Geomechanics and Engineering, *Vol. 14, No. 1 (2018) 83-90*
DOI: https://doi.org/10.12989/gae.2018.14.1.083

Pullout resistance of treadmats for reinforced soil structures

Keun-Soo Kim[1], Yeo-Won Yoon[*1,2] and Ki-Il Song[2]

[1]*Naru EMS, #206 KEPCO Venture Business Incubation Center 105 Munjiro, Yuseong-gu, Daejeon-si 34056, Republic of Korea*
[2]*Department of Civil Engineering, Inha University, 100 Inha-ro, Nam-gu, Incheon 22212, Republic of Korea*

(Received January 12, 2016, Revised March 20, 2017, Accepted June 29, 2017)

Abstract. A series of pullout tests were carried out on waste tire treadmats of various weave arrangements, with confining stresses ranging from 9 to 59 kPa approximately, in order to investigate the pullout behavior and to apply the results to the design of treadmat reinforced soil structures. A treadmat reinforcement can be considered as belonging to the extensible type thus progressive failure would develop in every tread. The pullout capacity of a treadmat was found to be generally equal to the sum of capacities of the longitudinal treads, with minor enhancement realized due to the presence of transverse treads. Pullout failures occurred in treadmats under light surcharge and with treadmats with higher material presence per unit area, while breakage failures occurred in treadmats under heavier surcharge and with treadmats with higher ratio of opening. The pullout capacity of a treadmat increased with increasing surcharge height and treadmat stiffness. A pullout test on a commercially available geogrid was also carried out for comparison and the pullout capacity of a treadmat was found higher than that of the comparable geogrid under identical loading conditions, indicating the merit of using the treadmat as an alternative to the chosen geogrid.

Keywords: pullout test; waste tire treadmat; geogrid; pullout capacity; reinforced structures

1. Introduction

Waste tires are produced at an increasing rate every year with the expansion of the vehicle industry. Therefore, waste tire disposal has become a major environmental issue in many countries. In advanced countries, the numbers of discarded waste tires in 2013 were 268.8 million, 99 million, and 30 million for United States, Japan and Canada, respectively (Takallou 2015, JATMA 2015, RMA 2015). In Korea, the generation of waste tires increased rapidly during the same year from 17 million to 29 million (KECO 2015).

In Korea, the recycling of waste tires was made possible after the 'Act on the promotion of saving and recycling of resources' was passed in December 1992. Since then, waste tires have been utilized in various ways such as in retreaded tires industry, rubber goods manufacturing, and tire derived fuel (TDF) production. The recycling of tires as rubber goods is currently steadily increasing; however, its rate is much lower than that of other recycling methods due to the related costs. In Korea, the most common waste tire recycling activity is for the TDF production. However, the incineration of tires associated with the TDF production emits toxic pollutants such as dioxins and furans, and a number of other harmful and carcinogenic chemicals as well as the greenhouse gases. Accordingly, the TDF production represents an extremely undesirable recycling method because of the harms it brings to human health and to the natural environment.

The application of waste tires as reinforcement or light-weight fill materials in geotechnical structures does not pollute the environment with greenhouse gases or other dangerous pollutants. In addition, the various geotechnical structures that incorporate waste tire products can be built with the aid of conventional construction equipment. In other words, using waste tires for geotechnical constructions is an efficient and beneficial method as compared to others.

Yoon *et al.* (2004a) and Yoon *et al.* (2008) respectively assessed the geotechnical performance of plain treadmats (in Fig. 1(d-2)) and three-dimensional cell-type tires (in Fig. 1(d-1)) by performing plate loading tests in a chamber filled with sand. Kim *et al.* (2011) confirmed the pullout behavior of cell-type tires in reinforced soil structures. Though a lot of laboratory or full scale investigations on geogrids and other reinforcement materials have been conducted up to now (Abdi and Arjomand 2011, Esfandiari and Selamat 2012 Chen *et al.* 2013, Niroumand and Kassim 2013, Suksiripattanapong *et al.* 2013, Vashi *et al.* 2013, Deb and Konai 2014, Mahdi and Katebi 2015, Kang *et al.* 2015, Kim *et al.* 2015), only few tests on treadmat have been conducted. This study conducted a series of field-scale pullout tests to investigate the pullout behavior of treadmats and to recommend the ultimate tensile strength of the treadmat for the design purposes.

2. Waste tires as soil reinforcement material

To utilize waste tires as geotechnical materials in a geotechnical structure, the adverse effects to humans and the environment must first be ascertained as to be contained

*Corresponding author, Professor
E-mail: yoonyw@inha.ac.kr

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

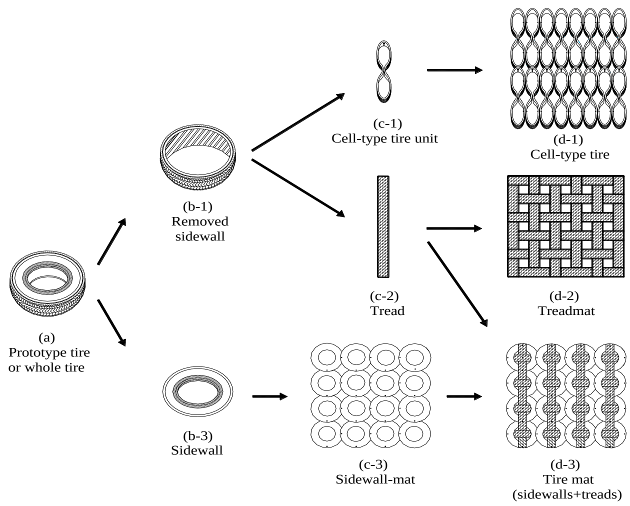


Fig. 1 Combination process to make tire reinforcement materials of four types

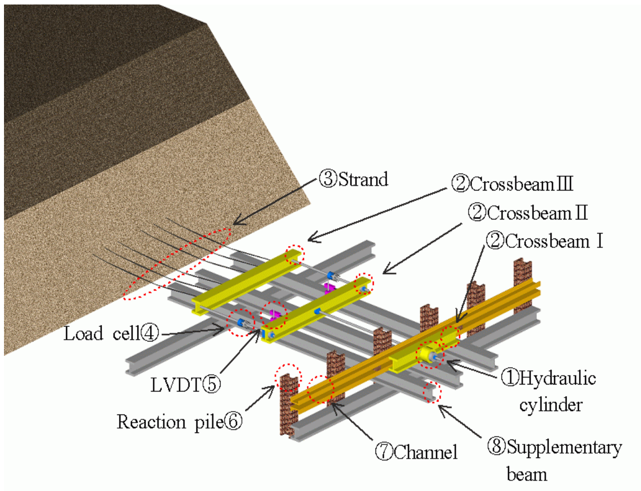


Fig. 2 Schematic of the pullout test apparatus

Table 1 Principal components of the pullout test apparatus

No.	Remarks
1	Hydraulic cylinder (cap.: 1370 kN, stroke: 200 mm)
2	Crossbeam (H beam: 300×300×12×10, unit: mm)
3	Strand (cap.: 78 kN/ea.)
4	Load cell (cap.: 195 kN, standard error: 0.098 kN)
5	LVDT (sens.: 0.01 mm, stroke: 200 mm)
6	Reaction pile (H beam: 300×300×12×10, unit: mm)
7	Channel
8	Supplementary beam (H beam: 300×300×12×10, unit: mm)
9	Test embankment

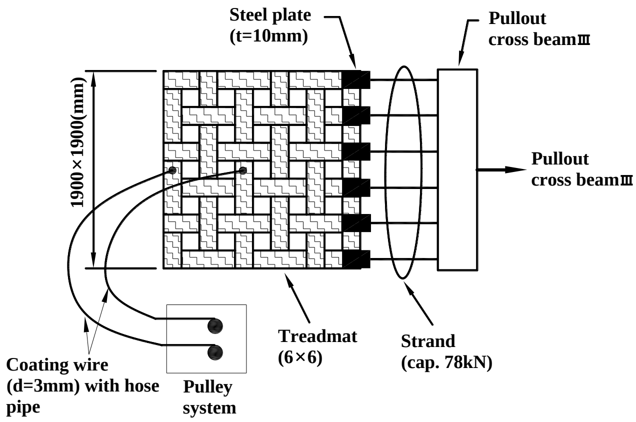


Fig. 3 Plan view of 6×6 treadmat embedded in the embankment

within the prescribed levels. Furthermore, the waste tire materials must have sufficient durability against the various internal or external possibilities, such as physical-chemical aging, creep, UV radiation, pH change, effects of sea water, and damage that may occur during the construction phase. Many studies have presented favorable results from the environmental assessments of waste tire related projects in the last decade. Humphrey and Katz (2000) and Humphrey and Katz (2001) reported that the toxic compounds of waste tire productd had no significant adverse effects on the ground-water quality above or below the water table over a period of five years. Since the steel wires, which may have an adverse effect on the quality of water or soil, are covered by vulcanized rubber or polymer materials, the recycling of waste tires as geotechnical materials has been quite harmless (Humphrey and Katz 2000, Humphrey and Katz 2001, O'Shaughnessy and Garga 2000b, Yoon *et al.* 2004b).

Furthermore, Yoon *et al.* (2007) reported that a high-strength steel wire with rubber surrounding it offer high tensile strength and frictional resistance when used as a reinforcement material. O'Shaughnessy and Garga (2000b) reported that the rubber of the tires does not show any physical-chemical aging or damage that may occur during the construction. Though macromolecular chains of polymer materials are susceptible to fire and UV radiation, a tire embedded in soil would not present such problems. Therefore, the use of tires as soil reinforcement materials is desirable and attractive especially when they are no longer suitable for their original purpose.

In order to study the reinforcement effects of waste tires, Yoon *et al.* (2004) and Yoon *et al.* (2008) performed a large number of plate load tests in a chamber filled with sand. Yoon *et al.* (2004) and Yoon *et al.* (2008) confirmed that soil improvements obtained by the use of treadmats and cell-type tire units are better than those achieved with the use of geogrid and geocell, respectively. These effects might have arised due to the high-strength steel wires present in the tires. Besides, the geometries of the treadmat and the cell-type tire unit are quite similar to those of the geogrid and geocell, respectively.

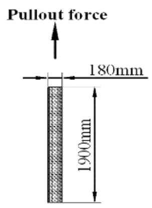
3. Field pullout test

In order to utilize waste tires in a reinforced soil structure governed by the lateral earth pressure, it is essential to compare the pullout behavior of waste tire reinforcements with that of the commercially available geogrids. A schematic diagram and a list of the principal components of the pullout test apparatus are given in Fig. 2 and Table 1, respectively. Further details of the test apparatus can be found in a literature by Yoon (2007).

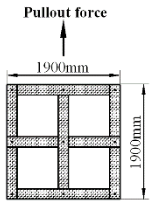
Fig. 3 depicts a treadmat embedded in a test embankment. The treadmat was connected to Crossbeam III by strands at the intersections of the first transverse tread and the longitudinal treads. To measure the amounts of rear displacement, two 3 mm diameter wires, covered with polyurethane, were attached to the center of the fourth and last transverse treads.

Table 2 Field pullout testing program for the treadmats

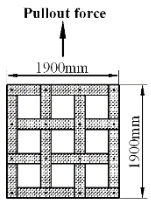
Reinforcement type	Notation	Reinforcement length (m)	Ratio of opening	Surcharge height (m)	Connection method
Treadmat (thickness 13±2 mm)	Single tread	1.9	-	0.5, 1.5, 2.5, 3.2	-
	3×3	1.9	0.51	1.5	Bolt
	4×4	1.9	0.39	1.5	
	3×6	0.95	0.19	1.5	
	6×6	1.9	0.19	0.5, 1.5, 2.5, 3.2	
	12×6	3.8	0.19	1.5	
Geogrid	1.9m×1.9m	1.9	0.70	1.5	Unitized



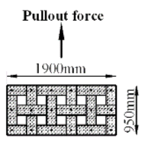
(a) Single tread



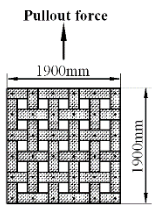
(b) 3×3



(c) 4×4

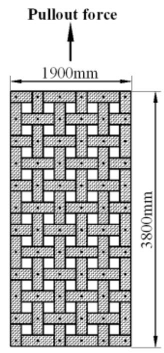


(d) 3×6



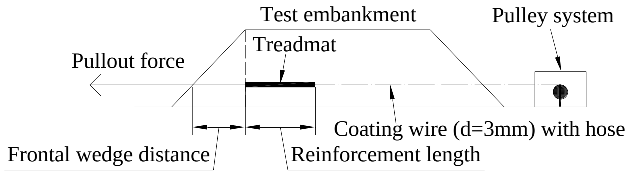
(e) 6×6

Fig. 4 Treadmat arrangements used in the field pullout tests

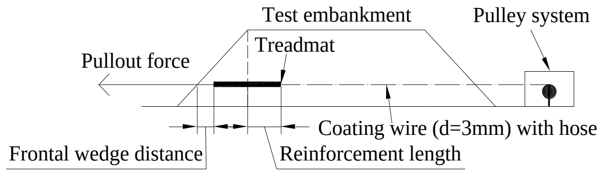


(f) 12×6

Fig. 4 Continued



(a) Treadmat fully embedded in the embankment



(b) Treadmat half embedded in the embankment

Fig. 5 Embedded location of treadmats to resist the pullout force

Table 3 Characteristics of geogrid (Samyang Co.)

Material	Weight (g/m^2)	Tesile strength (kN/m)		Tensile elongation (%)	
		MD [a)]	CD [b)]	MD	CD
PET/PVC	470	101.0	29.4	14	na

Note: [a)] MD: machine direction; [b)] CD: cross machine direction; [c)] na: not available

3.1 Experimental program

The pullout capacity of a treadmat is expected to depend on the degree of surcharge, or confinement or overburden; the frontal wedge distance; the strength of a tread; and the stiffness of a treadmat, which is reflected by the number of treads per unit area. The pullout test program is given in Table 2. The weave arrangements of treadmat tested in this research are shown in Fig. 4. In Table 2 and Fig. 4, the notation for the weave arrangement of a treadmat indicates 'number of treads perpendicular to pullout direction×number of treads parallel to pullout direction' or 'number of rows of treads×number of columns of treads'. For example, a "3×6 treadmat" as given in Fig. 4 denotes one with 3 rows and 6 columns. The longitudinal direction always refers to the pull direction.

The degree of surcharge of the treadmat within a soil mass may influence its load deformation behavior. This study also investigated the influence of confinement due to

Table 4 Index properties of backfill material

Water content (%)	G_s	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_g	USCS	$\gamma_{d\ max}$ (kN/m^3)	OMC (%)
11.7~12.3	2.71	0.02	0.08	0.25	12.5	1.28	SM	18.42	10.66

Table 5 Frictional parameters between soil and tire tread

Condition of test (R.C: 90%)	Strength parameter			
	Friction angle (°)	R_φ [a)]	Cohesion (kPa)	R_c [b)]
Soil-Soil	φ =34.7	-	c =39.7	-
Soil-Outside of tread	δ_{out} =33.9	0.97	$c_{a\text{-}out}$ =13.2	0.33
Soil-Inside of tread	δ_{in} =31.9	0.90	$c_{a\text{-}in}$ =18.4	0.46

Note: [a)] R_φ is reduction factor on friction=tanδ/tanφ and [b)] R_c is reduction factor on cohesion=c_a/c

various frontal wedge distances as well as due to the confining pressures or surcharge heights. As shown in Fig. 5, the frontal wedge distance refers to the horizontal distance between the front edge of the treadmat and the slope of the fill. The 6×6(F) treadmat is one which is fully embedded in the embankment. The 6×6(H) treadmat is one with half of it embedded in the embankment and the other half is under the sloping ground. The effect of various confining pressures was investigated by having the surcharge heights amounted to 0.5 m, 1.5 m, 2.5 m, and 3.2 m. The stiffness of a treadmat was indicated by the number of tread columns such as 6, 8, and 12 for the 3×3, 4×4 and 6×6 treadmats, respectively. A commercial geogrid was also tested for comparison, and its characteristics are given in Table 3.

3.2 Construction of test embankment

The soil used in the test embankment is a residual soil classified as SM based on the Unified Soil Classification System (USCS), and its index properties are provided in Table 4. The frictional parameters between the soil and the tire tread are presented in Table 5. The test embankment was built using conventional construction techniques and equipments. The reinforcement materials used in the tests were mounted on a compacted soil bed of 0.6 m height and were spaced at a distance of twice their width, thereafter surcharge was placed. Each layer of 300 mm thick surcharge was compacted to a 90% relative compaction, i.e., $\gamma_d \approx 16.6$ kN/m^3, by means of a 98 kN vibrating roller.

3.3 Pullout test

The front and rear displacements were measured at every loading step of 4.9 kN. The strain is defined as the ratio of the frontal displacement to the total reinforcement length. A test was terminated when the strain reached 20%, except in cases where a definite peak value occurred before the 20% mark. When an obvious peak value was observed, it became the pullout capacity. Otherwise, the pullout capacity would be the pullout force at 20% strain.

4. Results and discussion

4.1 Pullout behavior treadmat

4.1.1 Pullout test results

Pullout test results for the treadmats are given in Table 6 in terms of pullout capacity, $F_{po(ult)}$, frontal displacement at pullout capacity, d_{front}, strain of treadmats (i.e., the ratio of frontal displacement to total length of the treadmats), ε_{front}, and the failure mode of the treadmats. The frontal displacement was measured by LVDTs attached to both sides of crossbeam II (in Fig. 2). As the degree of confinement and the treadmat stiffness increased, the pullout force and the corresponding frontal displacement at the pullout capacity typically increased.

4.1.2 Deformed shape of treadmats at failure

Reinforcement materials can fail in two different ways (FHWA 2001), either by pullout or breakage of the reinforcement. Pullout can happen when the tensile force in the reinforcement materials is greater than its pullout resistance, that is, the force required to pull the reinforcements out of the soil mass. However, if the tensile force in the reinforcements becomes greater than the tensile strength of the reinforcements, the reinforcements will elongate excessively or break. The second mode is called failure by elongation or breakage of the reinforcements. Consequently, failure by both modes leads to a large amount of movement of soil mass or a possible collapse of the structures.

This study used visual assessment and measurement methods to determine the failure mode of the treadmats. Visual assessment confirms the deformed shape of the treadmats after the tests and the measurement monitors the rear displacement as well as the frontal displacement. Failures caused by pullout and breakage of the treadmat during the pullout test are shown in Fig. 6(a) and 6(b), respectively. Owing to the large movement of the soil mass, the tension crack arose on the top and slope of the test embankment, as shown in Fig. 7. Fig. 6(b) shows treadmats after failure under an embankment heights of 2.5 m and breakage happened in the longitudinal members only. Transverse members are flexible and passive resistance from the members seems small. Bergado *et al.* (1993) reported that the pullout capacity of geogrids without transverse members was about 90-100%.

The failure mode of all treadmats is given in Table 6. Pullout failure occurred in most of the treadmats, and breakage failure occurred in some of the treadmats. Kim *et al.* (2011) reported that most cell-type tires experienced pullout failure, while only a few failed by elongation.

(a) 6×6 treadmat failed by pullout

(b) 6×6 treadmat failed by breakage

Fig. 6 Deformed shape of the treadmats after the pullout test

Table 6 Field pullout test results

Type	Notation	d_{wedge} (m)	H (m)	σ'_v (kPa)	$F_{po(ult)}$ (kN)	d_{front} (m)	ε_{front} (%)	Failure mode
Tread	Single tread	0.5	0.5	9.12	19.13	0.291	15.3	Pullout
		1.5	1.5	27.36	37.94	0.161	8.5	Pullout
		2.5	2.5	45.60	67.85	0.217	11.4	Pullout
		3.2	3.2	58.37	66.22	0.134	7.1	Pullout
Treadmat[b]	6×6 (F)[a]	0.5	0.5	9.12	98.10	0.139	7.3	Pullout
		1.5	1.5	27.36	245.25	0.238	12.5	Pullout
		2.5	2.5	45.60	343.35	0.322	16.9	Breakage
		3.2	3.2	58.37	382.59	0.202	10.6	Breakage
	6×6 (H)[a]	0.55	1.5	27.36	137.34	0.110	5.8	Pullout
	3×6	1.5	1.5	27.36	166.77	0.318	16.7	Pullout
	12×6	1.5	1.5	27.36	196.20	0.240	6.3	Breakage
	3×3	1.5	1.5	27.36	112.91	0.147	7.7	Breakage
	4×4	1.5	1.5	27.36	156.96	0.203	10.7	Breakage
Geogrid		1.5	1.5	27.36	94.86	0.093	9.8	Breakage

Note: a) (F) and (H) refer to Fig. 5 and b) tensile strength of a new tread at 5% strain 43 kN/m (KATECH 2001)

Fig. 7 Tension crack occurred in test embankment during the pullout test

Although the treadmats which failed by pullout were only slightly deformed, as shown in Fig. 6(a), the treadmats which failed by breakage were torn, as shown in Fig. 6(b). The distribution of the tensile force in the treadmats is the highest in the frontal part, because they can be considered as a type of extensible reinforcement materials. However, the largest extension occurred between the first and the second row, because the steel plates were attached at the first row of the treadmats. The breakage mainly occurred in direction perpendicular to the pullout direction between the first and the second row.

4.1.3 Pullout behavior of treadmats failed by pullout

Fig. 8 presents typical behavior of the treadmats which failed by pullout. This figure is good to see relative force delivered and displacement among points. The frontal displacement indicates the displacement of crossbeam II measured by LVDTs (shown in Fig. 2), while rear

Table 7 Pullout behavior of the treadmats at measuring points

Notation	F_{po} (kN)	d_{front} (m)	ε_{front} (%)	d_{rear1} (mm)	d_{rear2} (mm)	E_p [a] (mm)	E_s [a] (mm)
6×6 (F)	181.5 [b]	128.6	6.7	0.2	-	128.4	-
	240.3 [c]	225.3	11.9	47.5	0.5	177.8	47.0
	245.3 [d]	238.2	12.5	58.2	1.0	180.0	57.2
4×4	137.3 [b]	164.9	8.2	0.1	-	164.8	-
	157.0 [d]	203.2	10.7	79.0	-	124.2	-

Note: a) $E_p = d_{front} - d_{rear1}$, $E_s = d_{rear1} - d_{rear2}$
b)~d) Pullout force b) at the observation of d_{rear1}; c) at the observation of d_{rear2}; d) at the peak value

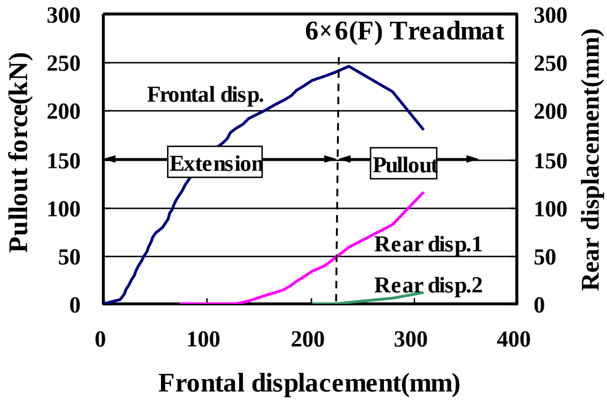


Fig. 8 Typical pullout behavior of the treadmats failed by pullout

displacement denotes the displacement measured with wires and a pulley system at the center of the fourth and last rows of the treadmat, as shown in Fig. 3. From Fig. 8, it can be recognized that point of Rear disp. 1 has no force until frontal point has about 180 kN. From this figure, pullout force transfers from the frontal part to rear part progressively as displacement increases. Also rear disp.2 has no pullout force until maximum pullout force reached at front. The pullout behavior shown in Fig. 8 is summarized in Table 7 in terms of pullout force, F_{po}, frontal displacement and strain at corresponding pullout force, d_{front} and ε_{front}, the middle and last displacement, d_{rear1} and d_{rear2}, and the amount of primary and secondary extension, E_p and E_s.

Long (1993), O'Shaughnessy and Garga (2000a), Gerscovich *et al.* (2001) and Kim *et al.* (2011), reported that progressive failure was clearly observed in three-dimensional tire reinforcements. Typically, as working the pullout force, the first row of the tire reinforcements is extended in the direction of the pullout force. The first row is entirely mobilized, and the force is then transferred to the next row. Finally, the last row is elongated after full mobilization of the previous row. After failure of the last row, the tire reinforcement begins to slide along the lower surface of the tire reinforcement and to carry the soil mass above it as well, as shown in Fig. 7.

This type of progressive failure also developed in every treadmat; however, the tightening of rope knots and the excessive tire deformation observed in earlier studies of three-dimensional tire reinforcements did not arise in these treadmats. When applying the pullout force, the pullout apparatus shown in Fig. 2 moved as a unit. Therefore, only the frontal displacement was measured; however, rear displacement did not occur at this point. The pullout force was increasingly transferred from the first row to the next row along the treads in the column direction. As shown in Fig. 8 and Table 7, at a pullout force of 182 kN with corresponding frontal displacement of 129 mm (ε_{front}=6.7%), the middle displacement of the 6×6 (F) treadmat was gradually measured. When the pullout force reached 240 kN, which is close to the peak value of 245 kN, the last displacement was also measured with corresponding frontal and middle displacement equal to 225 mm (ε_{front}=12%) and 48 mm, respectively. In other words, the treadmats only extend before the last displacement occurs. When the pullout force is greater than the pullout resistance of the treadmats, the treadmats start to slide along their bottom interface and the pullout force gradually decreases after reaching its peak value.

4.1.4 Pullout behavior of treadmats failed by breakage

While most treadmats failed by pullout, some treadmats failed by breakage, as shown in Table 6. The breakage of treadmats took place under high vertical stress levels (i.e., σ'_v=45.6 kPa, 58.4 kPa) or in the treadmats of low stiffness levels (i.e., 3×3, 4×4 treadmat). In these cases, the tensile force in the treadmats becames greater than tensile strength of the treadmats. Tensile strength of a new single tread is given in Table 6.

Typical deformed shape and pullout behavior of treadmats which failed by breakage are given in Fig. 6(b) and Fig. 9, respectively. Table 7 summarizes the pullout behavior of a 4×4 treadmat which failed by breakage. Its initial behavior shown in Fig. 9 was similar to that of the treadmats which failed by pullout. In other words, frontal movement was mobilized; however, rear movement did not develop at this point. The middle displacement of the 4×4 treadmat was measured at a pullout force of 137 kN, and the strain for corresponding frontal displacement, ε_{front}, was 8.2%. Because the pullout force and deformation of the tread are related to the stiffness of the treadmats or the number of treads, despite the fact that the pullout force of the 4×4 treadmat is smaller than that of the 6×6 (F) treadmat, its strain is larger. The last displacement was not measured at the pullout capacity of 157 kN because the pullout force was not transferred to the last row due to breakage of the tread. The pullout force rapidly decreased after the peak value.

4.2 Factors influencing pullout capacity

4.2.1 Degree of confinement

Fig. 10(a) shows the pullout behavior of single treads as pullout force versus the frontal displacement with various surcharge heights. As the frontal displacement increases, the pullout force increases until reaches its peak and then force gradually decreases. Fig. 10(b) shows the trend in the variation of the pullout capacity with effective vertical stress. The pullout capacity proportionally increases until reaching a surcharge height of 2.5 m (σ'_v=45.6 kPa), and it then converges at higher surcharge heights.

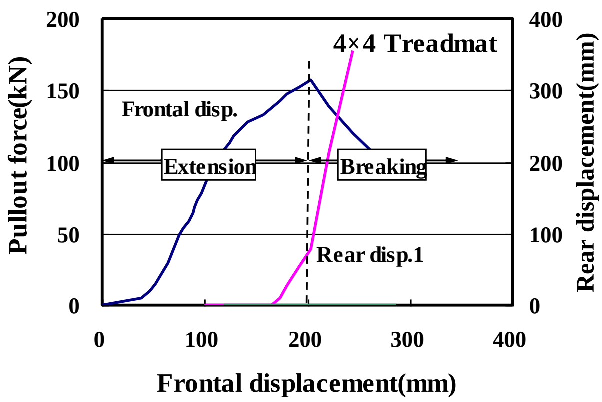
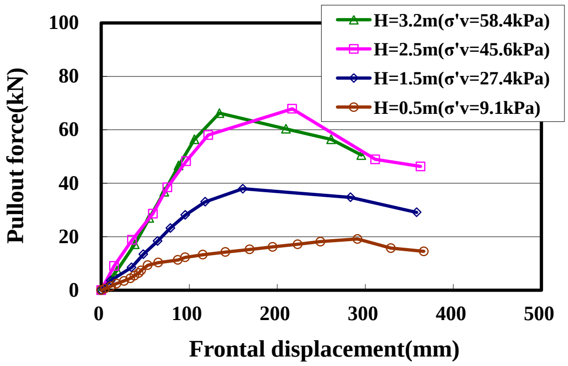
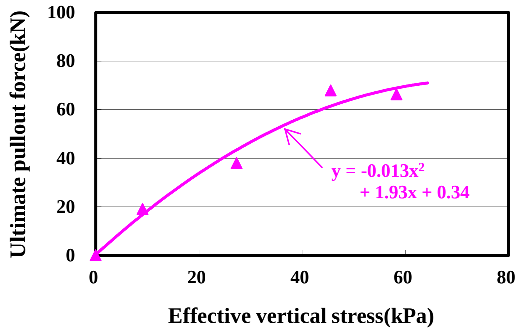


Fig. 9 Pullout behavior of a treadmat failed by breakage



(a) Pullout force versus frontal displacement



(b) Pullout capacity versus effective vertical stress

Fig. 10 Pullout behavior of single treads for various surcharge heights

This trend for single treads is similar to that of the cell-type tire units reported by Kim *et al.* (2011). The soil stress at any depth does not increase with the depth, and it converges without respect to increasing of the depth because it is redistributed or transferred by the arching effect. Therefore, the pullout capacity of single treads is expected to converge over a surcharge height of 2.5 m.

Fig. 11 shows the curves of the pullout force per unit width versus the frontal displacement for the treadmats with various arrangements at the same surcharge height of 1.5 m. Every curve has a definite peak before the strain reaches 20%, after which it gradually decreases. This peak value is the pullout capacity. The initial behavior of 6×6 (H) and 6×6 (F) shown in this figure is similar, while the pullout capacity of 6×6 (H) is 56% of that of 6×6 (F). In other words, the surcharge of sloping parts influences the pullout capacity rather than the pullout deformation.

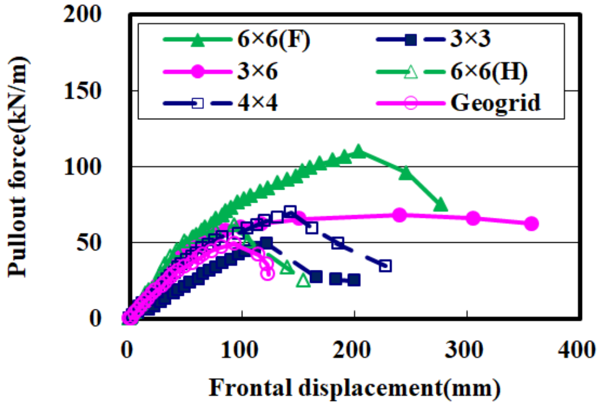


Fig. 11 Pullout behavior of the treadmats with various arrangements

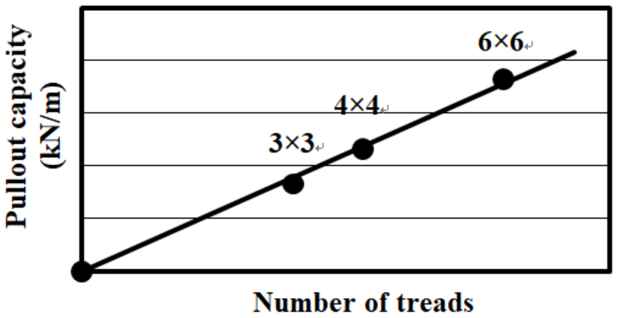


Fig. 12 Pullout capacity of the treadmats with the number of treads

Table 8 Interaction coefficients of treadmats

Notation	Height	Interaction coefficient
3×3	1.5	0.41
4×4	1.5	0.45
6×6	1.5	0.49
12×6	1.5	0.61

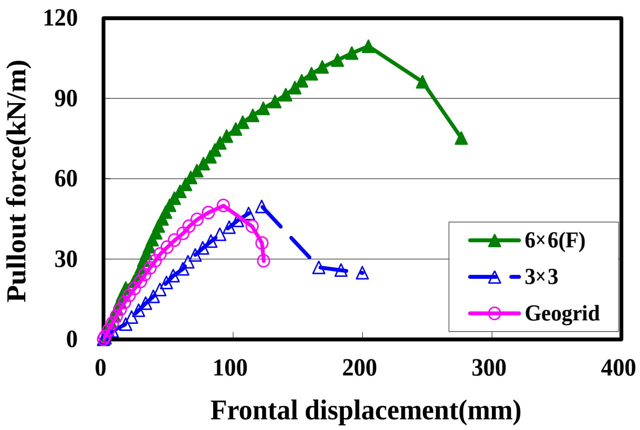


Fig. 13 Comparison between treadmats and geogrid

4.2.2 Stiffness of reinforcement material

Since the treadmats are loose grid structure, the contribution of transverse members on pullout resistance is insignificant. The pullout capacity of 6×6 (F) is six times that of single tread. That implies the pullout resistance of transverse members is negligible.

Based on the experimental test results, transverse members are very flexible and breakage failures were only observed in longitudinal members (Fig. 6(b)). And, if cross area between longitudinal and transverse member takes as longitudinal member, surface areas of transverse member of 3×3 and 6×6 are 4% and 2.4% of longitudinal member area, respectively. Bergado *et al.* (1993) reported that the pullout capacity of geogrids without transverse members was about 90-100% of that of the grids with transverse members. Also the difference in pullout resistance between geogrid and treadmats is from the tensile strength difference.

The longitudinal treads resist the pullout force and transfer the pullout force from the first row to the last row, while the transverse treads only distribute the pullout force. The transferred pullout force per tread decreases with an increase in the stiffness of treadmat, that is, the number of treads per unit area. Therefore, the pullout capacity is also governed by the stiffness of the treadmat as well as the degree of confinement.

The 3×3, 4×4 and 6×6 (F) treadmats have 6, 8 and 12 treads, respectively. Fig. 12 presents the pullout capacity of the 3×3, 4×4 and 6×6 (F) treadmats, equal to 50 kN/m, 70 kN/m and 110 kN/m, respectively. As shown in this figure, the pullout capacity proportionally increases with an increase in the number of treads. The 3×3 and 4×4 treadmats have fewer than 10 treads, and they broke in direction perpendicular to the pullout direction.

In this study, the commercially available geogrid was selected as comparison to the treadmat due to similarities between the two not only in terms of shape and failure mechanism, but also in terms of use in the field where the latter has been proposed to replace the former for reasons already stated. Nevertheless, the materials and dimensions involved in the geogrid were different than those in a geomat. The characteristics of the geogrid used are given Table 3, while the test results are shown in Fig. 13. The pullout capacities of 3×3 and 6×6(F) treadmats, and the geogrid were 50 kN/m, 110 kN/m and 50 kN/m, respectively. The pullout capacity of the 6×6(F) treadmat was approximately 2.2 times of that of the tested geogrid. The treadmat differed to the geogrid not only in the opening area ratios, as given in Table 2, but also in tensile strengths.

Kim *et al.* (2011) reported that the pullout capacity of the cell-type tire unit was about 1.25 times of that of a comparable geocell under identical test conditions. The cell-type tire unit and the geocell failed by pullout and breakage, respectively. The pullout capacity of the 3×3 treadmat, which had the lowest stiffness, was fairly similar to that of the geogrid. After testing, the breakages of 3×3 treadmat and geogrid at the frontal parts were observed. However, the middle and end displacements were not measured, because the 3×3 treadmat and geogrid have failed by breakage, thus the transfer of the pullout forces towards the other parts of the reinforcement did not occur. Accordingly, in cases where a waste tire treadmat is to be used in a reinforced soil structure, the 6×6 would be recommended.

The interaction coefficient, introduced by Jewell (1990) is a measure of reinforcement efficiency. The interaction coefficients associated with the treadmats are given in Table 8. The interaction coefficient was found increased with increasing number of treads used.

5. Conclusions

In this study a series of field-scale pullout tests was carried out on waste tire treadmats of various weave arrangements and under various confining stresses ranging from 9 to 59 kPa in order to investigate their pullout behavior when used in a reinforced soil structure. Treadmats can be considered as a type of extensible reinforcement; hence, progressive failure develops in every treadmat. The pullout capacity of a mat was found to be generally equal to the sum of capacities of longitudinal treads, with minor contribution realized due to the presence of lateral treads. Pullout failures occurred in treadmats put under light overburden while breakage failures occurred in treadmats put under heavier overburden. Also, pullout failures occurred in treadmats with more material presence per unit area while breakage failures occurred in treadmats with higher ratio of opening. The pullout capacity of a treadmat proportionally increased with increasing surcharge height up to 2.5 m, after which it converged. The pullout capacity also increased with increasing stiffness of the mat which is counted by the number of treads per unit width in the pullout direction. With a high enough stiffness, a pullout failure occurred instead of a breakage failure. The pullout capacity of a treadmat was higher than that of a comparable geogrid under identical loading conditions.

Acknowledgments

The authors are grateful to Inha University for the financial support. Thanks are extended to Mr. Kwang Soo Kyeon and Mr. Kyu Hwan Song for their assistance.

References

Abdi, M.R. and Arjomand, M.A. (2011), "Pullout tests conducted on clay reinforced with geogrid encapsulated in thin layers of sand", *Geotext. Geomembr.*, **29**(6), 588-595.

Bergado, D.T., Chai, J.C., Abiera, H.O., Alfaro, M.C. and Balasubramaniam, A.S. (1993), "Interaction between cohesive-frictional soil and various grid reinforcements", *Geotext. Geomembr.*, **12**(4), 327-349

Chen, C., McDowell, G.R. and Thom, N.H. (2013), "A study of geogrid-reinforced ballast using laboratory pullout tests and discrete element modeling", *Geomech. Geoeng.*, **8**(4), 244-253.

Deb, K. and Konai, S. (2014), "Bearing capacity of geotextile-reinforced sand with varying fine fraction", *Geomech. Eng.*, **6**(1), 33-45.

Esfandiari, J. and Selamat, M.R. (2012), "Laboratory investigation on the effect of transverse member on pullout capacity of metal strip reinforcement in sand", *Geotext. Geomembr.*, **35**, 41-49.

FHWA (2001), *Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines*, FWHA Demonstration Project 82, Federal Highway Administration, U.S. Department of Transportation, Washington D.C., U.S.A.

Gerscovich, D.M.S., Medeiros, L.V. and Sayao, A.S.F.J. (2001), "Field pullout test of scrap tire reinforcement layers under different soil surcharges", *Proceedings of the 15th International Conference on Soil Mechanics and Geotechnical Engineering*, Istanbul, Turkey, August.

Humphrey, D.N. and Katz, L.E. (2000), "Five-year field study of water quality effects of tire shreds placed above the water table", *J. Transport. Res. Board*, **1714**, 18-24.

Humphrey, D.N. and Katz, L.E. (2001), "Field study of water quality effects of tire shreds placed below the water table", *Proceedings of the Conference on Beneficial Use of Recycled Materials in Transportation Applications*, Arlington, Virginia, U.S.A., November.

JATMA (2015), <http://www.jatma.or.jp>.

Jewell, R. (1990), "Reinforcement bond capacity", *Geotechnique*, **40**(3), 513-518

Kang, Y., Nam, B., Zornberg, J.G. and Cho, Y.H. (2015), "Pullout resistance of geogrid reinforcement with in-plane drainage capacity in cohesive soil", *KSCE J. Civil Eng.*, **19**(3), 602-610.

KATECH (2001), <http://www.katech.re.kr/>.

KECO (2015), <http://www.keco.or.kr>.

Kim, K.S., Yoon, Y.W. and Yoon, G.L. (2011), "Pullout behavior of cell-type tires in reinforced soil structures", *KSCE J. Civ. Eng.*, **15**(7), 1209-1217.

Mahdi, M. and Katebi, H. (2015), "Numerical modeling of uplift resistance of buried pipelines in sand, reinforced with geogrid and innovative grid-anchor system", *Geomech. Eng.*, **9**(6), 757-774.

Niroumand, H. and Kassim, K.A. (2013), "A review on uplift response of symmetrical anchor plates embedded in reinforced sand", *Geomech. Eng.*, **5**(3), 187-194.

O'Shaughnessy, V. and Garga, V.K. (2000a), "Tire-reinforced earthfill. Part 2: Pull-out behaviour and reinforced slope design", *Can. Geotech. J.*, **37**(1), 97-116.

O'Shaughnessy, V. and Garga, V.K. (2000b), "Tire-reinforced earthfill. Part 3: Environmental assessment", *Can. Geotech. J.*, **37**(1), 117-131.

RMA (2015), htttp://www.rma.org, Scrap tire markets in the United States, Rubber Manufacturers Association.

Suksiripattanapong, C., Horpibulsuk, S., Chinkulkijniwat, A. and Chai, J.C. (2013), "Pullout resistance of bearing reinforcement embedded in coarse grained soils", *Geotext. Geomembr.*, **36**, 44-54.

Takallou, H.B. (2015), "Waste tire management and EPR programs in United States and Canada", *Proceedings of the 2015 RCBC Zero Waste Conference*, Whistler, British Columbia, Canada, May-June.

Vashi, J.M., Desai, A.K. and Solanki, C.H. (2013), "Behavior of geotextile reinforced flyash+clay-mix by laboratory evaluation", *Geomech. Eng.*, **5**(4), 331-342.

Yoon, Y.W. (2007), "Engineering characteristics of tire treads for soil reinforcement", *IW-TDGM 2007, International Workshop on Scrap Tire Derived Geomaterials*, Japanese Geotechnical Society, Yokosuka, Japan, March.

Yoon, Y.W., Cheon, S.H. and Kang, D.S. (2004a), "Bearing capacity and settlement of tire-reinforced sands", *Geotext. Geomembr.*, **22**(5), 439-453.

Yoon, Y.W., Cho, S.S. and Kim, K.S. (2007), "Engineering properties of tire treads for soil reinforcement", *J. Kor. Geoenviron. Soc.*, **8**(1), 49-55.

Yoon, Y.W., Heo, S.B. and Kim, K.S. (2008), "Geotechnical performance of waste tires for soil reinforcement from chamber tests", *Geotext. Geomembr.*, **26**(1), 100-107.

Yoon, Y.W., Moon, C.M. and Kim, G.H. (2004b), "Utilization of waste tires as soil reinforcement; (2) Environmental effects", *J. Kor. Geotech. Soc.*, **20**(3), 119-128.

JS