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LABORATORY CHARACTERIZATION OF A RECLAIMED RUBBER COMPOUND FOR LOW-COST ELASTOMERIC ISOLATORS

Fabrizia Cilento[1], Daniele Losanno[1], Luigi Piga[2]

[1] Department of Structures for Engineering and Architecture, University of Naples, Federico II, Via Claudio 21, Naples, Italy
{fabrizia.cilento, daniele.losanno}@unina.it

[2] Italgum srl, Via Vegri 27, Zanè (VI), Italy
luigi_piga@italgum.com

Abstract

Although seismic isolation devices are effective in protecting structures during an earthquake, they are generally large, heavy, and expensive, making their application prohibitive for housing buildings. In the last few years, different strategies have been investigated to make seismic isolators cheaper and lighter for housing buildings in developing countries. Lower costs can be obtained at different scales: simplifying the installation process of devices, reducing energy consumption during manufacturing, and using recycled materials. Both weight and cost of isolators could be reduced by adopting flexible reinforcements in place of steel reinforcing plates, also allowing easier installation without bolted connections in unbounded configuration. Costs can be further reduced by replacing natural rubber with a recycled elastomer. It has been demonstrated that trying to give a second life to rubber is challenging, since devulcanization process, capable of breaking chemical bonds between rubber and sulphur, is highly polluting and requires high consumption of energy. In the present work, a recycled compound has been preliminary developed with mechanical properties not significantly lower than virgin rubber. Obtained parameters are satisfactory for use in unbounded isolators with flexible internal reinforcement where internal stresses are significantly reduced. In particular, a novel compound has been properly formulated in order to be lower cost in comparison to traditional one. Mechanical characterization of the material showed excellent properties including shear modulus and hardness similar to those of a soft rubber, even if a reduced ultimate deformation capacity is achieved. Furthermore, rubber adhesion with different fabrics has been investigated. Preliminary results are very promising and pave the way for the development of high-performance and low-cost rubber isolators.

Keywords: Base isolation, fibre reinforced elastomeric rubber isolators, recycled rubber

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1 INTRODUCTION

Base isolation is one of the most effective technologies in seismic protection of structures [1]. Its objectives are the protection of human life and the reduction of damage caused to buildings during earthquakes. Despite all, the system is rarely used in emerging countries due to its relatively high cost and features of the design codes. In fact, classical steel-reinforced elastomeric isolators (SREIs) are generally large, heavy, and expensive due to the highly labor-intensive manufacturing process, making their application prohibitive in the case of housing buildings. In the last years, many efforts have been done trying to develop novel low-cost seismic devices, in order to expand the market of seismic protection systems also to ordinary housing buildings, particularly in high seismicity areas of developing countries [2,3]. Lower costs can be obtained by: (i) simplifying the installation process of the devices, (ii) reducing energy consumption during manufacturing process and (iii) using waste and recycled materials. The first approach was aimed to replace steel plates with fibre sheets [4]. In comparison with rigid reinforcements, flexible reinforcements are lighter and can be easily introduced in the manufacturing process of elastomeric rubber bearing to be installed under the structure in an unbonded configuration [5,6]. In fact, in masonry buildings, these devices are placed directly under the foundations of the structure, with no need for additional transfer elements, leading to a significant reduction of the construction costs [3]. These new devices are known as fiber reinforced elastomeric isolators (FREIs) [7]. Costs can be further reduced by replacing virgin rubber with a recycled low-cost elastomer, mitigating, at the same time, the threat of rubber scraps increasing all over the world. However, recycling rubber is challenging, due to its chemical structure and composition, which make it an insoluble and infusible material that cannot be easily reprocessed. One of the major methods of sustainable management of used tyres is grinding them and use the rubber particles to produce a new environmental-friendly polymer. The fabrication process of these material consists in grinding rubber into particles of different shape and dimensions, mixing them with a low amount of polyurethane and then hot pressing or cold forging the material in order to obtain recycled rubber pads. This material is characterized by density low and low mechanical properties [8]. Another method to obtain a 100% recycled rubber material consists in compression moulding of rubber granules at elevated temperature and pressure, necessary to break the crosslink bond, without the addition of any binder [9–11]. This material exhibits good mechanical properties and high density [12]. Some studies have shown the possibility of using rubber pads to produce recycled rubber isolators reinforced with carbon fibres (RU-FREI) avoiding the vulcanization process [13]. In fact, manufacturing cost of one RU-FREI is of a few Euros and about 1/10 of the cost of a traditional SREI. Shaking table tests, performed by Losanno et al. [14,15] confirmed the effectiveness of the RU-FREI isolation systems in reducing the accelerations and interstory drifts along the height of the building. However, RU-FREI could be employed as seismic isolation system for heavy structures, such as masonry buildings, because when designed for a lightweight frame, these bearings end up having a low aspect ratio, becoming unstable under large lateral deformations [7]. In the present work, the authors introduce a new compound whose characteristics are in between virgin natural rubber and recycled rubber. For this purpose, a novel compound has been formulated and the physical and mechanical properties have been investigated. The material has shown excellent mechanical properties compared to that of natural rubber, in terms of both shear modulus and hardness, even if a reduced ultimate deformation capacity is achieved. Most importantly, the material exhibited excellent adhesion both with metal and synthetic fabric, preventing debonding which characterized RU-FREI. Thus, the cost savings for raw materials combined with satisfactory mechanical performance could pave the way to a novel low-cost isolation system. Finally, the preliminary design of seismic isolator reinforced with nylon and polyester fabric is presented as prototypes to be tested in the near future.

2 DEVELOPMENT OF THE COMPOUND

Both physical and mechanical properties of the compound are investigated to assess hardness, stiffness, equivalent viscous damping, deformation, and durability properties of the compound.

The rheometric behaviour of the material has been investigated according to ISO 3417 [16]. Two moulding temperatures, 140°C and 177°C, are considered in order to find the optimal combination of curing temperature and time. This test describes precisely and quickly curing and processing characteristics of vulcanizable rubber compounds. A test piece of rubber compound is contained in a sealed test cavity under positive pressure and maintained at a specified elevated temperature. A rotor biconical disc is embedded in the test piece and is oscillated through small specified rotary amplitude. A complete cure in terms of applied torque versus cure time is obtained.

Shore Durometer A (UNI EN ISO 868 [17]) and international rubber harness degrees (IRHD) (ISO 48 Method N [18]) were evaluated. The hardness is evaluated by inducing reversible, elastic deformation by means of a specially shaped indenter. Five samples of 35 mm diameter and 6 mm thick, with smooth, flat surface are tested for 3 sec in case of Shore A and 30 sec for IRHD, and the average values of hardness are computed. Tests are conducted both on samples cured at 140°C for 25 minutes and 170°C for 9 minutes.

Tensile tests are conducted on dumb-bells specimens, according to ISO 37 [19], using tensile tester, equipped with 10 kN loadcell. Six samples of thickness 2 mm, width 4 mm and length 20 mm were tested and the average value was computed for the only rubber compound moulded at 140°C for 25 minutes. Test are conducted with a strain rate of 500 mm/min up to failure.

Tear tests are conducted following ISO 34-1 [20], using the trouser test pieces. It is preferred to other methods since providing information about the fundamental tear properties of the material and less sensitive to the length of the cut. The tearing force is applied by means of a tensile testing machine, which operates continuously at 100 mm/min until the test piece breaks. Five samples of thickness 2 mm, width 15 mm and length 100 mm were considered and a cut of length 40 mm was applied in the longitudinal direction.

Shear tests are conducted with a quadrupole setup. The test pieces consist of four rectangular rubber pads 4 mm thick, 25 mm long and 20 mm wide, bonded on four rigid plates of the same width. This system is connected to an actuator, which applies shear deflection with a strain rate of 5mm/min. Samples are subjected to four static half-cycles of shear amplitude 20%, 40%, 60%, 80% and then 100%. Also dynamic properties are estimated considering a frequency of 0,5 Hz.

Rubber aging behaviour is also investigated by performing accelerated aging, according to ISO 188 [21]. Samples are conditioned at 70°C for 168h (7 days).

Finally, the adhesion of rubber with different supports (steel, nylon, polyester) is investigated performing peeling tests, according to ISO 813 [22]. A strip of rubber is bonded to a single plate of rigid material and peeled with an angle of 90° with a strain rate of 50 mm/min. The applied force required to tear the rubber from the support is measured. The standard test piece consists of a strip 6 mm thick, 25 mm wide and 125 mm long, bonded to a square area of size 25 mm on the surface of a metal plate and of the fiber textiles bonded on a rigid support.

3 CHARACTERIZATION TESTS

3.1 Tyre rubber crumb

Use of tyre rubber crumb provides advantages during the moulding process due to the bonds that are activated during the grinding. In particular, styrene butadiene rubber (SBR) and natural rubber (NR), unlike butyl rubber, ensure good compatibility not only with the virgin rubber compound, but also with the fabric providing good adhesion. For this purpose, a rubber crumb composed by SBR and NR was chosen.

TGA analysis are performed by considering the temperature ramp of Figure 1a and the weight loss percentages are reported in Figure 1b and summarized in Table 1. A first weight loss of 14 wt% is observed at around 350°C due to the plasticizers, followed by significant weight loss of 54 wt% at around 545°C, which corresponds to SBR and NR. Residuals are attributed to other fillers, such as silica, typical of tyre compounds, or other additives.

Table 1. Reclaimed rubber composition

Components	***T* [°C]**	***wt %***
Absorbed water	70	0.47
Plasticizer (oil, volatile components)	350	13.63
Polymers (NR and SBR)	545	54.96
Carbon black	700	25.13
Ash, inorganic components (ZnO, SiO_2,...)	>700	5.85

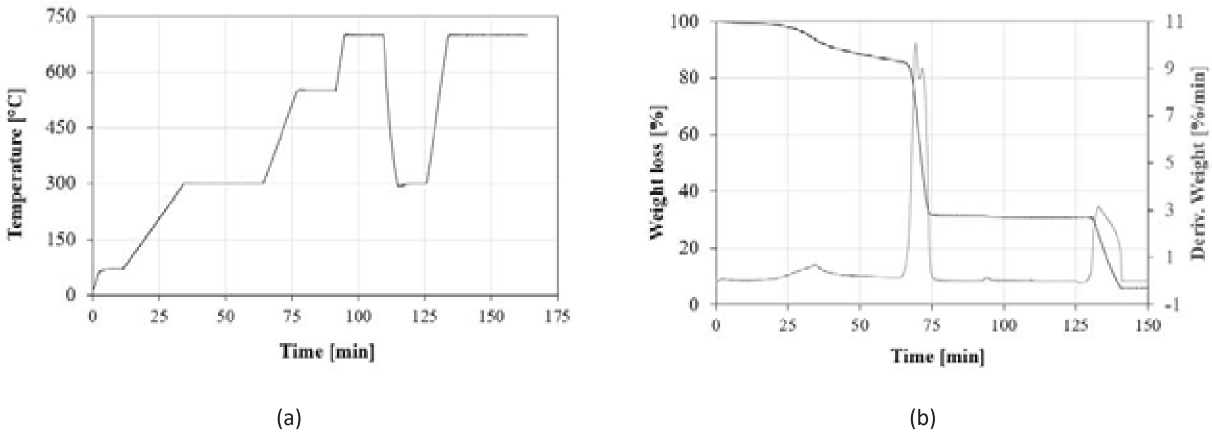


Figure 1. TGA analysis of tyre reclaimed rubber: (a) Temperature-Time procedure; (b) Weight loss

3.2 Novel rubber compound investigation

The vulcanization process of the compound at different temperature was investigated. Rheometric curves at 140°C and 177°C are reported in Figure 2. Curing is governed by activators, catalysts, cross-linking agents, hardeners, and accelerators. The time required to obtain the curing curve is a function of the test temperature and the vulcanization characteristics of the rubber compound [23]. By increasing the testing temperature from 140°C to 177°C, the time to achieve the 90% of cure decreases of about 8 times. The material also shows a stable behaviour at 140°C, since the curve reaches a plateau, without experiencing a reversion of torque [24].

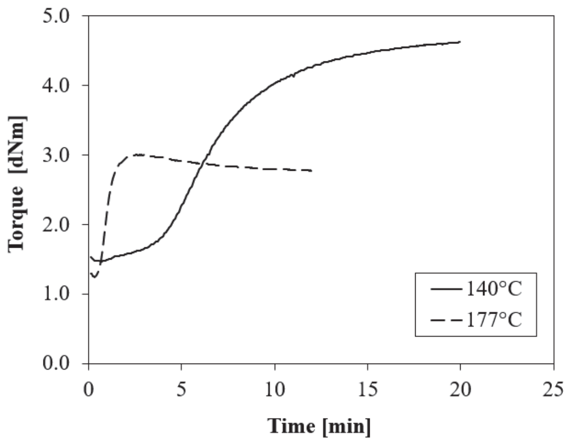


Figure 2. Rheometric curves of the novel rubber compound at 140°C and 177°C

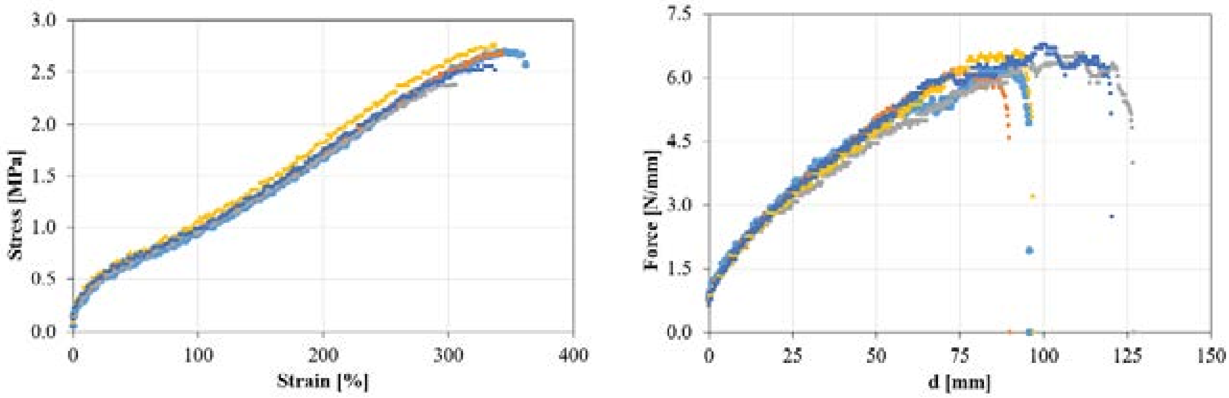
Average values of hardness are reported in Table 2, for samples cured at both 140°C and 170°C. Durometer values are typical of a soft vulcanized rubber [17]. These results indicates that hardness is sensitive to the vulcanization process. In particular, the curing cycle of sample moulded at 140°C is longer than that of samples moulded at 170°C. In fact, slower vulcanization processes at lower temperature allow the formation of stronger networks, which results in higher hardness of the material.

Table 2. Hardness values

	Shore A		**IRHD**	
Test temperature	140°C	170°C	140°C	170°C
Average value	47.4	45.1	41.32	34.65

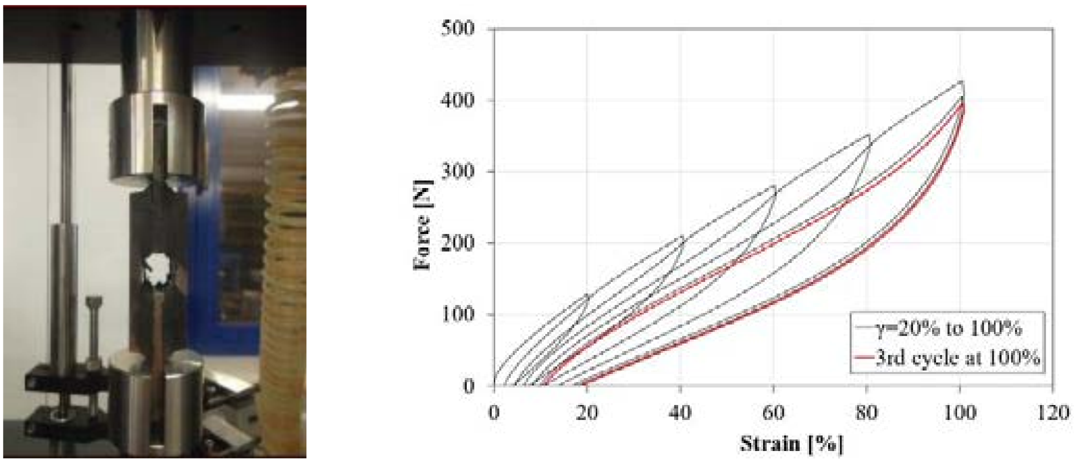
Tensile and tear tests on rubber specimens cured at 140°C for 25 min, revealed an excellent behaviour of rubber compound (Figure 3a-b). The maximum average stress and strains are 2.6 MPa and 330%, respectively. Even if these values are lower than virgin rubber compounds, they are significantly higher than previously adopted reclaimed compounds for RU-FREIs [8,12]. A tear resistance of 6.94 N/mm was measured, which is lightly lower than the minimum requirements, i.e.8 N/mm [20]. However, these results are highly promising for applicability to elastomeric seismic isolators in unbounded configuration. Unlike isolators in bolted configuration, in unbonded application rubber ends are not constrained by steel plates and are free to strain with very limited internal stress. With increasing shear deformations, the ends at contact with the supports tend to rolls-off and vertical faces rotate in a roll-over mechanism [25]. This also results in a significantly lower internal peeling stress at rubber-fibre interface.

Hardness and mechanical properties of the material are also investigated after accelerated aging. In particular, after conditioning rubber at 70°C for 7 days a hardness and tensile strength increase of 9% and 36% were measured, while elongation at break decreased of 8.5%.



(a) (b)

Figure 3. (a) Tensile test and (b) tear test



(a) (b)

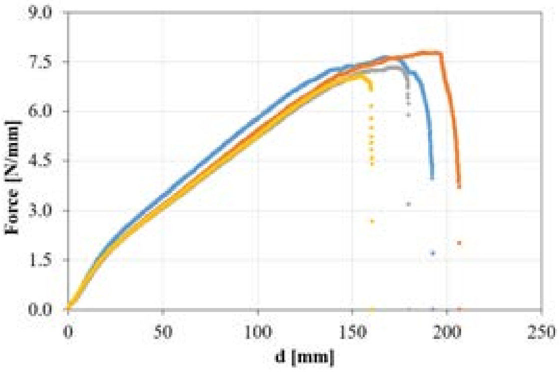
Figure 4. Shear test on rubber: (a) Setup of quadrupole test; (b) Results

Shear modulus and damping were evaluated for a shear strain γ=100% being 0.39 MPa and 4.9% respectively, while dynamic properties were estimated around 0.52 MPa and 10.4 %, respectively. A low shear modulus of the compound, combined with a higher shear strain capacity, can lead to design of seismic isolators with higher shape factors, thus preventing lateral instability which strongly limited previous investigations on RU-FREIs.

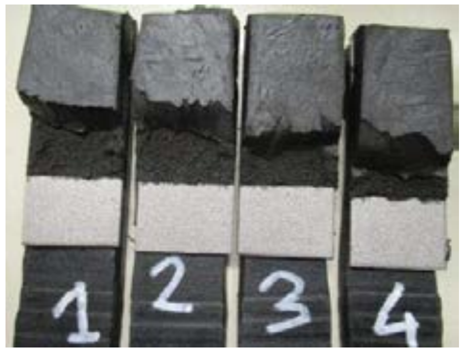
In FREIs, the bonding between layers is of paramount importance since it may govern the failure of the bearing. Tests showed an excellent adhesion of rubber with metal. For all samples rubber tearing occurred before any debonding from the support (Figure 5), providing optimal adhesion between the two materials. For nylon and polyester fabric, a proper adhesive was introduced to impregnate the textiles in order to promote the adhesion. Also in this case, tests showed and excellent behaviour with the tearing of the rubber from the support both for nylon and polyester (Table 3).

Table 3. Strength of adhesion of steel vs synthetic fabric (nylon and polyester)

	Steel	***Nylon***	***Polyester***
d_{max} [mm]	181	170	181
F_{max} [N/mm]	7.46	7.01	7.46



(a)



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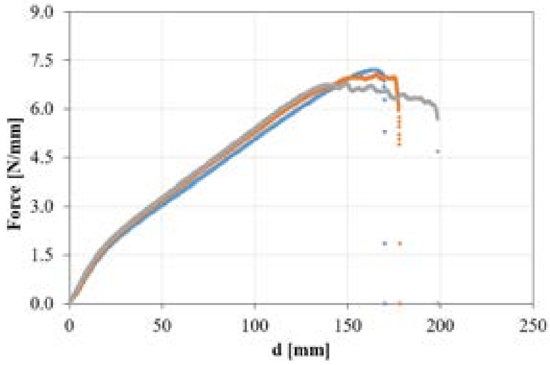

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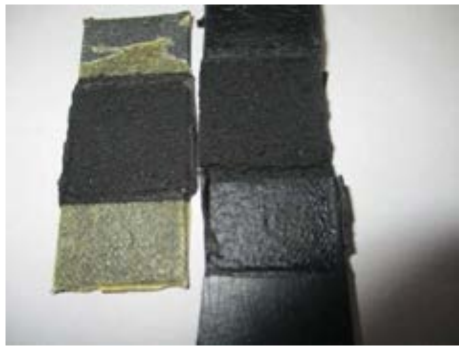

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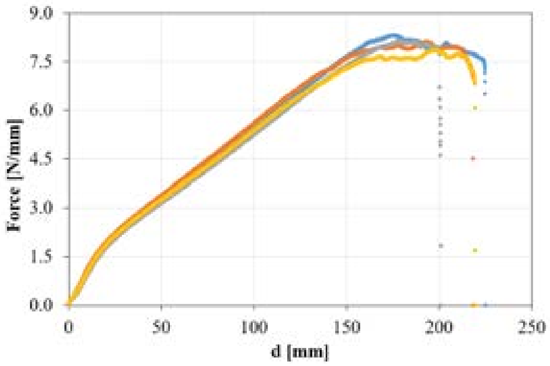

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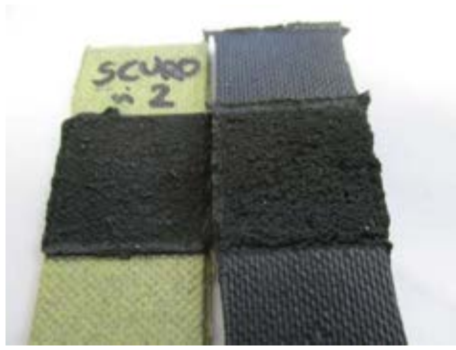

(f)

Figure 5. Quality of adhesion between rubber and (a-b) steel, (c-d) nylon; (e-f) polyester

Table 4. Technical datasheet of novel rubber compound

Properties	***Value***	***Specification***
Hardness (Shore A)	47.4	ISO 868
Hardness (IRHD)	41.3	ISO 48
Tensile strength	2.6 N/mm^2	ISO 37 Type 2
Elongation at break	330%	ISO 37 Type 2
Tear resistance	6.5 N/mm	ISO 34-1
Specific gravity	1.18 g/cm^3	ISO 1183-1
Shear modulus	0.52 MPa	UNI 1827
Damping	10.40%	UNI 1827
Adhesion to metal	7.5 N/mm	ISO 813
Adhesion to nylon	7.0 N/mm	ISO 813
Adhesion to polyester	7.5 N/mm	ISO 188

4. PRELIMINARY DESIGN OF ISOLATORS

On the basis of the preliminary characterization of the novel rubber compound whose main properties are summarised in Table 4, prototype isolators reinforced with polyester and nylon fabric have been designed. Nylon fabric and Polyester fabric coated with graphene were adopted as reinforcement. These are balanced fabrics with a very low cost with respect to conventional steel shims. The geometry of the devices is summarized in Table 5 and sketched in Figure 6.

Table 5. Geometry of rubber isolator reinforced with polyester/nylon fabrics

Device	n° of rubber layers	D [mm]	H [mm]	t_r [mm]	t_f [mm]	S [-]
RR - Nylon	8	200	49.5	5.17	1.16	9.7
RR - Polyester	9	200	49.5	5.02	0.54	10.0

Compared to RU-FREIs from literature [13–15], these prototypes are characterized by a higher shape factor roughly equal to 10. These values are consistent with those of FREI devices fabricated with virgin rubber. Differently, in case of RU-FREIs, the relatively large shear modulus of the rubber and the limited shear strain (γ=50%), resulted in a slender geometry with an aspect ratio close to 1. Consequently, the use of softer compound with higher deformation capacity allows to design more squat geometry thus preventing instability issues [26]. Lateral stability will be investigated up to complete roll-over of the vertical faces under shear tests. In addition to this, vertical behavior will be tested in order to assess the compressibility of the bearing and the influence of limited elastic modulus of the reinforcement in comparison to conventional steel plates and carbon fibers.

Finally, it will be necessary to select the most suitable hysteretic model, among those introduced in the literature [27–31], to allow for an accurate simulation of their nonlinear response.

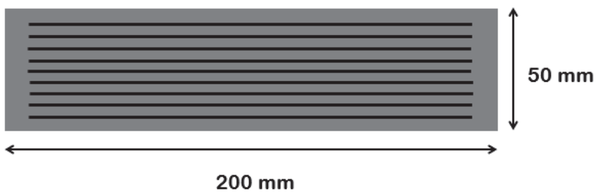

Figure 6. Elastomeric rubber isolator reinforced with polyester/nylon fabrics

4 5 CONCLUSIONS

A new recycled compound with promising mechanical properties has been developed. The material has been extensively characterized and its physical and mechanical properties have been investigated and properly calibrated.

The shear properties of the material are in between natural rubber and totally-recycled rubber pads, exhibiting shear strain up to 100%, i.e. around two times higher than the latters. Also, tensile strength is satisfactory for use in unbounded configuration with flexible internal reinforcement where internal stresses are significantly released.

In addition to this, the novel compound has shown excellent adhesion not only with steel but also with different fabrics such as nylon and polyester. These are very common, cheap textiles commonly used for industrial application such as conveyor belt or work clothes. They can be easily purchased and inserted in the manufacturing process. Devices can be produced by direct molding, overlaying rubber layers and flexible reinforcements. Consequently, not only the weight of the devices is significantly reduced, but also the efforts associated to their fabrication.

The lower shear modulus and the higher shear strain of the compound compared to that of recycled rubber pads allow the fabrication of devices with higher shape factors. This can significantly increase the stability limits that were poorly investigated in previous investigations.

The next step of the study is aimed to develop prototype of isolators to be experimentally tested. The proposed technology is very promising and could pave the way for the development of high-performance and low-cost rubber isolators.

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