

ENHANCING THE RESILIENCE OF LOW-RISE BUILDINGS: A NEW ZEALAND PERSPECTIVE

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Abstract: *Recent earthquakes in New Zealand proved that a shift is necessary in the current design practice of structures to achieve better seismic performance. Following such events, the number of new buildings using innovative technical solutions (e.g. base isolation, controlled rocking systems, damping devices, etc.), has increased, especially in Christchurch. However, the application of these innovative technologies is often restricted to medium-high rise buildings due to the maximum benefit to cost ratio. In this context, to address this issue, 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 a foundation system which will improve the seismic performance of medium-density low-rise buildings. Such foundation is characterized by two main elements: 1) granulated tyre rubber mixed with gravelly soils to be placed beneath the structure, with the goal of damping part of the seismic energy before it reaches the superstructure; and 2) a basement raft made of steel-fibre rubberised concrete to enhance the flexibility of the foundation under differential displacement demand. In the first part of this paper, the overarching objectives, scope and methodology of the project will be briefly described. Then, preliminary findings on the materials characterization, i.e., the gravel-rubber mixtures and steel-fibre rubberised concrete mixes, will be presented and discussed with focus on the mechanical behaviour.*

INTRODUCTION

The 2010 and 2011 Christchurch 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 in the country, especially in Christchurch (CERC 2012). Nonetheless, the application of these innovative technologies is often restricted to medium-high rise buildings due to the maximum benefit to cost ratio, resulting in a lack of resilience in low-rise buildings.

Moreover, in conjunction with seismic performance issues, environmental concerns have urged civil engineers to identify viable ways to reuse of waste tyres through large-scale recycling engineering projects. The current rate of waste tyres production in New Zealand is over 5 million units per year and is expected to grow over time with increased population and number of vehicles on the road. An estimated 70% of such waste tyres are destined for landfills, stockpiles, illegal disposal or are otherwise unaccounted for (Ministry for the Environment 2015), giving rise to piles of tyres that do not readily degrade or disintegrate.

Waste tyres are a great source of environmentally-friendly and sustainable building materials that can be made affordable and readily available through technological innovations. 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.

Based on the above-mentioned background and aimed at addressing this problem, a multi-stage comprehensive geo-environmental-structural experimental research programme is being currently carried out at the University of Canterbury to investigate sustainable options for the reuse/recycling of waste tyre in civil engineering applications. One such option is to employ waste tyre (in the form of

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granulated tyre rubber - GTR) mixed with gravelly soils and concrete to develop seismic-isolation foundation systems for low-rise residential buildings.

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).

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 the brief summary of the MBIE Smart Idea project "Eco-rubber seismic isolation foundation system" that aims at developing this technology is introduced.

RECYCLED RUBBER IN STRUCTURAL CONCRETE

The partial substitution of mineral aggregates in concrete with recycled rubber particles has become an area of increased international interest over the past three decades, due to the potential to combine both performance and sustainability advantages. Research thus far has shown that the inclusion of rubber particles, as seen in Figure 1, can have significant impacts on the fresh state properties, mechanical properties and dynamic characteristics of structural concrete (e.g., Eldin and Senouci 1992, Topcu 1995, Khatib and Bayomy 1999, Khaloo et al. 2008, Najim and Hall 2010, Raffoul et al. 2016, Bompa et al. 2017). To effectively implement this novel and eco-friendly, composite material within structural load-bearing members, a thorough understanding of its local and global behaviour is imperative.

Fresh state properties

Eldin and Senouci (1992) have shown that workability of rubberised concrete mixtures depends on the size, shape, surface texture and content of rubber particles. Decreasing slump test values have been reported when increasing rubber content, using longer and angular particles or rougher particles (Eldin and Senouci 1992, Youssf et al. 2014). Khatib and Bayomy (1999) have suggested a maximum rubber content of 50% approximately (total aggregate volume) as an upper limit to maintain workable mixtures. Youssf et al. (2014) have informed the use of a superplasticiser (Polycarboxylic acid water-reducing agent) to achieve the required concrete workability, concluding that slump values can be controlled, without a major issue, using superplasticisers in the range recommended by the ASTM 494 (1-3 % of cement weight).

Because of the lower unit weight of rubber particles compared to mineral aggregates, and higher air content reported in rubberised concrete than plain concrete, a unit weight reduction is expected (Fedroff et al. 2007). It seems that owing to the tendency of rubber particles to repel water; air may adhere in their rough surfaces, increasing air content. Hence, an increase in rubber content led also to higher air content, thereby decreasing unit weight (Siddique and Naik 2004).

Mechanical Properties

As in conventional concrete, mechanical properties of rubberised concrete largely depend on the properties of aggregates. It is notorious the mechanical behaviour of mineral aggregates compare to waste tire rubber particles are fundamentally different. On the one hand, mineral aggregates are strong and brittle; on the other hand, rubber aggregates are resilient and ductile. Because of this, depending on the percentage of rubber content, decreases in compressive and tensile strength are anticipated; nonetheless improvements in toughness and dynamical characteristics are also expected. (e.g., Eldin and Senouci 1992, Eldin and Senouci 1994, Topcu 1995, Khatib and Bayomy 1999, Fedroff et al. 2007).

Xue and Shinozuka (2013) performed compressive tests on 27 standard cylinders with crumb rubber replacement ratios varying between 5% and 20% of coarse aggregate volume. The effect of silica fume (SF) on improving compressive behaviour was also investigated. The results showed a reduction in compressive strength in the range of 39-47% and modulus of elasticity (24% and 40%) for replacement ratios of 10% and 20%, respectively. However, the use of silica fume reduced the negative impacts on both properties as shown in Figure 2.

Raffoul et al. (2017) investigated the effect of large rubber replacement ratios on compressive behaviour of concrete cylinders. Replacing 60% of coarse and fine aggregates with crumb rubber resulted in a decrease in compressive strength from approximately 62 MPa to 7 MPa. However, if external confinement in the form of Aramid Fibre-Reinforced Polymer wraps restrain the excessive lateral

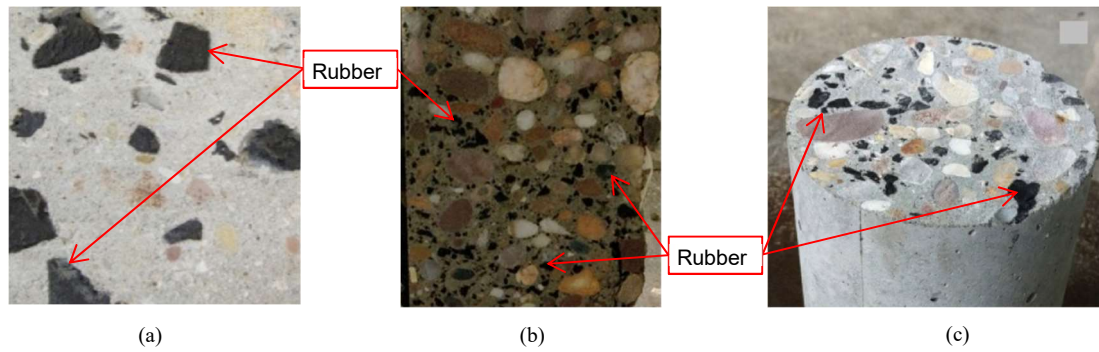


Figure 1. Concrete members with rubber replacing 10% coarse aggregate (a), 40% fine aggregate (b) and 100% fine aggregate (c). Adapted from Raffoul *et al.*, 2016.

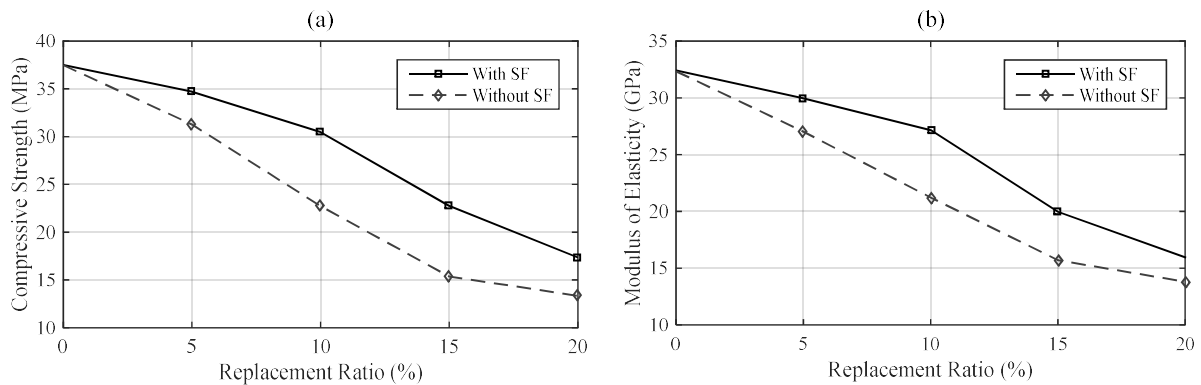


Figure 2: Reduction of concrete compressive strength (a) and modulus of elasticity (b) for varying crumb rubber replacement ratios (Adapted from Xue and Shinozuka 2013).

expansion of the concrete, the concrete cylinders can reach over 70 MPa whilst achieving ultimate axial strains of up to 5% - fourteen times more than the conventional concrete cylinder.

Reda Taha *et al.* (2008) based on microstructural investigations linked the mentioned strength reductions to two reasons: (1) the inherently softer response of rubber particles (behaving as voids in the concrete matrix); and (2) the lack of effective bond forming between the rubber and cement in the interfacial transition zone, leading to the initiation and propagation of micro-cracks around the rubber particles. In order to counter the bonding issue, pre-treatment of rubber particles has been investigated. Studies indicate that rubber particles with a rougher surface, intrinsic or given treatment, can develop an adequate bond interface with the surrounding matrix, which may result in higher compressive strength (Segre and Joekes (2000), Ma and Yue (2013), Youssf *et al.* (2014)). The treatment may vary from washing particles with water to acid etching, plasma pre-treatment and various coupling agents (Siddique and Naik 2004).

Among the surface treatments tested to enhance the rubber-cement interface adhesion, sodium hydroxide (NaOH) solution has been the most investigated treatment for rubber particles. Youssf *et al.* (2014) have described a procedure to pretreat rubber particles with NaOH. The effect of rubber pretreatment with NaOH solution on rubberised concrete mixtures with 20% of rubber content. A decreasing of approximately 25% on the concrete slump of the pretreated mixture. This reduction was attributed to rougher surfaces of pretreated rubber particles. Nonetheless, the authors demonstrated that workability could be improved with the use of a superplasticiser without major issue. Compressive strength and modulus of elasticity increased by about 15% and 12.5%, respectively. Tensile strength decreased 12.5%; however, authors attributed this reduction to the normal range of test values since only 1 cylinder was tested for tensile strength for each mix.

Dynamics characteristics

Despite reductions in mechanical properties, the inclusion of recycled rubber particles can result in significant enhancements in deformability, energy absorption capacity and dynamic performance when compared to conventional concrete. Moreover, a gradual (ductile instead of brittle) failure mode has been reported for rubberised concrete (Eldin and Senouci 1994, Khatib and Bayomy 1999). Noaman *et*

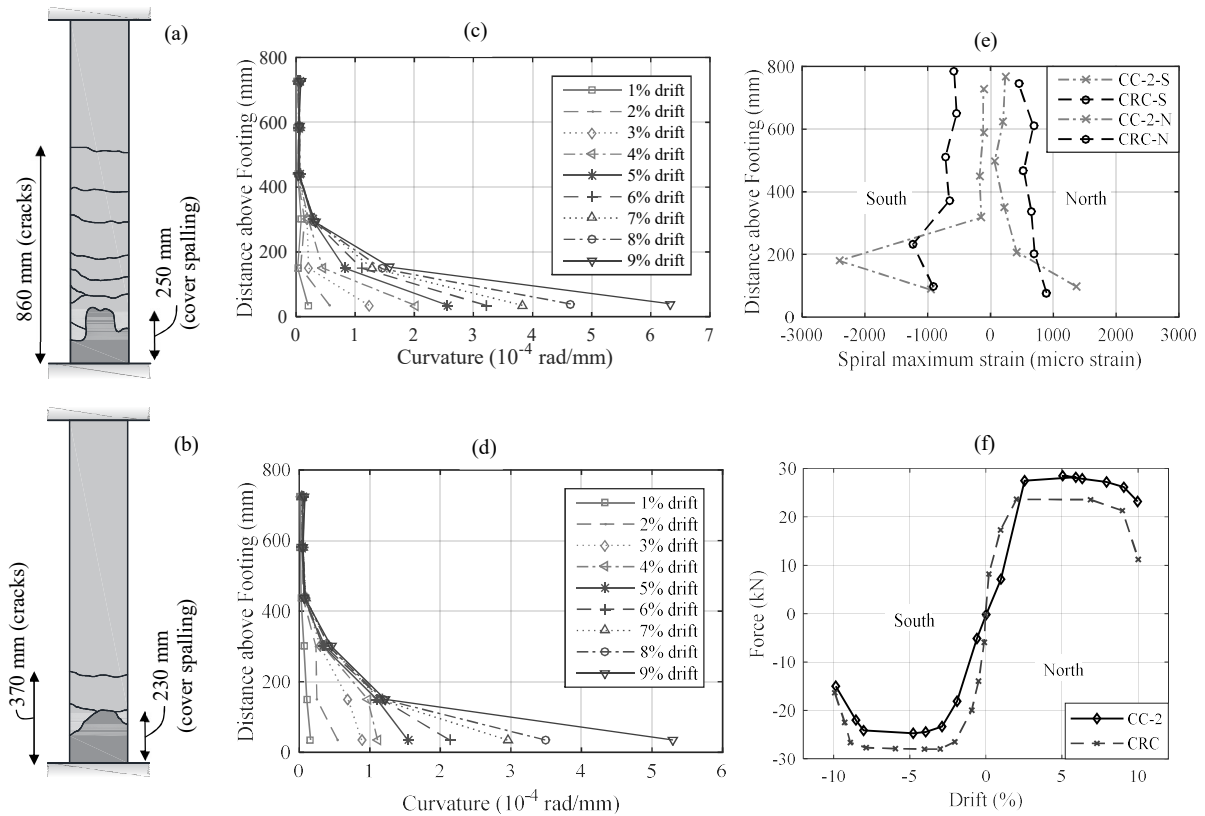


Figure 3: Post-failure propagation of cracks in conventional concrete CC-2 (a), rubberised concrete CRC (b); curvature distribution along column height CC-2 (c), CRC (d); Spiral lateral strain profile; backbone curve. Adapted from Youssf *et al.* (2015).

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. Youssf *et al.* (2015) investigated the seismic performance of two reinforced concrete columns incorporating crumb rubber at 20% of sand volume and testing under axial compression load and incrementally increasing reversed cyclic loading. Despite a significant loss of compressive strength (28 % lower), the column sustained a lateral load of approximately 98% of the conventional column (at same axial load), all whilst dissipating 2.5 times more energy up until a drift ratio of 4%. It was observed that the higher ductility and the ability of rubber particles to increase the area of the failure surface (Eldin and Senouci 1994), delayed concrete spalling and minimised the spreading of cracks as shown in Figure 3.

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 rubberised concrete column – a desirable attribute for concrete structures in seismic environments.

STEEL FIBRE-REINFORCED RUBBERISED CONCRETE

As discussed, rubberised concrete better performs in terms of energy absorption and flexibility, but it presents lower strength. Therefore, several authors (e.g., Noaman *et al.*, 2015, Li and Li, 2017, Alsaif *et al.*, 2018, Hu *et al.*, 2018b, Hu *et al.*, 2018a) investigated the use of steel fibres to improve compressive, tensile and flexural strength. Steel fibres can be manufactured (MSF) or recycled from

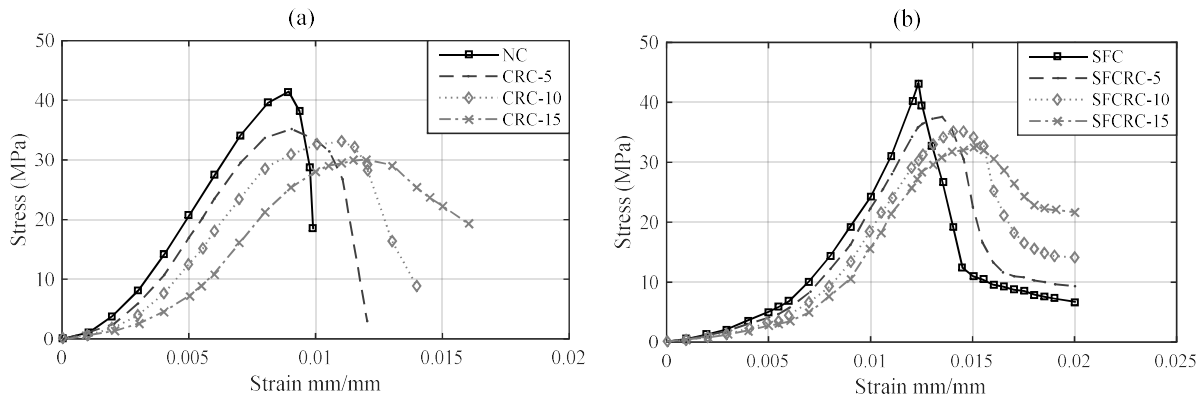


Figure 4: Stress-strain relationship variation with the inclusion of crumb rubber only (a) and crumb rubber and steel fibres (b). Adapted from Noaman *et al.* (2016).

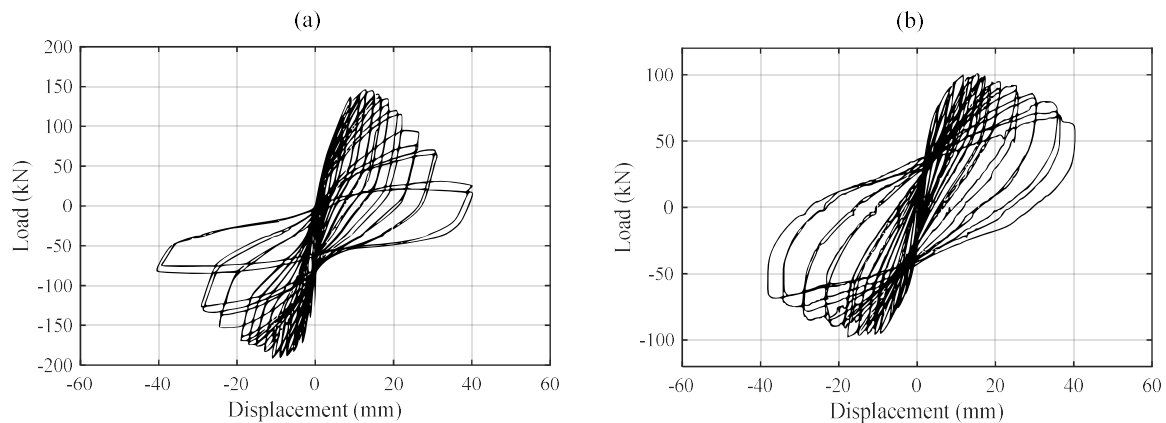


Figure 5. Hysteretic behaviour of conventional reinforced concrete column (a) and steel fibre-reinforced rubberised concrete column (b). Adapted from Li and Li (2017).

tyres (RTSF). In addition, Hu *et al.* (2018b) have investigated the use of processed high-specification steel cords (RTSC) extracted from unvulcanised rubber belt off-cuts.

As expected, the introduction of MSF to rubberised concrete has positive impacts on the compressive and splitting tensile strengths, along with further increases in toughness, ductility and energy absorption as seen in Figure 4. Naoman *et al.* (2016) found that the addition of steel fibres to rubberised concrete increased the 28-day and 56-day compressive strengths by 15 and 17%, respectively. The average increase in the splitting tensile strength was 34%; however, only a very small impact on the modulus of elasticity was recorded.

Li and Li (2017) studied the effects of MSF and rubber particles on the flexural and seismic behaviour of concrete. Four-point bending tests on un-reinforced beams were conducted to investigate the flexural behaviour. The resulting data indicated a 36% increase in flexural strength and a deflection at failure of over three times that of conventional concrete. This was primarily attributed to the bridging effect of fibres in the post-cracking stage. Seismic behaviour was investigated via low-cycle lateral loading of a reinforced concrete column. Despite withstanding a lower peak load, the columns incorporating steel fibres and rubber particles failed at a peak displacement 45% higher than the conventional column, resulting in a significant increase in the ductility factor. The energy dissipation also increased by 67%, producing fuller hysteretic curves as shown in Figure 6. Cyclic tests on beam-column joints by Ganesan *et al.* (2013) corroborate the enhanced deformability and energy dissipation of steel fibre-reinforced rubberised concrete, along with the reduction in residual drifts and stiffness degradation.

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 conventional concrete). Increasing were measured in compressive and modulus of elasticity (up to 12.5% and 28.4%, respectively). 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 of MSF and 20 kgf/m³ of RTSF).

Therefore, observations from state-of-the-art literature suggest, 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 (Cubrinovski *et al.*, 2012). 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 envisaged 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.

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 (Edinçililer and Cagatay 2013, 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 6. For better comparison, the proposed curves by (Seed, Wong *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 7). 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° 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

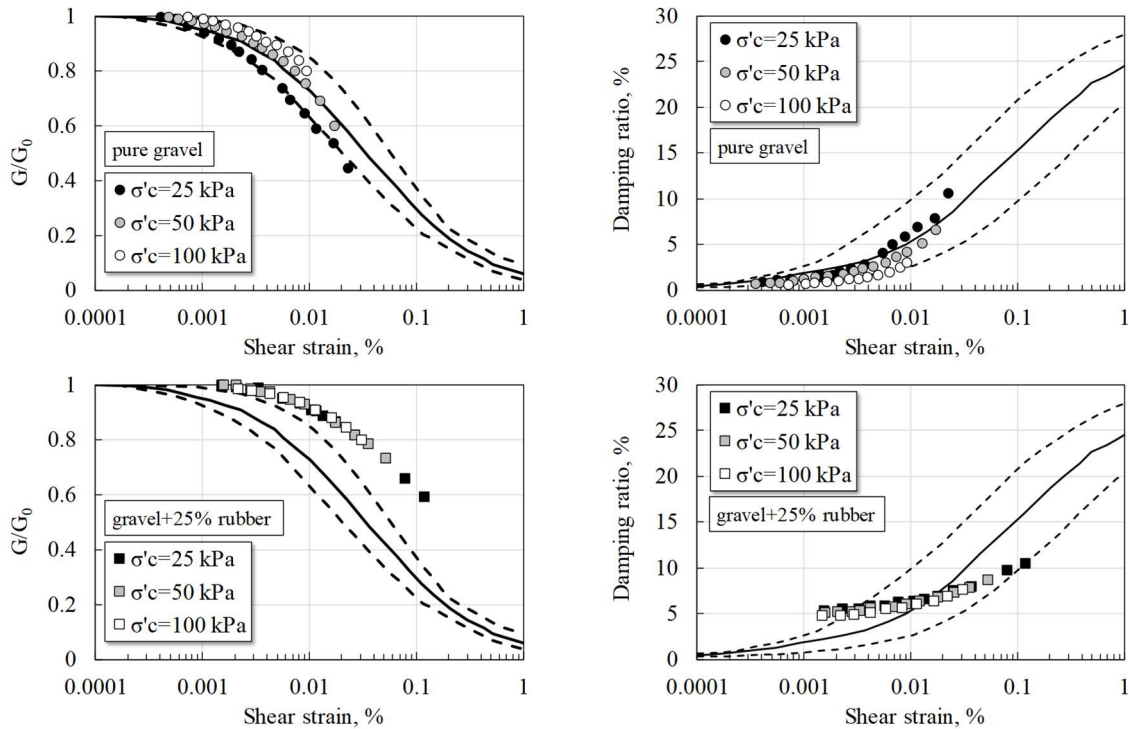


Figure 6: Effect of confining pressure and rubber content on the small-strain shear modulus and damping ratio of gravel-rubber mixtures (Senetakis *et al.* 2012).

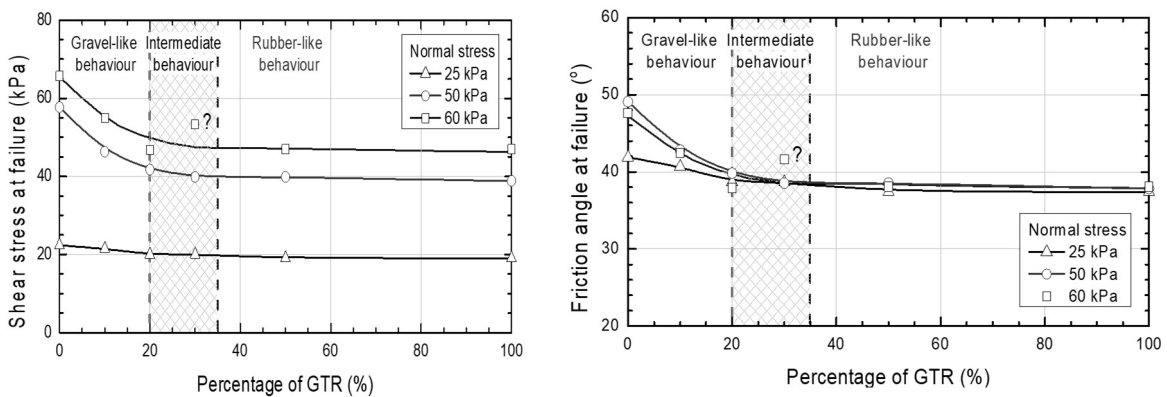


Figure 8: Shear strength for gravel-GTR mixtures (a), Peak friction angle for gravel-GTR mixtures (b). (adopted from Chiaro *et al.* 2019a).

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 (Ministry for the Environment 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 (MWH 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. (MWH 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

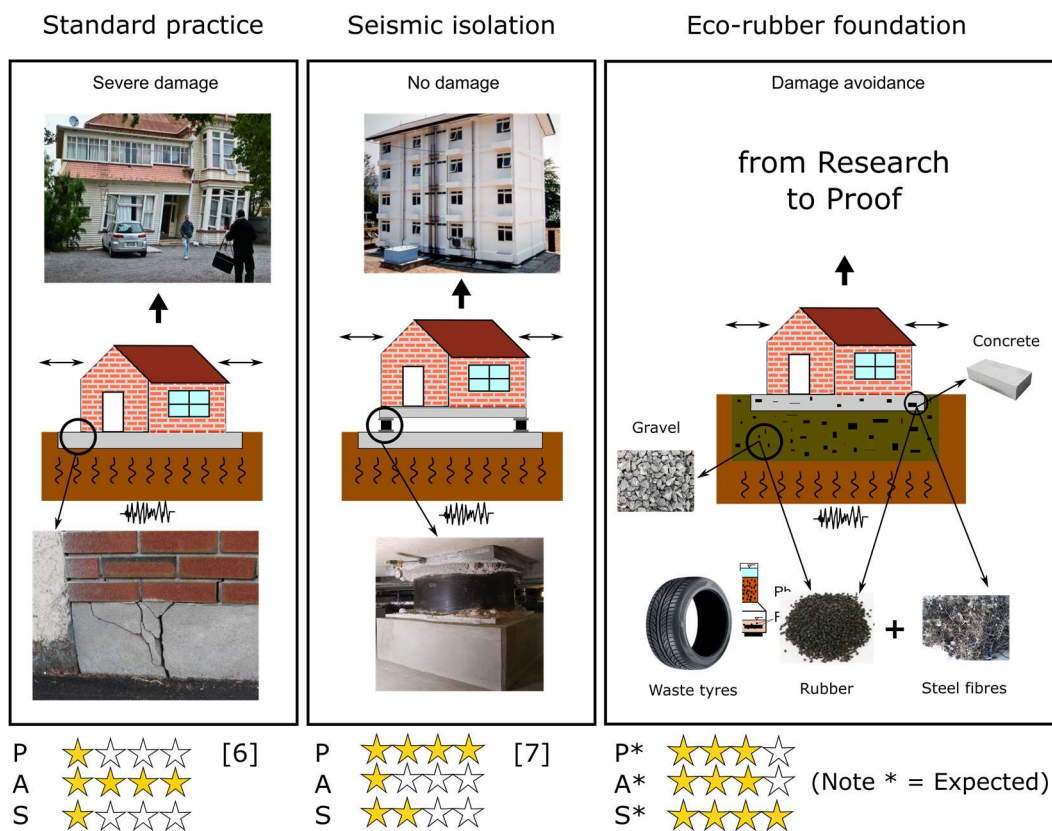
Seismic isolation (SI) with energy dissipation has the ability to significantly improve the seismic performance of buildings and structures. Historically, SI has been applied to buildings with special functional requirements and bridges. Nevertheless, its application to create new earthquake-resilient 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.

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



P,A,S= Performance, Affordability, Sustainability

Figure 8: Performance, affordability and sustainability of traditional foundation and SI systems, and the proposed “Eco-rubber” SI foundation system (Chiaro *et al.* 2019 b).

- 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. Unfortunately, most of the research is strictly focused either on geotechnical or structural aspects. The MBIE project “eco-rubber seismic isolation system” aims to interface the two disciplines and develop geo-structural solutions that will be cost-effective and performant for the New Zealand context. While detailed experimental and numerical results are not available yet, several numerical analyses carried out by the research community indicated that by using this technology accelerations and seismic inertial forces will be drastically reduced.

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