ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA

Revista de la Construcción
Journal of Construction

Research Article

Model studies on recycled whole rubber tyre reinforced granular fillings on weak soil

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Received: 21.12.2021; **Accepted:** 30.06.2022; **Published:** 26.08.2022

Citation: Geçkil, T., Sarici, T. and Ok, B. (2022). Model studies on recycled whole rubber tyre reinforced granular fillings on weak soil. Revista de la Construcción. Journal of Construction, 21(2), 264-280. https://doi.org/10.7764/RDLC.21.2.264.

Abstract: The main purpose of this study is to determine the stress-strain behaviour of a rigid circular footing placed on recycled rubber tyre-reinforced granular filling built on weak soil. For this purpose, model plate loading tests were carried out on reinforced/unreinforced granular filling built with natural aggregates (NA) or construction and demolition waste materials (CDW). The rubber tyre used for reinforcement has become a waste material by completing its service life but it has retained its typical cylindrical shape. In model plate loading tests, the effects of the granular fillings, the type of fillings material and the placement of whole rubber tyre and/or geotextile in the granular fillings were investigated. Depending on the results of tests, it was determined that the bearing capacity was increased by reinforcing with the rubber tyre and/or the geotextile. Furthermore, it was specified that the highest increase in bearing capacity was occurred case of by reinforcing with the geotextile together with the rubber tyre of the granular filling. The CDW and the NA fills reinforced with geotextile together with the rubber tyre increased the bearing capacity of weak soils by 6.59 and 8.49 times, respectively, for the 5% deformation ratio. On the other hand, it was reported that although the bearing capacity of the NA was higher than that of the CDW, the bearing capacity of the reinforced CDW approached that of the NA.

Keywords: Rubber tyre, geotextile, soil improvement, granular fillings, construction, demolition waste.

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1. Introduction

Traditionally, one of the most preferred methods for improving weak soils is to build a granular filling onto them. In this method, first of all, a type of granular fill material with higher bearing capacity, and lower settlement under pressure than that of weak soil is selected in order to build the granular filling. Then, either after the weak soil is removed by excavating up to the required height or directly on the weak soil, the selected granular soil is laid in layers and compacted with a suitable method. The weak soil and the granular fill layer form such a composite system that the load on the composite soil system is jointly carried by the weak soil and the granular fill layer. Nonetheless, since the stiffness of the granular fill layer is much higher than that of the weak soil generally, the majority of the load is carried by the granular filling (Meyerhof and Hanna 1978). In geotechnical structures, as the bearing capacity of the weak soil decreases, the amount of pressure applied to it can be reduced by increasing the thickness of the granular fill layer. Indeed, it becomes possible to spread the pressure on a larger area because the load acting from the soil surface is distributed over an increasing area as it transmits downwards. It means that the granular filling reduces the stress on the weak soil by retaining some of the stress within itself. Thus, the bearing capacity of the weak soil-granular fill composite system increases and the settlement decreases. As the thickness of the granular fill layer increases, the failure of the composite system occurs entirely within the more rigid granular fill layer (Das, 2017; Ornek et al., 2012).

Processes of obtaining granular soil from quarries, which are very harmful to the environment, have been becoming increasingly difficult with new laws and regulations. This makes the supply of granular soil, which is the only and most important material of granular filling, more expensive. Because the supply of granular soil creates both economic and environmental problems, it has led the researchers seeking to various solutions. The first of these is to improve the engineering properties of the granular filling itself. So, this solution can decline in the consumption of the granular soil due to causing a decline in its thickness. This application can also be considered as a soil improvement.

In recent years, the employing of geosynthetic products has been accepted as a remarkable solution to improve the engineering properties of a granular filling (Chen, 2007; Krishna & Biswas, 2021; Kayadelen et al, 2018). The bearing capacity of granular filling can be improved by placing a geotextile or geogrid, which are geosynthetic products, at the granular fillings-weak soil interface (Kazimierowicz-Frankowska, 2007; Bearden & Labuz, 1998; Das et al., 1998; Khing et al., 1994; Sarici, 2019). Kiptoo et al. (2017) determined the behaviour of the granular base layer reinforced with geotextile on a weak soil using static and dynamic model plate loading tests. They placed the geotextile at the interface of the weak soil and granular base layer in one series of their experiments and after all, stated that the usage of geotextile increased the bearing capacity and the service life while reducing the settlement. Furthermore, Ingle and Bhosale (2017) investigated the effect of the geotextile, which was placed at the granular base layer-subgrade interface, by performing full-scale cycling plate loading tests. According to their experiment results, the presence of geotextile significantly reduced the value of vertical stress and the granular base layer thickness. They stated that this improvement may occur by stretching the geotextile depending on the tendency of lateral spreading of granular soil.

On the other hand, geocell, which has a three dimensional and honeycomb-like shape of cells interconnected at joints, can also be preferred for the reinforcement of granular fillings (Sitharam and Hegde, 2013; Zhang et al., 2010; Arias et al.,2020; Ok, 2018; Altay et al., 2021a; Altay et al., 2021b). The geocell ensures to improve the soil by occurring soil-geocell friction and confining the soil all-around. Pokharel et al. (2010) experimentally examined the effects of parameters such as shape, type, embedment, height, and infill material's quality on the behaviour of reinforcement with a single-cell geocell. According to their study, reinforcement with a single-cell geocell increased the bearing capacity. Their test results also showed that the geocell placed in a circular shape had a higher bearing capacity and stiffness than those of an elliptical shape. Besides, they determined that the single-cell geocell reinforcement had a lower bearing capacity and stiffness than those of the multiple geocell reinforcements. Zhang et al. (2010) carried out a series of laboratory model tests on geocell reinforced embankment overlaying soft subgrade. They highlighted that the usage of the geocell remarkably increased the soft subgrade's bearing capacity.

Another method that is used to improve the granular filling itself is to use waste rubber tyres in different ways. Recycling and reusing waste rubber tyres not only improve the engineering properties of granular filling but also contributes to environmental problems and sustainability. The most popular reuse method of this waste in the geotechnical application is the addition of the reduced size rubber tyre into a granular filling. In such applications, the waste tyre is resized to the size of the material produced from it, such as carbon products, pyrolytic char, devulcanisate, reclaim, buffing, powder, crumb, fibre, granulated, chips, shreds, cuts (CWA, 2002; ASTM D6270, 2008; Liu et al., 2020). Akbarimehr and Aflaki (2018), Cetin et al. (2006), Balunaini et al. (2014), Dunham-Friel and Carraro (2014), Yadav et al. (2016), Trouzine et al. (2012) and Cabalar et al. (2014) carried out various studies using powder type, chips type, shred type, granulated type, crumb type, fibre type and buffing type rubber tyre, respectively. The consensus of these authors was that the waste rubber tyre improved several properties of the soils.

In some cases, it is not necessary to process waste rubber tyres in order to reuse them. In some applications such as retaining structures, erosion control barriers, lightweight embankment, tyres safety barriers for car races, landscaping, etc., waste whole rubber tyres are used without any recycling process. However, investigations related to reuse in this way remains limited. Further research is needed on the behaviour of whole rubber tyres in the soil, as there are differences in parameters such as the geometry of the whole rubber tyre, the saturation degree of soil, the type of soil, environmental effect and loading conditions. In fact, more research is needed for all forms (whole, powder, chips, shred, granulated, crumb, etc.) of the waste rubber tyre, because the waste rubber tyres are generated so much around the world and the reuse of these wastes will bring significant benefits to both environment and economy (Mohajerani et al., 2020).

Duda and Siwowski (2021) performed stability and settlement analyses for rubber tyre-baled lightweight embankment on weak soil. The rubber tyre-bales they used were composed of whole rubber tyres compressed into a lightweight block. They studied the tyre-baled structures with medium sand or rubber aggregate interlayers over sandy clay or silty clay. As a result of their studies, they emphasized that the usage of rubber tyre-bales increased the stability of embankment while decreasing the amount of embankment settlement and the normal stress in the weak soil. Indraratna et al. (2017) conducted plate loading tests on a single whole rubber tyre filled with subballast material. They also analysed their experimental work with the finite element method to examine and measure the interaction between the rubber tyre and granular soils. Their results showed that the rubber tyre increased the modulus and ultimate bearing capacity of the granular soil. They also reported that the usage of whole rubber tyre and geotextile reduced the stress on the subgrade thus it can effectively reduce the ballast's design thickness. However, they emphasized that the cylindrical shape of whole rubber tyres confined the infill material, reduced lateral deformation and created a more rigid layer as it provided a significant reduction in lateral stresses.

Another solution that the researchers focused on against the difficulties in the supply of granular soil is the use of construction and demolition wastes (CDW) as a granular material. In recent years, the use of recycled materials instead of natural granular materials has been an increasing research topic (Arulrajah et al., 2013; Vieira and Pereira, 2015). Nevertheless, it is necessary to comprehensively determine the geotechnical properties of these wastes to be accepted as a good alternative to filling material. Because there may be some problems due to the formation of these wastes. In general, wastes generated from various construction activities such as demolition, repair and reconstruction of structures are defined as CDW. Since the materials used in construction activities vary widely, CDW material is also a heterogeneous mixture.

The type and amount of substances in CDW depend on the materials used at the place where the waste is taken. Substances such as concrete, wood, glass, brick, ceramics, tile, plastic, bitumen-based materials, petroleum products, various metals, soil, insulation materials, gypsum-based materials may be found in CDW (Reis et al., 2021; Vieira and Pereira, 2015). If CDW, which is formed in very large quantities, is not recycled, it needs very large storage areas. In addition, the ever-increasing rapid growth in the construction industry has increased the need for natural granular aggregates. For this reason, if CDW is used instead of natural granular aggregate, the need for the required storage areas for CDW is reduced, damage to nature is reduced by reducing the need for quarries, economic gain is achieved by reducing the consumption of natural granular aggregate, environmental sustainability and energy savings are provided. (Sivakumar et al., 2004; Han et al., 2011; Saribas and Ok 2019; Ok et al., 2020).

Molenaar and van Niekerk (2002) determined the effect of grain size, composition and degree of compaction on the behaviour of the granular base layer formed with CDW materials. They stated that these investigated parameters were important because the quality of CDW materials could vary from region to region. As a result of their studies, they mentioned that the investigated factors had an effect on the mechanical properties however the most important factor was the degree of compaction. They also reported that a good quality road base course layer can be built using CDW. Mehrjardi et al. (2020) investigated the physical and mechanical properties of CDW. For this purpose, they performed laboratory tests to compare with the values in the standards. They also conducted cyclic plate loading testing to determine the behaviour of geocell-reinforced CDW materials. As a result, they reported that the examined physical and mechanical properties of the CDW was suitable for the standard criteria to be used as sub-base materials. In addition, they emphasized that by reinforcing the geocell, the bearing capacity of the CDW material was increased.

Considering the literature, it was seen that the research of the reuse of the CDW has been popular in recent years and this usage could contribute economically and environmentally. However, it was also observed that the usage of the CDW as granular fill material did not provide sufficient strength and durability in some cases. Therefore, some researchers proposed to improve the engineering properties of the CDW by various methods. Moreover, the usage of geosynthetics to improve the engineering properties of the CDW has been one of the most researched methods in recent years. Also, the usage of waste rubber tyres in soil improvement has been also included in the literature in recent years. However, the majority of relative studies were carried out by mixing waste rubber tyres physically divided into small particles with the soil.

In this study, stress-deformation behaviours of granular fillings which were reinforced with whole waste rubber tyre were investigated by performed model plate loading tests. By considering the whole rubber tyre can provide the lateral confinement in a similar way to the geocells for reinforcement, the rubber tyre was employed as a whole without chopping. The granular fillings in the tests were built with the NA or the CDW to compare with the performance of natural and waste aggregates. Thus, both the reinforced and the waste-formed granular fillings were examined as well. Furthermore, in some tests, the effective usage of the geotextile together with the whole rubber tyre in the granular fillings consisting of CDW or NA were also studied by placing the geotextile. The results of this study showed that placing rubber tyre and/or geotextile in the granular fillings increased the bearing capacity. It was estimated that waste aggregates such as the CDW, which was improved by various soil improvement methods, can be used as an alternative to natural fillings.

2. Materials and methods

2.1. *Material Properties*

For the model plate loading tests, the CDW and the NA materials were obtained and exposed with some processes to construct fill layers. Besides, a type of fine-grained soil was obtained and prepared in suitable water content to provide weak soil conditions as a subgrade. On the other hand, in cases of reinforced granular fillings, geotextile for separation and reinforcement functions and whole rubber tyre for reinforcement function were supplied. The properties of these mentioned materials are given in the following titles.

2.1.1. CDW and NA materials

The CDW material used in this research was obtained from a building that was decided to be demolished as a result of earthquake performance analysis. The mean compressive strength of concrete core samples which was taken from the buildings was 14.5 MPa. First of all, this building was demolished. Then, various metals that were existed in the debris generated resulting from the building demolition process were removed with the help of magnets and hands. Finally, the debris was crushed by using a crusher to form granular CDW material between 0 mm and 20 mm grain sizes. On the other hand, the NA was obtained from a quarry in the Mesopotamia region (Malatya/TURKEY). The grain size of this supplied NA material was ranged from 0-20 mm. The images of the CDW and the NA samples were given in Figure 1.

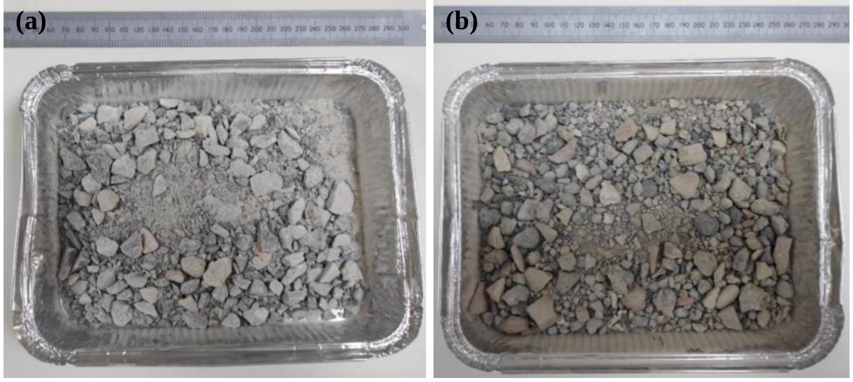

Figure 1. The (a) NA; (b) CDW.

Sieve analysis tests were performed to determine the particle size distribution of the CDW and the NA materials. The sieve analysis tests were carried out depending on the procedure specified in ASTM C136-06. Particle-size distributions obtained as a result of the sieve analysis tests were as seen in Figure 2.

Compaction parameters of the CDW and the NA were determined by performing the modified proctor tests as described in ASTM D1557-12. As a result of these tests, optimum water content (ω_{opt}) and maximum dry unit weight (γ_{kmax}) values of the CDW and the NA were obtained. Moreover, California bearing ratio (CBR) tests on the CDW and the NA materials were carried out as specified in ASTM D1883-14. The test samples for these tests were prepared at their ω_{opt} and γ_{kmax} values. For mentioned two filling materials, both compaction curves obtained from the modified proctor tests and stress-deformation curves resulting from CBR tests were presented in Figure 3.

The results obtained from laboratory tests performed to determine the engineering properties of the CDW and the NA were shown in Table 1. These tests were performed in accordance with the related standards (ASTM C136-06, EN 933-3, ASTM C131–06, ASTM C127–12, ASTM C128-12, ASTM D1557-12, ASTM D1883-14 and ASTM D2487-11).

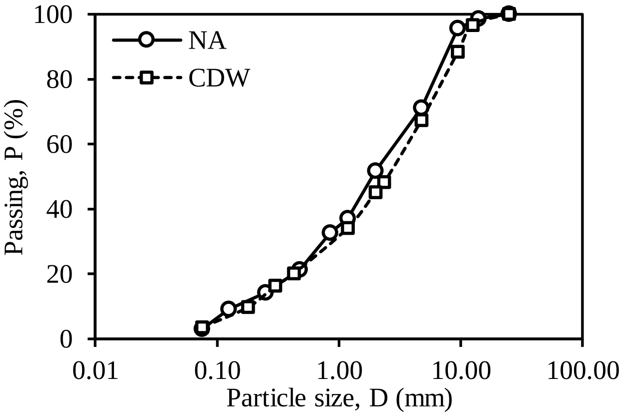

Figure 2. The grading curve of the CDW and the NA.

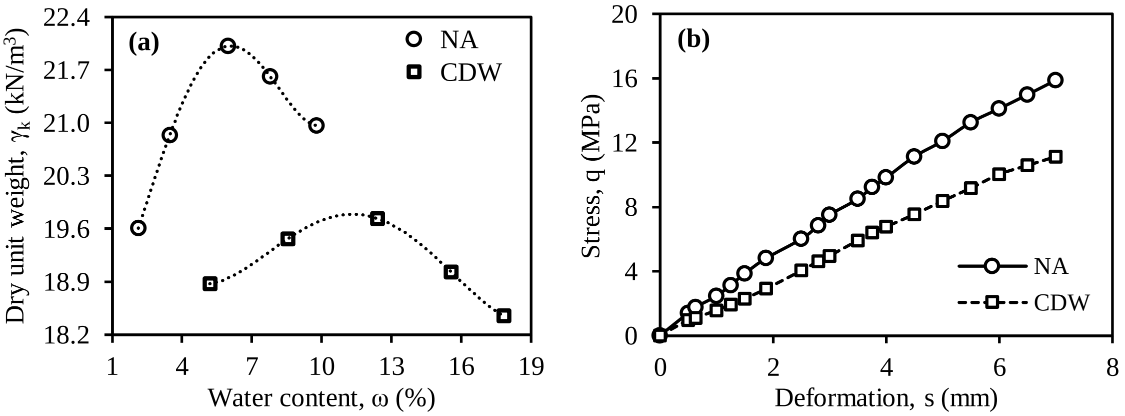

Figure 3. (a) Compaction curves; (b) stress-deformation curves.

Table 1. Engineering properties of the CDW and the NA.

Properties	Units	Values for CDW	Values for NA
Coefficient of uniformity (C_u)	-	20.00	19.8
Coefficient of curvature (C_c)	-	1.12	1.26
Flakiness index	%	11.14	13.99
Los Angeles abrasion loss	%	32.38	25.25
Specific gravity (G_s)	-	2.62^f-2.62^c	2.71^f-2.72^c
Water absorption	%	6.91^f-3.94^c	0.89^f-0.68^c
Maximum dry unit weight (γ_{kmaks})	kN/m^3	19.79	22.00
Optimum water content (ω_{opt})	%	11.25	6.10
California bearing ratio (CBR)	%	81.28	117.42
Soil classification	-	SW	SW

Note: f: Fine particle, c: Coarse particle

2.1.2. Weak soil

The weak soil (WS), which is subsoil under the fill layers in the model plate loading tests, was obtained from the Mesopotamia region (Malatya/TURKEY). It has been determined that this soil, which was preferred to build a soil layer with low bearing capacity, was cohesive (fine-grained) and existed in large grain sizes due to sticking and drying its particles in the field. Therefore, this soil was first dried in an oven, then it was crushed by a crusher to form a soil sample with a maximum grain size of 2 mm. Finally, the sieve analysis and hydrometer tests were carried out to find the grain sizes of the WS and to determine the soil classification. In these tests, the procedures specified in ASTM C117 and ASTM D7928 were applied. Depending on the results obtained from these tests, the particle-size distribution of the WS was composed (Figure 4). Furthermore, the standard proctor test was conducted as described in ASTM D 698-12 to determine the ω_{opt} and γ_{kmax} values of the WS. The compaction curve of the WS determined by the standard proctor test was also given in Figure 4.

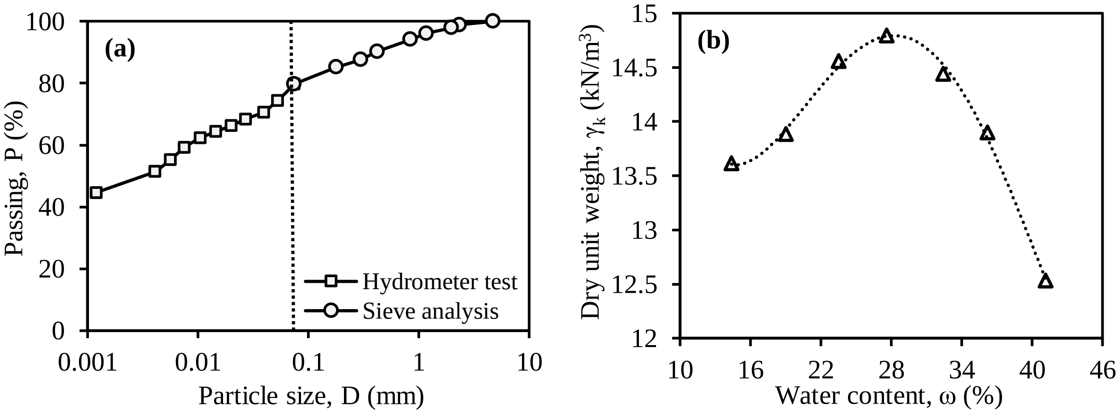

Figure 4. (a) Grading curve; (b) compaction curve of the WS.

The subsoil under the granular filling was demanded to be low-bearing capacity. For this reason, the required water content was determined to create low-bearing capacity soil conditions. According to CBR and unconfined compression tests, a water content of 46% was preferred to build the weak soil layers in the model plate loading tests. The results obtained from the laboratory tests conducted to determine the engineering properties of the WS were as seen in Table 2. These tests were carried out in accordance with the related standards (ASTM D4318-17, ASTM D854-10, ASTM D698-12, ASTM D1883-14, ASTM D2166-06 and ASTM D2487-11).

Table 2. Engineering properties of the WS used in the experiments.

Properties	Units	Values
Liquid limit (LL)	%	58.08
Plastic limit (PL)	%	36.32
Plasticity index (PI)	%	21.76
Specific gravity (G_s)	-	2.61
Maximum dry unit weight (γ_{kmaks})	kN/m^3	14.80
Optimum water content (ω_{opt})	%	28.25
CBR (at ω=28.25%)	%	20.61
Undrained shear strength (c_u) (at ω=28.25%)	kPa	204.36
CBR (at ω=46%)	%	2.19
Undrained shear strength (c_u) (at ω=46%)	kPa	26.05
Soil classification	-	MH

2.1.3. Geotextile

In the model plate loading tests, the effect of placing geotextile at the interface of granular filling and weak soil on the stress-deformation behaviour was investigated. First of all, the effect of the usage of geotextile in the granular fillings on the bearing capacity was examined (reinforcement function of geotextile). In addition, it was observed whether the geotextile prevents two different soil layers from mixing with each other (separation function of geotextile). The planar geotextile with a diameter of 60 cm was used in model plate loading tests. The image of the geotextile was presented in Figure 5 and its various properties were shown in Table 3.

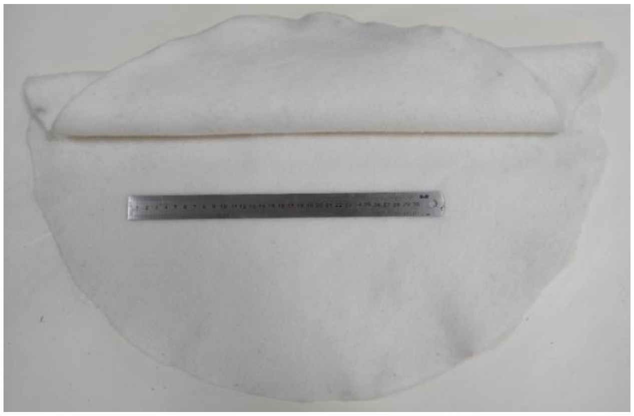

Figure 5. The geotextile used in this study.

Table 3. Material properties of the geotextile used in the experiments.

Properties	Units	Values
Raw material	-	Polypropylene
Type	-	Non-woven
Unit Weight	g/cm^2	250
Thickness	mm	1.5
Opening size	mm	0.12
Tensile strength (MD/CMD)	kN/m	13/15
Elongation	%	50
Static puncture resistance	N	2500
Dynamic perforation	mm	20
Permeability	m/s	0.06
UV resistance	%	70

Note: MD: Machine direction, CMD: Cross machine direction

2.1.4. Rubber tyre

To investigate the effect of the whole recycled rubber tyre on the stress-deformation behaviour of the filling, model plate loading tests, in which the rubber tyre is placed into their fillings, were conducted. The sidewall of the rubber tyre was removed so that the granular materials (CDW and NA) could be better placed and compacted inside the rubber tyre. In fact, this part included a metal rope that can be reused in many industries and so is precious even if rubber tyre ended the service life. So, removing this part was sensible for reusing at other sectors. The image of the rubber tyre used in the experimental tests was given in Figure 6.

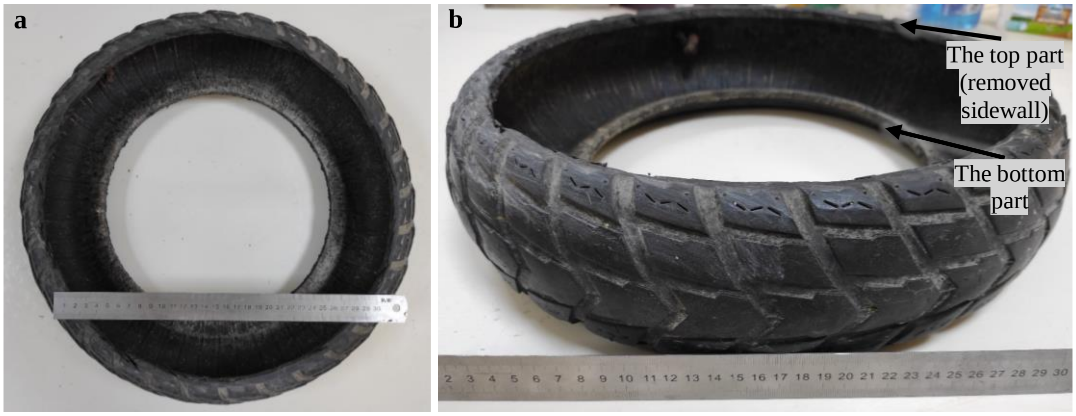

Figure 6. (a) Top; (b) view of the whole rubber tyre.

The height of the rubber tyre was 8.5 cm and the diameter from the outside was 40.6 cm. The wall thickness of the rubber tyre varied between 0.83 cm and 1.34 cm. The diameter of the openings of the top (the removed part is on the top side) and bottom of the rubber tyre was 34 cm and 24.5 cm, respectively. The weight of the rubber tyre was measured as 1895.1 g. In order to determine the total volume and density of the whole rubber tyre, the amount of rise of the pure water was measured by immersing the whole rubber tyre in the pure water. From this process, the volume of the rubber tyre itself was determined as 1690.3 cm^3. In addition, in order to determine the amount of granular materials that could be filled into the interior of the rubber tyre, pure water was filled into the interior of the rubber tyre and then the mass of this filled water was determined. The bottom part of the whole rubber tyre was covered with a thin waterproof nylon membrane so that only the inside of the whole rubber tyre was filled with water. By this mentioned measurement, the value of the internal volume was determined as 9480.5 cm^3.

2.2. *Test setup and procedures*

The general view of the model plate loading test setup was given in Figure 7. The test setup consisted of the loading frame, of which capacity is 20 tons, the servo motor, where the piston can move downward and upward at a constant speed, the load control panel for adjusting the piston speed, the cylindrical tank, the data logger for collecting the test data, computer, and measuring instruments such as load cell and LVDTs (displacement transducers). The test tank was produced with the steel material and its wall thickness was 1 cm. Besides, the test tank's inner diameter and height were 60 cm. To place the soils into the test tank in a controlled manner, the height of the test tank was marked at 5 cm intervals. On the other hand, the data logger and computer had the ability to gather and convert data coming from measuring instruments with the help of special software. Measuring instruments included a load cell with a capacity of 50 kN to measure the applied load on the model plate and two different LVDTs with 50 mm capacities to measure the model plate's displacement. Meanwhile, mentioned the model plate's diameter and thickness were 15 cm and 2.5 cm, respectively. Furthermore, the load was transmitted to the model plate from the piston by getting help from a metal ball that was inserted into the hole on the surface of the model plate and at the point of the piston.

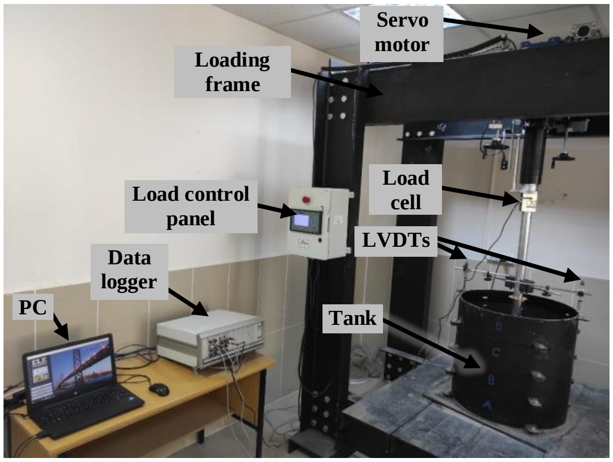

Figure 7. Model plate loading test system.

For the model plate loading tests, it was determined that the desired weak soil condition was obtained when the WS had 46% water content. Because of that, the WS was mixed with water to obtain 46% water content, and this soil-water mixture was kept in the curing room for one day and finally, its water content was checked by taking a water content sample. After that, the WS was placed layer by layer in 5 cm layers up to the desired height by providing that its wet unit weight and undrained shear strength are 17.45 kN/m^3 and 26.05 kPa, respectively. For cohesion control of compacted WS, the soil pocket penetrometer and the hand vane tests were carried out at various points on the upper surface of each layer. Also, to control the compacted WS's water content, samples were taken as well.

On the other hand, the granular fill layers, which were the CDW or the VA, were prepared at their own optimum water content and placed on the WS layers to provide their own maximum dry unit weights. In the preparation of granular filling materials, processes similar to those performed in the WS were conducted and prepared granular filling materials were placed on the WS layer by layer by getting help from a vibratory hammer. In addition, to control the compacted granular fillings' water content, samples were taken as well. After the WS layers and granular fill layers were prepared, the model plate was placed at the center of the surface of the top layer and the model plate loading test was carried out via to be moved the piston with the speed of 1mm/min.

In some model plate loading tests, the rubber tyre and/or the geotextile were utilised in accordance with the purpose of the study. In these tests, the geotextile was placed at the interface of the granular filling and the WS, the rubber tyre was located on the surface of the WS or the geotextile as well. After that, the granular filling was placed by compacting into the mentioned the rubber tyre and/or on the geotextile. These mentioned locations of the geotextile and/or the rubber tyre was determined depending on the relevant literature (Love et al., 1987; Kiptoo et al., 2016; Ingle and Bhosale, 2017).

The summary of the model plate loading tests carried out within the scope of this study was given in Table 4. The cross-sectional drawings of the model plate loading tests were as seen in Figure 8. Model plate loading tests in this study could be classified into five groups. In the first series (Series A), the stress-deformation behaviour of the WS was studied. In the next series (Series B), tests were carried out on the granular fill layer formed with the NA or the CDW on the WS. Subsequently, the effects of geotextile, rubber tyre and geotextile-rubber tyre on stress-deformation behaviour were investigated in Series C, Series D and Series E tests, respectively.

Table 4. Summary of the model plate loading test schedules

Series no	Abbreviation of test	Fill material	Presence of the geotextile	Presence of the rubber tyre	Total layer height
Series A	WS	✗	✗	✗	25 cm WS
Series B	NA-Fill	NA	✗	✗	25 cm WS in the lower part and 15 cm granular fill material in the upper part
	CDW-Fill	CDW	✗	✗	
Series C	NA-Fill with G	NA	✓	✗	
	CDW-Fill with G	CDW	✓	✗	
Series D	NA-Fill with T	NA	✗	✓	
	CDW-Fill with T	CDW	✗	✓	
Series E	NA-Fill with T&G	NA	✓	✓	
	CDW-Fill with T&G	CDW	✓	✓	

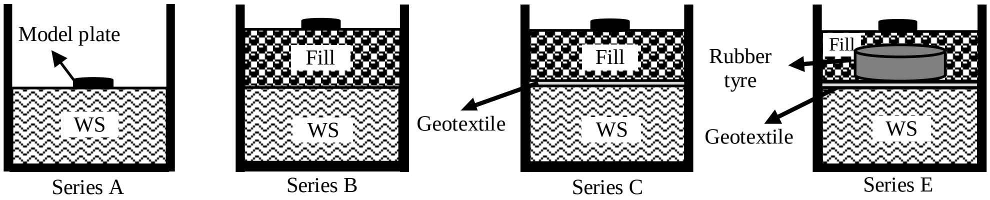

Figure 8. The cross-sectional drawings of the model plate loading tests.

3. Experimental results and discussions

The results of the model plate loading tests were presented in the form of graphs plotted with the deformation ratio values (s/D) corresponding to compressive stress values (q). The deformation ratio value, expressed as a percentage, was obtained by dividing the deformation value (s) at the model plate by the diameter of the model plate (D) which is constant as 15 cm. In the curves where the test results were given, there was "q" in kPa on the horizontal axis and "s/D" in percentage on the vertical axis. In the literature, some methods have been proposed to determine the ultimate bearing capacity from the "q"-"s/D" curves obtained as a result of such model plate loading tests.

In this study, the 0.1D method, which is more practical to use and gives more objective results than other methods suggested in the literature, was used. Accordingly, by expanding the limit deformation ratio, the compressive stress values corresponding to the deformation ratio values of 0.05D (s/D=5%), 0.10D (s/D=10%), 0.15D (s/D=15%) were accepted as the ultimate bearing capacity values (q_u) (Briaud and Jeanjean, 1994; Ornek, 2009). Besides, the contributions of geotextile and/or rubber tyre on the bearing capacity were also presented by the Bearing Capacity Ratio (BCR). The BCR is frequently used to present the bearing capacity values of reinforced and non-reinforced soils more clearly and to compare with each other. This ratio was calculated by dividing the bearing capacities of the reinforced or unreinforced fillings by that of the WS (Binquet and Lee,1975). In the curves where the BCRs were given, there were "BCR" on the vertical axis and "s/D" on the horizontal axis.

3.1. *Granular filling effect*

To discuss the effect of the granular filling, the results of the Series B tests were compared with that of the Series A. Figure 9 presents the "q"-"s/D" curves and BCR values obtained as a result of the Series A and B tests, and they show that the granular fillings developed the bearing capacity. It was thought that the bearing capacity was improved as the compacted granular fillings acted like a rigid slab and distributed the load to the underlying weak soil. The most important reason for this was that granular fills were stiffer and stronger than weak soils (Ornek, 2012).

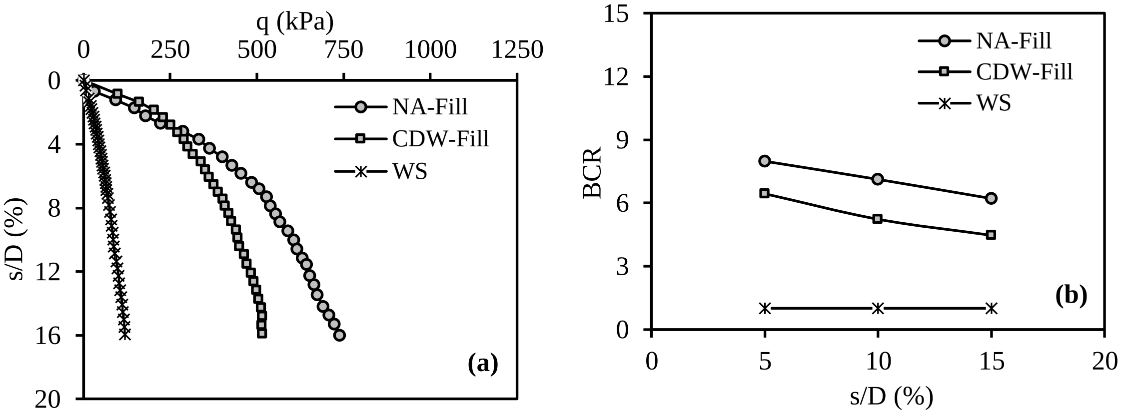

Figure 9. (a) “q”-“s/D”; (b) “BCR”-“s/D” curves for series A and B tests

Although both the CDW filling and the NA filling improved the bearing capacity, it was observed that the NA increased the bearing capacity more than the CDW. It was estimated that the cause of this situation was that the NA was stiffer and stronger than the CDW. Figure 9 also shows that the BCR value is greater than 1 (i.e. there was an improvement) in all cases that have a granular filling. However, BCR decreased with an increase in the s/D. The reason for this was that the stress values did not increase linearly according to the deformation ratio. Furthermore, BCR values of the NA were always greater than those of CDW fill, as expected.

3.2. *Geotextile effect*

The effect of geotextile has been examined by comparing the results of the Series C tests with the results of the Series A and B tests. The stress-deformation ratio and the BCR-deformation ratio curves obtained from Series A, B, and C and are given in Figure 10. It can be seen from Figure 10 that when the deformation ratio value is small, the geotextile reinforcement has no effect, but as the deformation ratio value increases, the effect of the geotextile reinforcement appears. It was thought that this result was obtained due to reinforcement and membrane effect, which are reinforcement mechanisms of geotextile. It has been also observed that the geotextile placed at the interface between the granular filling and the weak soil prevented the mixing of two different materials, in other words, it acted as a separator (Holtz et al, 1998). Moreover, BCR values of the geotextile reinforced granular filling were always bigger than those of unreinforced granular filling, as expected.

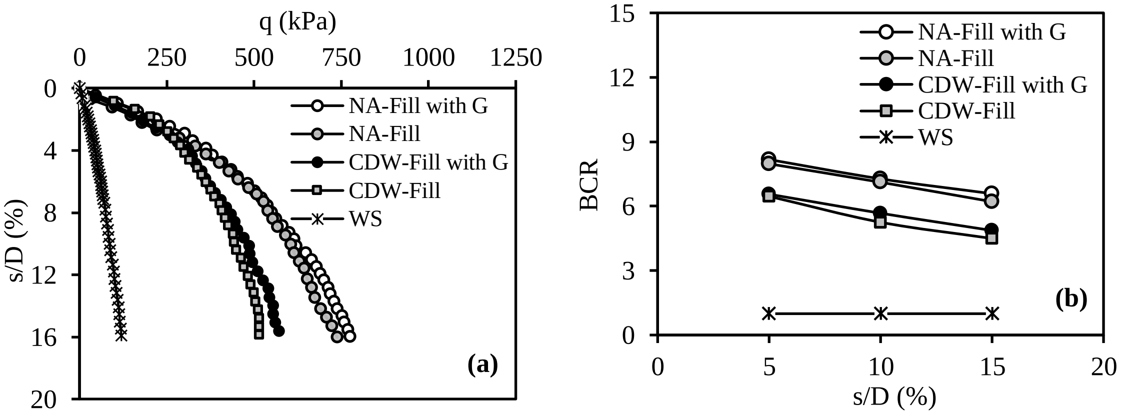

Figure 10. (a) “q”-“s/D” ; (b) “BCR”-“s/D” curves for Series A, B and C tests.

3.3. *Rubber tyre effect*

The “q”-“s/D” and “BCR”-“s/D” plots of the CDW and the NA fillings that were reinforced with the rubber tyre are shown in Figure 11 in comparison with both the WS and unreinforced filling. As can be clearly seen in Figure 11, it was determined that the rubber tyre did not make any contribution until the deformation ratio value of about 8% from the beginning of the tests, but it contributed when the deformation ratio value was between about 8% and 13%. However, the failure stress was observed when the deformation ratio value was about 13%.

In other words, according to Figure 11, the rubber tyre reinforced the granular filling at the deformation ratio of 10%. The “BCR”-“s/D” curves given in Figure 11 also reveal this situation. The phenomenon causing this situation can be explained: (1) the lateral movement of the granular materials was limited at small deformations, (2) at approximately 10% deformation ratio the mentioned lateral movement increased, and so, the confinement effect of the rubber tyre emerged and the bearing capacity increased (3) finally, the failure occurred due to the fact that the rubber tyre directed the stress towards the weak soil at large deformation values.

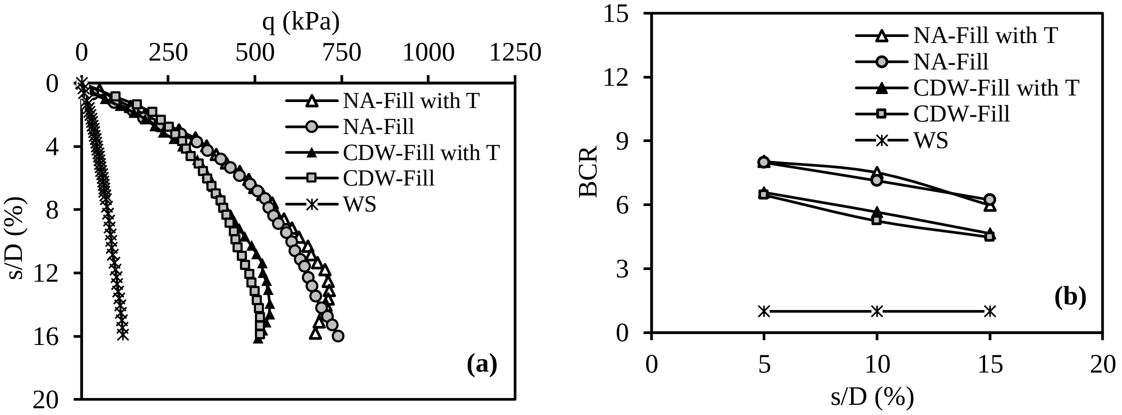

Figure 11. (a) “q”-“s/D”; (b) “BCR”-“s/D” curves for series A, B and D tests.

3.4. *Geotextile-rubber tyre effect*

The series E tests, in which the geotextile-rubber tyre reinforced granular filling were examined, are presented in Figure 12 together with the Series A and B tests. According to Figure 12, the presence of the geotextile-rubber tyre in the granular filling increased the bearing capacity. However, while the reinforcement effect of the rubber tyre was very low at small deformations, its reinforcement effect occurred significantly at large deformations. It was thought that the main factors constituting this reinforcement were the confinement effect of the rubber tyre and resisting the stress transmitted by the rubber tyre to the weak soil by the geotextile. Accordingly, it was also determined that the BCR values of the geotextile-rubber tyre reinforced granular fillings were higher than those of unreinforced granular fillings.

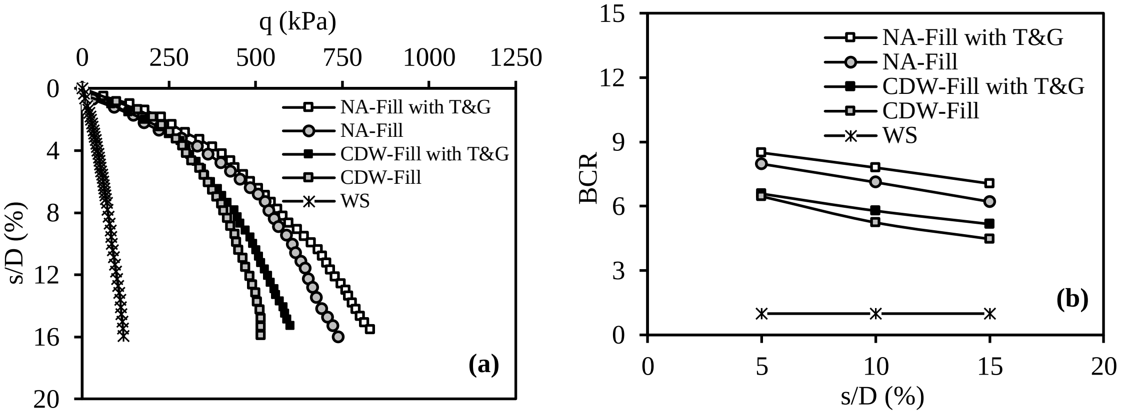

Figure 12. (a) “q”-“s/D”; (b) “BCR”-“s/D” curves for series A, B and E tests.

3.5. *Comparison of all test series within themselves*

Figure 13 shows the “q_u”-“s/D” and “BCR”-“s/D” curves for Series B, C, D and E tests. It is clearly seen in Figure 13 that the geotextile-rubber tyre had the most effective reinforcement effect. In addition, reinforcement with rubber tyre was more effective than reinforcement with geotextile at both 5% and 10% of deformation ratios. However, there was a peak load (i.e., a definite point of failure) in the rubber tyre reinforced granular fillings. In other words, although the rubber tyre reinforcement was better at certain deformations than geotextile reinforcement, its bearing capacity dramatically decreased when the deformation ratio was about 15%. When the rubber tyre supported with geotextile, it was seen that this failure was eliminated. Finally, it was determined that NA fillings performed better than CDW fillings in terms of bearing capacity in both reinforced and unreinforced conditions. However, the reinforcing of the CDW filling had got the bearing capacity value closer to that of the unreinforced NA filling.

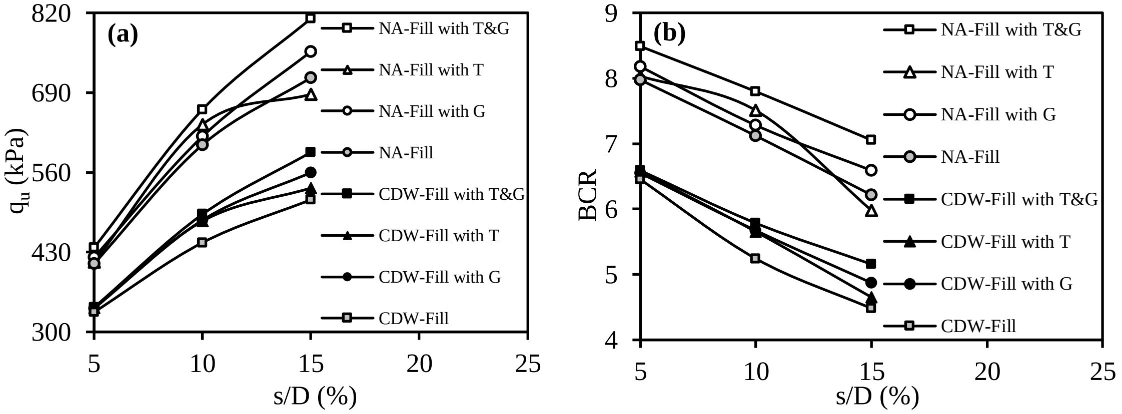

Figure 13. (a) “q_u”-“s/D”; (b) “BCR”-“s/D” curves for Series B, C, D and E tests.

4. Conclusions and comments

This paper is focused on the investigation of stress-deformation behaviour based on model plate loading tests of the CDW and the NA fillings, which are reinforced with geotextile and/or rubber tyre or unreinforced. Depending on the results of model plate loading tests conducted in this study, the following main conclusions can be drawn:

1. By building one of the CDW or the NA fillings on the weak soil, the bearing capacity could be increased and settlement could be reduced. By building a stiffer soil layer on the weak soil, it may be ensured that the applied stress is carried by this stiffer soil layer and the stress coming to the weak soil is decreased;

2. The placing of the geotextile at the interface of the granular filling and the weak soil increased the bearing capacity slightly while performing the separation function perfectly. Geotextile's reinforcement effect was not observed in small deformations, but it was observed as deformations increased. It was considered that the reinforcement and membrane effect of the geotextile caused this situation;
3. By placing the rubber tyre in the granular filling, the bearing capacity was increased only when the deformation ratio was around 10%. Due to the unique cylindrical form of the rubber tyre, it was assumed that it increased the bearing capacity by confinement the granular fill material inside. However, a definite failure load was observed when the deformation ratio was about 13%. It was evaluated that this circumstance occurred due to the fact that the rubber tyre directed the stress towards the weak soil. Considering the boundary conditions as the reason for this, it was thought that whole rubber tyre restrained the stress coming to the fillings inside it like a geocell, thus affecting the stress-deformation behavior. Thus, it was predicted that while the whole rubber tyre resisted some of the stress on it, it directed the rest to the weak soil below. It was one of the main outcomes expected from this study;
4. Reinforcing with the geotextile-rubber tyre of a filling placed on weak soil helped to reduce the deformation and increased bearing capacity. It was predicted that reinforcement mechanisms of both the geotextile and the rubber tyre were effective in this reinforcing. Because both the bearing capacity was increased more than the other reinforcement cases and the definite failure point, which was seen only in the rubber tyre reinforced section, was not observed;
5. In cases that were unreinforced and the geotextile and/or the rubber tyre reinforced, the NA had a higher bearing capacity and lower deformation than the CDW in all conditions. However, the performance of reinforced CDW approximated that of unreinforced NA;
6. It was put forward that a usable filling can be produced by employing the recycled whole tyre, the geotextile, and the CDW, which is a heterogeneous mixture of wastes. It is clear that recycling materials such as CDW and rubber tyre can contribute to nature, sustainability, and the economy. For this reason, using such waste materials can be a good alternative to natural materials. Nonetheless, it should be underlined that the necessity of conducting further studies related to determination of their characteristics of these waste materials has a vital importance before they use in applications.

5. Limitations and future directions

Some limitations should be mentioned. The test sections created in this study were a layered soil problem formed by cohesive soil-granular fillings material (CDW or NA) in the test setup with a model plate's diameter of 15 cm and a tank diameter of 60 cm. Considering the test results in this paper and the studies in the literature, it was predicted that the dimensions of the rubber tyre, the characteristics of the rubber tyre, thickness of the granular fillings material and the weak soil, the soils conditions, the engineering properties of the soils may affect the results significantly. In addition, it was thought that different stress-strain behaviors may occur under different loading conditions.

It was also recommended to perform cyclic plate loading tests, if a whole rubber tyre-reinforced granular fillings will be subjected to cyclic loads. Since the effect of only one whole rubber tyre was investigated in this study, it was suggested that it is necessary to conduct model tests or full-scale experiments for the behavior of whole rubber tyre groups. Due to the energy absorption feature of rubber or geosynthetics, there are important advantages not only under static loading but also in dynamic cases. Therefore, it is essential to conducted studies that include earthquake analysis such as Edinçliler and Yildiz (2017), Edinçliler and Yildiz (2018) and Yildiz (2021). Therefore, further studies were recommended to better understand the behavior of whole rubber tyre-reinforced granular fillings.

Author contributions: Tacettin Geçkil: Data curation, supervision. Talha Sarici: conceptualization, methodology, validation, formal analysis, resources, investigation, data curation, conducting experiments, writing - original draft. Bahadır OK: methodology, resources, investigation, data curation. All authors have read and agreed to the final version of the manuscript.

Funding: This research received no funding.

Acknowledgments: This study was supported by Inonu University Scientific Research Project Department with FBG-2018-957 project number.

Conflicts of interest: There is no conflict of interest.

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