Direct shear behaviour of gravel-granulated tyre rubber mixtures

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ABSTRACT: The objective of the work presented in this paper is to investigate the direct shear strength of gravel and granulated tyre rubber (GTR) mixtures for possible use as seismic-isolation foundation systems for low-rise buildings. Specimens of gravel, GTR, and selected mixtures (10%, 20%, 30% and 50% GTR - % by mass) were tested in the direct shear apparatus under three normal stress levels of 25, 50 and 60 kPa. The addition of GTR significantly influenced the shear strength and volumetric response of the mixtures. In particular, it is observed that the mechanical behaviour of the mixtures progressively changed from gravel-like (i.e. strain-softening/dilative) to rubber-like (i.e. strain-hardening/contractive), the transition occurring for GTR content between 20% and 35%. Importantly, although a progressive decay of the peak shear strength with GTR content is observed, the friction angle at failure is found to be equal to or greater than 39° for all mixtures.

1 INTRODUCTION

The current rate of waste tyres production in New Zealand is over 5 million 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. With the ever-growing volume of waste tyres, environmental concerns have urged the reuse of waste tyres through large-scale recycling engineering projects.

Waste tyres are a great source of environmentally-friendly and sustainable building materials that can be made affordable and ready available through technological innovations. For example, they may provide novel and effective engineering solutions to attain structures with enhanced seismic resilience (e.g. 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 granulated tyre rubber - GTR) mixed with gravelly soils to develop seismic-isolation foundation systems for low-rise buildings. This is achieved by a combination of:

- Geotechnical and environmental engineering investigations to identify optimum gravel-GTR mixtures, having excellent mechanical properties and minimal leaching attributes;
- Structural engineering tests to design flexible, fibre-reinforced, rubberised-concrete raft foundations with satisfactory structural performance; and
- Numerical and physical models to prove the concept, evaluate the seismic performance of the entire foundation system, and quantify the level of reduction in the seismic response of prototype buildings.

Using gravel-GTR blends in engineering structures require understanding of the mechanical behaviour and engineering properties of such materials, among which shear strength characteristics are the most important and common criteria (Mashiri et al. 2015). To this regard, in this paper, preliminary experimental results of a geotechnical laboratory examination aimed at evaluating the direct shear strength of gravel-GTR mixtures are presented and discussed in terms of influence of GTR percentage and normal stress effects.

2 TESTING MATERIALS AND PROCEDURE

In this study, experimental investigations were carried out in a medium scale direct shear box with 100 mm x 100 mm cross-section and 40 mm height.
A uniformly-graded grey pea gravel \( (D_{50} = 6 \text{ mm}) \) and shredded tyres in the form of GTR \( (D_{50} = 0.9 \text{ mm}) \) have been employed. The GTR is composed of waste tyres that had been mechanically shredded using multiple shredding steps and sieved to be of approximately uniform size. The tests were carried out on gravel-GTR mixtures with different gravimetric percentages of GTR \( (0\%, 10\%, 20\%, 30\%, 50\% \text{ and } 100\%) \) - the gravimetric percentage of GTR is defined as the ratio of the mass of GTR to the total mass of gravel and GTR. The particle size distribution curves of the pea gravel, GRT and selected mixtures are shown in Figure 1. The gravel has rounded-shape grains (Fig. 2a) and its specific gravity was measured as 2.66. The GTR (shredded tyres currently commercially available in New Zealand) are shown in Figure 2b. The specific gravity of GTR was measured as 1.15. This is within the range of the specific gravities of scrap tyres \( (1.02 \text{ to } 1.30) \) reported by different investigators (e.g., Edil & Bosscher 1994, Foose et al. 1996, Ghazavi & Sakhi 2005, Mashiri et al. 2015).

The gravel and GTR specimens were prepared by thoroughly mixing and placing three equal-mass layers of gravel and GTR in the shear box. Each layer of gravel-GTR mixture was compacted in the shear box to achieve the required gravel matrix unit weight. Particular care was required while preparing the specimens to avoid any possible segregation between gravel and rubber. As summarised in Table 1, a total of 18 tests were carried out on dry specimens subjected to three normal stress levels of 25, 50 and 60 kPa. The specimens were sheared at a constant horizontal displacement rate of 1 mm/min. For completeness, the dry density measured just before the shearing process (i.e. after the application of the normal stress) is also reported in Table 1, along with the corresponding void ratio and the specific gravity of each mixture.

![Figure 1](image1.png)
Figure 1. Particle size distribution curves for tested materials.

![Figure 2](image2.png)
Figure 2. (a) Pea gravel; and (b) GTR used in this study.

### Table 1. Direct shear tests carried out in this study and specific gravity of tested materials

<table>
<thead>
<tr>
<th>Test</th>
<th>GTR (%)</th>
<th>Specific gravity</th>
<th>Normal stress (kPa)</th>
<th>Dry density* (kg/m³)</th>
<th>Void ratio*</th>
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<tr>
<td>T1</td>
<td>0</td>
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<td>T2</td>
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<td>T3</td>
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<td>60</td>
<td>1598</td>
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<tr>
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<td>25</td>
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<tr>
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<td></td>
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<td>0.856</td>
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</table>

*after compression due to normal stress (i.e. before shearing)

### 3 TEST RESULTS AND DISCUSSIONS

#### 3.1 Void ratio for gravel-GTR mixtures

The void ratio of soil-rubber mixtures is dependent on the properties (shape and size) of the soil and rubber, as well as their gravimetric percentage (Mashiri et al. 2015). Figure 3 shows the dependence of the void ratio of the examined gravel-GTR mixtures on the GTR percentage in the mixture. It can be observed that the void ratio initially decreases with the increase in the GTR percentage up to 30%. Afterwards, the void ratio increases with the increase in the GTR content.

Such a trend in the void ratio of gravel-GTR mixtures is related to the change in the proportion of large-size and small-size particles in the total volume of solids and how this affects the packing of particles with two different sizes (Cubrinovski & Ishihara 2002, Iolli et al. 2015). That is, initially adding small-size GTR particles into the fraction of large-size gravel particles leads to a decrease in the volume of voids since the GTR particles fill the voids between the gravel particles. Upon adding GTR particles beyond 30%, a reverse trend is observed in which the
volume of voids increases with the percentage of the small-size GTR fraction. In this replacement-of-solids zone, the large-size gravel particles are gradually replaced by the small-size GTR ones until the entire volume of solids is comprised of GTR particles.

3.2 Expected mechanical behaviour for gravel-GTR mixtures

According to the concept of skeleton material (Lee et al. 2007, Kim & Santamarina 2008), a skeleton is formed when particles of the same material are in contact with each other and are able to transfer loads. The material forming the skeleton becomes the matrix material that governs the overall mechanical behaviour of a mixture. In the case of gravel-GTR mixtures, two matrix materials can be expected: i) a gravel matrix, which will lead to a gravel-like behaviour of the mixtures; and ii) a GTR matrix that will produce a rubber-like response of the mixtures.

A three-zone behavioural model for soil-rubber mixtures can be used to define the likely material matrix (Mashiri et al. 2015). Following this approach, the plot shown in Figure 3 is divided into three zones: i) Zone 1 that corresponds to gravel-like behaviour where gravel forms the skeleton (GTR < 20%); ii) Zone 2, within which gravel and rubber form a binary skeleton (20% ≤ GTR ≤ 35%); and iii) Zone 3 that corresponds to rubber-like behaviour where GTR forms the skeleton (GTR > 35%).

3.3 Gravel-like and rubber-like behaviours

In this section, insights into the gravel-like and rubber-like behaviours of gravel-GTR mixtures are provided by examining the variation of shear stress and vertical displacement with the horizontal displacement for the two reference materials (i.e. pea gravel and pure GTR) subjected to three different normal stress levels of 25, 50 and 60 kPa.

Gravel-like behaviour – As shown by Figure 4a, regardless of the normal stress level, pea gravel shows a strain-softening behaviour that is characterised by a distinct peak stress state followed by a sudden decay of shear strength. Such a strain-softening response is accompanied by a dilative volumetric behaviour (i.e. increase in volume) during the sharing phase (Fig. 4b).

Rubber-like behaviour – Alternatively, irrespective of the normal stress level, GTR shows a strain-hardening response characterised by a gradual increase of shear strength during the shearing process (Fig. 5a), which is complemented by a contractive volumetric behaviour (i.e. decrease in volume) as shown by Figure 5b.

![Figure 3. Void ratio characteristics and estimated behavioural zones for gravel-GTR mixtures.](image-url)

![Figure 4. Direct shear box behaviour of pea gravel.](image-url)

![Figure 5. Direct shear box behaviour of pure GTR.](image-url)
3.4 Influence of GTR percentage on the direct shear shearing behaviour of gravel-GTR mixtures

Figures 6a, 7a and 8a display the variation of shear stress with the horizontal displacement for different gravel-GTR mixtures subjected to the three different normal stress levels of 25, 50 and 60 kPa, respectively. Alternatively, Figures 6b, 7b and 8b show the corresponding variation of the vertical displacement with the horizontal displacement for various percentages of GTR.

It is evident from these figures that the addition of GTR has a significant influence on the shear and volumetric behaviour of the mixtures that progressively changes from gravel-like (strain-softening/dilative) to rubber-like (strain-hardening/contractive), the transition occurring between 20% and 30% GTR content.

Figure 6. Direct shear box behaviour of gravel-GTR mixtures subjected to a normal stress of 25 kPa.

Figure 7. Direct shear box behaviour of gravel-GTR mixtures subjected to a normal stress of 50 kPa.

Figure 8. Direct shear box behaviour of gravel-GTR mixtures subjected to a normal stress of 60 kPa.

3.5 Influence of normal stress on the direct shear shearing behaviour of gravel-GTR mixtures

Figure 9 reports the variation of shear stress at failure for the gravel-GTR mixtures investigated in this study, where failure is assumed to occur at the peak shear stress state for materials showing a gravel-like behaviour and at a horizontal displacement of 16 mm (i.e. maximum horizontal movement possible in the tests) for materials showing a rubber-like response.

For all the mixtures the shear stress at failure (i.e. shear strength) increases with increasing normal stress, the upper bound being for hard-grained pea gravel and the lower bound being for the soft-grained pure GTR. Such increase in the shear strength with normal stress is a result of the increased interlocking between particles.

Figure 9. Variation of shear stress at failure with normal stress for gravel-GTR mixtures.

3.6 Shear strength characteristics of gravel-GTR mixtures

The variation of shear strength with percentage of GTR is summarised in Figure 10. It is obvious that, irrespective of the normal stress level applied, the shear strength decreases with the increase in the percentage of rubber content up to 30% GTR, and afterwards it became steady. Such decrease in shear strength with GTR content is a result of the decreased interlocking between gravel/gravel and gravel/GTR particles (i.e. transition between gravel-skeleton and rubber-skeleton).

The variation of friction angle at failure with percentage of GTR is shown in Figure 11. It can be seen that, in as similar way of the shear strength, the friction angle decreases with the increase in the percentage of rubber content up to 30% GTR, and afterwards it became steady. However, while for the gravel skeleton fractions the friction angle decreases with the normal stress level applied, for the rubber skeleton fractions the friction angle is constant and approximately 39° irrespective of the normal stress.

The preliminary findings of this study demonstrate that the addition of GRT to gravel may be suitable to
produce lightweight synthetics materials for foundation engineering application with acceptable strength requirement (i.e. the friction angle required for common geotechnical engineering applications is > 30°, Chiaro et al 2015).

While the preliminary findings of this study may suggest that, to fully exploit the beneficial properties of rubber mixed with gravel, the gravel-GTR mixtures for use in foundation engineering projects should contain proportions of GTR within 20% and 35%, further investigations are required to be able to properly design seismic-isolation foundation made of gravel-GTR mixture. This is because the one-dimensional compressibility and dynamic properties of the gravel-GTR mixtures need to be properly understood. Moreover, while in this study, only relatively small shredded tyre fragments were used (due mainly to their commercial availability), other gravel-rubber mixtures made of larger GTR fragments are envisaged to become available in the near future, so that further investigations are planned by the authors to provide new and more in-depth insights into the suitability of gravel-GTR mixtures as suitable materials for foundations engineering projects.

4 CONCLUSIONS AND FUTURE RESEARCH

In this paper preliminary findings on direct shear strength of gravel and granulated tyre rubber (GTR) mixtures for possible use as seismic-isolation foundation systems for low-rise buildings were presented. The following main conclusions can be drawn from the study:

a) The addition of GTR significantly influences the shear strength and volumetric response of the mixtures. In particular, the mechanical behaviour of the mixtures progressively changed from gravel-like (i.e. strain-softening/dilative) to rubber-like (i.e. strain-hardening/contractive);

b) The transition between gravel-like and rubber-like behaviours occurred at a GTR content between 20% and 35%;

c) A progressive decay of the peak shear strength and friction angle with GTR content was observed; however, the friction angle at failure is found to be 39° or greater for all mixtures, indicating that gravel-GTR mixtures are suitable materials for foundation engineering applications.

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