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Experimental seismic characterisation of gravel-granulated tyre mixtures and design implications

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ABSTRACT

Worldwide, due to the large amount of end-of-life tyre (ELT) stockpiles, reusing and recycling of ELTs in civil engineering applications have become a priority, significantly contributing to lessen environmental and health issues related to the ever-growing ELT disposal. In this context, in Aotearoa New Zealand, ELT-derived granulated tyre rubber has been blended with gravel and concrete to form synthetic materials for use in the development of "eco-rubber geotechnical seismic-isolation (ERGSI) foundation systems" for medium-density low-rise residential buildings. The specific purpose of the study reported in this paper is to quantify the seismic mitigation provided by different percentage of rubber to gravel to create an optimum energy-dissipative layer placed beneath a fibre-reinforced rubberised concrete raft foundation. To do so, a prototype ERGSI foundation system placed on gravel-rubber layers with 0, 10%, 25%, and 40% of rubber (by volume) were tested in the laboratory by means of impact tests. By using the wave propagation theory and cross power spectral density frequency response function, modal parameters such as the natural frequency and damping ratio of the different layers were obtained. It was found that, at the foundation level, the peak acceleration decreased and the natural frequency increased with increasing the rubber content. This corresponds to an increase in both the damping and seismic-isolation effects, confirming the effectiveness of ERGSI systems. Considering also strength and compression requirements under static loads, it is proposed that the optimum seismic dissipative gravel-rubber layer for ERGSI foundation systems should have 25-30% rubber content.

1 INTRODUCTION

Ever-growing ELT landfilling and illegal disposal concerns many countries including Aotearoa New Zealand. ELTs can cause serious environmental problems (i.e. groundwater and land contamination), wildfires and health threats if not properly disposed. Thus, in recent years, improved management of such wastes become one of the top priorities in NZ. To date, only 30% of 5 million ELTs are reused/recycled and the rest ends up in landfills, illegal disposal or dumped in stockpiles around the country (Chiaro et al., 2021). Yet, ELTs are a great source of environmentally-friendly and sustainable building materials that may provide novel and effective engineering solutions to attain structures with enhanced seismic resilience (Tsang, 2008). This makes them ideal materials for developing affordable, medium-density, low-rise buildings that are in high demand in New Zealand (Chiaro et al., 2019; Hernandez et al., 2020).

The 2010-11 Canterbury earthquakes presented a challenge and an opportunity for New Zealand engineers to design new buildings with innovative seismic-resilient technologies. As a result, the use of base isolation, controlled damage systems, and damping devices has increased, especially in Christchurch (CERC, 2012). Nonetheless, the application of these innovative technologies has been restricted to medium-high rise buildings, buildings with special functional requirements and bridges due to the maximum benefit to cost ratio, resulting in a lack of resilience in low-rise buildings.

Seismic isolation with energy dissipation has the ability to significantly improve the seismic performance of buildings and structures. Traditionally, *structural seismic isolation* consist of a flexible or sliding interface positioned between a structure and its foundation for the purpose of decoupling the motions of the ground from that of the structure. Yet, in recent years, novel *geotechnical seismic isolation* (GSI) methods have been proposed, in which the flexible or sliding interface is in direct contact with geological sediments and the isolation mechanism primarily involves geotechnical elements (Tsang, 2008). Smooth synthetic liners have been proposed beneath foundations or between soil layers for dissipating seismic energy through sliding. Soil-rubber blends have also been proposed around foundations for absorbing seismic energy with a function similar to that of a cushion. The low cost of such GSI methods can greatly benefit residential buildings for which, otherwise, the use of expensive *structural seismic isolation* techniques is not feasible (Tsang, 2008; Tsang et al, 2012; Brunet et al., 2016; Triavos et al., 2019; Dhanya et al., 2019).

To date, in the GSI framework, research has primarily focused on the mechanical characterization of sand-rubber mixtures due to their low-shear modulus and high damping properties. Yet, from a practical viewpoint, the high compressibility of SRMs may results in low bearing capacity and high foundation settlement (Dhanya et al., 2019). Moreover, in the selection of the soil type and recycled rubber size to form soil-rubber mixtures for use in any geotechnical applications, the availability and the cost efficiency of both materials should be carefully considered (Hazarika and Abdullah, 2016). That is, to avoid inherent segregation of binary mixtures made of large and small particles (Lee et al., 2007; Kim and Santamaria , 2008), the recycled rubber should be cut into smaller (sand size-like) pieces when mixed with sandy soils, which will inevitably increase the implementation costs. Hence, it has been recommenced to use larger-size gravel-rubber mixtures (GRMs) instead (Hazarika and Abdullah, 2016).

Considering the large amount of ELT available in New Zealand, the suitability and cost-effectiveness of using GSI foundation systems beneath residential buildings to enhance seismic resilience and bearing in mind that in New Zealand it is already a common practice to replace the topmost liquefiable sandy soil deposits or problematic soil layers with a compacted layer of free-draining well-graded gravel as part of foundation systems for residential buildings, the development of an improved and distinctive GSI system, namely “ERGSI foundation system” (Fig. 1a) has been proposed by the authors. The ERGSI foundation system is essentially composed of two key elements:

i) a seismic energy-absorption shallow horizontal layer of GRM, and

ii) a flexible fibre-reinforced rubber-concrete raft foundation.

As shown by Fig. 1(b), the two main benefits of the ERGSI are:

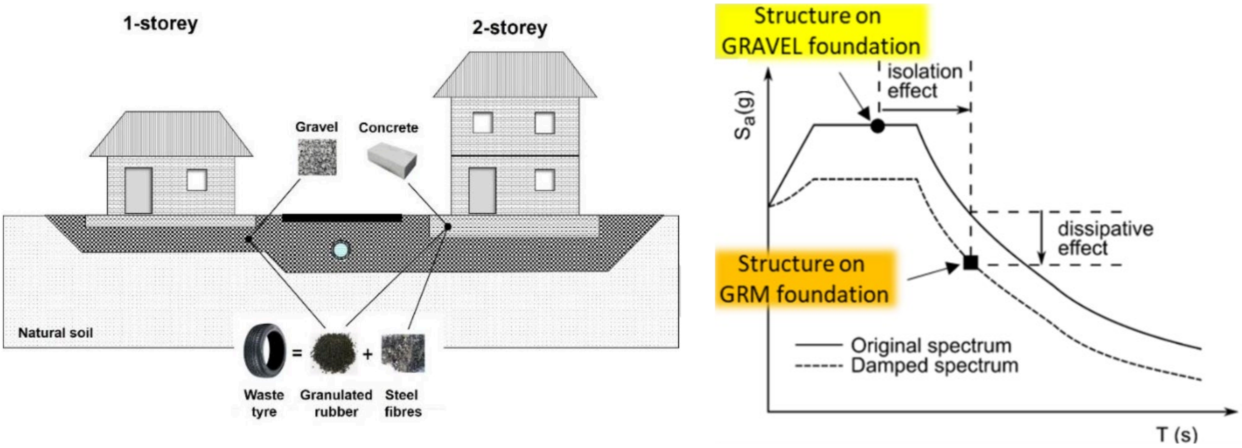

Figure 1: a) a schematic view of ERGSI foundation systems and b) isolation and damping effects on the acceleration- natural period response plane expected for ERGSI (adopted from Chiaro et al., 2020)

(a) *Isolation effect*: the natural period of the system is increased. This occurs because GRMs are more deformable than the natural soil.

(b) *Energy dissipation*: part of the seismic energy is dissipated before reaching the foundation and superstructure, in turn reducing the seismic acceleration on the foundation and superstructure. This is due to the fact that G-GTR mixtures possess higher energy absorption properties (or damping) than the natural soil (Senetakis et al. 2012).

In view of the above background, this study deals with the evaluation of the dynamic effects, including natural frequency and damping effect of G-GTR mixtures for design and optimisation purposes. To do so, a series of impact tests were conducted on a prototype ERGSI foundation system placed on GRM layers with 0, 10%, 25%, and 40% of rubber (by volume). In this paper, the results of natural frequency and dissipative effect of various mixtures are presented and discussed. Design considerations and GRM optimisation criteria are introduced and discussed as well.

2 EXPERIMENTAL PROGRAM

Impact tests were undertaken to investigate the dynamic properties of rounded gravel mixed with granulated tyre rubber, referred as GRMs hereafter. The materials and test procedure are described in the following sections.

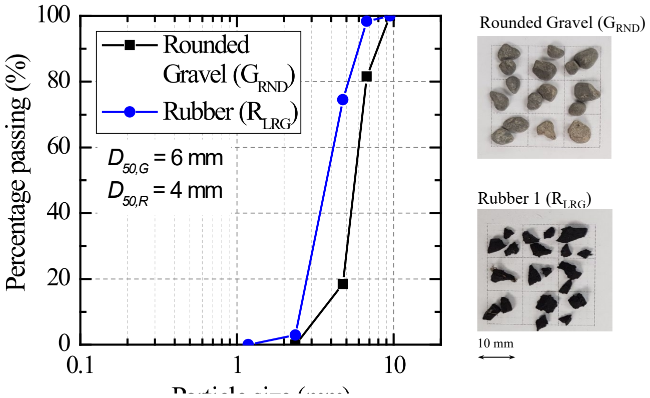

Figure 2: Particle size distribution and photos of tested materials

2.1 Materials

In this research investigation, pure gravel and GRMs were tested. Rounded poorly-graded gravel (G_{RND}) sourced from a local quarry was mixed with large rubber granules (R_{LRG}). Specific gravity (G_s) of gravel and rubber was measured as 2.72 and 1.15, respectively. Particle size distribution (PSD) curves and photos of tested materials are shown in Fig. 2. The figure shows that mean particle size of gravel ($D_{50,G}$) and rubber ($D_{50,R}$) is 6 mm and 4 mm. This means that the aspect ratio ($D_{50,G}/D_{50,R}$) is 1.5.

Impact tests were carried out on GRMs at volumetric rubber content (*VRC*) of 0%, 10%, 25%, and 40%. *VRC* is defined as:

$$VRC = \frac{V_{rubber}}{V_{rubber}+V_{gravel}} \tag{1}$$

where V_{rubber} = volume of granulated tyre chips; and V_{gravel} = volume of gravel in mixtures.

2.2 Test procedures

The impact test apparatus consisted of a tall Plexiglass cylinder with an inner diameter of 190 mm and height of 600 mm as shown in Fig. 3(a). This set-up is adopted following Gatto et al. (2020) with a modification of using taller specimens. The impact hammer and the accelerometer used to excite the specimens and measuring the impact force, respectively, are shown in Fig. 3(b). The tip of the hammer is fitted with a load cell, thus the impact load can be measured for each hit. As per the test setup, to mimic the foundation and the static load for the superstructure, a mass of 7kg (equivalent of 16kPa) was placed over the GRM layers. Moreover, two accelerometers were used, one placed at the base of the cylinder to measure input acceleration (generated by impact hammer) and the other one placed at the top of the specimen (under the mass) to measure arrival waves. These accelerometers were able to record a maximum acceleration of 5g.

Impact tests were performed on fully dried GRMs prepared at a relative density (D_r) of 50% that was calculated based on the values minimum and maximum dry densities reported in Table 1. A summary of the (theoretical) wave propagation properties of GRMs is also presented in Table 1 along with the specific gravity (G_s). All specimens were prepared in 4 equal 150mm layers inside the Plexiglass cylinder, using the under compaction method.

A data logger recorded impact load throughout the test, including the input (exciting) acceleration at the base and output acceleration at top of the specimens. To eliminate the effect of the boundary (Plexiglass) on wave propagation through the specimens, the impact load was applied vertically at the base of the cylinder. Therefore, it was assumed that the recording waves from accelerometers are mainly compression or P-waves (Gatto et al., 2020).

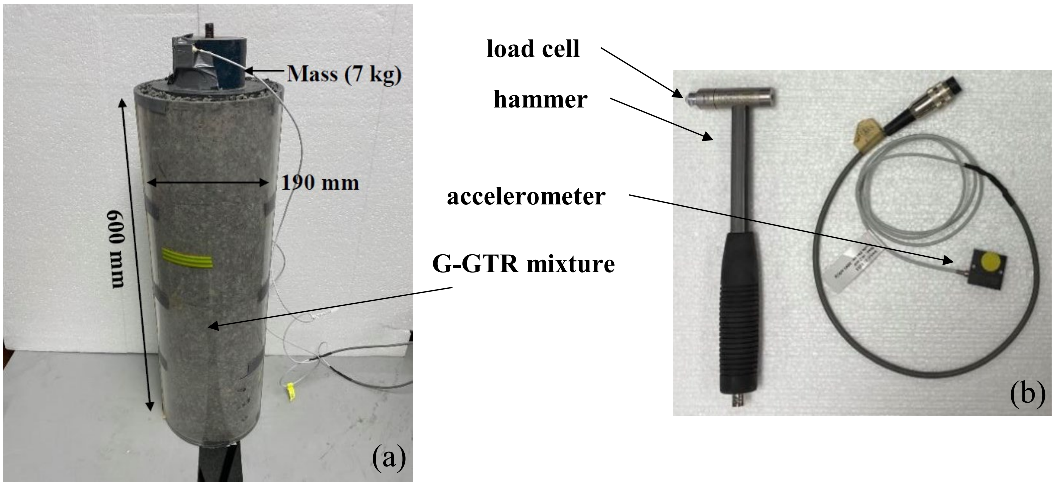

Figure 3: (a) impact test set-up and (b) impact hammer and accelerometer used in this study

Table 1: Summary of index and wave propagation properties of GRMs

VRC (%)	*Gs*	Density (g/cm³)			Theoretical	
		Min	Max	*Dr* = 50%	Wave velocity (m/s)	Natural frequency (Hz)
0	2.71	1.57	1.75	1.66	287.30	119.71
10	2.51	1.44	1.62	1.52	229.66	95.69
25	2.33	1.28	1.49	1.37	182.48	76.03
40	2.09	1.09	1.31	1.19	161.33	67.22

The effect of *VRC* on the isolation effect of GRMs was investigated by determining the natural frequency of various mixtures. The frequency response function (FRF) (Čelič and Boltežar 2008) of the system was calculated by using an estimators based on the cross power spectral density (CPSD) as:

$$FRF = s_{OO} \quad [dB] \tag{2}$$

$$s_{OO} = CPSD(O, O) \tag{3}$$

Where s_{OO} = the estimator that CPSD operation performed on output acceleration only.

Since in this study, the impact load is applied vertically at the base of the cylinder, it can be assumed that the majority of the generated waves would travel vertically through the specimen (P-waves). Therefore, the theoretical natural frequency of the specimen can be calculated as:

$$f_n = \frac{v_p}{4H}(2n - 1) \tag{4}$$

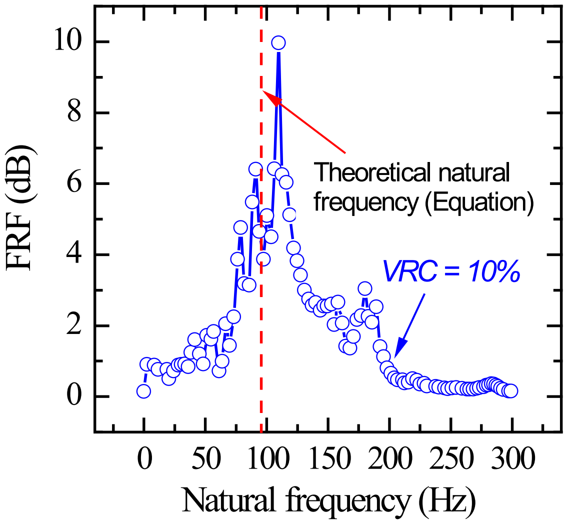

Figure 4: FRF plot obtained for the GRM with VRC = 10%

where v_p = P-waves velocity; H = height of the specimen; n = mode number.

P-wave velocity (v_p) can be determined as:

$$v_p = \sqrt{\frac{M}{\rho}} \tag{5}$$

where M = constrained modulus; ρ = specimen density.

Since most of the *FRF* plots demonstrated local peaks at various frequencies, the peak closer to the theoretical natural frequency (calculated using Eqn. (4) and shown in Table 1) were chosen. An example of *FRF* plot for GRM with *VRC* = 10% and an impact load of 40 N is illustrated in Fig. 4.

3 RESULTS AND DISCUSSION

The effects of rubber inclusion on the dynamic properties of gravel was evaluated considering the natural frequency and damping characteristics. These parameters influence the overall performance of such mixtures to be considered as an energy dissipative and base isolation layer under raft foundation (Fig. 1b).

3.1 Effect of VRC on natural frequency

Two levels of impact load (40 N and 120 N) were applied on each GRMs. The level of loads were measured by the load cell that was fitted at the tip of the hammer. For each specimen, several impact load were applied until the accurate impact load was applied on the specimen. The natural frequency corresponding to the peak value of the *FRF* plot was chosen as the experimental natural frequency of GRMs. Table 2 summarises the results of both theoretical (using Eqn. 4) and experimental natural frequencies. Results indicate that for any level of impact load (40 N or 120 N), the natural frequency decreases with increasing *VRC*.

In order to have a better comparison between different GRMs, the natural frequency of each GRM (f_{G-GTR}) is normalised to the natural frequency of pure gravel (f_G), and the results are illustrated in Fig. 6. As expected, for any level of impact load, both the theoretical and experimental natural frequency of GRM decreased with an increase in *VRC*. Also, the reduction of natural frequency is more significant for *VRC* up to 25% and beyond that, the effect of *VRC* is less evident

Table 2: Summary of the natural frequency of GRMs

***VRC* (%)**	**Natural frequency, *f* (Hz)**		
	Theory	**Experiment (40 N)**	**Experiment (120 N)**
0	119.71	188.7	188.04
10	95.69	110.82	150.47
25	76.03	89.63	83.83
40	67.22	84.65	44.29

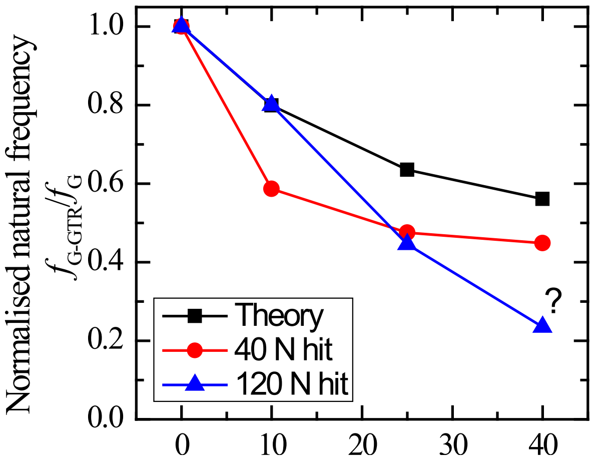

Figure 5: Variation of normalised natural frequency of GRMs with VRC

According to Eqns. (8) and (9), the theoretical natural frequency depends on an estimation of the constrained modulus that is governed by the confining pressure. An average confining pressure was calculated for this purpose, which may not be the same as actual confining pressure experienced by the specimen. Therefore, there may be some differences between the theoretical and experimental natural frequencies as depicted in Fig. 5.

The trend of 40 N hit is very similar to the theoretical one, while for the 120 N hit is slightly different, in particular for 120 N hit at *VRC* = 40% (indicated in Fig. 5). This is mainly due to the limitation of the accelerometers that could record only a maximum acceleration of 5g.

Fig. 6 validates the expected effect of rubber inclusion into gravel, which contributes to an increase in the effect of isolation and a decrease in natural frequency (or increase in natural period).

3.2 Effect of VRC on damping properties

Damping effect of G-GTR mixtures was evaluated by comparing the output acceleration from the arrival waves. Although this is an indirect measurement of the damping effect, it provides strong evidence of the effectiveness of rubber inclusion in gravel for seismic improvement. Fig. 6 shows the variation of output acceleration versus *VRC* and impact load.

Specifically, Fig. 6(a) illustrates that for any level of impact load, the output acceleration decreased with increasing *VRC*. From 0% to 25% rubber content, the effect of rubber inclusion is significant. For instance, at an impact load of 40 N, the output acceleration for pure gravel (*VRC* = 0%) is 0.275 g, while for GRM with *VRC* = 40% is 0.075 g. This is a nearly 70% reduction of the output acceleration (dissipative effect). The influence of rubber appears to be even more dominant for specimens tested at a higher level of impact load.

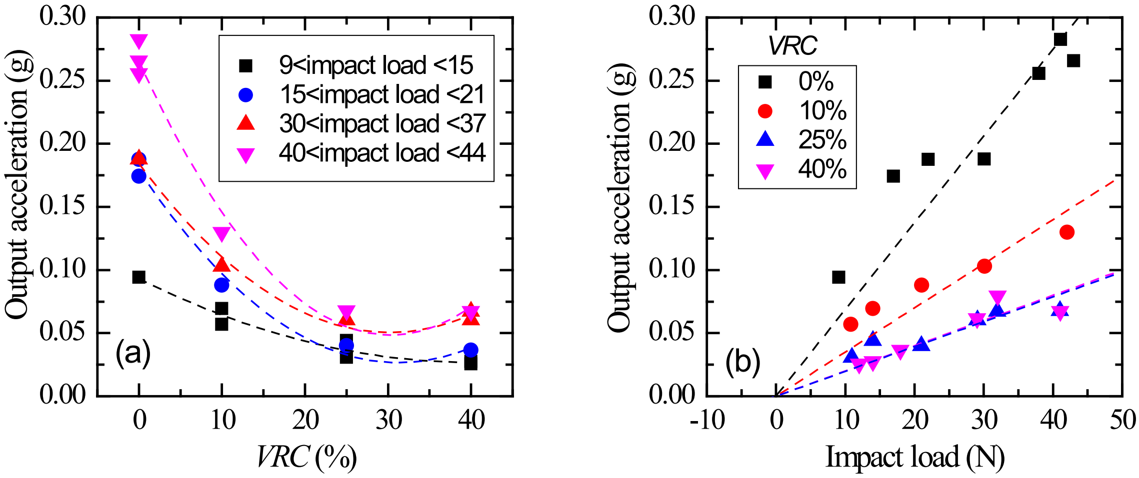

Figure 6: Effect of (a) VRC and (b) impact load on the dissipative effect of GRMs

Fig. 6(b) shows a linear increase of output acceleration with increasing impact load for all G-GTR mixtures. However, the rate of increase is less for mixtures with higher rubber content. It is also evident that even a small amount of GTR (i.e. *VRC* = 10%) contributes significantly in the dissipation of wave energy. On the other hand, *VRC* of 25% and 40% almost follow the same trend. In other words, it seems that *VRC* = 40% does not provide any additional dissipative effects compared to *VRC* = 25%, and all the mixtures in this range could be used.

4 DESIGN IMPLICATIONS AND OPTIMISATION

While this paper mainly deals with the evaluation of the dynamic properties of GRMs for the development of ERGSI foundation systems, from a practical viewpoint it is important also to consider strength (i.e. bearing capacity) and compressibility (i.e. vertical settlement) properties of these synthetic materials as well as suitable performance-based design criteria that can be used for ERGSI foundation design purposes (Chiaro et al., 2020; Tasalloti et al., 2020).

The experimentally-derived charts developed by Chiaro et al. (2020) that are reported in Fig. 7 refer to values of friction angle and volumetric strain for various mixtures and applied vertical stress (σ_v') levels that of relevance for many geotechnical applications. Such charts can be then used for the design of ERGSI foundation systems for 1- to 2-storeys NZ residential buildings, where the σ_v' induced by the structure is typically less than 20 kPa.

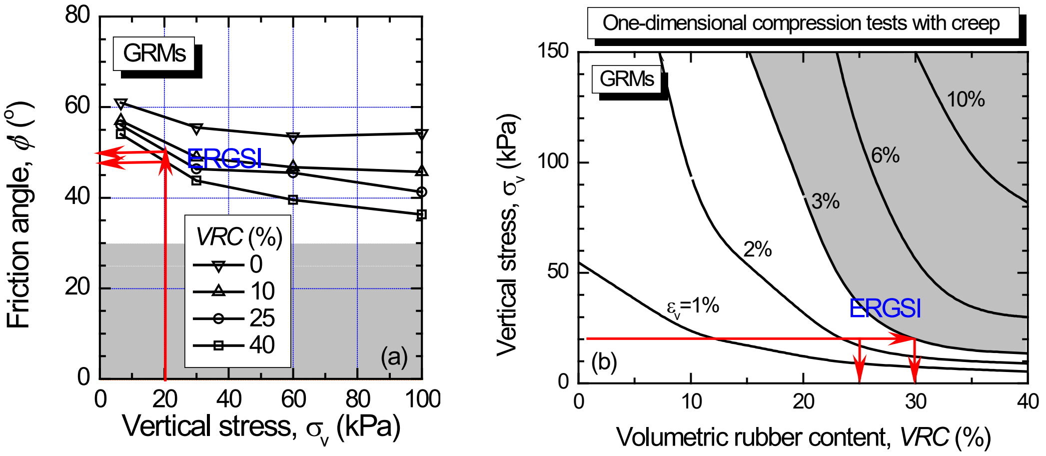

Figure 7: (a) friction angle and (b) one-dimensional compressibility of GRMs (Chiaro et al. 2020)

To avoid shear failure of a foundation and provide adequate allowable bearing capacity, a friction angle greater than 30° is usually required in the case of granular materials. From Fig. 7(a), it is evident that all the mixtures with 25% ≤ *VRC* ≤ 40% (that possess very good dynamic properties) have also friction angle much greater than 30° for $\sigma_v' \leq 20$kPa that amply satisfy strength requisites.

On the other hand, to guarantee the serviceability after construction (including avoid damage to pipelines and other essential services embedded in the foundation), typically the recommended maximum acceptable vertical strain (ε_v) is usually 3% or less. By entering the chart in Fig. 7(b) with a $\sigma_v' = 20$kPa and intersecting the line for $\varepsilon_v = 3\%$, it appears that all the mixtures with *VRC* ≤ 30% would meet the serviceability criterion.

Based on the above and considering the best possible dynamic response, it can be recommended that the range of suitable GRMs for ERGSI foundation systems should be limited to 25% ≤ *VRC* ≤ 30%.

5 CONCLUSION

This paper presented the experimental results obtained by testing gravel-granulated tyre rubber mixtures (GRMs) to evaluate the potential of eco-rubber geotechnical seismic isolation systems in reducing the seismic acceleration at the foundation level and, therefore, more importantly on the superstructure.

GRMs with volume rubber content (*VRC*) equal to 0, 10, 25 and 40% were tested by means of impact test, and the acceleration recorded at the foundation level was analysed in both the time and frequency domain. Results show that there is a significant reduction in the natural frequency by increasing *VRC* in GRMs, independently on the impact load applied. For example, adding 25% rubber to gravel reduced the natural frequency by 50%, which is equivalent as increasing the natural period of a structure by 50%. Therefore, GRMs can be an effective solution to reduce the seismic acceleration on the super structure by shifting the response on right side of the acceleration-natural period plane.

Furthermore, this study has shown that the acceleration at the foundation level is reduced up to 70% with increasing *VRC*, with the highest relative increment for *VRC*=25%. This occurs because of the GRMs capacity to dissipate energy.

Taking into account also the strength and compressibility properties required to satisfy stability and settlement performance-based criteria for foundation (Tasalloti et al. 2020; Chiaro et al., 2020), it is evident that 25% ≤ *VRC* ≤ 30% represents an optimum range of values for ERGSI foundation systems.

In conclusion, the results of this study suggest that GRMs are a promising and attractive solution to lessen environmental issues related to ELT disposal and improve in a cost-effective way the seismic performance of medium-density low-rise buildings in New Zealand that are in high demand.

6 ACKNOWLEDGMENTS

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