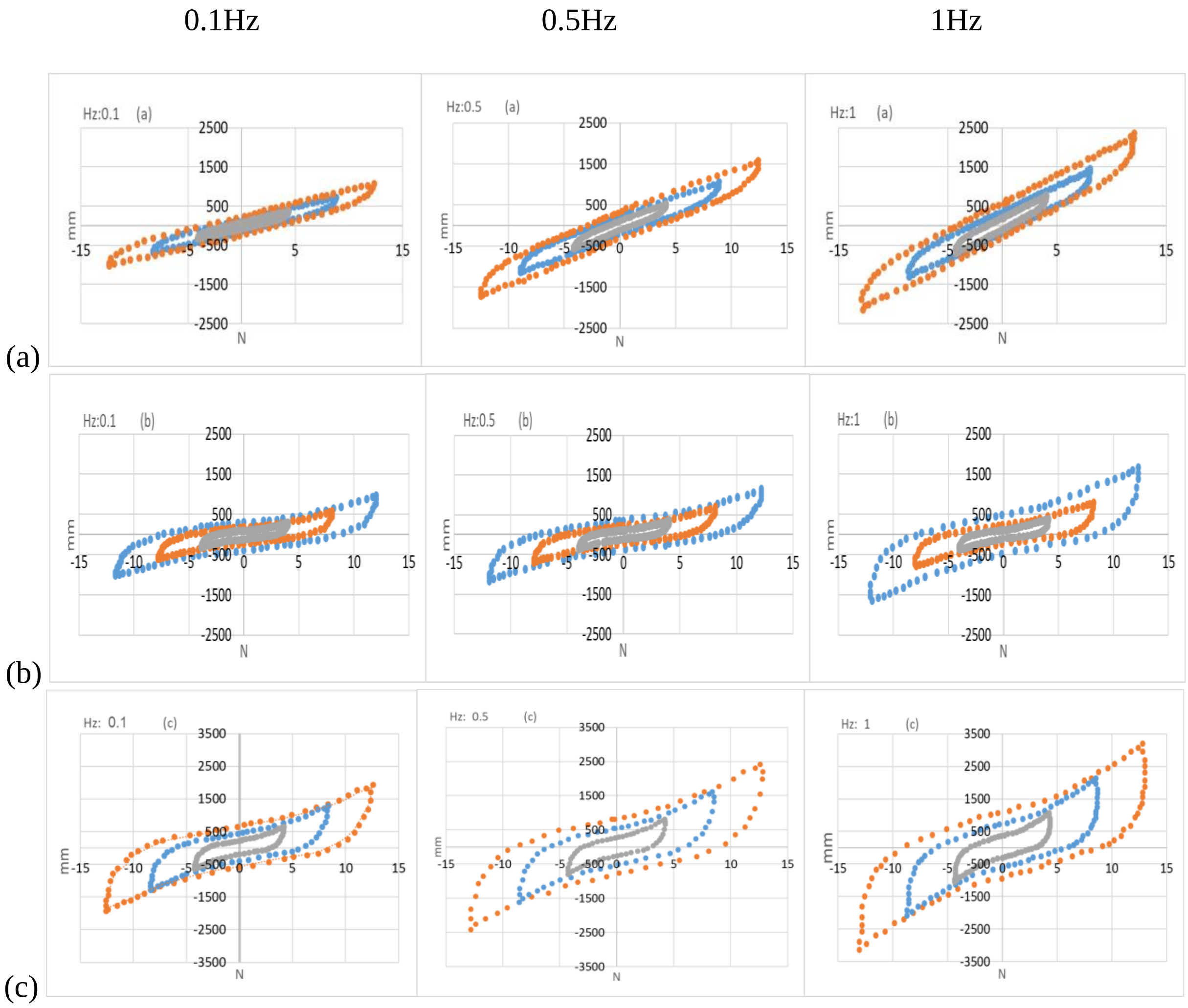


Figure 6. Hysteresis diagrams obtained from the experiment.

4. Conclusion

In this study, the hysteresis behavior of two different viscoelastic materials, based on natural rubber (NBR) and chlorobutyl rubber (CIIR), was investigated under sinusoidal loading with varying amplitudes and frequencies. Additionally, two types of viscoelastic dampers, one with a plate shape and the other cylindrical, both made from chlorobutyl rubber, were manufactured with approximately the same dimensions. The hysteresis behavior of these two damper types was also evaluated to compare their performance. The primary focus was on understanding how the shape and material composition influence the damping capacity of the viscoelastic dampers, providing insight into the optimal design of energy dissipation devices. By analyzing the hysteresis loops generated during cyclic loading, the energy absorption and dissipation properties of each material and damper type were quantified. The results indicated that viscoelastic materials based on natural rubber exhibited less damping compared to materials made from chlorobutyl rubber but demonstrated slightly higher stiffness. Additionally, the cylindrical damper made from chlorobutyl rubber exhibited significantly higher damping capacity compared to the plate-shaped damper made from the same material, along with an increase in load-bearing capacity. The results suggest that cylindrical dampers may offer greater advantages over plate-shaped dampers, requiring further attention and more extensive research.

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