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Damping Ratio of Foundation Bed with Multi-layered Rubber-Soil Mixtures

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Abstract. In this paper, a series of plate load tests on a sandy soil bed containing multiple layers of granulated rubber-soil mixture (RSM) under incremental cyclic loading was performed. To evaluate the settlement response and damping ratio of foundation bed, incremental cyclic loading in five steps with amplitudes of 140, 280, 420, 560 and 700 kPa were applied to the loading plate. The results show that both the total and residual settlements of the loading plate decrease with increase in the number of RSM layers, regardless of the level of applied cyclic load, but the rate of reduction in both settlements reduces with increase in the number of RSM layers. There is also an appreciable improvement in the value of the damping capacity with increase in the number of RSM layers as the damping ratio increases by 4-5% beyond the value of 12-15% obtained on untreated sand. On the basis of the study, the concept of using multiple RSM layers not only is a very attractive material to achieve less settlement and vibration attenuation for machine foundation and railway track beds, but also, the environmental impacts of waste tires are attenuated by using as composite materials in geotechnical applications.

1. Introduction

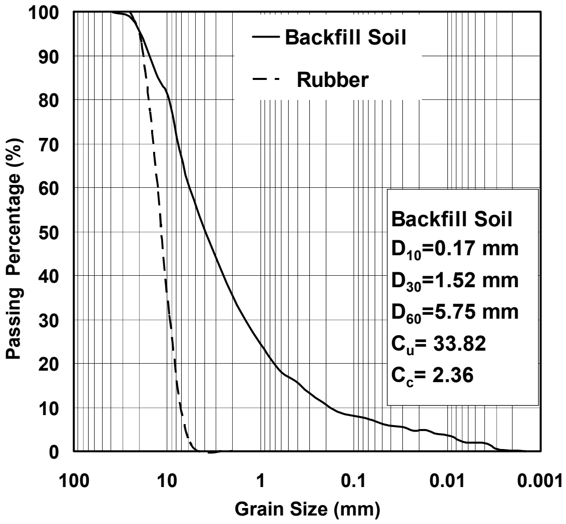
In last decades, due to developing industry and growing population, the huge volume of scrap tire has been generated in the world and their disposals have become a major environmental problem worldwide. Accumulated waste tires make them harder and more expensive to dispose of safely without threatening human health hazard and environment problems [1, 2]. Due to willingness to use alternative sources, the use of waste tires in the form of shreds, chips, strips, granules are now considered as construction materials [3, 4]. Using waste tires, mixed/combined with soil can be advantageously employed to increase soil strength and damping properties depending on the rubber type, the size of rubber particles the rubber content [4]. The cyclic load response of rubber-soil mixtures has shown the well potential as a composite material, particularly in applications in pavement, highways, and embankments [3, 4, 5]. The tire-chips in backfill soil, subjected to simulated repeated loads has been used in a laboratory model embankment [7]. The feasibility of using tire shred–sand mixtures as a fill material in embankment construction was investigated by Yoon [8]. The reinforcing effect of extensible buffing rubber inclusions by observing the CBR performance of the rubber-soil mixtures was investigate by Edincliler and Cagatay [4]. All researchers reported the beneficial effect of rubber in mixture for use in geotechnical applications [4, 5, 9].

This paper investigates the beneficial effect of RSM layers in a foundation bed which would have application, potentially, to roads, highways, embankments, machine foundations and pavement foundations. The main objective of the present study is to determine the effects of the multi-layered of RSM on settlement response and damping ratio of foundation bed.

2. Test Materials

A sandy soil with a specific gravity, Gs, of 2.6 and grain size distribution was used for soil layers and construction of the RSM layers (Fig. 1a). The soil is classified as well-graded sand and symbolized as SW in the Unified Soil Classification System (ASTM D 2487-11). Based on modified proctor compaction (ASTM D 1557-12), the maximum dry density an optimum moisture content was obtained 20.62 kN/m3 and 5.7%, respectively.

The granulated tire rubber with a mean particle size of 14 mm (particles between 2-25 mm) and a specific gravity, Gs, of 1.17 was used. Fig. 1b shows the grading and a photograph of the rubber particles. To produce a reasonably uniform rubber-soil mixture, the rubber particles were carefully blended by weight, into the soil with manual intervention.



(a)

(b)

Figure 1. (a) Particle size distribution curves for soil and granulated rubber (ASTM D422-07) [14], (b) A view of the granulated tire rubber

3. Model Test

All plate load tests were conducted in an outdoor test pit, measuring 2000 mm × 2000 mm in plan, and 720 mm in depth, to construct the soil layers, RSM layers as shown in Fig. 2 schematically. This figure also shows the geometry of the test configurations, test set-up containing a model test pit trench, layers of the untreated soil and RSM layers, loading system, loading plate and data measurement system (dial gauges). The load application system was a hydraulic jack supported against a strong reaction beam. According to the ASTM D1196-04 and ASTM D1195-09 [10,11], the footing model of 300 mm in diameter and 25.4 mm in thickness was used and placed on the surface at the center of the installation.

To measure the settlement of footing model, three linear dial gauges with an accuracy of 0.01% of full range (100 mm) were attached to a reference beam and their tips placed about 10 mm inwards from the edge of the plate.

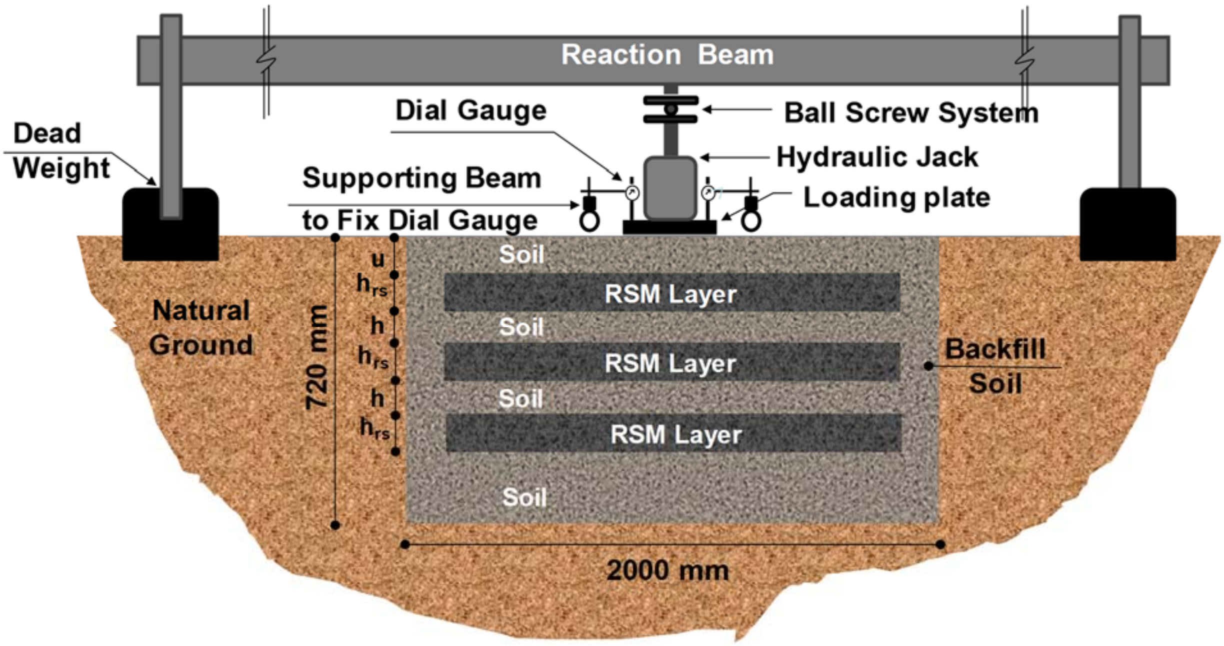


Figure 2. Schematic cross-section of the test set-up (Not in scale).

To achieve the required density of backfill layers, the soil and RSM layers were compacted at thickness of 60 mm and at an optimum moisture content of 5.7% with one and three passes, respectively, using a walk-behind vibrating plate compactor, 450 mm in width. In all tests containing RSM layers, granulated rubber was used at a mass replacement rate of 8% (R_c=8%) by weight (Moghaddas Tafreshi et al., 2013) and were placed at $h_{rs}/D=0.4$ and $u/D=h/D=0.2$ (Moghaddas Tafreshi et al., 2014). The average (from three sand cone tests) measured dry densities of the soil and of the RSM mixture after compaction were about 17.52 kN/m^3 (approximately 85% of maximum soil dry density) and 13.6 kN/m^3, respectively. The incremental cyclic loads of 140, 280, 420, 560 and 700 kPa ($q_{cycl.}$) was applied to the surface of footing model, for only one cycle of loading and unloading, at a rate of 1.5 kPa per second.

4. Test Program

Table 1 shows the details of the testing program. Test series containing zero (untreated: Test Series 1), and one, two and three layers of RSM (Test Series 2) were conducted. Test Series 1 provided reference, untreated, performance data. Test Series 2 were performed to examined the beneficial effect of RSM layers (N=1, 2, 3) on deformation and damping ratio of foundation bed. According to Yoon et al. (2008) for multi-layered 'Tirecell'-reinforcement, the layers of mixture in Test Series 2, placed at u/D=h/D=0.2 which the parameter of "u" and "h" are the depth of the first layer of RSM beneath the loading plate, and the thickness of the soil layer between the RSM layers, respectively. The width of the RSM layers (b) is expressed in non-dimensional form with respect to loading plate diameter (D=300 mm) as, b/D. In line with the findings of Yoon et al., (2008), the parameter b/D was held constant in all the tests at b/D=5.

In order to assess the utility of the apparatus, the accuracy of the measurements, the repeatability of the system, the reliability of the results and finally to verify the consistency of the test data, many of the tests described in Table 1 were repeated at least twice which revealed a close match between results of the two or three trial tests with maximum differences in results of around 3-6%.

Table 1. Scheme of the incremental cyclic load tests for untreated beds and beds containing RSM layers

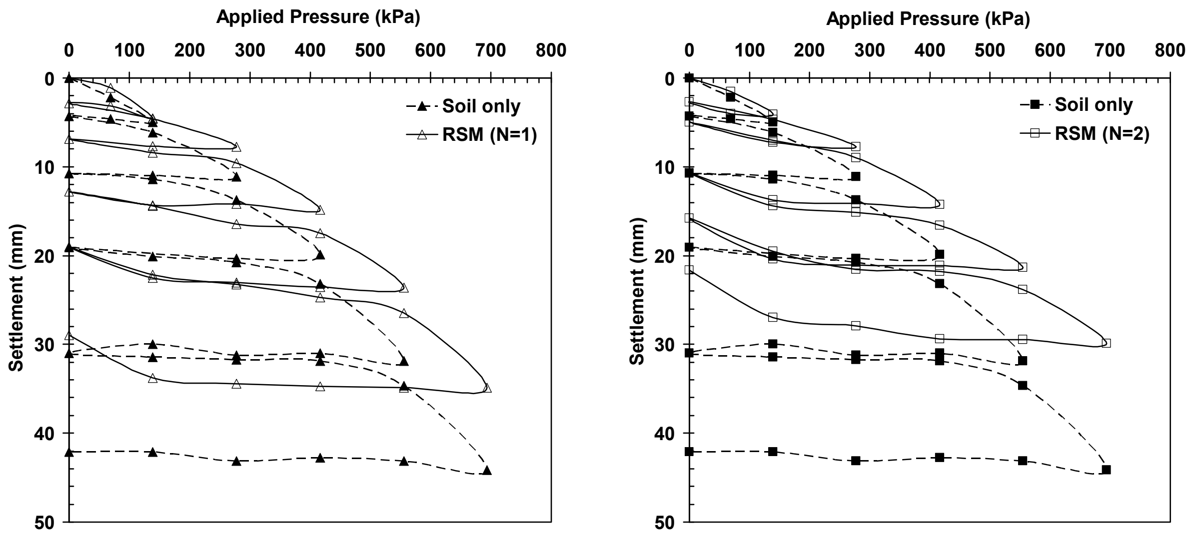
Test Series	Type of foundation bed	Values of parameters studied in tests		No. of Tests	Purpose of the tests
		$q_{cycl.}$ *(kPa)*	*N*		
1	Untreated (Soil only)	140, 280, 420, 560, 700	----	1+2[a]	To quantify the improvements in Test Series 2
2	Containing RSM layer(s)		1, 2, 3	3+6[a]	To determine the effect of number of RSM layers

[a] *The tests which were performed two or three times to verify the repeatability of the test data*

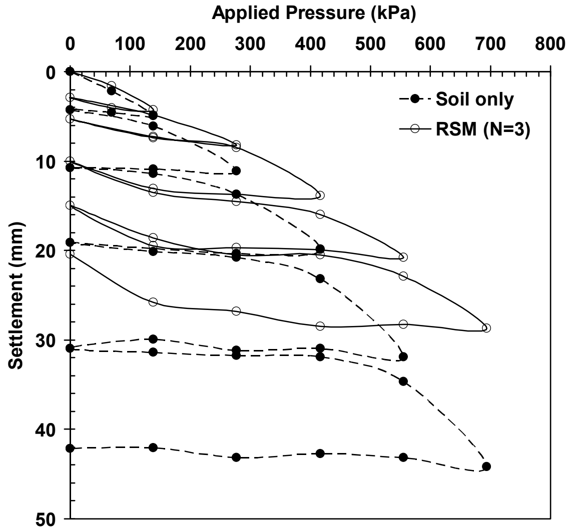
5. Results and Discussion

5.1. Deformation properties of rubber-soil mixture

Figure 3 shows the pressure-settlement response of the foundation bed with none (soil only), one, two, and three layers of RSM (N=0, 1, 2, 3) subjected to incremental cyclic loading and unloading. The layers of RSM were employed at hrs/B=0.4 with the same rubber content of 8% (Rc=8%) [15]. The hysteresis curves in Fig. 3 show that at a given level of applied pressure, with increase in the in the number of mixture layers, the total and residual settlements of foundation bed decrease. It could be attributed to internal confinement provided by the RSM layers, mobilized by the tensile strength of the rubber particles and the friction at the soil-rubber interface which would restrict lateral displacement [16] of the foundation bed, and thus limit the foundation settlement.



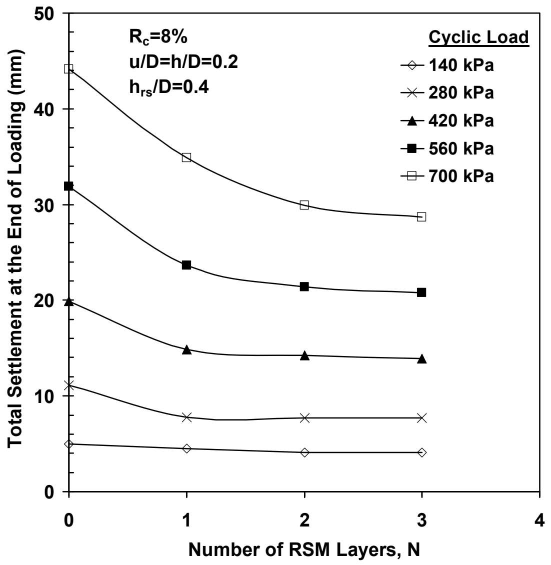
(a) (b)



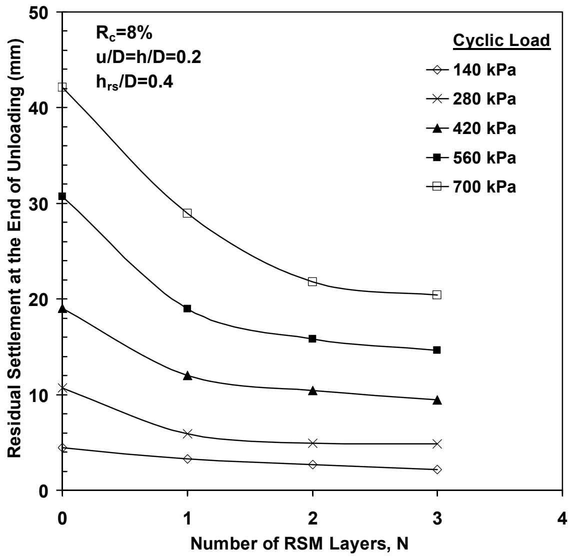
(c)

Figure 3. Comparison of the pressure-settlement response of foundation beds with 0, 1, 2 and 3 RSM layers (R_c=8%, h_{rs}/D= 0.4 and u/D= h/D=0.2) (a) N=1, (b) N=2, (c) N=3

Figure 4 illustrates the variation in total and residual settlements of the foundation beds with RSM layers (extracted from Figure 3) for different amplitudes of cyclic load. This figure indicates that, for all applied load levels the total and residual settlements of the footing model, significantly reduces as compared with the settlement of the untreated backfill. For example, at 560 kPa amplitude of applied cyclic load, the residual settlement values (Fig. 4b) are about 31, 19, 16, and 15 mm for none, one, two and three layers of RSM, respectively. This example also implies that how the rate of reduction in the total and residual settlement reduce with increase in the number of RSM layers, as insignificant decrease in the total and residual settlements occurs when the third layer of RSM is added.



(a)



(b)

Figure 4. Variation of (a) total, and (b) residual settlement with the number of RSM layers

5.2. Damping Ratio

Damping ratio is a measure of a material's ability to absorb energy and to limit vibrations during cyclic loading. Lee and Sheu [17] proposed a method to compute damping which is followed in this paper (see Figure 5) in which a loading-strain sequence OBDACB is assumed. In this approach Emax represents the maximum Young's modulus which is experienced only on first loading and on unloading. In fact, for granular soils, the Emax value during unloading is usually significantly higher than the maximum modulus on first loading due to strain hardening. Ec is the secant Young's modulus represented by the line connecting the origin with the point of maximum stress and strain (ε_c).

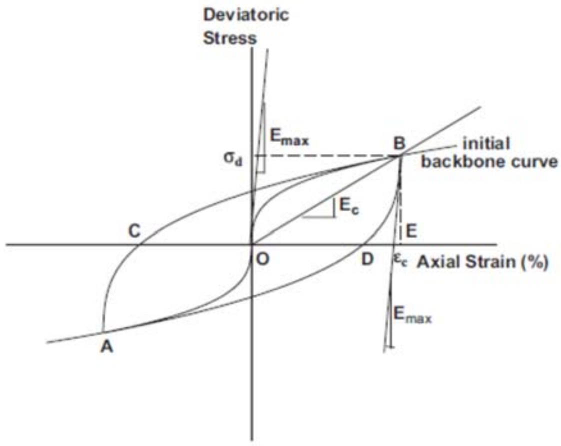


Figure 5. Schematic illustration of a symmetric stress–strain loop during the first cycle [17]

According to the Ramberg–Osgood formulation [18], the equation of the "initial backbone curve" (BOA) is:

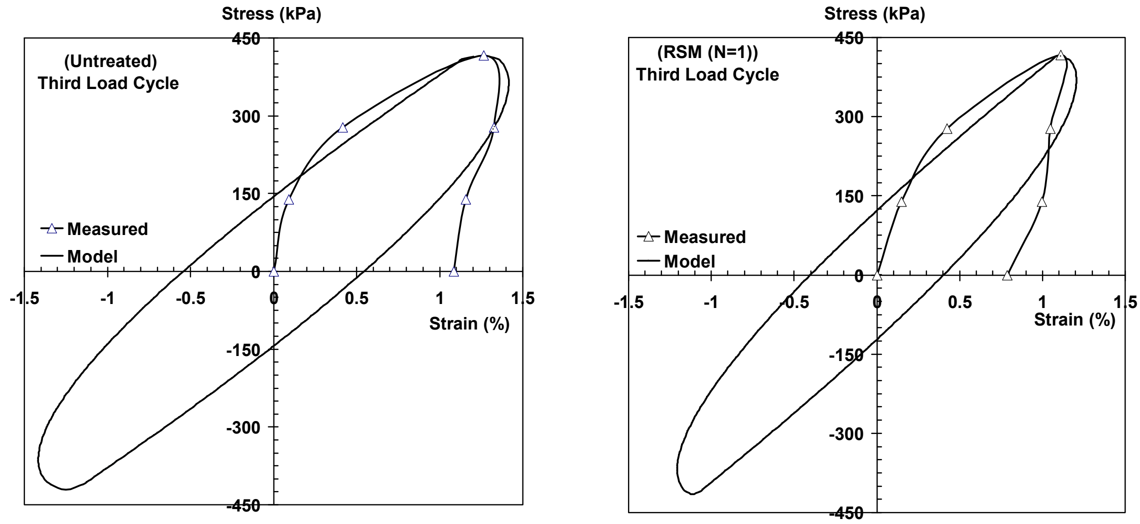
$$\varepsilon_c = \varepsilon_y \left(\frac{\sigma_d}{E_{\max} \varepsilon_y} \right) \left(1 + \alpha \left| \frac{\sigma_d}{E_{\max} \varepsilon_y} \right|^{r-1} \right) \tag{1}$$

where α and *r* are constants and ε_y is a reference axial strain with the other parameters previously defined. From the initial backbone curve, hysteresis loops can readily be constructed following the method proposed by Masing [19,20]. Hence the ACBDA loop may be written as Eq. 2 and the secant modulus as Eq. 3.

$$\varepsilon \pm \varepsilon_c = \varepsilon_y \left(\frac{\sigma \pm \sigma_d}{E_{\max} \varepsilon_y} \right) \left(1 + \frac{2\alpha}{2^r} \left| \frac{\sigma \pm \sigma_d}{E_{\max} \varepsilon_y} \right|^{r-1} \right) \tag{2}$$

$$E_c = \frac{E_{\max}}{1 + \alpha \left| \dfrac{\sigma_d}{E_{\max} \varepsilon_y} \right|^{r-1}} \tag{3}$$

Using Eq. 1 to 3, together with some programming in MATLAB (MathWorks Inc. [21]), the values of α, r, E_{max} and ε_y were obtained by trial and error. Figure 6 shows two typical reconstructed stress-strain loops for cases when N=0 (Untreated) and N=1 (one layer of RSM). The theoretical model assumes loading to be uniaxial which, clearly is not the case here, so the deduced moduli (obtainable from the gradients of the plotted lines) can only be indicative of the true values.



(a) (b)

Figure 6. Two typical reconstructed stress- strain loops (a) untreated, (b) single layer of RSM

According to vibration theory, the damping ratio, D is defined as follows:

$$D = \frac{1}{4\pi}\frac{A_L}{A_T} \quad (4)$$

Where A_L is the area of the hysteresis loop ACBDA and A_T is the maximum strain energy denoted by the area of the triangle OBE (see Figure 5). Values of damping ratio are tabulated against number of RSM layers in Table 2. The table clearly shows that damping ratio increases with the number RSM layers (N), irrespective of load cycle number. The increase with stress and the amount of rubber in the system suggests that soil treatment with rubber could have useful application where damping is of concern for foundation design (e.g. to mitigate the effects of vibrations from anthropogenic or geologic sources).

Table 2. Damping ratio of the soil-only and RSM systems at different load cycles

	Load cycle No. / Applied stress (kPa)				
No. of RSM layers (N)	1 / 140	2 / 280	3 / 420	4 / 560	5 / 700
0	11.8	12.1	13.9	14.7	15.6
1	13.9	14.4	16.4	17.5	18.5
2	15.3	16.1	18.3	19.4	19.8
3	16.2	17.4	19.7	20.2	20.9

6. Conclusion

Based on the incremental plate load tests on soil bed and bed containing RSM layers, the following conclusions can be made:

- The use of RSM layers in bed decreases the footing settlement. Under the last cycle of loading repeated in this paper (at 700 kPa with three layers of RSM (N=3)), the residual, plastic, deformation is only about 65% of the value for the conventional case.
- Reduction rate in total and residual settlement of footing, decreases with increase in the number of RSM layers.

- The RSM layers increase the damping ratio by 4-5% beyond the value of 12-15% obtained on sand alone. This makes it, potentially, a very attractive material to achieve vibration attenuation for machine foundation and railway track beds.

The tests were conducted only one type of soil, one type and size of rubber, and one load diameter. In spite of these limitations, the obtained results in this paper provide considerable encouragement for the use of multi-layered RSM system with inter-layers of untreated soil and for addressing localized soft foundation conditions. Considering these limitations, future tests on larger scale trials with a detailed economic and sustainability evaluation are recommended. Further numerical studies can also be performed considering cyclic loading application.

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