Geomechanics and Engineering, *Vol. 9*, *No. 2* (*2015*) *219-241*
DOI: http://dx.doi.org/10.12989/gae.2015.9.2.219

Application of waste rubber to reduce the settlement of road embankment

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(*Received October 01, 2014, Revised April 07, 2015, Accepted April 09, 2015*)

Abstract. In this paper, a series of repeated load tests were carried out on a 150 mm diameter plate simulative of vehicle passes, to demonstrate the benefits of soil-rubber shred mixture in decreasing the soil surface settlement of road embankment. The results show that the efficiency of rubber reinforcement is significantly a function of the rubber content, thickness of rubber-soil mixture and soil cap thickness over the mixture. Minimum surface settlement is provided by 2.5% of rubber in rubber-soil mixture, the thickness of mixture layer and soil cap of 0.5 times the loading surface diameter, giving values of 0.32-0.68 times those obtained in the unreinforced system for low and high values of amplitude of repeated load. In this installation, in contrast with unreinforced bed that shows unstable response, the rate of enhancement in settlement decreases significantly as the number of loading cycles increase and system behaves resiliently without undergoing plastic deformation. The findings encourage the use of rubber shreds obtained from non-reusable tires as a viable material in road works.

Keywords: rubber-soil mixture; soil cap layer; rubber content; settlement; repeated load; road embankment

1. Introduction

The volume of used tire rubbers in the world is significantly increasing every year due to the developing industry and growing population (WRAP 2007, RMA 2007, RRI 2009) and their disposals have, therefore, become a major environmental problem worldwide. Large number of scrap tires are either dumped in landfills or stockpiled across the landscape in huge volume (Cetin *et al*. 2006, Chiu 2008, Wu and Tsai 2009). Waste tire piles are dangerous because they not only cause environmental pollution but also provide breeding sites for mosquito vectors of human disease and they pose a fire risk. Tires in landfills are problematic because they take up large amount of space, which are not compactable, and can ‘float’ to the top, potentially damaging or breaking the landfill cap (Cetin *et al*. 2006, Lee *et al*. 2007). Consequently, safe beneficial use of the rubber underground is also beneficial for the waste tires, from an environmental point of view, as they are removed from sunlight (Collins *et al*. 2002). As a widely applied regenerated material,

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http://www.techno-press.org/?journal = gae&subpage = 7 ISSN: 2005-307X (Print), 2092-6219 (Online)

crumb rubber produced by waste tires is mainly used as an elastomer for improving the impact resistance of materials, elastic layers for elastic paving, and functional composites which have the characteristics of safety and water permeability (Fang *et al*. 2001).

The use of tires shreds in construction projects, such as embankment roads, may be feasible as an alternative way to consume the huge stockpile of scrap tire, with a better understanding of the behavior of rubber-soil mixture. In the last decade, numerous researches have been investigated some fundamental engineering properties of rubber-soil mixtures, such as compaction characteristics, compressibility, California Bearing Ratio (CBR), shear strength, modulus of elasticity, Poisson's ratio, and permeability (e.g. Edil and Bosscher 1994, Warith and Rao 2006, Cetin *et al*. 2012). Recently the application of waste tires has been developed in civil engineering. There are currently strong potentials for the use of waste materials and recycled tires such as reinforcing soft soil in road construction, highway embankments, backfilling in retaining structure as lightweight materials, road embankment, asphalt mixes and other earthworks (Upton and Machan 1993, Smith *et al*. 2001, Yoon *et al*. 2004, Cao 2007, Yoon *et al*. 2008, Wu and Tsai 2009, Edincliler *et al*. 2010, Fontes 2010, Arabani *et al*. 2010, Wang *et al*. 2012, Celauro *et al*. 2012, Mishra and Igarashi 2013, Arabani *et al*. 2013, Edincliler and Cagatay 2013, Keskin and Laman 2014, Sellaf 2014, Karabash and Cabalar 2015). Using of these waste materials in different applications can provide an alternative way to consume the huge stockpile of scrape tires from all over the word and consequently can be cost-effective and reduce some environmental problems from waste tires and give these wastes an ecological value.

Majority of studies on rubber-soil mixtures are mainly reported on static stress-strain behavior or rubber-soil interface behavior and the available studies about the dynamic or cyclic properties of wastes and recycled rubber or rubber-soil mixture are limited. However, with the increase in using the wastes, a need for further understanding of rubber-soil mixture behavior under repeated loads is required. In the present study, an approach for recycled waste rubbers mixed with soil is illustrated with a series of cyclic laboratory model tests.

2. Literature review on dynamic behavior of rubber-soil mixture

In recent years, experimental and numerical results on dynamic behavior of rubber-soil mixture are reported by various researchers (Bosscher *et al*. 1997, Feng and Sutter 2000, Edincliler *et al*. 2004, Prasad and Prasada Raju 2009, Lazizi *et al*. 2014). They showed that the recycled rubber mixed with soil is a potential composite material, which can be advantageously employed in improving the dynamic behavior of new composite materials, particularly in the case of roads, highways, and embankments. Bosscher *et al*. (1997) conducted a study related to rubber-soil mixture. They used a laboratory model test of tire-chips embankment to generate deformation response data of various tire chips-embankment construction configuration under repetitive loads. To simulate traffic loading, a repeated load was applied at a frequency of 0.25-0.5 Hz up to 200 kPa. They reported a better performance in decreasing the surface plastic displacement, when the tire-chips covered by a relatively thick soil cap compared to use the tire-chips in whole of the fill. The soil cap over the tire-chips not only reduces the ongoing settlement, but also prevents tire shreds from possible igniting.

Feng and Sutter (2000) investigated dynamic properties of granulated rubber/sand mixtures such as shear modulus and damping ratio using a torsional resonant column test. Specimens were constructed using different percentages of granulated tire rubber and Ottawa sand at several different percentages. They reported that shear modulus and damping ratio of the mixtures are strongly influenced by the percentage of the rubber. Shear modulus decreases and damping ratio increases by increasing the rubber content. Edincliler *et al*. (2004) investigated behavior of recycled materials for highways under static and dynamic loads. They indicated that tire buffings may be used to modify the strength-deformation behavior and dynamic behavior of sand and their use is economically feasible. Prasad and Prasada Raju (2009) investigated the performance of flexible pavement on expansive soil subgrade using gravel/fly ash as subbase course with waste tire rubber as a reinforcing material. They observed that the maximum load carrying capacity associated with less value of rebound deflection is obtained for rubber mixed with gravel subbase compared to rubber mixed with flyash subbase.

Soil particles are very stiff and thus dissipate very little energy in particle deformation. In contrast, the rubber consumes energy through the deformation of rubber particles themselves (Feng and Sutter 2000). Therefore, the rubber-soil mixture is able to exhibit a higher capacity to absorb energy than soil alone, so it is expected to reduce the energy applied on the backfill surface due to repeated loading and is expected to decrease the transfer of stress to the deeper layer. Overall, the waste tires in the form of shredded rubbers when mixed with soil, under repeated loading, may result two important advantages in improving the backfill behaviour. One is its behaviour as reinforcement elements in soil that can demonstrate a substantial increase in shear strength of mixture compared to soil alone. The other is the exhibition of higher capacity to absorb and to dissipate more energy than soil alone and tending to decrease the stress and shocks transferred into the ground. Besides, use of waste rubbers causes the reduction in consumption of competent natural soil and its cost saving benefit.

To promote the recycling of tire wastes on a large-scale in geotechnical applications where bulk utilization of waste materials is possible, in the current study, experimental results to investigate the response of relatively dense soil with randomly distributed tire shreds to repeated loading are presented. The studies include a series of different tests by placing a circular metal plate on the model flexible road embankment, to evaluate the surface settlement at different amplitude of repeated loads. The various parameters studied in this testing program include the percentages of rubber content mixed with soil, the thickness of rubber-soil mixture as a subbase layer, and the thickness of unreinforced soil cap over the rubber-soil mixture which it may presumably increase the performance of rubber-soil mixture (Bosscher *et al*. 1997), the details of which are presented in later sections. Testing was arranged so as to determine the parameters controlling best usage.

3. Laboratory model tests

A physical model test was used to provide rather realistic test conditions. The schematic representation of the physical model test setup and its attachments comprising a testing tank, loading system and data measurement system is shown in Fig. 1.

3.1 Testing tank

The testing tank is designed as a rigid box with plan dimensions of 1200 mm × 1200 mm, and 800 mm in height, encompassing the unreinforced natural soil, the replaced rubber-soil mixture, the unreinforced soil cap layer, and the loading plate (as loading surface). The back and side faces of the tank consist of smooth MDF sheets of 20 mm thickness, which are permanently fixed to

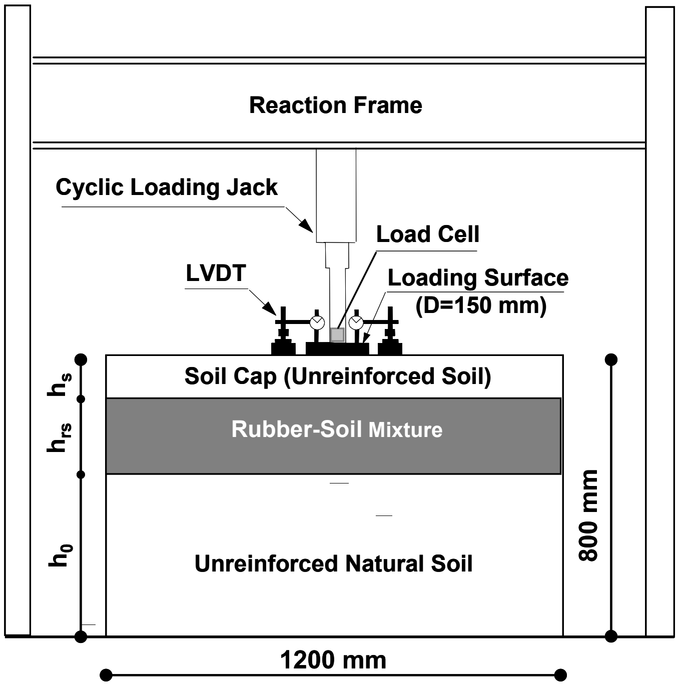


Fig. 1 Schematic representation of the test setup and layout of the trench (Not to scale)

channel sections. To allow the probable visual observations of the road embankment, as well as photo scanning, the front face of the tank is made of 20 mm thick Plexiglas. To prevent undesirable movement of the four sides of the tank the rigidity of the tank has been guaranteed by using a stiff steel section of U-100 on four sides of the tank. According to some preliminary test results (not further reported here), under a maximum applied loading stress of 650 kPa on the loading plate, the measured deflection of sides of the tank were insignificant demonstrating that they would be negligible at the stress levels applied in the main tests program. Also during the tests, no differential settlement between the two ends of the footing (loading plate) was observed.

3.2 Loading system

Loading system includes loading frame, pneumatic cylinder, and controlling unit. The loading frame consists of two stiff and heavy steel columns and a horizontal beam that support the pneumatic actuator. Two pneumatic actuators which have the internal diameters of 80 and 160 mm may produce monotonic or repeated loads with maximum capacity of 12 kN depending on the intensity of the input compressed air.

3.3 Data measurement system

The data measurement system was developed to read and record both load and settlement automatically. An S-shaped load cell with an accuracy of ±0.01% and a full-scale capacity of 15 kN was placed between the loading shaft and the loading plate to precisely measure the pattern of the applied repeated load. Throughout the tests, the average settlement of loading plate (soil surface settlement) was monitored during loading, unloading and reloading by two linear variable differential transducers (*LVDTs*) with an accuracy of 0.01% of full range (100 mm), located on opposite edges of the loading plate. To ensure accurate readings, all of the devices were calibrated prior to each series of tests.

4. Test materials

4.1 Soil

The natural granular soil passing through 25.4 mm sieve was used as natural ground, soil cap, and in mixture of rubber-soil as reinforced layer. It has grain sizes between 0.07 and 25.4 mm and a specific gravity, G_s of 2.64. It has a Coefficient of uniformity, C_u of 10.9, Coefficient of curvature, C_c of 0.77, an effective grain size, D_{10} of 0.22 mm, and mean grain size, D_{50} of 1.65 mm. The maximum and minimum void ratio (e_{max} and e_{min}) of the soil were obtained as 0.88 and 0.4, respectively. The soil is classified as poorly graded sand with letter symbol "*SP*" according to the Unified Soil Classification System (ASTM D 2487). The maximum dry density and optimum moisture content of soil were 19.2 kN/m^3 and 6.5 %, respectively. The angle of internal friction of soil at moisture content of 6.5% and wet density of 18.4 kN/m^3 was 34.5°.

4.2 Shredded rubber

Shredded rubbers used in this study, as an alternative reinforcement material are provided from cutting the waste soft tube tires of motorcycle with a special cutter into rectangular shape. The nominal size of the tire shreds of 10 mm in width and about 30-50 mm in length was selected (aspect ratio between 3 and 5). This range of aspect ratio (ratio of length/width) was selected to achieve the maximum performance in increasing the bearing capacity of foundation bed and in decreasing the soil surface settlement (Hataf and Rahimi 2005). Properties of the rubber used, are presented in Table 1 and a view of the shredded rubber used, is shown in Fig. 2.

Fig. 2 A view of shredded tire rubbers used in this study (the scale of ruler is cm)

Table 1 Properties of rubber used

Description	Value
Total unit weight (kN/m^3)	10.9
Thickness (mm)	1.2
Angle of internal friction (degree)	21.5
Cohesion (kN/m^2)	0
Strain at Ultimate tensile strength (%)	220
Ultimate tensile strength, T_u (kN/m)	6.84
Axial stiffness at 2% strain, J (kN/m)	6.15
Axial stiffness at 5% strain, J (kN/m)	5.20

5. Model test preparation and test procedure

The schematic layout of the simulated flexible road embankment, which contains the unreinforced soil as natural ground, the rubber-soil mixture layer, the unreinforced soil cap, and the loading surface, is shown in Fig. 1. To simulate the three aforementioned parts of the backfill matrix in the testing tank, the compaction method was used. The compaction energy produces by means of pneumatic cylinder which applies constant pressure on a wooden stiff plate (the soil surface is divided to four parts in plan and a wooden stiff plate of 600 mm × 600 mm in plan dimensions placed at each quarter of soil surface). Before compaction the soil layers, compaction system was calibrated at different compaction energy (i.e. using the uniform pressure on the wooden plate) and number of compaction repetitions for the soil layers of 25 mm in thickness, so that the compaction effort and consequently compaction energy was kept the same in all the tests. The necessary compaction energy and number of compaction effort can be selected to achieve the desired density for each test.

The unreinforced soil layers to simulate the natural ground and the topmost unreinforced soil layer as a soil cap layer (see Fig. 1) were compacted at moisture content about 6.5% to achieve the wet density of around 18.4 kN/m^3 (corresponding to the dry density of 17.28 kN/m^3, approximately 90% of maximum dry density). This value of soil density was obtained by using constant pressure of 30 kPa which applied three times on wooden plate. It should be noted that the same compaction effort used to prepare the rubber-soil mixture in all tests. Tire shred content, R_c was selected of 2.5%, 5% and 7.5% volume of the total volume of soil-rubber mixture layer (see Table 2). For obtaining a desirable mixture, the soil and the tire shreds were carefully mixed using a mixer. Special care was taken to mix thoroughly the tire shreds and the soil, in order to produce a reasonably uniform rubber-soil mixture. The dry density of rubber-soil mixture layers, after compaction, for rubber contents of 2.5%, 5% and 7.5% were measured around 16.22, 15.06 and 13.62 kN/m^3, respectively. Note the reduction in density as a consequence of the partial replacement of mineral by the less dense rubber particles and of the differing void ratios. To ensure that the calibration system produces the proper compaction, the density of compacted layers (soil layers and rubber-soil mixture layer) was measured for several tests, and the maximum difference in density was around 1%-2%.

The foundation bed with total thickness of 800 mm includes natural ground, rubber-soil mixture and soil cap was compacted in layers of 25 mm in thickness until the soil cap reached the soil surface level. The repeated loading was done through a circular steel plate of 150 mm diameter (and 20 mm in thickness) laid on the center of the simulated flexible road embankment. The diameter (= 150 mm) and thickness (= 25 mm) of the loading plate are selected according to the AASHTO T 221 and ASTM D1195. These standards recommend using the repeated plate load test on a circular steel plate having a thickness not less than 25.4 mm and a diameter ranging from 150 and 750 mm for use in evaluation and design of airport and highway pavements under wheel load. Also, Hsieh and Mao (2005) used two steel circular plates with diameters of 150 mm and 300 mm to simulate the footprint of various sized tires on different size of soils. They reported when the load plate diameter is larger than 15 times the D_{50} of the test soil, no marked influence of plate size on surface settlement would be expected. Hence, according to the D_{50} value of soils (see soil properties in Section 4.1) using a plate size of 150 mm diameter can provide a workable compromise that minimizes the scale effect in model tests.

An additional 5 mm thick rubber base was attached at the bottom of the loading plate to simulate rubber tire contact. To provide vertical loading alignment, a small semispherical indentation was made at the center of the loading surface model. A load cell was placed on the loading shaft to record the applied loads, and two *LVDTs* were placed on the loading surface model to measure the settlement of the loading surface during the repeated load. The details of the shredded rubber content, the thickness of rubber-reinforced soil layer, and the soil cap thickness in each model test are given in Table 2.

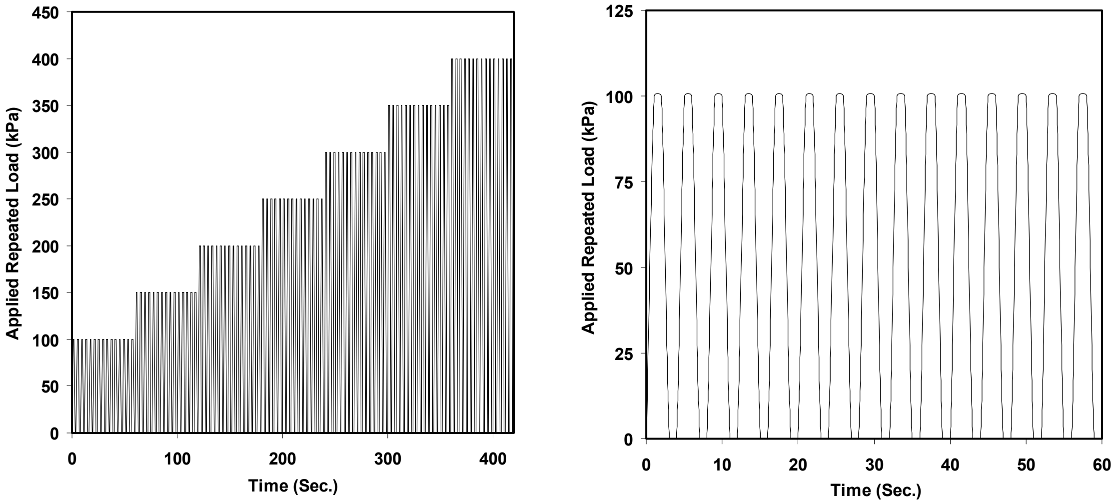
6. Pattern of applied repeated load

To simulate the traffic loading (tire pressure), a repeated loading includes loading, unloading and reloading were imposed on the loading surface at a frequently of 0.25 Hz. The maximum applied pressure was chosen to replicate that of a semi-heavy vehicle half-axle as used on the common semi-heavy trailers (6 axles and a mean pressure 400 kPa) (Brito and Dawson 2007). It was divided into seven stages which are 100, 150, 200, 250, 300, 350, and 400 kPa to simulate the light to semi-heavy traffic loadings. For each stage, fifteen loading and unloading cycles were applied, and afterward the loading and unloading continued at the next level, and so on. The disuse of load cycles number more than fifteen for each stage of repeated loads, was due to limitation in producing the adequate air pressure by air compressor system. The schematic view of the repeated loading pattern is presented in Fig. 3. The wave frequency was chosen based on previous studies to simulate field traffic speed (Bosscher *et al.* 1997). They simulated wheel load using cyclic pressures of 7 to 200 kPa at a frequency of 0.25-0.5 Hz by wooden plate.

It should be noted that all the following results are related to repeated plate load tests which simulated wheel track loading conditions. Although, the rotating stress field applied by a wheel passage is rather different from the cyclic axial loading applied in these tests, yet according to research done by Weissman (1999) and Kim and Tutumluer (2005), cyclic plate load test can present some sort of satisfactory results in the absence of moving wheel load test. However, since AASHTO T 221 and ASTM D1195 recommend using the repeated plate load test for use in designing airport and highway pavements, therefore, this limitation in the present work isn’t expected to be very influential on the outcomes.

7. Test parameters and testing program

The geometry of the test configuration for fully unreinforced and shredded rubber-reinforced backfills, considered in these investigations is shown in Fig. 1. Also, Table 2 gives the details of all



(a) Seven stages of loading and unloading cycles with amplitude of 100, 150, 200, 250, 300, 350, and 400 kPa

(b) Fifteen loading and unloading cycles of the first stage

Fig. 3 Repeated loading pattern on soil surface

Table 2 Scheme of the repeated load tests

Test series	Type of test	Thickness of soil cap; h_s/D	Rubber content; R_c (%)	Thickness of rubber-soil mixture; h_{rs}/D	Thickness of natural ground; h_0/D	No. of Tests	Purposed of the tests
1	Fully unreinforced backfill	-	-	-	7	1+2*	To quantify the improvements due to reinforcements
2	Reinforced backfill with shredded rubber	0, 0.25, 0.5	2.5%, 5%, 7.5%	0.25, 0.5, 1	**Variable	27+9*	To study the effect of R_c , h_s/D , and h_{rs}/D

*The tests which were performed two or three times to verify the repeatability of the test data.
**The total thickness of foundation bed beneath the loading surface is kept constant equals 700 mm.

the test series done in this study. Test series 2 on the rubber-soil mixture layer was conducted by changing the percentage of rubber content (R_c), the thickness of rubber-reinforced soil layer (h_{rs}/D), and the thickness of unreinforced soil cap (h_s/D). In the Test series 2, the thickness of unreinforced soil cap (h_s/D) was limited to 0.5 and selected as 0, 0.25, and 0.5. Increasing h_s/D beyond 0.5 can be located the layer of reinforcement (i.e., the layer of rubber-soil mixture) out of the most effective zone of a surface loading, so that stress applied on backfill concentrates on the unreinforced soil mass (Moghaddas Tafreshi and Norouzi 2012). Since, the influence zone beneath the surface loading in foundation engineering has been known between 1D to 2D, to obtain the optimum value of h_{rs}/D, the values of 0.25, 0.5, and 1 was examined. Also, according to the findings of Moghaddas Tafreshi and Norouzi (2012) and Prasad and Prasada Raju (2009), the rubber contents of 2.5%, 5%, 7.5% was examined in the tests. To provide a reference soil surface settlement against which to quantify the improvements due to rubber soil reinforcement, Test series 1 on fully unreinforced soil was carried out.

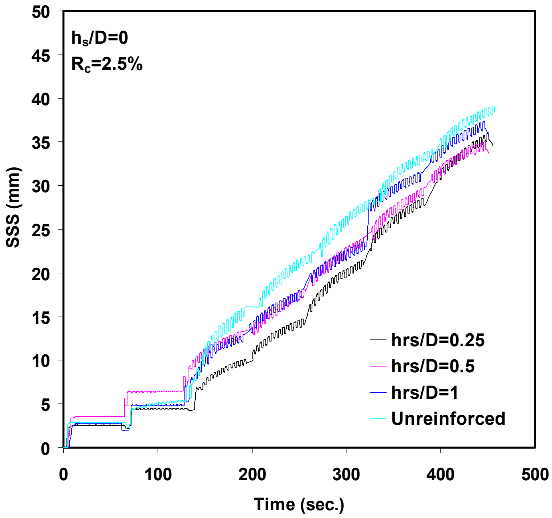
In order to assess the utility of the apparatus, the accuracy of the measurements, the repeatability of the system, the reliability of the results and finally to verify the consistency of the test data, many of the tests described in Table 2 were repeated at least twice. The results revealed a close match between results of the multiple trial tests with maximum differences in results of around 8-10%. This difference was considered to be small so mean results are presented in this paper. The consistency of the results demonstrates that the procedure and technique adopted can produce repeatable tests within the bounds that may be expected from geotechnical testing apparatuses. In deciding on the parameters to be investigated and their values, the authors have attempted to replicate likely in-situ usage (geometry, type of soil and rubber, stress level, etc.), albeit at reduced scale.

8. Results and discussions

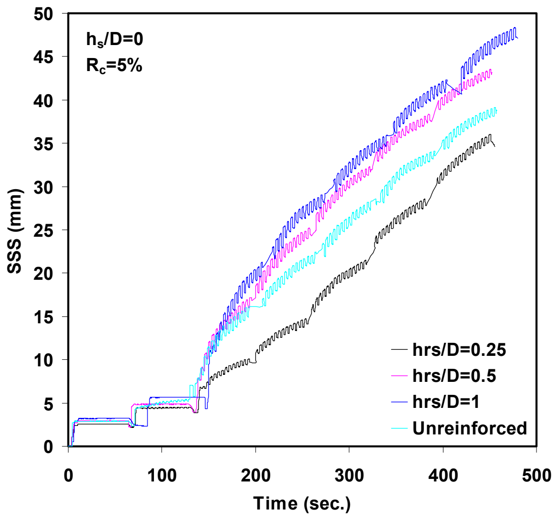
In this section, the tests results of the laboratory model are presented with a discussion highlighting the effects of the different parameters. The value of soil surface settlement (*SSS*) of the unreinforced bed and the rubber-reinforced bed, at different levels of repeated pressure is investigated.

The variation of *SSS* with time (or number of load cycles) for unreinforced and rubber-reinforced backfills (Test Series 1 and 2) under the repeated load through all the cycles of loading and unloading are as shown in Figs. 4-6. The results illustrated in these figures were obtained by varying the thickness of soil cap layer (h_s/D = 0, 0.25, 0.50), the thickness of rubber-reinforced soil (h_{rs}/D = 0.25, 0.5, 1), and the content of tire shreds (R_c = 2.5%, 5%, 7.5%). These figures illustrate the beneficial effect or harmful effect of the rubber-reinforced installation on surface settlement response, when compared with the fully unreinforced installation. This behaviour is significantly a function of three parameters of R_c, h_s/D, and h_{rs}/D. According to the results presented in Figs. 4-6, although some of the rubber-soil backfill installations show a reinforcement effect in decreasing the backfill settlement (positive influence) compared to the settlement of the unreinforced bed, some of them lead to more deformation (negative influence) than the unreinforced installation due, it is assumed, to more plastic properties of the rubber-soil mixture.

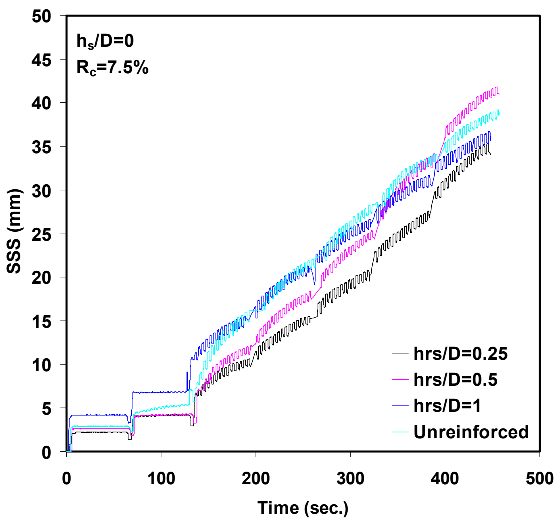
These figures show that the settlement of the unreinforced base and some of the rubber-soil mixture bases, tend to be increased with increase in the number of load cycles, so that a non-stabilizing response, eventually leading to failure, particularly for higher level of cyclic loads (i.e. 300 and 400 kPa) would be probable expected. For the some of the reinforced bases, the rate of change in settlement of loading surface, reduces as the number of load cycles increases, so that their variation tend to become approximately stable at the end of fifteen load cycles (or due to more load cycles) of each applied repeated load levels, particularly for the reinforced base with $h_s/D = h_{rs}/D$ = 0.5, and R_c = 2.5% (Fig. 6(a)). This behaviour is a consequence of the shakedown process as the structure of the foundation bed becomes arranged into a progressively a more stable arrangement better able to behave resiliently without undergoing plastic deformation. Likewise, the performance of rubber-soil mixture layer in decreasing the settlement of loading plate could be attributed to the superior confinement offered by the mixture layer, so that allows to develop a lateral resistance that increases the bearing capacity and decreases the settlement of the foundation



(a) R_c = 2.5%



(b) R_c = 5%

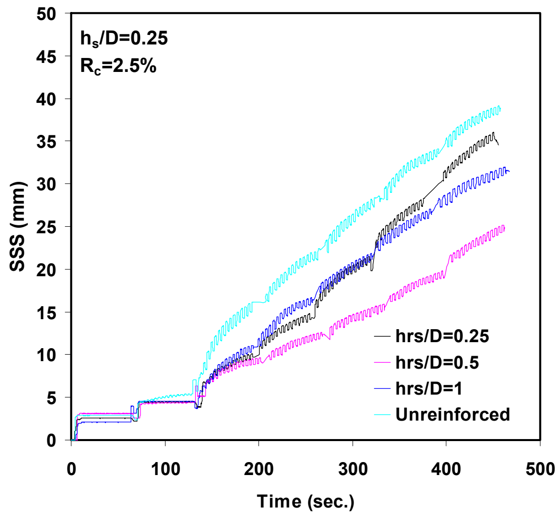


(c) R_c = 7.5%

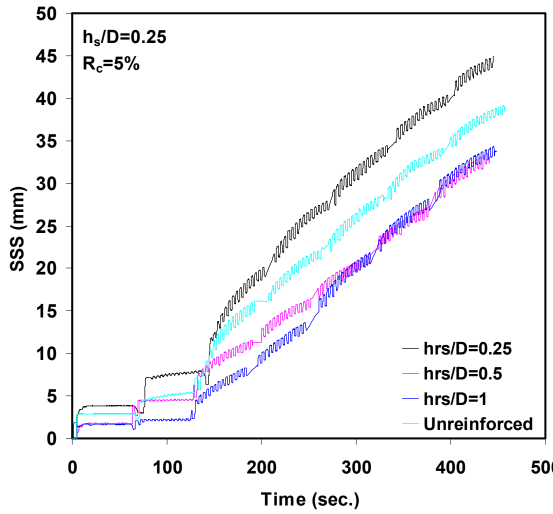
Fig. 4 Variation of soil surface settlement (SSS) with time for unreinforced and rubber-reinforced soil at h_s/D = 0 and different values of h_{rs}/D, for three rubber contents, R_c. Loading amplitude of repeated load were 100, 150, 200, 250, 300, 350 and 400 kPa

bed. The concept of confinement reinforcement, which may be called internal confinement, was explained by Yang in 1974. The confinement effect is dependent on the tensile strength of the reinforcement and the friction at the soil-rubber interface. Tavakoli Mehrjardi *et al.* (2012) reported the similar results of soil surface settlement with the number of loading cycles for the rubber-reinforced foundation bed including pipe.

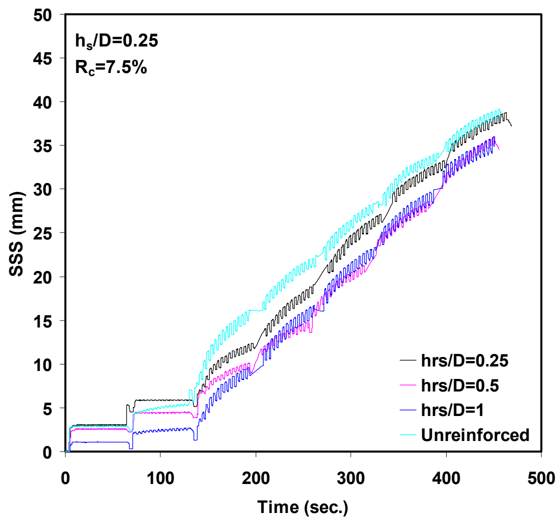
In order to investigate more clearly the performance of rubber-soil mixture layer on the backfill response, the variation of *SSS* for different backfill installations (different values of h_s/D, h_{rs}/D and



(a) $R_c = 2.5\%$



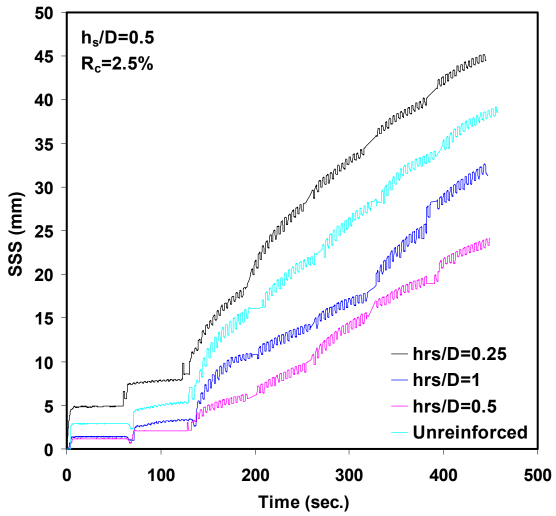
(b) $R_c = 5\%$



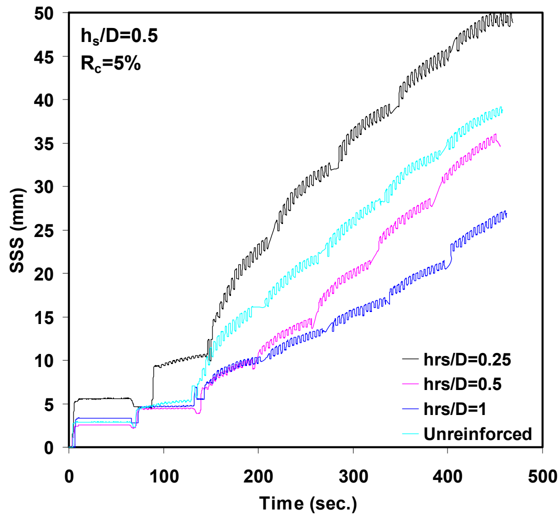
(c) $R_c = 7.5\%$

Fig. 5 Variation of soil surface settlement (SSS) with time for unreinforced and rubber-reinforced soil at h_s/D = 0.25 and different values of h_{rs}/D, for three rubber contents, R_c. Loading amplitude of repeated load were 100, 150, 200, 250, 300, 350, and 400 kPa

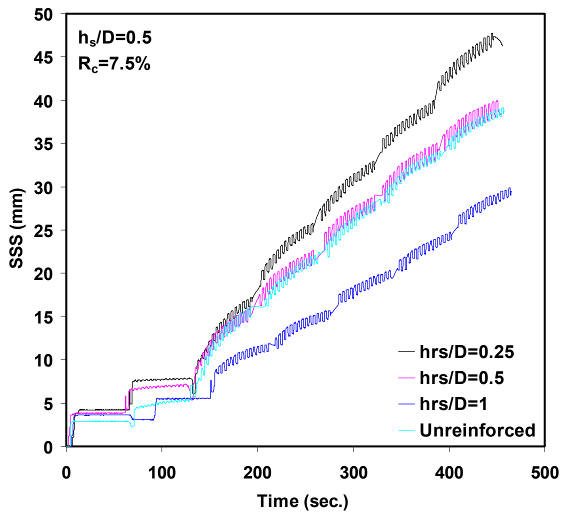
R_c) at the last cycle of each stage of loading and unloading cycles are presented in Tables 3-5. These tables show that the performance of rubber-soil mixture may be positive or negative, depending on the h_s/D, R_c, and h_{rs}/D values. Its performance is positive where the use of rubber-soil mixture layer decreases the settlement of the rubber-reinforced installation compared with the settlement of the unreinforced installation ($SSS_{rein.} < SSS_{unrein.}$). Likewise, the performance of rubber-soil mixture is negative where the use of rubber-soil mixture layer increases the settlement of the rubber-reinforced installation compared with the settlement of the unreinforced installation (SSS_{rein}



(a) $R_c = 2.5\%$



(b) $R_c = 5\%$



(c) $R_c = 7.5\%$

Fig. 6 Variation of soil surface settlement (SSS) with time for unreinforced and rubber-reinforced soil at $h_s/D = 0.5$ and different values of h_{rs}/D, for three rubber contents, R_c. Loading amplitude of repeated load were 100, 150, 200, 250, 300, 350 and 400 kPa

> SSS_{unrein}). Overall, the negative performance of backfill means that, due to swapping the soil grains with soft material, like rubber, the behaviour of the mixture changes from a soil-like behaviour towards a rubber-like behaviour (large settlements). In addition, the increase in the settlement of the backfill may be a consequence of an increased void ratio of a non-homogenous mixture, which would tend to increase the compressibility of the backfill. Obviously, the negative or positive influence of rubber-reinforced layer on the *SSS* values is a function of the percentage of

Table 3 Summary of results in terms of soil surface settlement (*SSS*) for h_s/D = 0, h_{rs}/D = 0.25, 0.5, and 1 and for three rubber content of 2.5%, 5%, and 7.5% under seven amplitudes of repeated load of 100, 150, 200, 250, 300, 350 and 400 kPa

Amplitude of applied repeated load (kPa)	Unreinforced backfill (h_{rs}/D = 0)	Soil Surface Settlement, *SSS* (mm) h_s/D = 0								
		R_c = 2.5% h_{rs}/D			R_c = 5% h_{rs}/D			R_c = 7.5% h_{rs}/D		
		0.25	0.5	1	0.25	0.5	1	0.25	0.5	1
100	2.89	2.57	3.56	2.58	2.56	2.95	3.24	2.23	2.62	4.23
150	5.44	4.38	6.41	5.22	4.42	4.89	5.68	3.92	4.12	6.87
200	16.13	10.06	13.27	12.97	10.07	16.91	21.24	10.57	12.03	15.28
250	22.23	15.72	17.94	17.95	14.52	25.11	28.89	15.26	18.35	21.09
300	28.53	21.46	23.85	23.86	21.21	31.94	35.9	20.57	25.18	26.35
350	34.12	28.66	29.77	31.86	28.53	38.25	42.26	27.21	34.16	31.67
400	39.14	35.98	34.91	37.28	35.23	43.18	48.32	35.35	41.82	36.52

Table 4 Summary of results in terms of soil surface settlement (*SSS*) for h_s/D = 0.25, h_{rs}/D = 0.25, 0.5, and 1 and for three rubber content of 2.5%, 5%, and 7.5% under seven amplitudes of repeated load of 100, 150, 200, 250, 300, 350 and 400 kPa

Amplitude of applied repeated load (kPa)	Unreinforced backfill (h_{rs}/D = 0)	Soil Surface Settlement, *SSS* (mm) h_s/D = 0								
		R_c = 2.5% h_{rs}/D			R_c = 5% h_{rs}/D			R_c = 7.5% h_{rs}/D		
		0.25	0.5	1	0.25	0.5	1	0.25	0.5	1
100	2.89	2.91	3.11	2.09	3.86	1.76	1.35	3.04	2.57	1.43
150	5.44	4.54	4.31	4.53	7.92	4.48	2.32	5.76	4.47	2.52
200	16.13	10.26	9.62	10.92	20.06	11.27	8.22	12.42	10.19	9.54
250	22.23	14.77	12.41	16.42	27.83	16.27	13.46	19.12	14.8	16.29
300	28.53	21.45	17.98	21.78	34.45	21.65	21.84	27.12	21.34	23.42
350	34.12	28.5	21.87	26.84	40.36	26.91	27.93	33.25	28.48	29.97
400	39.14	36	26.02	31.92	44.87	33.52	34.32	38.71	35.91	35.91

rubber in rubber-soil mixture and thickness of mixture (reinforced layer) for both backfill with and without soil cap.

As can be seen in Fig. 4 and Table 3, in the case of h_s/D = 0 (the installations with no soil cap), the worst behaviour belongs to the mixture with h_{rs}/D = 1, containing 5% of shredded rubber and particularly at higher load level (Fig. 4(b), load level higher than 200 kPa). However, the mixture with h_{rs}/D = 0.25 could be delivered the best performance amongst the others, irrespective of rubber content. Figs. 5-6 and Tables 4-5 illustrate the response of the soil surface settlement under repeated loads for the installations in the presence of soil cap layer (h_s/D = 0.25, 0.5). These figures and tables indicate that the best performance is delivered by using h_s/D = h_{rs}/D = 0.5

Table 5 Summary of results in terms of soil surface settlement (*SSS*) for h_s/D = 0.5, h_{rs}/D = 0.25, 0.5 and 1 and for three rubber content f 2.5%, 5% and 7.5% under seven amplitudes of repeated load of 100, 150, 200, 250, 300, 350 and 400 kPa

Amplitude of applied repeated load (kPa)	Unreinforced backfill (h_{rs}/D = 0)	Soil Surface Settlement, *SSS* (mm)								
		h_s/D = 0								
		R_c = 2.5%			R_c = 5%			R_c = 7.5%		
		h_{rs}/D			h_{rs}/D			h_{rs}/D		
		0.25	0.5	1	0.25	0.5	1	0.25	0.5	1
100	2.89	4.91	1.18	1.39	5.62	2.56	3.35	4.21	3.86	3.63
150	5.44	8.11	2.09	3.21	10.58	4.32	4.82	7.89	6.96	5.62
200	16.13	18.41	6.11	10.8	24.07	10.07	10.38	17.12	15.87	11.85
250	22.23	27.78	9.72	13.98	32.72	14.77	13.39	25.48	22.59	15.7
300	28.53	34.2	15.56	17.91	39.44	21.18	17.05	32.91	29.02	20.26
350	34.12	40.22	19.76	25.54	45.97	28.53	21.22	39.77	34.99	24.71
400	39.14	45.19	24.13	32.61	49.95	35.99	26.99	47.77	39.87	29.89

containing 2.5% of shredded rubber (R_c = 2.5%) (the gray marked column in Table 5 and the pink curve in Fig. 6(a)).

The variation of the backfill settlement, *SSS* with amplitude of applied repeated load as a consequence of the repeated loading pattern (as illustrated in Fig. 3), is plotted in Fig. 7. The data are presented for unreinforced backfill and two cases of rubber-reinforced backfills (first case: h_s/D = 0, R_c = 2.5%, h_{rs}/D = 0.25 and second case: h_s/D = 0.5, R_c = 2.5%, h_{rs}/D = 0.5). These two last cases were selected corresponding to the best performance of rubber reinforcement in decreasing the soil surface settlement of backfill without soil cap (h_s/D = 0) and with soil cap (h_s/D = 0.5). The curves in Fig. 7 show the final measurement at the last cycle of each load level.

As expected, the increase in the magnitude of the repeated load directly causes the soil surface settlement, *SSS* to increase for both unreinforced and rubber reinforced backfills (Fig. 7). For example, the final *SSS* for the reinforced backfill with h_s/D = 0.5 at the end of loading are 1.18, 6.11, 15.56, and 24.13 mm for magnitudes of repeated load that are 100, 200, 300, and 400 kPa, respectively.

From this figure, it is very clear that the settlement response of backfill is superior in the presence of a soil cap thickness of 0.5 (h_s/D = 0.5), a rubber-soil mixture layer of 0.5 in thickness (h_{rs}/D = 0.5) and 2.5% waste rubber mix (R_c = 2.5%), regardless of applied load level – a clear objective of a successful backfill. This behaviour, due no doubt to the rubber properties and to its reinforcing efficacy within a soil layer, may help reduce accumulation of SSS under continued cycling of loading and unloading at any given repeated loading. Consider, for example, the final settlement of soil surface, *SSS* supported by unreinforced backfill and subjected to a repeated load level equal to 300 kPa. At the end of loading, the final settlement (*SSS*) is 28.53 mm. This value can be compared with the settlement of the backfill supported on the rubber-reinforced layer, which decreases to 21.46 mm and 15.56 mm for h_s/D of 0 (R_c = 2.5% and h_{rs} = 0.25) and 0.5 (R_c = 2 .5% and h_{rs} = 0.5), respectively.

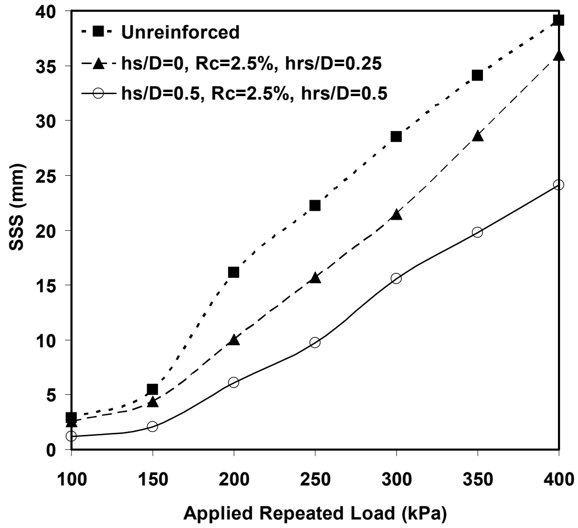


Fig. 7 Comparisons between the two best-improved rubber-reinforced and unreinforced backfills for variation of soil surface settlement, *SSS* with applied repeated load

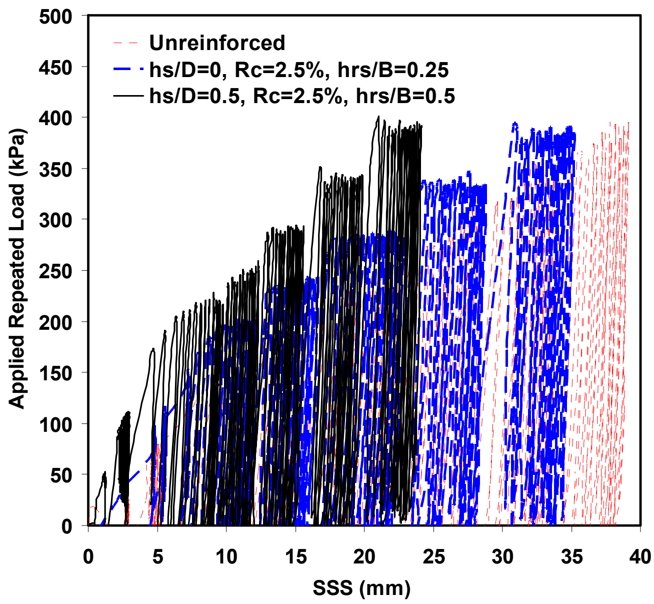


Fig. 8 Comparison of two rubber reinforced installations (installations with $h_s/D = 0$, $R_c = 2.5\%$, $h_{rs}/D = 0.25$ and $h_s/D = 0.5$, $R_c = 2.5\%$, $h_{rs}/D = 0.5$) and unreinforced installations under the repeated loading

Furthermore, to make a better comparison between the two rubber reinforced installations (the installations with $h_s/D = 0$, $R_c = 2.5\%$, $h_{rs}/D = 0.25$ and $h_s/D = 0.5$, $R_c = 2.5\%$, $h_{rs}/D = 0.5$) and no-rubber installation, their hysteresis loop of soil surface settlement, SSS are shown in Fig. 8. This figure depicts that the rubber-soil reinforced installation in the presence of a soil cap ($h_s/D = 0.5$) was successful in reducing the soil surface settlement between 40% and 60% compared with the soil-only installation, whereas the rubber-reinforced installation without soil cap (h_s/D = 0) delivers a reduction in SSS between 8% and 38% compared with the unreinforced installation. The performance of rubber reinforcement in decreasing SSS of a soil bed subjected to repeated loads of various amplitudes might be attributable to the energy absorbance properties of rubber-soil mixtures. Probably, the rubber-soil mixture is able to exhibit a higher capacity to absorb energy than soil alone under repeated loading and tends to decrease the stress and shocks transferred into the lower soil in the backfill. Together the ability to absorb stresses and the reinforcing efficacy of rubber-soil mixture would lead to decrease the SSS value, thereby reducing probable excavation and backfilling compaction requirements for unpaved system. Overall, the results illustrated in Figs. 7 and 8 indicate a possible positive performance when rubber is added to the soil; benefits that depend on the rubber content, thickness of rubber- soil mixture, and the mixture position.

8.1 The influence of the soil cap thickness

The performance of soil cap cover and its thickness in decreasing the settlement of rubber-reinforced backfill is the subject of Fig. 9. This figure indicates the variation in SSS, at the peak of each load pulse, with h_s/D. The rubber-reinforced layer was placed at the depths of 0, 0.25, and 0.5 times of the loading surface diameter (h_s/D = 0, 0.25, and 0.5) from the base of the loading surface. Note that the best installation ($h_s/D = h_{rs}/D$ = 0.5 and R_c = 2.5%) in Fig. 9 (also see Fig. 7) is compared with the other installations with h_s/D = 0 and 0.25 having R_c = 2.5% and h_{rs}/D = 0.5.

This figure shows that, at all the repeated load levels, the SSS value decreases steadily due to further additional thickness of soil cap layer whereas the rate of reduction in SSS reduces with increase in the value of h_s/D. On the whole, the reinforced backfill using soil cap (h_s/D = 0.25 and 0.50) depicts results in a better performance compared to that of the reinforced backfill without soil cap (h_s/D = 0). The final settlement of backfill (*SSS*), at the last cycle of loading levels of 200 kPa was 13.27, 9.62, and 6.1 mm respectively for the backfill with h_s/D of 0, 0.25, and 0.50. On the other hand, the SSS value was reduced by 17.7%, 40%, and 62% respectively for the backfill with h_s/D of 0, 0.25, and 0.50, in comparison with the unreinforced backfill. The corresponding reduction in *SSS* values at the last cycle of loading level of 400 kPa were about 11%, 35%, and 40%. The beneficial effect of soil cap layer over the rubber-soil mixture on the responses of system (i.e. settlement of backfill, *SSS*) may be attributed to two following reasons: (1) For h_s/D = 0 the overburden is not sufficient to develop enough frictional resistance at the interface of the soil cap and rubber-reinforced layer, and (2) the presence of soil cap over the rubber-soil mixture prevents punching failure and distributes the stress more uniform on the mixture. On the other hand, the soil cover above the mixture, acts as a cushion, prevents the direct contact of the loading surface base with the mixture, and consequently decreases the settlement of backfill due to distribution of the applied pressure more uniformly over the mixture. The beneficial effect of soil cap in reduction of SSS confirms the result of Bosscher *et al*. (1997) to use the soil cap over the tire chips-soil mixture. They reported that, the mixture of soil and rubber used as a replacement for fill, delivers the best performance when covered by an adequate soil cap thickness.

Increasing h_s/D beyond 0.5 may locate the layer of rubber-soil mixture out of the most effective zone, so that an increase in value of soil surface settlement and consequently a decrease in performance of backfill could be expected. It would be anticipated that, with increasing the soil cover to more than load surface diameter, the mixture layer lies outside the effective zone beneath the load and so that the SSS value tends to the unreinforced one. Moghaddas Tafreshi and Dawson (2010) reported that the settlement of footing improves significantly when the first geotextile layer

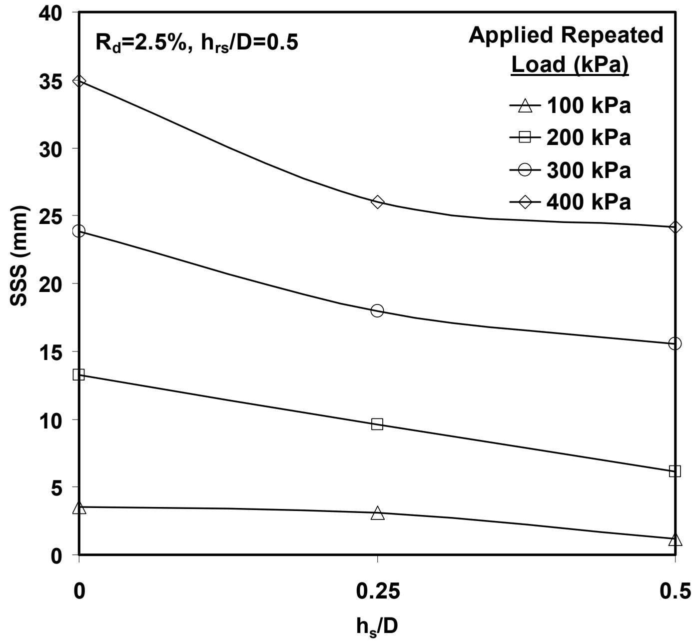


Fig. 9 Variation of soil surface settlement (SSS) with soil cap thickness (h_s/D) for thickness of rubber-soil mixture of 0.5 (h_{rs}/D = 0.5) and rubber content of 2.5% (R_c = 2.5%) at different levels of applied repeated load

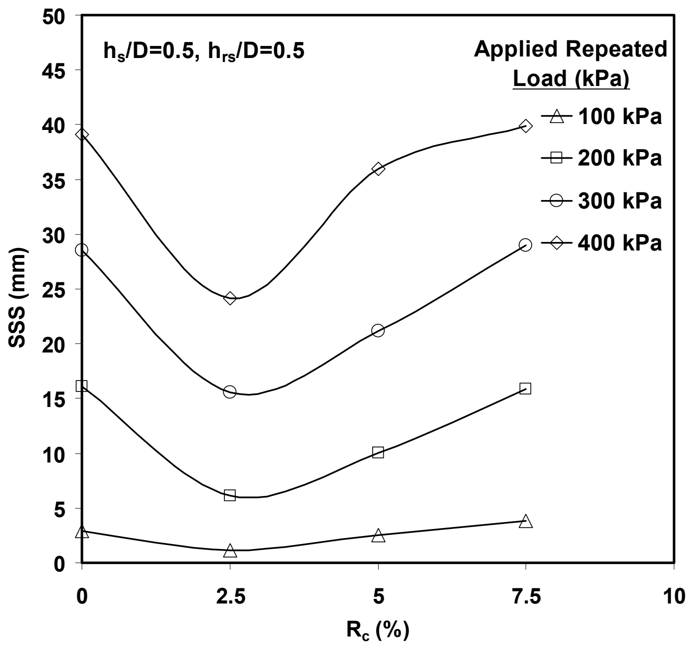


Fig. 10 Variation of soil surface settlement (SSS) with rubber content, for soil cap thickness of 0.5 (h_s/D = 0.5) and thickness of rubber-soil mixture of 0.5 (h_{rs}/D = 0.5) at different levels of applied repeated load

was embedded in the soil bed around 0.35 times of footing width. Likewise, they reported that when the top layer of geotextile was placed beyond this depth, an increase in the value of footing settlement will observe. With increase in the soil cover to 1.2 times of the footing width, the reinforcement layer lies outside the failure zone, and so the influence of reinforcement on the footing behaviour becomes negligible.

8.2 The influence of rubber content

The variation of the SSS values at the end of load cycle of different amplitude of repeated load with rubber content, R_c are shown in Fig. 10. This figure compares the best installation ($h_s/D = h_{rs}/D = 0.5$ and $R_c = 2.5\%$) (see Tables 3-5 and Fig. 7) with the other installations with rubber content of 5% and 7.5% ($R_c = 5\%$ and 7.5%) having $h_s/D = h_{rs}/D = 0.5$.

From Fig. 10, it is clear that the superior response was achieved for the backfill containing 2.5% of rubber content ($R_c = 2.5\%$). This figure shows that, regardless of the repeated load level, the improvement in SSS value initially increasing when rubber content increases from 0% to around 2.5%, but that, thereafter, the value of SSS increases with rubber content and may tend to the unreinforced installation. For example, at the last cycle of loading levels of 200 kPa, the final settlement of backfill (*SSS*) was 16.13, 6.11, 10.07, 15.87 mm, respectively for the unreinforced backfill ($R_c = 0$) and for the reinforced backfill having R_c of 2.5%, 5%, and 7.5%. The corresponding *SSS* values at the last cycle of loading level of 400 kPa were about 39.14, 24.13, 35.99, and 39.87 mm. These results introduce an optimum rubber content around 2.5%, which delivers the maximum decrease in the *SSS* value. The increase in performance improvement with rubber content of 2.5% could be due to the available competent rubber-soil mixture as a reinforced layer. The increase in the *SSS* value after optimum content of rubber may be attributed to swapping the soil grains with soft material, like rubber, and possible increasing the void ratio and compressibility of non-homogenous mixture. It might be expected when the rubber content increases to more than 7.5%, the SSS of backfill becomes greater than the SSS of unreinforced one (note that the SSS value for $R_c = 7.5\%$ is around the SSS value of unreinforced backfill). The excess of soft rubber particles separates soil particles, forms a soft rubber fabric and consequently increases the SSS value due to compressible backfill.

Edil and Bosscher (1994) reported that depending on the packing and the rubber/soil mixing ratio, the compressibility of rubber/soil mixtures can be relatively high. In such conditions, the behaviour of the mixture changes from competent rubber-soil mixture-like behaviour to rubber-like behaviour as the rubber content increased. Hataf and Rahimi (2005) reported somewhat similar findings in the absent of soil cap, for existence an optimum value of rubber content used in rubber soil mixture, after that increasing shreds rubber led to decrease in bearing capacity, although their results is not consistent, quantitatively with the results of current study. Prasad and Prasada Raju (2009) reported a similar finding in that the maximum angle of friction value and California Bearing Ratio (CBR) value are obtained using a mixture of rubber-soil containing 5%-6% of waste tire rubber chips by volume.

8.3 The influence of the rubber- soil mixture thickness

The variation of the SSS, at the end of load cycles of different repeated load level, with the thickness of rubber-reinforced soil (h_{rs}/D) is as shown in Fig. 11. This figure depicts the SSS values for the unreinforced experiment and for the reinforced experiments with $h_s/D = 0.5$ and $R_c =$

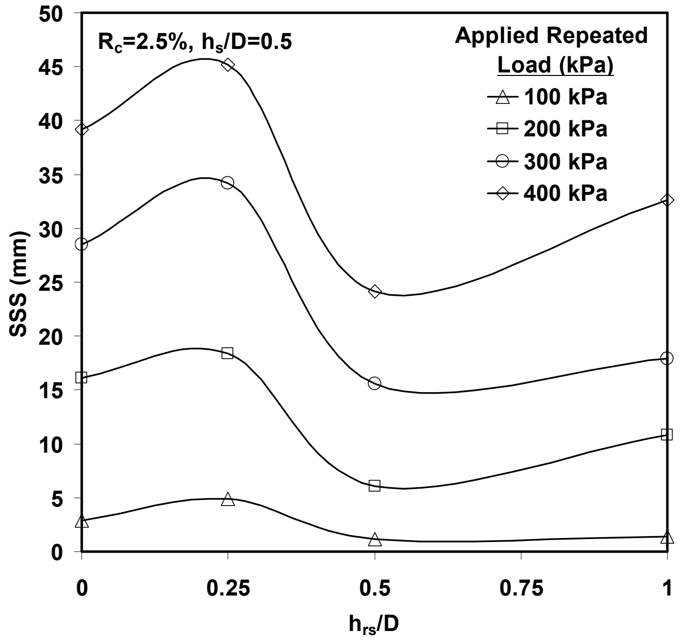


Fig. 11 Variation of soil surface settlement (SSS) with thickness of rubber-soil mixture (h_{rs}/D) for s oil cap thickness of 0.5 (h_s/D = 0.5) and rubber content of 2.5% (R_c = 2.5%) at different lev elsof applied repeated load

2.5%. On the other hand, this figure compares the best installation (h_s/D = h_{rs}/D = 0.5 and R_c = 2.5%) with the other installations with h_{rs}/D of 0, 0.25, and 1 includes R_c = 5% and h_s/D = 0.5.

From this figure, it has been observed that, at all repeated load levels with an increase the h_{rs}/D ratio beyond 0.25, the value of SSS decreases up to the value of h_{rs}/D = 0.5, approximately, after which, with further increase in h_{rs}/D ratio, the value of SSS increases. As can be seen from Fig. 11, for the repeated loading level of 200 kPa, the final settlement of backfill (*SSS*) was 16.13, 18.41, 6.11, and 10.8 mm, respectively for the unreinforced backfill (h_{rs}/D = 0) and for the reinforced backfill having 0.25, 0.5, and 1 of rubber-reinforced layer thickness ratio (h_{rs}/D). This comparison depicts that the *SSS* value reaches around 1.14, 0.38, and 0.67 times of the unreinforced bed, respectively for h_{rs}/D of 0.25, 0.5, and 1. These results reveal that there is an optimum thickness of rubber-soil mixture, which increases the reinforcing efficacy in decreasing the SSS of backfill, irrespective of the amplitude of repeated load.

In the case of h_{rs}/D = 1, the value of SSS, under repeated load of 400 kPa, reaches around 0.84 times of the unreinforced bed. Therefore, it would be anticipated with increase in h_{rs}, greater than one times of the loading surface (h_{rs}/D>1), more significant enhancement in SSS value delivers, compared to that of the unreinforced backfill. The observed enhancement in SSS after the optimum thickness of rubber-soil mixture reinforced layer may be attributed to high increase in the thickness of the compressible layer of mixture, which may likely attenuate the reinforcing effect of rubber in mixture. In this case, although the void ratio of mixture layer is kept constant, but the total void space between soil particles and compressibility of mixture is increased. On the other hand, with increase in the thickness of rubber-soil mixture, the behavior of mixture changes from a reinforcing material to high compressible material, which decreases the stiffness of the backfill and consequently increases the SSS.

9. Conclusions

In this research, laboratory model tests were used to investigate the potential benefits of reinforcing backfill soil with randomly distributed rubber shreds to reduce the settlement of flexible road embankment subjected to repeated load. The various parameters studied in this testing program include the thickness of soil cover (h_s/D), the thickness of rubber-soil mixture (h_{rs}/D), rubber content (R_c), and the amplitude of the repeated load. Based on the results, the following conclusions can be made:

- The performance of rubber-soil mixture in decreasing the soil surface settlement, may be positive ($SSS_{rein.} < SSS_{unrein.}$) or negative ($SSS_{rein} > SSS_{unrein}$), depending on the h_s/D, R_c, and h_{rs}/D values.
- The mixture including 2.5% of shredded rubber (R_c = 2.5%), the thickness of soil cover and rubber soil mixture of 0.5 ($h_s/D = h_{rs}/D = 0.5$) delivers the best performance amongst the others. The *SSS* value could be reduced by 38-62% compared with the soil-only installation depending on the repeated load level. In this installation, in contrast with unreinforced bed the unstable response was changed to the stable response as the system behaves resiliently without undergoing plastic deformation.
- In general, with the installation of a soil cap layer over the rubber-soil mixture, the soil surface settlement (*SSS*) could be reduced in comparison with that in an unreinforced installation, when the best values of h_{rs}/D, and R_c were used.
- The large value of h_s/D (probably more than load surface diameter), located the layer of rubber-soil mixture out of the effective zone beneath the loading surface, concentrates stress applied on the unreinforced soil cap, so that the SSS value tends to the unreinforced one.
- The large value of h_{rs}/D, and R_c made the backfill more compressible than the soil alone and allowed greater settlement of backfill due to change the embankment behaviour from a rubber-reinforced soil-like towards a compressible rubber-like behaviour.
- Based on the findings, the re-use of tire waste in the form of shredded rubber mixed with soil as a reinforcement layer is very promising and should be promoted as reinforcing elements in road embankment construction. Large earthwork projects using recycled tires such as those encountered in highway construction could be an ideal application for shredded tires because there is potential to use vast quantities of tires. Additionally, this use is beneficial to the environment in that a waste material is recycled and leads to overall saving in competent soil material costs and re-use of tires waste.

Since the tests results are obtained for only one type and one size of rubber, one type of soil, one size of loading surface and one type of loading pattern, generalization and specific applications may be needed, therefore, before these findings directly applied. However, to correlate the results of a prototype-scale auto-tyre to a model-scale test, directly, the probable scale effects should be considered on geometrical dimensions of effective factors and the properties of rubber and soil used, if any. Generally, these results will be helpful in designing other laboratory and field model tests, for use in numerical models, for simulation studies and in the application of the concepts in future studies.

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CC

Nomenclature

D_{10}	Effective grain size
D_{50}	Medium grain size
C_u	Coefficient of uniformity
C_c	Coefficient of curvature
G_s	Specific gravity
$e_{\min}$	Minimum void ratio
$e_{\max}$	Maximum void ratio
D_r	Relative density of soil
R_c	Rubber content
D	Diameter of loading surface
h_0	Thickness of soil cap
h_{rs}	Thickness of rubber-soil mixture
h_s	Thickness of soil cap
SSS	Soil surface settlement
SSS_{unrein}	Soil surface settlement of unreinforced bed
SSS_{rein}	Soil surface settlement of reinforced bed
T_u	Ultimate tensile strength
J	Rubber reinforcement stiffness