SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

DYNAMIC RESPONSES OF RUBBER COMPOUNDS FOR ANTI-SEISMIC ISOLATORS

Giacomo VAZZANA[1], Paolo DUBINI[2], Virginio QUAGLINI[3] and Emanuele GANDELLI[4]

ABSTRACT

The mechanical properties of the elastomers used in the manufacture of seismic rubber isolators are sensitive to mechanical and environmental working conditions, therefore resulting in large variation ranges of the performance of seismic isolation systems installed in buildings and structures. The study investigates the cyclic stress–strain behavior of several elastomer compounds used in the manufacture of anti-seismic rubber bearings. The influence of mechanical and environmental factors, including strain amplitude, number of cycles, frequency, air temperature, and application of concurrent compressive and shear stresses, on the shear properties of the compounds is assessed. The results are analyzed and used to calculate modification factors of design properties for each compound. The variability of the mechanical properties is studied and compared to the requirements on production rubber bearings set in the current European standard on anti-seismic devices.

INTRODUCTION

Rubber Bearings, introduced in the ‘70s for seismic isolation of bridges, are nowadays among the most popular devices for protection of civil and industrial buildings and structures from earthquakes (Taylor et al., 1992; Skinner et al., 1993; Naeim and Kelly, 1999). Today the most widely used types of rubber isolators are the High Damping Rubber Bearings (HDRB) and the Lead Rubber Bearings (LRB). The stiffness and damping capacity of HDRBs depend intrinsically on the mechanical properties of the rubber compound. On the contrary, in LRBs the elastomer is required to provide the horizontal stiffness to the isolation system, while the damping capacity relies on the irreversible deformation of the lead core

A variety of compounds is today available for either HDRBs or LRBs, with different damping capacity, shear modulus, and vulcanization profile, according to the current European standard LRBs are identified by values of viscous damping lower than 6%, while HDRBs generally ranges from 6% to 20% as shown in fig.1.

The mechanical characterization of the elastomer is an important part of the design process of rubber bearings (Constantinou et al., 2007): the mechanical properties of elastomers can vary significantly due to ageing deterioration (Itoh et al., 2006), and are affected from a number of factors like the strain amplitude, the frequency of loading, the repetition of loading cycles, and the effective air temperature (Cardone et al., 2011). As a result, the seismic response of a structure protected with rubber bearings can be influenced by each of the above mechanical and environmental parameters (Thompson et al., 2000). Current codes, like the European (CEN, 2009) and American (AASHTO, 2010) standards on anti-seismic devices, prescribe to assess the dependency of the shear properties of

[1] MSc, Politecnio di Milano, Milan, giacomo.vazzana@polimi.it
[2] PhD, Politecnico di Milano, Milano, paolo.dubini@polimi.it
[3] PhD, Politecnico di Milano, Milano, virginio.quaglini@polimi.it
[4] MSc, Politecnico di Milano, Milano, emanuele.gandelli@polimi.it

the elastomer over typical ranges of service conditions within the scope of Initial Type Testing or Qualification Testing.

According to the standards' provisions, cyclic shear tests must be performed either on complete elastomeric isolators, or on double/quadruple shear block specimens of the rubber compound.

Nevertheless an important factor that is not taken into consideration by the standards is the influence of the compression stress on the shear behaviour.

The present study investigates the functional properties of several elastomer compounds currently used in bearing manufacturing with the aim of providing an overview of the influence of the distinct operational parameters. The tests are carried out on rubber blocks loaded in shear, according to the method recommended by the European standard on anti-seismic devices (CEN, 2009), and additionally the influence of a concurrent compression stress on the shear properties, which is generally not accounted for in the current standards (CEN, 2009; ISO, 2010), is assessed. The results are analyzed and the variability of the shear properties is quantified by introducing suitable modification factors.

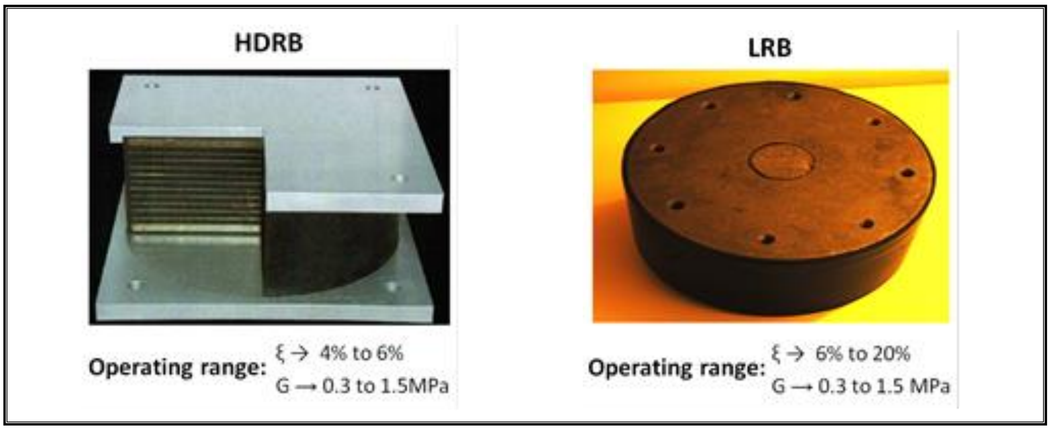

Figure 1. High Damping Rubber Bearing (HDRB) and Low Damping Rubber Bearing (LRB)

MATERIALS AND METHODS

The tests were carried out on different natural rubber – based compounds developed by five different manufacturers (Table 1).

Quadruple shear block specimens in accordance with ISO 1827 (2011) were used. The test piece consists of four square blocks of elastomer, symmetrically disposed and vulcanised on their two largest opposite faces to the mating faces of four parallel steel plates of the same width, to obtain a symmetrical double sandwich arrangement. The dimensions of each block were either 40×40×10 mm or 80×80×20 mm (compounds F2, S2, T2), in any case the dimension of the elastomer in the direction of shear being four times the thickness.

The tests were conducted on a MTS servohydraulic machine rated 100 kN. The test piece was aligned to the direction of load of the testing machine so that the blocks of elastomer were loaded in shear, and secured at its ends to the testing machine with two universal joints in order to avoid transmission of any bending moment (Figure 2).

Table 1.a and Table 1.b Elastomer compounds and real properties evaluated at 100% shear strain, 0.5 Hz frequency and 23°C temperature: *G*, = secant shear modulus, ξ = equivalent viscous damping.

1.a) Low Damping rubber Bearings			
ID		*G*	ξ
Compound	Manufacturer	(MPa)	(–)
A	1	0.7	0.06
B	1	0.7	0.04
C	1	0.6	0.03
D	1	0.9	0.06
E	1	1.2	0.05
F	2	0.6	0.05
G	3	0.4	0.06

1.b) High Damping rubber Bearings			
ID		*G*	ξ
Compound	Manufacturer	(MPa)	(–)
H	3	0.4	0.12
I	3	0.8	0.16
L	3	1.2	0.15
M	3	0.7	0.08
N	4	0.7	0.09
O	5	0.4	0.13
P	5	0.5	0.09
Q	5	0.7	0.11
R	5	0.9	0.13
S	2	1.1	0.08
T	2	1.3	0.17

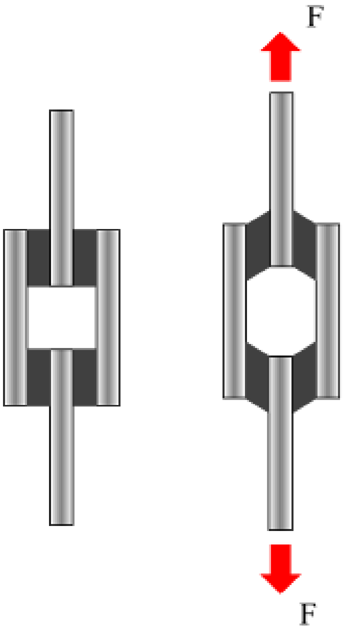

Fig. 2. Test set-up: principle of testing quadruple shear block specimens (left); test piece installed on the testing machine (right).

The test protocol is illustrated in Table 2. For every compound, each test was performed on a different set of three specimens.

Test No 1 was aimed at evaluating the cyclic behaviour of the elastomer in shear at different strain amplitudes. Four complete sinusoidal cycles were applied for each amplitude at the frequency of 0.5 Hz and air temperature of 23°C, and the test sequence was performed in order of increasing amplitude.

The effect of repeated cycles was investigated in Test No. 2; eleven sinusoidal cycles were conducted at the shear amplitude of 100%, frequency of 0.5 Hz and ambient air temperature.

In Test No. 3, sinusoidal cycles at 100% amplitude were conducted at three different frequencies (0.1, 0.5 and 2.0 Hz), in order of increasing frequency.

In Test No. 4, aiming at investigating the influence of temperature, the specimens were conditioned at the various temperature levels before the execution of the cycles. The length of the conditioning was enough to reach the specific temperature within the test sample, avoiding at the same time the occurrence of rubber crystallization in case of prolonged exposure at low temperature (Fuller et al., 2004). The test sequence was performed in order of decreasing temperature.

In test No. 5, that was conducted only on specimens of the compounds F2, S2, T2 the effect of the compression stress perpendicular to the direction of shear was assessed. The test sequence was performed in order of increasing compression stress, from 0 MPa (no compression) to a maximum of

27 MPa, at steps of 3 MPa each one. The compression load was applied to the two external steel plates of the sandwich by means of two hydraulic jacks, and the mean rubber pressure was calculated by dividing the load by the area of the faces of two rubber blocks. Four cycles were performed at each pressure level.

Table 2. Test protocol; test parameters: ε = strain amplitude; f = frequency; T = temperature; p = compressive stress; N = number of cycles at each level of the test parameter.

Test No.	Parameter	ε (mm/mm)	f (Hz)	T (°C)	p (MPa)	N (#)
1	Shear amplitude	0.05 / 0.1 / 0.2 / 0.5 / 1.0 / 1.5 / 2.0 / 2.5	0.5	23	0	5
2	Repeated Cycling	1.0	0.5	23	0	10
3	Frequency	1.0	0.1 / 0.5 / 2.0	23	0	4
4	Temperature	1.0	0.5	40...23...-30	0	4
5	Compressive load	1.0	0.5	23	0…27	4

RESULTS

Figure 3 reports the hysteretic shear stress – strain curves obtained in cyclic sinusoidal tests on a rubber compound under various conditions: (a) at increasing strain amplitude, (b) at increasing number of cycles, (c) at increasing loading frequency, (d) at increasing air temperature.

From the hysteretic stress – strain curves the following quantities were calculated:

- the secant shear modulus G, defined as the ratio between the stress at maximum shear strain, and the maximum shear strain, and
- the equivalent viscous damping ξ, based on the Jacobsen formula

$$\xi = \frac{W}{4\pi \cdot G_{\sec} \cdot \varepsilon^2} \tag{1}$$

where W is the area inside the hysteresis loop and ε is the shear strain amplitude.

In the analysis of the results, the values of mechanical properties calculated at the third cycle of each test sequence were considered, consistently with the prescription of the standard (CEN, 2009) of assessing the effective stiffness and damping of rubber bearings at the third cycle of qualification tests.

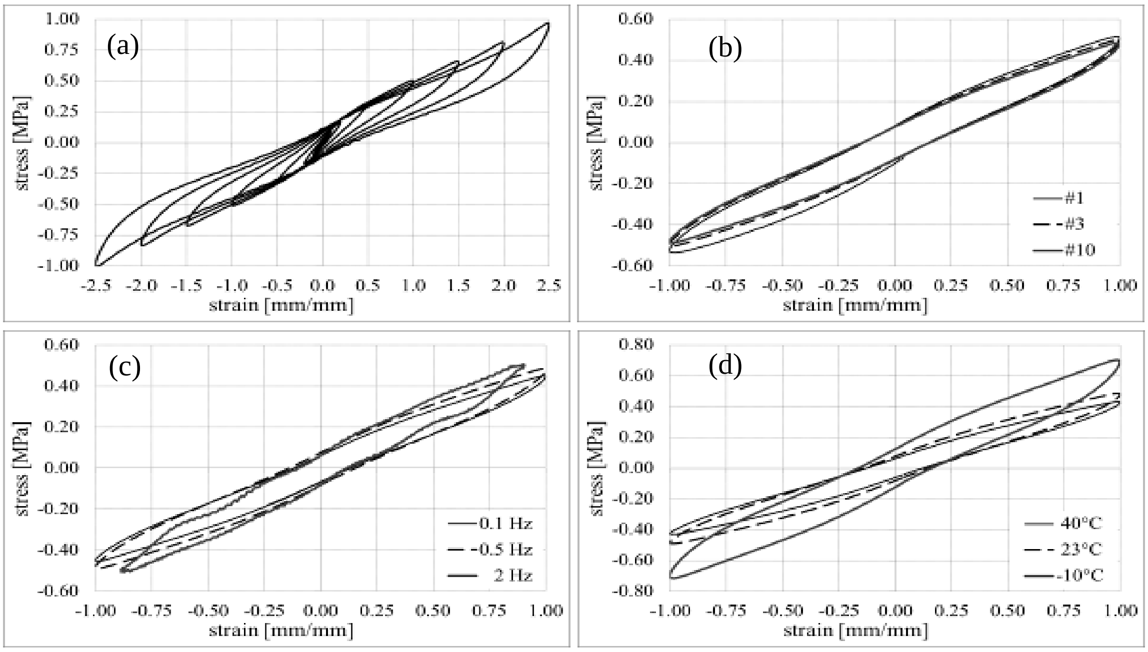

Fig. 3. Hysteretic stress – strain diagrams of an elastomer loaded in shear; influence of: (a) strain amplitude; (b) repeated cycling; (c) frequency of loading; (d) air temperature variation.

3.1 Effect of strain amplitude

Figure 4 illustrates the influence of the strain amplitude on the properties of the elastomer compounds. At magnitudes less than 0.5 mm/mm, which are compatible with those produced in standard bridge bearings under typical service actions (e.g. induced from thermal effects on the civil structure), the shear modulus considerably decreases of about two times for low damping compounds and of four times for high damping compounds, while increasing amplitude. At the large deformation levels typical of those produced in the bearings during strong earthquake shaking, the modulus is more consistent for each compounds (*G* changes less than 0.25 times while the strain amplitude increases from 100% to 250%), though two different behaviors are disclosed: for some elastomers (compounds E1, D1, H3, M3) the modulus increase at larger strains, while other compounds show the opposite trend. This behavior seems to be dependent on the composition of the compounds rather than related to their mechanical properties.

All the compounds shown a continuous decrease of the equivalent viscous damping while increasing deformation, though at a lower rate than the modulus' (ξ decreases from 0.15 to 0.35 times while the strain amplitude is increased from 0.5 to 2.5 mm/mm).

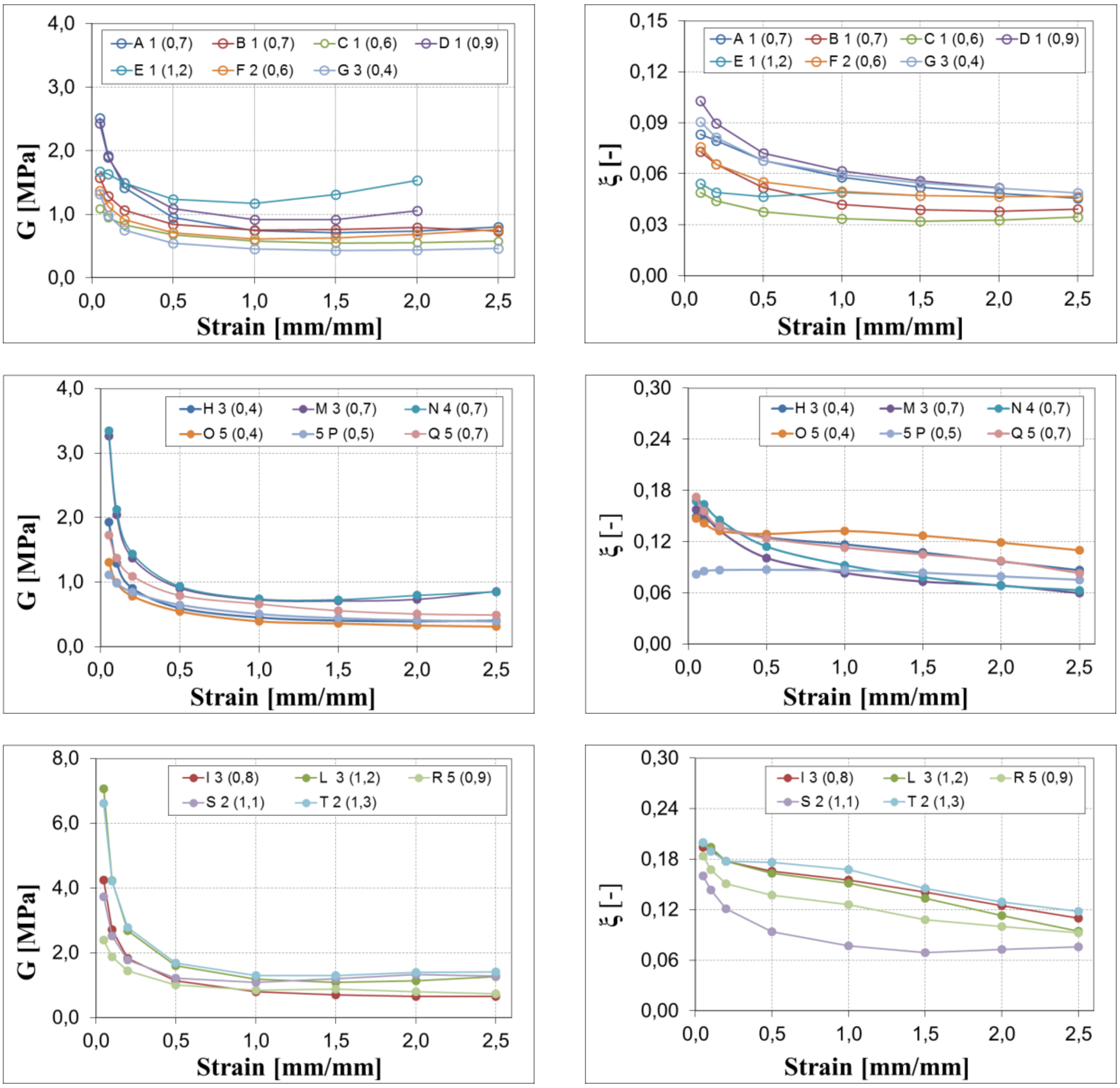

Fig. 4. Dependence of shear properties on strain amplitude.
Specimens H3, M3 N4, O5, 5P, Q5 - Low Damping Compound (ξ ≤ 0,06).
Specimens H3, M3 N4, O5, 5P, Q5 - High Damping Compound with Modulus G ≤ 0,8 (reference conditions).
Specimens I3, L3 R5, S2, T2 - High Damping Compound with modulus G >0,8 (reference conditions)

3.2 Effect of repeated cycles

Figure 5 illustrates the change in the shear properties while increasing the number of cycles performed at constant strain amplitude (1.0 mm/mm).

Both low damping compounds and high damping compounds shown that the modulus and the equivalent viscous damping undertake a sensible decrease (between -5% and -15%) from the first to the second cycle; over the subsequent cycles the damping holds virtually constant, while the modulus continues to decrease though at a lower rate, this effect being more evident for the stiffer compounds (the last diagram of Figure 5, G>0,8MPa). The phenomenon is termed as "scragging" and identifies the changes in the cyclic properties of elastomers that occur during the few cycles of deformation at room temperature, due to a change in the molecular structure of the elastomer (Thompson et al., 2000).

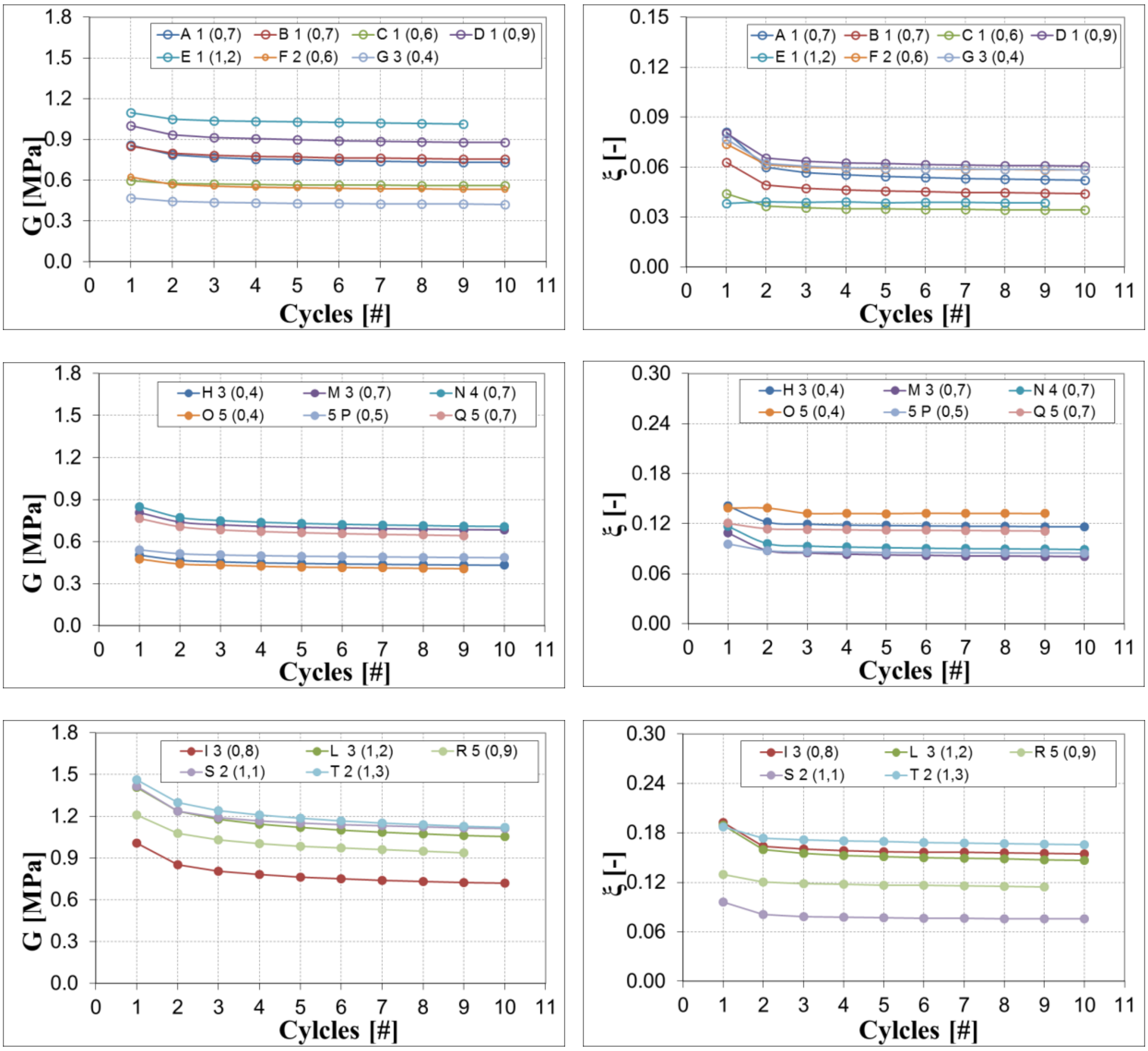

Fig. 5. Dependence of shear properties on repeated cycles.
Specimens H3, M3 N4, O5, 5P, Q5 - Low Damping Compound ($\xi \leq 0,06$).
Specimens H3, M3 N4, O5, 5P, Q5 - High Damping Compound with Modulus $G \leq 0,8$ *(reference conditions).*
Specimens I3, L3 R5, S2, T2 - High Damping Compound with modulus $G > 0,8$ *(reference conditions)*

3.3 Effect of frequency

Figure 6 compares the values of shear modulus and equivalent viscous damping at three distinct frequencies, chosen to cover the range considered in the design of seismic rubber bearings.

The shear modulus and the viscous damping remain almost constant with frequency for the low damping compounds (variations less than 10% over the whole range).

Only the high damping compounds shown an increase on the order of 20% ÷ 30% in the shear modulus while the influence of frequency on equivalent viscous damping can be considered as negligible.

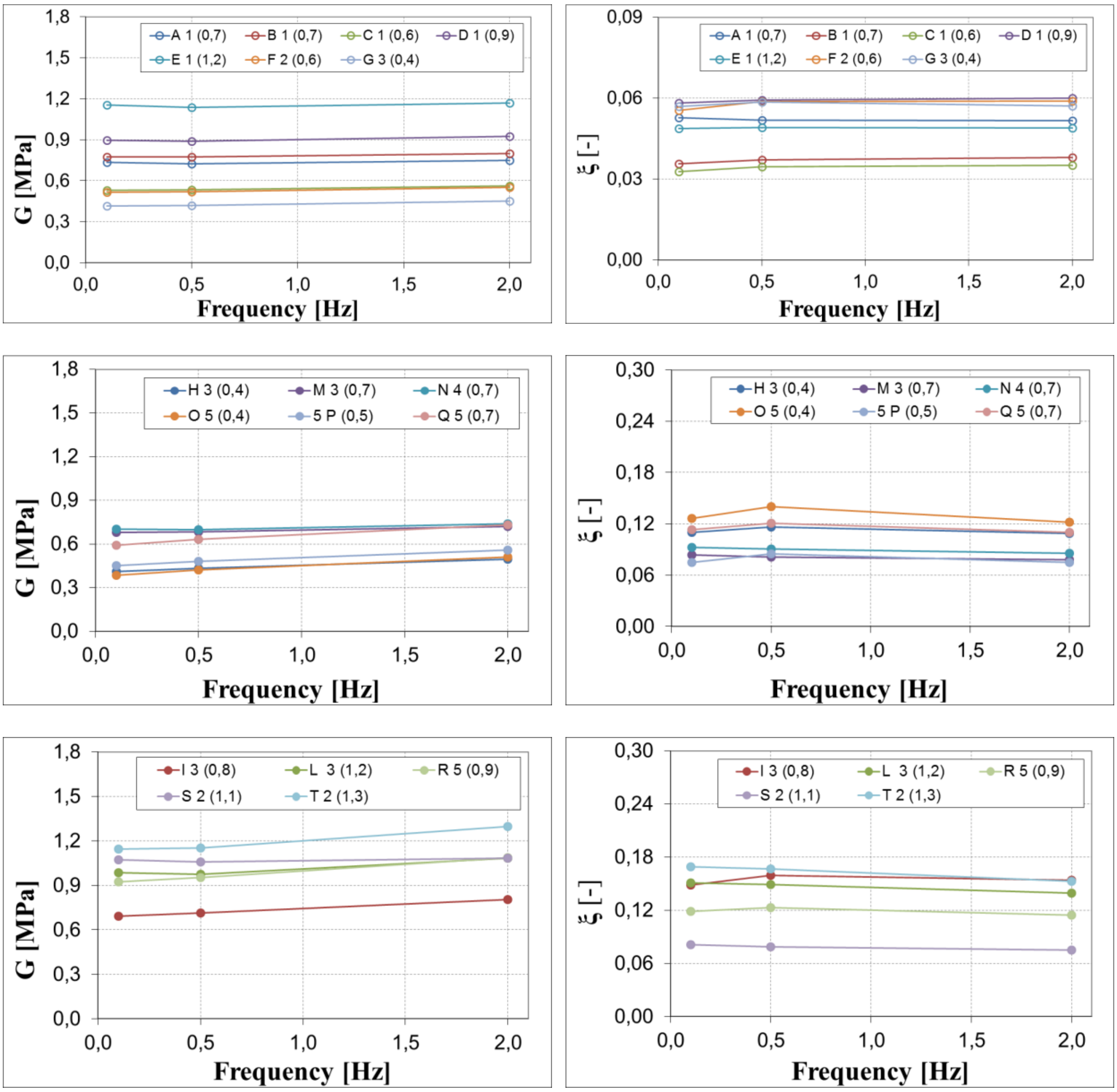

Fig. 6. Dependence of shear properties on frequency.

Specimens H3, M3 N4, O5, 5P, Q5 - Low Damping Compound (ξ ≤ 0,06).

Specimens H3, M3 N4, O5, 5P, Q5 - High Damping Compound with Modulus G ≤ 0,8 (reference conditions).

Specimens I3, L3 R5, S2, T2 - High Damping Compound with modulus G >0,8 (reference conditions)

3.4 Effect of temperature

The change in mechanical behavior of the elastomers after exposure to different air temperatures is illustrated in Figure 7.

Both low damping compounds and high compounds increase the stiffness more than linearly while decreasing air temperature, but low damping compounds increase with a minor rate (G increase of about 1,5 times at -30°C) than high damping compounds (G increase of about 3 times at -30°C). On the contrary, increasing temperature has only a moderate effect on the modulus, with value between 10-20% for the upper temperature.

The influence of temperature on the equivalent viscous damping shows large differences for the different elastomer compounds. In general ξ tend to decrease while air temperature increasing especially for low damping compounds (ξ increase two times from 23°C to -30°C) while high damping compounds show a small or moderate dependence on temperature.

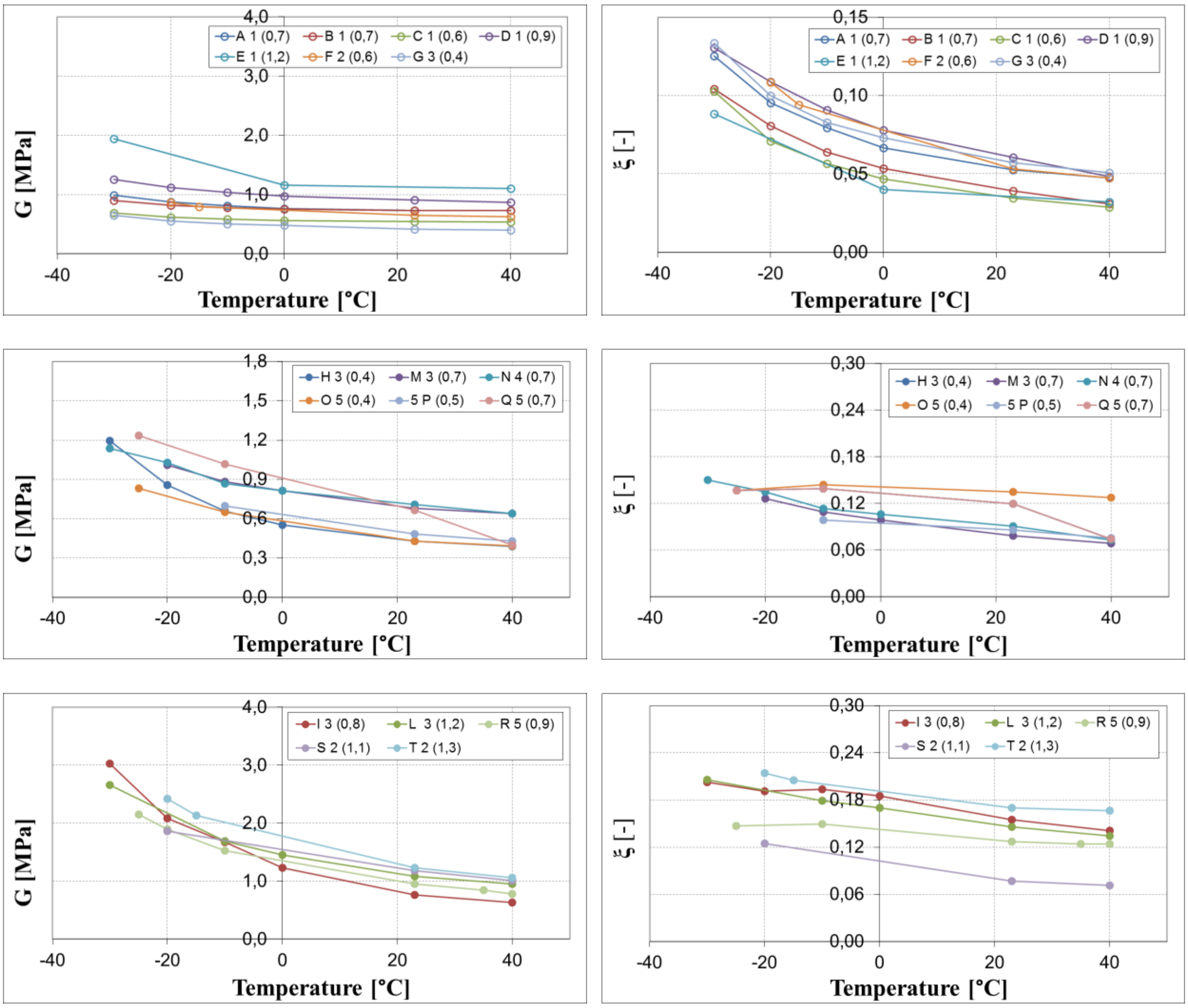

Fig. 7. Dependence of shear properties on temperature.

Specimens H3, M3 N4, O5, 5P, Q5 - Low Damping Compound ($\xi \leq 0{,}06$).

Specimens H3, M3 N4, O5, 5P, Q5 - High Damping Compound with Modulus $G \leq 0{,}8$ (reference conditions).

Specimens I3, L3 R5, S2, T2 - High Damping Compound with modulus $G > 0{,}8$ (reference conditions)

3.5 Effect of compression stress

As shown in Figure 8, the application of a compression load to the rubber blocks affects the shear behavior of the specimens. In general, increasing the compressive stress produces an increase of both the modulus and the equivalent viscous damping: over the pressure range from 0 MPa to 27 MPa the increase in *G* ranges from a minimum of +50% for compound T2 to a maximum of +74% for compound T2, while ξ increases of about +42% (compound S2) and +98% (compound T2); only for compound F2 the effect on ξ is negligible. It is worth noting that in the pressure range between 6 to 20 MPa the equivalent viscous damping of compound F2 meets its design value (ξ = 0.10), while in the test sequences performed on transversally unloaded specimens (Tests No. 1 to No. 4) the measured damping was 30% to 50% less than the design value.

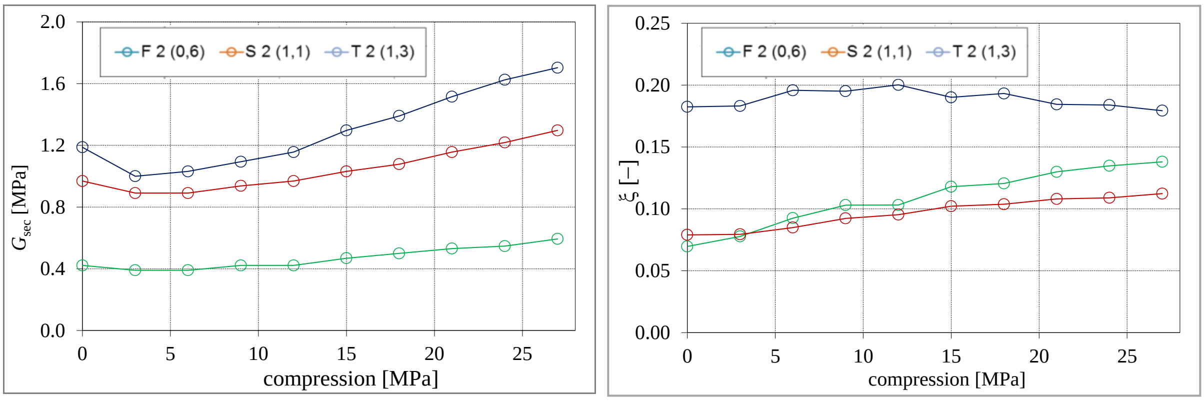

Fig.8 . Dependence of shear properties on compression stress applied to elastomer block.

DISCUSSION

The study confirms the influence of mechanical and environmental factors on the secant shear modulus *G* and the equivalent viscous damping ξ of the elastomer compound. The qualitative behavior is consistent among the investigated elastomers, though the values of the mechanical properties are different even for elastomers with the same nominal value of shear modulus, probably due to different chemical composition and manufacturing process of the compounds developed by the manufacturers.

To quantify the influence on the shear properties of the elastomers, for each design parameter two property modification factors λ_{min} and λ_{max}, are introduced. The two figures are calculated respectively as the ratio between the value of G and ξ at different levels of the property investigated versus the value measured in the reference condition at 1.0 mm/mm shear strain, 23°C and 0.5 Hz (Tables 3 and 4). The variation of lambda factor are shown in fig. 9 and fig.10.

In agreement with a previous study (Cardone et al., 2011), the largest influence is played from the effective ambient temperature, especially below 0°C. The effect of low temperature is a considerable increase of stiffness and in some cases also of damping especially for low damping compound. This change has a direct effect on the final performance of the anti-seismic bearings, as it entails an increase of the shear base forces and vibration frequency induced in the structure by the bearings. On the contrary, the frequency, the number of cycles and the strain amplitude have less influence on the shear properties, at least within the typical operational ranges.

A second important outcome of the study is that the influence of concurrent compression stress on the shear properties of the elastomers is not negligible, and the secant modulus markedly increases while increasing the compression load. Tests performed on full scale rubber bearings lead to similar conclusions (Aiket et al., 1992; Ryan et al., 2004). Nevertheless the coupling between compression and shear stresses is generally not accounted for by the current test standards on elastomers. Based on the findings of the present study, the shear properties of the elastomers determined in absence of a specific compression stress are expected to be not conservative for the design of the bearings, with consequent underestimation of the maximum stresses induced in the structure.

Table 3. Property modification factors for Low Damping Rubber Bearings:

Low Damping rubber Bearings								
Ratio of shear modulus *G*								
Compound	Amplitude		Cycles		Frequency		Temperature	
	$\lambda_{min,\varepsilon}$ (a)	$\lambda_{max,\varepsilon}$ (b)	$\lambda_{min,N}$ (c)	$\lambda_{max,N}$ (d)	$\lambda_{min,f}$ (e)	$\lambda_{max,f}$ (f)	$\lambda_{min,T}$ (g)	$\lambda_{max,T}$ (h)
A1	1.28	1.08	0.85	0.93	1.02	1.04	1.35	1.00
B1	1.12	0.97	0.89	0.95	1.00	1.04	1.24	1.00
C1	1.18	1.00	0.94	0.97	1.00	1.05	1.27	0.99
D1	1.19	1.15	0.88	0.94	1.01	1.04	1.39	0.96
E1	1.06	1.32	0.93	0.97	1.02	1.03	1.87	1.06
F2	1.15	1.24	0.85	0.93	0.99	1.06	1.34	0.96
G3	1.21	1.02	0.90	0.95	0.99	1.08	1.57	0.95
Ratio of viscous damping ratio ξ								
Compound	Amplitude		Cycles		Frequency		Temperature	
	$\lambda_{min,\varepsilon}$ (a)	$\lambda_{max,\varepsilon}$ (b)	$\lambda_{min,N}$ (c)	$\lambda_{max,N}$ (d)	$\lambda_{min,f}$ (e)	$\lambda_{max,f}$ (f)	$\lambda_{min,T}$ (g)	$\lambda_{max,T}$ (h)
A1	1.17	0.79	0.64	0.87	1.02	1.00	2.39	0.90
B1	1.23	0.94	0.70	0.90	0.96	1.02	2.65	0.79
C1	1.11	1.02	0.78	0.94	0.95	1.01	2.98	0.83
D1	1.17	0.84	0.75	0.92	0.98	1.01	2.15	0.80
E1	0.95	0.96	0.98	0.99	0.99	1.00	2.27	0.83
F2	1.11	0.94	0.79	0.95	0.94	1.00	2.04	0.89
G3	1.14	0.82	0.76	0.94	0.97	0.98	2.33	0.89

effect of amplitude : *(a) between 0.5 and 1.0 mm/mm; (b) between 2.5 and 1.0 mm/mm;*
effect of cycles : *(c) between cycle #10 and cycle #1 ; (d) between cycle #10 and cycle #2;*
effect of frequency : *(e) between 0.5 and 1.0 Hz ; (f) between 2.0 and 1.0 Hz;*
effect of temperature : *(g) between -30°C and +23°C ; (h) between +40°C and 23°C*

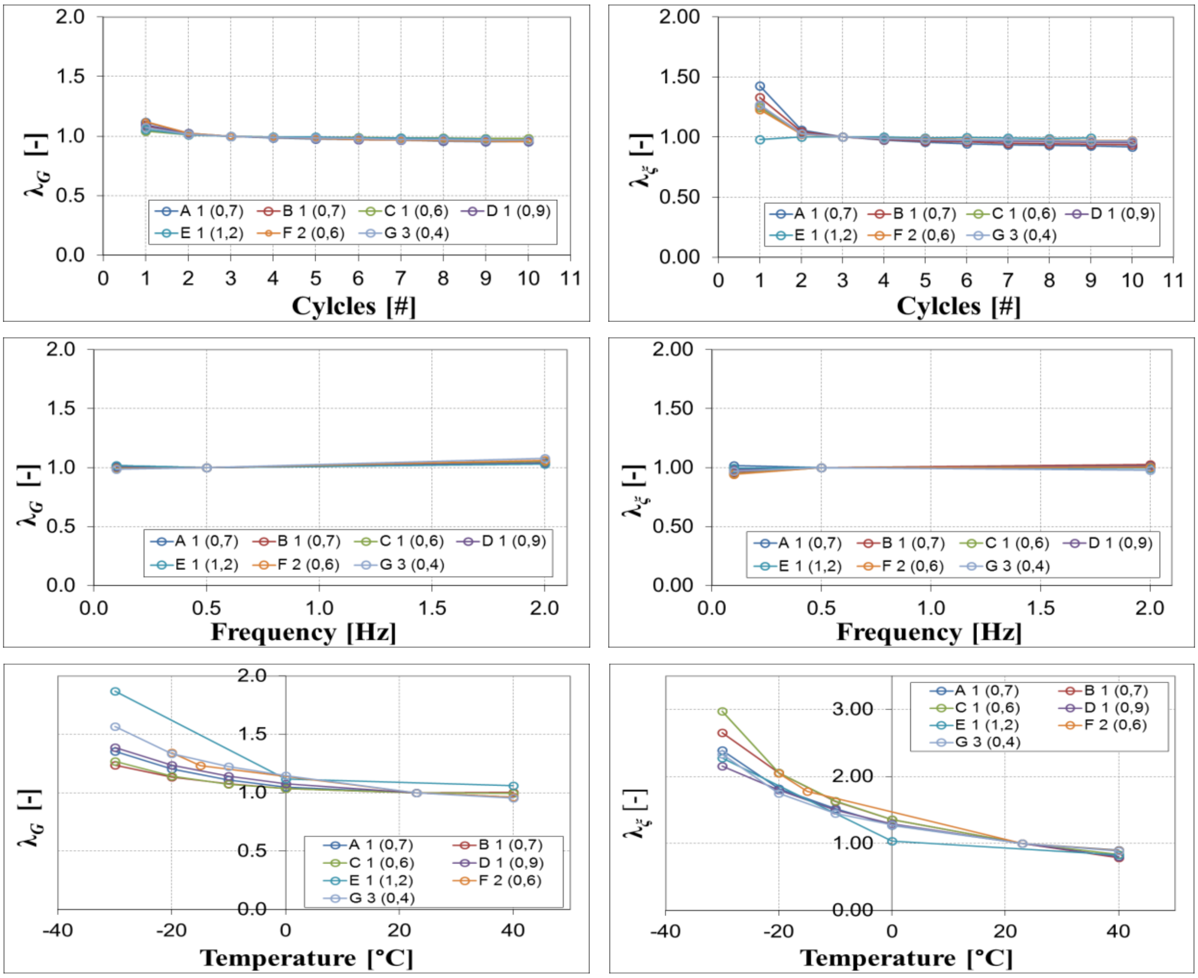

Fig. 9. Dependence of Property modification factors on Low damping rubber compound.

Table 4. Property modification factors for High Damping Rubber Bearings:

High Damping rubber Bearings								
Ratio of shear modulus *G*								
Compound	Amplitude		Cycles		Frequency		Temperature	
	$\lambda_{min,\varepsilon}$ (a)	$\lambda_{max,\varepsilon}$ (b)	$\lambda_{min,N}$ (c)	$\lambda_{max,N}$ (d)	$\lambda_{min,f}$ (e)	$\lambda_{max,f}$ (f)	$\lambda_{min,T}$ (g)	$\lambda_{max,T}$ (h)
H3	1.32	0.89	0.86	0.92	0.95	1.14	2.80	0.91
I3	1.40	0.82	0.71	0.85	0.97	1.13	3.98	0.84
L3	1.36	1.08	0.75	0.85	1.01	1.11	2.45	0.88
M3	1.25	1.19	0.85	0.92	1.00	1.06	1.49	0.94
N4	1.26	1.15	0.83	0.92	1.00	1.06	1.60	0.90
O5	1.39	0.79	0.85	0.92	0.91	1.20	1.93	0.92
P5	1.28	0.77	0.90	0.95	0.94	1.16	1.50	0.89
Q5	1.20	0.74	0.84	0.91	0.94	1.16	1.85	0.60
R5	1.18	0.86	0.78	0.87	0.97	1.14	2.25	0.82
S2	1.12	1.17	0.78	0.90	1.02	1.03	1.58	0.85
T2	1.30	1.10	0.77	0.86	0.99	1.12	1.96	0.86
Ratio of viscous damping ratio ξ								
Compound	Amplitude		Cycles		Frequency		Temperature	
	$\lambda_{min,\varepsilon}$ (a)	$\lambda_{max,\varepsilon}$ (b)	$\lambda_{min,N}$ (c)	$\lambda_{max,N}$ (d)	$\lambda_{min,f}$ (e)	$\lambda_{max,f}$ (f)	$\lambda_{min,T}$ (g)	$\lambda_{max,T}$ (h)
H3	1.07	0.74	0.82	0.95	0.95	0.94	1.71	0.90
I3	1.06	0.71	0.80	0.94	0.93	0.97	1.31	0.91
L3	1.08	0.63	0.78	0.92	1.01	0.93	1.41	0.92
M3	1.21	0.72	0.74	0.92	1.03	0.96	1.62	0.88
N4	1.24	0.68	0.76	0.93	1.02	0.95	1.65	0.80
O5	0.97	0.83	0.95	0.95	0.90	0.87	1.01	0.94
P5	1.01	0.87	0.88	0.97	0.88	0.88	1.14	0.87
Q5	1.10	0.73	0.92	0.98	0.94	0.91	1.14	0.62
R5	1.09	0.74	0.88	0.95	0.97	0.93	1.16	0.98
S2	1.22	0.99	0.79	0.93	1.03	0.96	1.62	0.93
T2	1.05	0.70	0.88	0.95	1.01	0.92	1.26	0.98

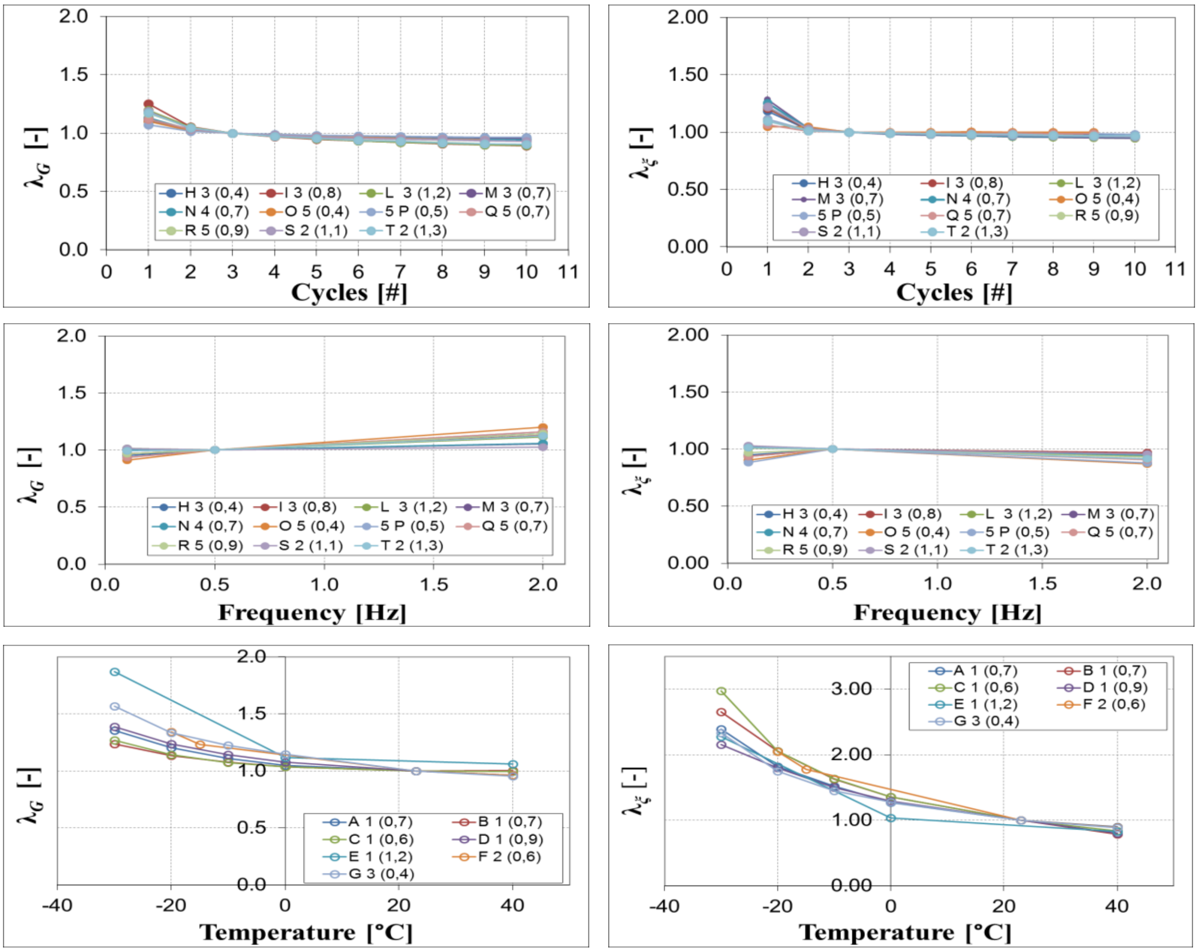

Fig. 10. Dependence of Property modification factors on High damping rubber compound.

CONCLUSIONS

An extensive experimental study on different elastomer compounds used in the manufacture of anti-seismic rubber bearings has been performed with the scope of investigating the effects of the typical working conditions experienced by seismic isolators on their cyclic mechanical properties and to evaluate provisions and limitations reported in the current standards. Based on the results of this study the results evidence that:

- mechanical and temperature factors influence the shear modulus and equivalent viscous damping of elastomer compounds;
- the importance of the chemical composition and manufacturing process of the elastomer compounds developed by the manufacturers;
- the factor with the largest influence is the ambient temperature, especially below zero. Frequency and number of cycles have less influence on the shear properties;
- Low damping rubber results more consistent than High damping rubber at the different levels of frequency, number of cycles and amplitude;
- the application of compression stress has a considerable influence on the shear properties as well. Nevertheless this factor is not accounted for by standards.

REFERENCES

Aiken I D, Kelly J M, et al. 1992. Experimental studies of the mechanical characteristics of three types of seismic isolation bearings, *Proceedings of the 10thWorld Conference on Earthquake Engineering*, Madrid

Constantinou M C, Whittaker A S et al. (2007) Performance of Seismic Isolation Hardware under Service and Seismic Loading. Technical Report MCEER-07-0012, Multidisciplinary Center for Earthquake Engineering Research, Buffalo

Cardone D, Gesualdi G, et al. (2011), Effects of air temperature on the cyclic behavior of elastomeric seismic isolators, Bulletin of Earthquake Engineering 9. 1227-1255

Fuller K N G, Gough J, et al. (2004), The effect of low temperature crystallization on the mechanical behaviour of rubber. Journal of Polimer Science 42. 2181-2190

ISO (International Organization for Standardisation), 2010 ISO 22762: Part 1,Elastomeric seismic protection

ISO (International Organization for Standardisation) 2011 ISO 1827: Rubber. vulcanized or thermoplastic - Determination of shear modulus and adhesion to rigid plates, Quadruple-shear methods

Itoh Y, Gu H, et al. (2006) Experimental investigation on ageing behaviors of rubbers used for bridge bearings. Structural Engineering / Earthquake Engineering JSCE 23

Naeim F, Kelly J M (1999). Design of Seismic Isolated Structures, Wiley New York

Ryan K L, Kelly J M, et al. (2004) Experimental observation of axial load effects in isolation bearings, *Proceedings of the 13th World Conference on Earthquake Engineering*, July 1-6. Vancouver

Skinner R I, Robinson W H, et al. (1993) An Introduction to Seismic Isolation. Wiley, New York

Taylor A W, Lin A N, et al. (1992) Performance of elastomers in isolation bearings: a literature review, Earthquake Spectra 8. 279–304

Thompson A C T, Whittaker A S, et al. (2000) Property modification factors for elastomeric seismic isolation bearings, *Proceedings of the 14th World Conference on Earthquake Engineering*, October 12-17, Beijing