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AN INNOVATIVE AND ECO-FRIENDLY FOUNDATION SYSTEM TO ENHANCE THE RESILIENCE OF LOW-RISE BUILDINGS

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SUMMARY

A multi-disciplinary geo-structural-environmental engineering project funded by the Ministry of Business Innovation and Employment (MBIE) is being carried out at the University of Canterbury. The project aims at developing an eco-friendly seismic isolation foundation system which will improve the seismic performance of medium-density low-rise buildings. Such system is characterized by two main elements: 1) granulated scrap rubber mixed with gravelly soils to be placed beneath the structure, with the goal damping part of the seismic energy before it reaches the superstructure; and 2) a basement raft made of steel-fibre reinforced rubberised concrete (SFRRuC) to enhance the flexibility and toughness of the foundation, looking at better accommodating the displacement demand. In this paper, the main objectives, scope and methodology of the project will be briefly described. A literature review of the engineering properties of steel-fibre reinforced rubberised concrete (RuC) will be presented. Then, preliminary results on concrete mixes with different rubber and steel fibres content will be exhibited.

INTRODUCTION

The recent Christchurch and Kaikoura earthquakes (Dizhur et al. 2017; Kam & Pampanin 2011) evidenced the required shift in current design practice of structures to achieve better seismic performance. An opportunity for New Zealand engineers to design new buildings with innovative seismic-resilient technologies was presented, resulting in an important number of new buildings using innovative technical solutions, e.g. base isolation, controlled rocking systems, damping devices, etc., especially in Christchurch (CERC 2012). However, the application of these innovative technologies is often restricted to medium-high rise buildings due to the maximum benefit to cost ratio. Consequently, low-rise buildings e.g. residential houses and small commercial buildings, continue being susceptible to damage that can lead to displacements of residents and significant economic loss (Figure 1).

In addition, environmental concerns have urged civil engineers to identify sustainable ways to reuse of waste tyres through large-scale recycling engineering projects. Globally, an estimated one billion tyres reach the end of their useful lives every year (WBCSD 2018). In New Zealand, the current rate of waste tyres production is over 5 million units per year and is expected to grow over time with increased population and number of vehicles on the road. The country estimates 70% of such waste tyres are destined for landfills, stockpiles, illegal disposal or are otherwise unaccounted for (MFE 2015), giving rise to piles of tyres that do not readily degrade or disintegrate. Compared to the recovery tyre rate of other developed countries, e.g. Japan or United States, more than 85% (WBCSD 2018), the 30% recovery rate of New Zealand results deficient.

(a) (b)

Figure 1: Examples of residential damage after 2011 Christchurch Earthquake. a) Soft storey failure of timber framed house. b) Differential settlement (Buchanan et al. 2011)

Waste tyre constituents (Table 1) are a great source of high quality and sustainable materials (Figure 2) that can be made affordable and readily available through technological innovations. One of such innovations is to recycle waste tyre (in the form of granulated tyre rubber - GTR) mixed with gravelly soils and concrete to develop seismic-isolation foundation systems for low-rise residential buildings (Chiaro et al. 2019b; Tsang et al. 2012). While this system is conceptually similar to conventional discrete elastomeric seismic isolation on rubber bearings (i.e. base-isolation), it differs in that the proposed system will be continuously distributed along the contact surface separating the building or series of multi-storey/multi-dwelling complexes from the ground. It is expected that the accelerations and consequent seismic inertial forces will be reduced at least by 40% (Tsang 2008).

Table 1 Typical composition of manufactured tires by weight (Siddique & Naik 2004)

Composition (%wt)	Automibile tire	Truck tire
Natural rubber	14	27
Synthetic rubber	27	14
Carbon black	28	28
Steel	14-15	14-15
Fabric, filler, accelerators and antiozonants	16-17	16-17

In order to address the development of this seismic enhanced and eco-friendly foundation system, a multi-stage comprehensive geo-environmental-structural experimental research programme is being carried out at the University of Canterbury. Although complete experimental and numerical results are not available yet, the authors aim to overview some preliminary experimental results, a state-of-the-art literature review for both geotechnical and structural applications and brief on the MBIE Smart Idea project “Eco-rubber seismic isolation foundation system” goals and objectives.

EFFECTS OF RECYCLED RUBBER PARTICLES IN STRUCTURAL CONCRETE

Over the past three decades, the effects of the use of RRP in fresh state, hardened properties of concrete (Figure 3) have been investigated by several authors (Eldin & Senouci 1992; Khatib & Bayomy 1999; Najim & Hall 2010; Raffoul et al. 2016; Topcu 1995; Youssf et al. 2015; Youssf et al. 2019). Nowadays, it is well known that RuC properties are significantly modified by the

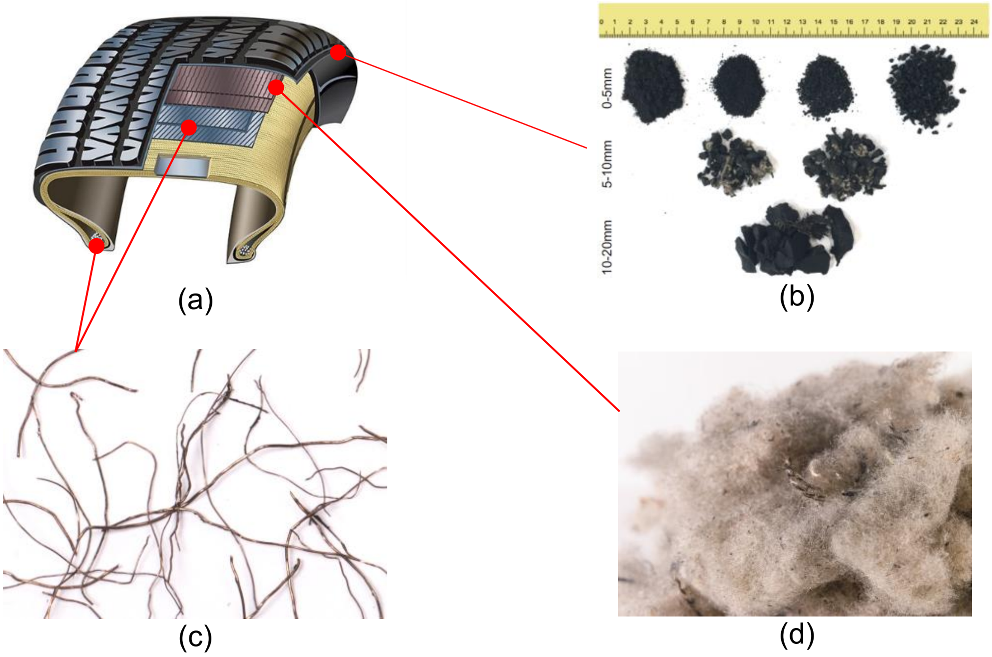

Figure 2: Recycled tyre materials, a) Cross section of a passenger tyre b) Recycled rubber particles (RRP) used to replace sand (0–5 mm) and gravel (5–10 mm and 10–20 mm) (Raffoul et al. 2017), c) Recycled steel fibres (RTFS) (Hu et al. 2018a) and d) Recycled tyre polymer textile (RTPT) (Baričević et al. 2018).

size, content, shape and surface texture of the RRP. Moreover, due to its low modulus of elasticity and lack of bond, between rubber particles and cement paste, rubber aggregates tends to behave as weak inclusions (pores) in the hardened concrete mass, decreasing compressive and tensile strength, flexural strength and modulus of elasticity. However, rubber particles improved control of cracks, energy absorption, ductility and toughness, results that are commendable for seismic applications (Zheng et al. 2008b). Base on the aforementioned, an in-depth understanding of the micro and macro RuC behaviour is essential to implement this novel material effectively within structural load-bearing members.

Fresh state properties

Workability of RuC depends on content, size, shape and texture of recycled rubber particles (Eldin & Senouci 1992). Khatib and Bayomy (1999) suggested an upper value of 50% (total aggregate volume) rubber content to maintain workable mixtures. Youssf et al. (2014) and Raffoul et al. (2016) informed the use of plasticizers and superplasticizers to reach the required concrete workability without a major issue. Youssf et al. (2014) suggested the use of superplasticizers in the range of 1% to 3% by cement. Besides, unit weight reduction is expected due to the lower unit weight of rubber particles compare to mineral aggregates, and the higher air content reported (Fedroff et al. 1996).

Hardened properties

The mechanical properties of RuC, as conventional concrete (CC), depend on the properties of its constituents. It is evident that properties of mineral aggregates differ from recycled rubber particles. Mineral aggregates exhibit a strong and brittle behaviour, while rubber particles behave in a ductile and resilient manner. As a result, the behaviour of RuC largely depends on the rubber content in the mixture. Mechanical properties, such as compressive and tensile strength, flexural strength, modulus of elasticity, strain-stress behaviour has been widely investigated (Alsaif et al. 2018; Eldin & Senouci 1992; Hu et al. 2018a; Khatib & Bayomy 1999; Topcu 1995; Toutanji 1996; Xue & Shinozuka 2013; Youssf et al. 2014; Youssf et al. 2019;

(a) (b)

Figure 3: Concrete specimens fine rubber content a) 40%, and b) 100% (Raffoul et al., 2016).

(a) (b)

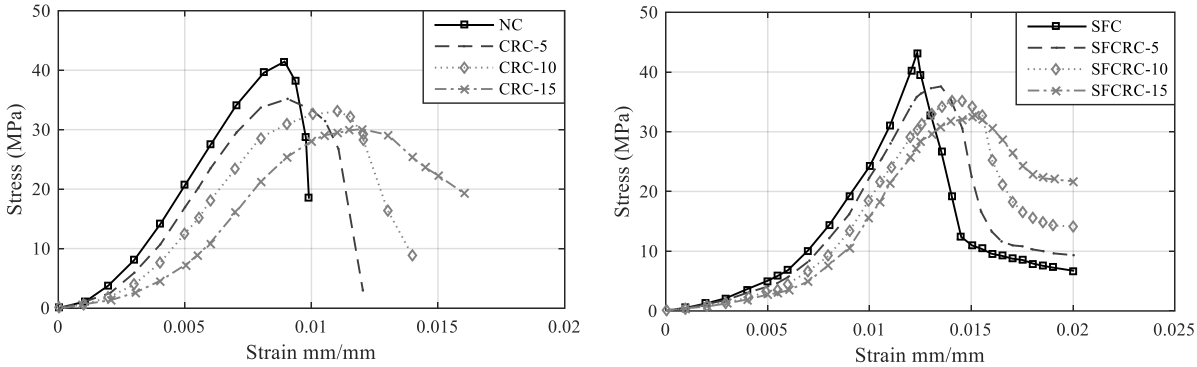

Figure 4: Enhancement in deformability of concrete due to the inclusion of RRP only (a) and RRP and steel fibres (b). Adapted from Noaman et al. (2016).

Zheng et al. 2008a). Authors reported losses in strength and stiffness when total volume of rubber in the mixture was increased, but enhancements in toughness, ductility and energy absorption at the same time. Noaman et al. (2016) proved the potential of crumb rubber to change the post-peak behaviour of concrete from brittle to ductile, as shown by the stress-strain behaviour presented in Figure 4a. The results also displayed the increased strain capacity, flexibility and levels of energy absorption (area under the curve) that were achievable.

Recent investigations have demonstrated that an appropriate mix design, mixing procedure and RRP pre-treatment; can minimise reductions in strength of RuC. Raffoul et al. (2016) examined the effects in RuC of size, content and pre-treatment of rubber particles; water and admixture contents, silica fume (SF) and pulverised fuel ash (PFA). The authors proposed an optimise mixture design, replacing 20% of the cement mass by SF and PFA, and using plasticizer and superplasticizer to increase the workability. The optimise mixture minimised the adverse effect of rubber particles in fresh state and hardened properties. For instance, at 40% of fine aggregates replacement the compressive strength was reduced 70% by the original mix, whereas 49% by the optimised mixture.

Youssf et al. (2019) investigated the influence of mixing procedures, rubber pre-treatment and fibre additives in the compressive, tensile and flexural strength of RuC with 15%, 20% and 30% rubber content. The results showed enhancements in workability by an average of 22% only by doubling the net mixing time. Chemical pre-treatments of rubber particles resulted in a reduction of workability and had no significant increases on the compressive strength of RuC. The authors concluded that simply washing the rubber particles to remove impurities, mixing cement with rubber particles at the beginning of the mixing process and using longer mixing times, can better workability and concrete strength, with no additional cost.

Dynamics characteristics

Inclusions of RRP can result in significant improvements in the dynamic response of RuC when compared to CC. Zheng et al. (2008b) examined the dynamic modulus of elasticity, natural and vibration damping of RuC. Compared to CC, the damping ratios of both RuC with fine (FR) and coarse (CR) aggregate replacements was improved. For FR and CR rubberised concrete at the first 40 cycles, increases as high as 75.3% an d 144.0%, respectively, were measured. Besides, it was observed that RuC damping properties were more sensitive to vibration response than CC. At higher maximum response amplitude, increases in RuC damping ratio became larger.

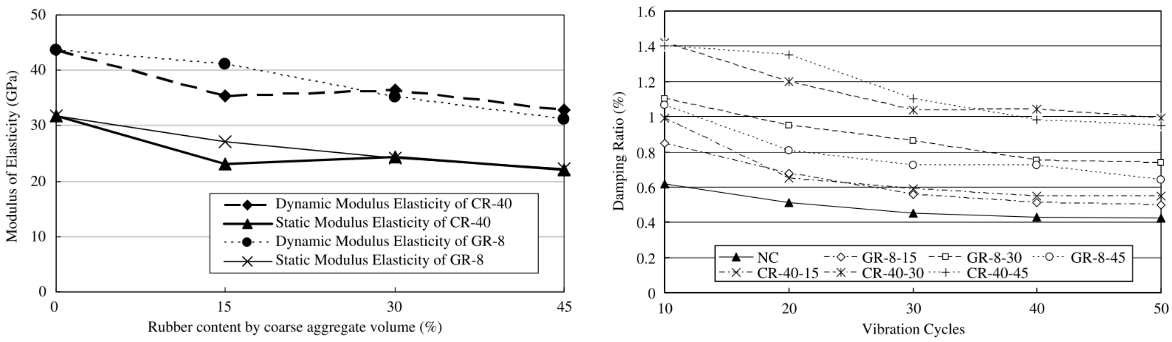

Figure 5: Comparison between rubberised and conventional concrete (a) Modulus of elasticity (b) Damping ratio. Adapted from (Zheng et al. 2008b)

Xue and Shinozuka (2013) investigated the damping and seismic response of small-scale concrete columns with crumb rubber replacing 15% of total aggregate volume. Free vibration tests resulted in an average damping ratio of 4.75% and 7.70% for conventional and rubberised concrete, respectively. This 62% increase indicates the energy dissipation capability of rubberised concrete and is attributed to the hyper-elastic nature of rubber, along with its high tensile strength and Poisson ratio. Seismic shake table testing showed that, on average, adding crumb rubber to concrete reduced the seismic response acceleration by approximately 27%. Such a decrease in acceleration results in less seismic forces being transferred to the RuC column – a desirable attribute for concrete structures in seismic environments.

STEEL FIBRE REINFORCED RUBBERISED CONCRETE USING RECYCLED FIBRES

An effective method of limiting strength reductions in RuC is the inclusion of steel fibres. These fibres act as micro reinforcing within the concrete, “bridging” over micro tensile cracks and therefore resisting the propagation of cracking within the interfacial transition zone. The introduction of these fibres has positive impacts on the compressive and splitting tensile strengths, along with further increases in toughness, ductility and energy absorption as seen in Figure 4b and Figure 6.

Furthermore, a typical automobile tyre has approximately 1.4 kg of steel belts and bead wires (15% of its weight). The type of steel used in tyres manufacturing is a high strength steel with a nominal tensile strength of 2750 MPa (RMA 2000), higher strength than typical manufactured steel fibres 1345 MPa. On top of that, life cycle assessment studies have demonstrated that recycling of steel fibres in waste tyres need less than 5% of the energy input required to produce typical manufactured steel fibres (MSF), which highlights the environmental benefits of using RTSF in concrete (Hu et al. 2018b).

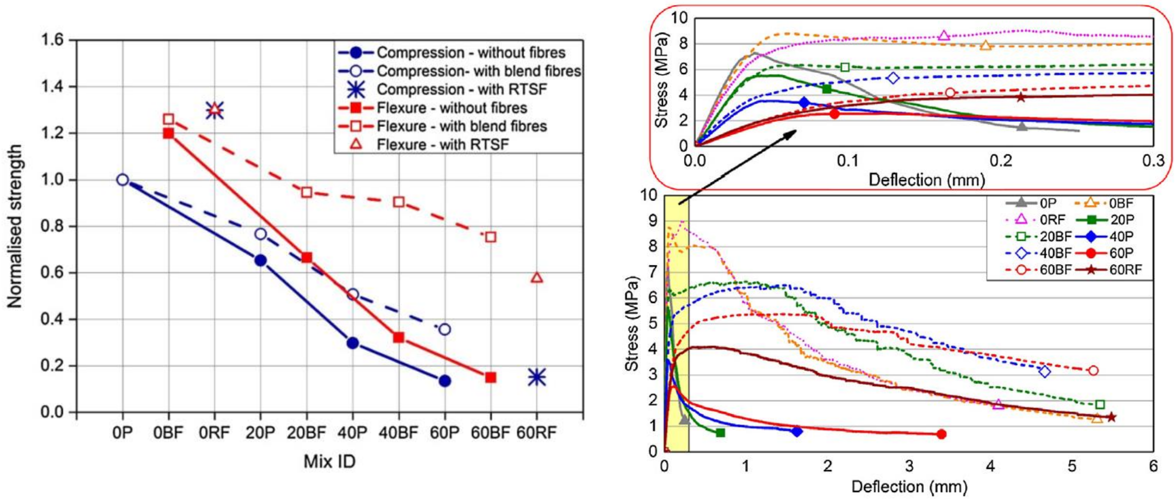

Figure 6: Enhancement in deformability of concrete due to the inclusion of RRP only (a) and RRP and steel fibres (b). (Alsaif et al. 2018)

Alsaif et al. (2018), investigated the use of steel fibre reinforced rubberised concrete for flexible concrete pavements. Ten concrete mixes, with different percentage of rubber and steel fibres (MSF and RTSF) were tested. It was reported that the addition of steel fibres mitigates the loss in flexural strength from 50% to 9.6% loss, compared to CC (Figure 6a). Increasing were measured in compressive and modulus of elasticity, up to 12.5% and 28.4%, respectively (Figure 6a). The authors concluded that high performance and highly flexible steel fibre reinforced rubberised concrete can be produced with 60% rubber content and blended fibres (20 kgf/m3-MSF and 20 kgf/m3-RTSF).

SOIL-TYRE RUBBER IN FOUNDATION SYSTEMS

In recent decades, scrap tyre derived materials (in form of chips, crumbs, granules, and shreds) mixed with granular soil (mainly sand) have been used in civil/geotechnical applications such as light backfill material, drainage layer, slope stabilisation and landfill construction. More recently, investigation on the dynamic properties of soil-rubber mixtures exhibited interesting results that enable them to be used as seismic isolation material as part of foundation design. In order to analyse the feasibility of waste tyre rubber particles as an improving component of foundation systems, engineering properties need to be investigated. An overview of the dynamic properties and leachate characteristic is presented in this section.

Soil-rubber mixture: dynamic geotechnical properties

A numerical modelling conducted by (Tsang et al. 2012) indicated that by inclusion of a soil-rubber layer around foundation of a low-rise building, the maximum horizontal acceleration at roof and footing under earthquake loading could be reduced up to 70%. Similarly, (Brunet et al. 2016) reported that a layer (between 2 to 3 m) consisted of soil-rubber mixture underneath a two-story building could decrease peak acceleration at the base by 54%.

There are several factors influencing on the dynamic response of soil-rubber mixtures such as rubber content, soil type and shape (sand, gravel, rounded, angular), rubber type (fibres, crumbs, shreds, buffing, granules), relative particle size between soil and rubber ($D_{50,s}/D_{50,r}$), confining pressure, and etc. These parameters were extensively considered in the past for mixtures of sand-rubber under monotonic and dynamic loading and the behaviour of these blends have been well determined. Although rubber improved the dynamic properties of soil (mainly increasing damping ratio), there is a threshold for maximum rubber content in this regard. Beyond this threshold (generally 35% to 45% by weight), shear strength of the mixture reduces significantly due to lack of soil-soil particle interactions (Edincliler & Cagatay 2013;

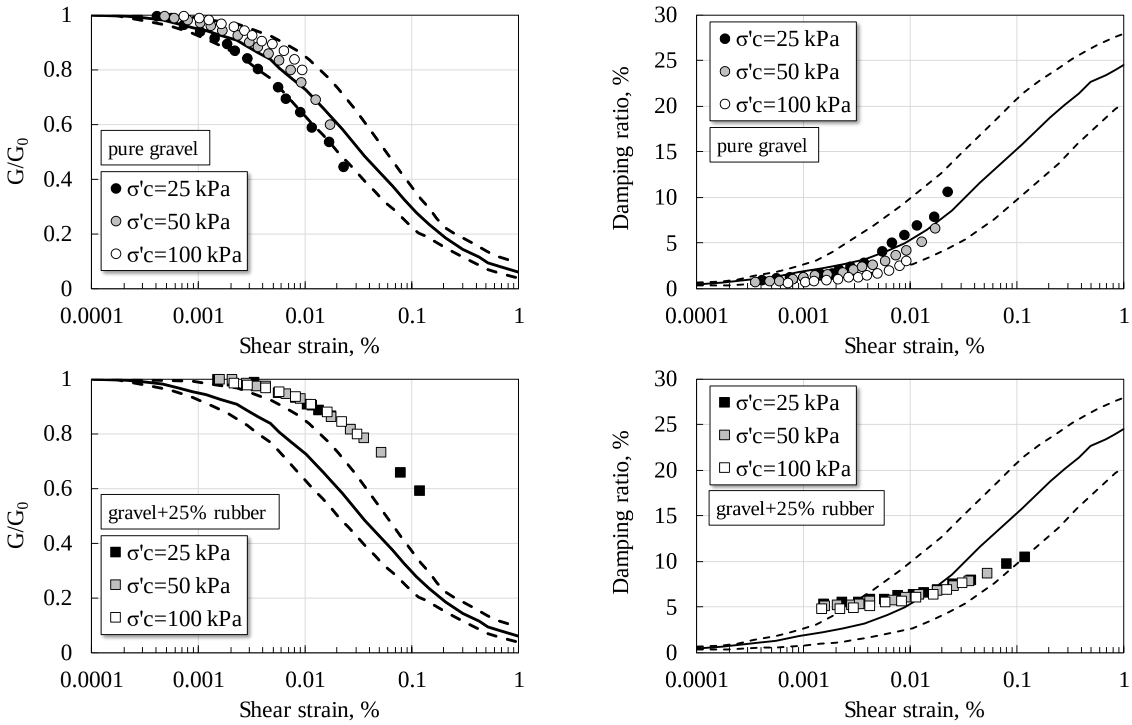

Figure 7: Effect of confining pressure and rubber content on the small-strain shear modulus and damping ratio of gravel-rubber mixtures (Senetakis et al. 2012).

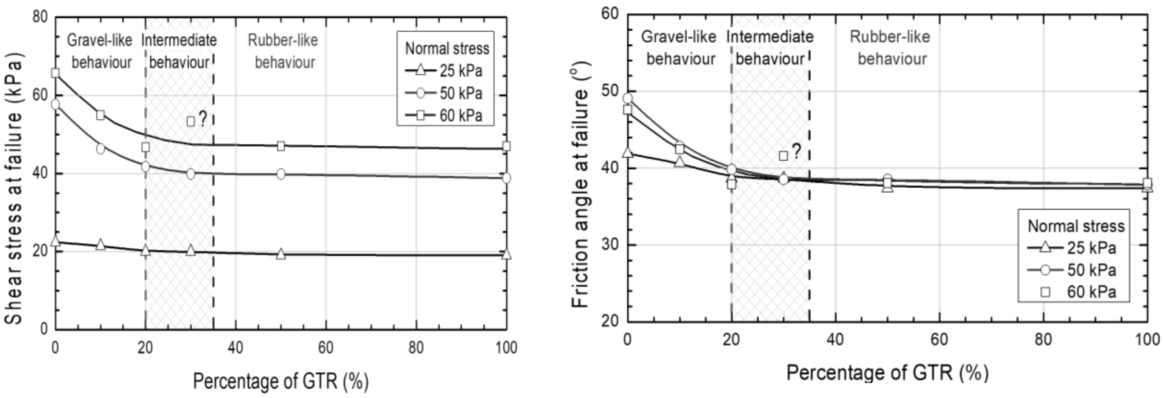

Figure 8: Shear strength for gravel-GTR mixtures (a), Peak friction angle for gravel-GTR mixtures (b). (adopted from Chiaro et al. (2019a)).

Lee et al. 2014; Mashiri et al. 2016). Therefore, the rubber content in the matrix should be limited to some extent. Experimental research on both sand-rubber and gravel-rubber mixtures conducted by Senetakis et al. (2012) revealed that by increasing rubber content in the mixture, damping ratio increases whereas small-strain shear modulus decreases. The effect of confining pressure and rubber content on the small-strain shear modulus decay (G/G_0) and damping ratio of gravel-rubber mixtures is illustrated in Figure 7. For better comparison, the proposed curves by Seed et al. (1986) for sandy soil are presented by solid and dashed lines. It is evident that by increasing confining pressure and rubber content, more linear behaviour is observed. More importantly, damping ratio for mixture with 25% rubber increased significantly. However, the effect of confining pressure for mixture with 25% rubber is less pronounced. These results show the suitability of soil-rubber mixture in the reduction of inertia force generated during earthquake on infrastructure owing to the fact that damping ratio increases.

Chiaro et al. (2019a) investigated the shear strength and friction angle characteristics of gravel-granulated tyre rubber mixtures (GTR). They reported that shear strength and friction angle decrease with the increase in the percentage of rubber content up to 30% GTR, and afterwards they became steady (Figure 8). The shear strength decreasing was attributed to the interlocking reduction between gravel/gravel and gravel/GTR particles. In the case of the friction angle, while for the gravel skeleton fractions the friction angle decreases with the normal stress level applied, for the rubber skeleton fractions the friction angle was reported constant and approximately 39^{o} irrespective of the normal stress.

Soil-rubber mixture: leachate characteristics

The introduction of new or alternative (recycled waste) materials in building foundations may have benefits in terms of cost reductions and increased seismic resilience of low-rise buildings. However, it is essential to ensure that such innovations do not result in long-term negative impacts on the environment e.g. through the leaching of toxic chemicals into the surrounding soil environment, groundwater and surface water.

While tyre rubber itself, which makes up 75-80% of the weight of car and truck tyres (Basel Convention Working Group 1999), can be considered inert under ambient foundation conditions (MFE 2015), tyres contain approximately 1.5% by weight of hazardous compounds. Additives used in the manufacture of tyres are potentially harmful to the environment (e.g. organohalogen compounds, acidic solutions) and the steel fibres within the tyres can leach heavy metals (e.g. zinc, manganese, lead, cadmium) (Basel Convention Working Group 1999). A review of the leachate characteristics of tyres (MFE 2004) showed that, depending on the whether the steel components of the tyres are exposed, there may be elevated manganese and iron levels within the leachate and in groundwater (although at levels below relevant environmental standards). Levels of aluminium, zinc and organic compounds may be elevated in groundwater; however, the majority of the studies reported negligible levels. While these results were based on field and laboratory investigations, the risk of groundwater and soil contamination through tyre leachate is related to a number of different factors (tyre size, amount of exposed steel, distance to groundwater, permeability and chemistry of the soil, contact time with water, vertical water flow through soil, horizontal groundwater flow, leachate control systems etc. (MFE 2004)) and these results cannot be directly related to specific sites. As far as the research team is aware of, no previous test results are available from the literature on the leaching properties of tyre rubber mixed with gravelly soils. These issues need to be assessed in future studies.

THE “ECO-RUBBER SEISMIC-ISOLATION FOUNDATION SYSTEMS” PROJECT

Seismic isolation (SI) with energy dissipation has the ability to significantly improve the seismic performance of buildings and structures. Historically, SI has been applied to buildings with special functional requirements and bridges. Nevertheless, its application to create new earthquake-resilient residential housing is feasible and would be of great significance in New Zealand.

On the other hand, waste tyres production and management are posing great environmental problems in New Zealand. However, waste tyres are a great source of environmentally-friendly and sustainable building materials. For example, they may provide novel and effective engineering solutions to attain structures with enhanced seismic resilience (Tsang 2008; Tsang et al. 2012). This makes them ideal materials for developing affordable, medium-density, low-rise buildings that are in high demand in New Zealand.

To investigate if it is possible to develop a cost-effective “earthquake proof” engineered foundation-soil system for low-to-medium-density low-rise residential housing composed of a) shallow and resilient layer of mixed shredded tyres and gravel, and b) flexible rubber-concrete raft foundation (Figure 9), a multi-stage comprehensive geo-environmental-structural experimental research programme, funded by the MBIE Smart Idea research programme is being currently carried out at the University of Canterbury.

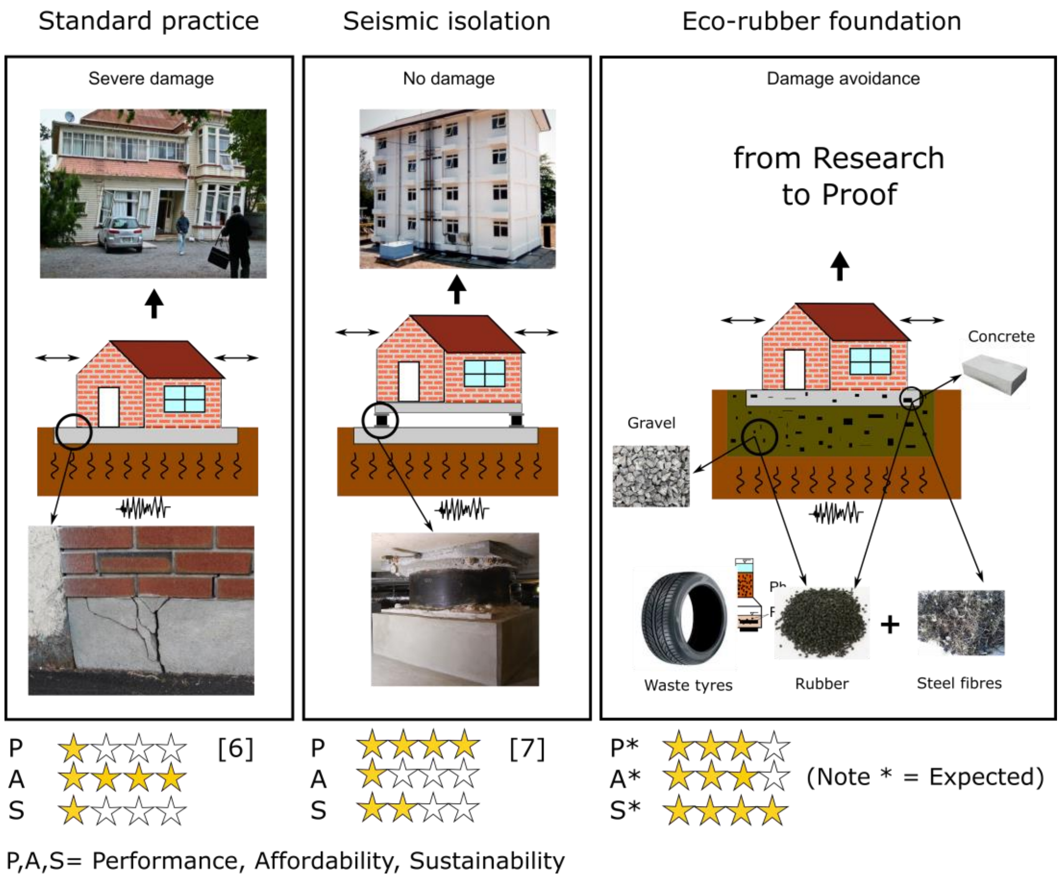

Figure 9: Performance, affordability and sustainability of traditional foundation and SI systems, and the proposed "Eco-rubber" SI foundation system (Chiaro et al. 2019b).

In this project five primary methodologies are used:

1. Geotechnical laboratory investigations to understand i) the macro-mechanical properties (i.e. shear strength, dynamic response, compressibility and permeability) of various rubber-gravel mixtures prepared at different densities and subjected to different levels of confining stress, and ii) the friction at the soil-foundation interface;
2. Structural laboratory tests to identify the mechanical characteristics (e.g. cracking strength, damping etc.) of rubber-concrete for different mix designs i.e. percentage/dimensions of tyre shreds in the compound. This includes the effects of steel wires on the crack control;
3. Environmental laboratory tests to identify and quantify the degradation profile of the shredded rubber, and the potential for soil/groundwater contamination including dispersion of contaminants (if any) on surrounding environments from the use of the proposed gravel-rubber mix. This data will then be used to assess the environmental impact and identify suitable countermeasures against contamination e.g. use of a reactive geomembrane to remove contaminants that would pollute the groundwater;
4. Numerical models. Finite element methods (e.g. Abaqus and Plaxis) incorporating key information from (i) and (ii) to optimise the proposed foundation system (i.e. rubber-gravel mixture thickness; thickness of rubber-concrete foundation structure; possible use of alternate layers of rubber-gravel and rubber-concrete). Discrete element method (i.e. PFC3D to supplement (i) and provide insights on the micro-mechanical (grain size

level) shear and compressible behaviour of gravel-rubber mixture and their interaction under externally applied loads;

5. Proof-of-concept testing of the physical model of the ideal foundation system (obtained from iv) i.e. reduction of accelerations on the superstructure and no damage of structural elements in the superstructure

CONCLUSIONS

The extensive state of art on rubberised concrete and soil tyre-rubber highlights the importance of using recycled materials for our next generation of structures. Observations from state-of-the-art literature suggests, that the combination of fibres with rubber can become a viable alternative for low reinforcement ration members such as foundation beams and raft. Moreover, the increased flexibility of the material results in a resilient solution against differential settlements induced by liquefaction and/or lateral spreading. The enhanced damping and energy dissipation will lead to reduced earthquake demands, whilst the increased ductility and deformability will decrease the extent of concrete cracking and delay the brittle failure of the concrete. The resulting solution, mainly envised for the residential market (medium density low-rise) is likely to enhance the overall seismic performance and therefore become a cost-effective alternative to current practice.

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