

# Pullout Response of Uniaxial Geogrid in Tire Shred–Sand Mixtures

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**Abstract** Use of tire shred–soil mixtures as backfill materials in mechanically stabilized earth walls has several advantages over other backfill materials: (1) good drainage, (2) high shear strength, and (3) low compacted unit weight. This paper presents the results of laboratory pullout tests performed on uniaxial geogrid embedded in tire shred–sand mixtures. The effects of tire shred size, tire shred–sand mixing ratio and confining pressure on the interaction between the geogrid and tire shred–sand mixtures are evaluated. Three sizes of tire shreds are considered: tire chips (with 9.5 mm nominal size), tire shreds 50-to-100 mm long and tire shreds 100-to-200 mm in length, with mixing ratios of 0, 12, 25 and 100 % of tire shreds in the mixtures (by weight). Based on compaction testing of a number of mixtures, the optimal mixing

proportion of tire shreds and sand was found to lie between 25/75 and 30/70 (by weight of tire shred and sand); this is equivalent to approximately 40/60 and 50/50, respectively, by volume of tire shreds and sand. The pullout resistance of a geogrid embedded in tire shred–sand mixtures is significantly higher than that of the same geogrid embedded in tire shreds only. The size of the tire shreds has negligible effect on the pullout resistance of a geogrid embedded in mixtures prepared with either low (12/88 mix) or high (100/0 mix) tire shred content. However, when the 25/75 mixture is used, greater geogrid pullout resistance was obtained for the geogrid embedded in tire chip–sand mixtures than in tire shred–sand mixtures.

**Keywords** Tires · Backfill · Pull-out resistance · Geogrid · Waste material · Compaction

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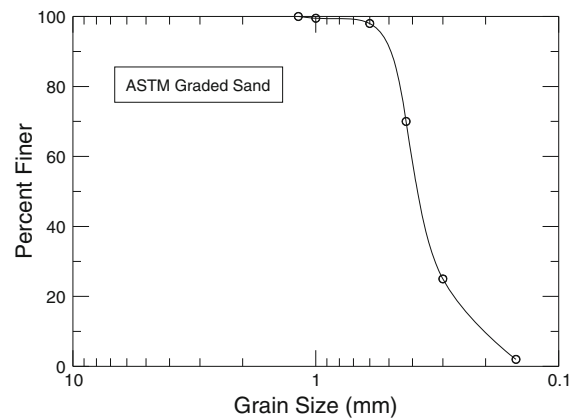
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## 1 Introduction

According to the Rubber Manufacturers Association (RMA), nearly 292 million scrap tires were generated in the US in 2009, while 112 million scrap tires still remained in stockpiles (RMA 2011). Huge quantities of scrap tires are generated in other parts of the World as well. For example, nearly 2,600,000 tons (equivalent to approximately 260 million passenger car tires) of scrap tires were produced in the European Union in the year 2003 (Shulman 2004), 106 million tires were generated in Japan in 2006 (Japan Automobile Tire Manufacturers

Association 2007), whereas 112 million scrap tires per year were estimated to be produced in India (Rao and Dutta 2006). Land filling or stockpiling of these tires pose problems mainly associated with (a) health hazards (as they provide a natural breeding place for disease-causing insects and rodents) and (b) self-ignition of the stockpiled tires, leading to fire hazards and air pollution. For these reasons, there has been a continuous effort to find beneficial uses for scrap tires that has led to a sharp increase in their overall utilization from 11 % of what was generated in 1990 to 85 % in 2009 (Rubber Manufacturers Association 2011). A major portion of the generated scrap tires (about 40 %) is used as fuel in cement kilns, in the paper and pulp industries, and in other industrial boilers. Efforts to identify innovative ways to take advantage of the durable properties of tires in civil engineering applications are on the rise. Current civil engineering applications for shredded tires mainly include use as embankment fill material (Bosscher et al. 1992; Eldin and Senouci 1992; Upton and Machan 1993; Dickson et al. 2001; Khan and Shalaby 2002), as drainage material to collect leachate in landfills (Hall 1991; Warith et al. 2004), as vibration-dampening material underneath railway tracks (Basma and Robinson 2003; Wolfe et al. 2004), as a thermal-insulation layer (Lawrence et al. 1999; Shalaby and Khan 2002), and as an asphalt-rubber-paving layer (Kuennen 2004). Composite materials consisting of tire shreds mixed with sand are used in geotechnical applications because fills consisting of tire shreds only are susceptible to combustibility problems and are more compressible than tire shred–sand mixture fills.

Results of laboratory tests and field demonstration projects using tire shred–sand mixtures have been reported by Bernal et al. (1997), Lee et al. (1999), Youwai and Bergado (2003), Salgado and Prezzi (2004), Siddiki et al. (2004), Zornberg et al. (2004), Bergado et al. (2005), Yoon et al. (2006), Balunaini et al. (2008), and Tanchaisawat et al. (2010). However, studies on the use of tire shred–sand mixtures as backfill materials in mechanically stabilized earth (MSE) walls are very limited. Selection of the optimum mix proportion for tire shred–sand mixtures and quantification of the degree of interaction between geogrids and mixtures are essential for the satisfactory performance of tire shred mixtures as backfill material. The main goal of this study was to determine the pullout response of a uniaxial geogrid embedded in tire shreds and tire shred–sand mixtures. A series of pullout tests were performed to



**Fig. 1** Grain size distribution of ASTM graded sand

investigate the effects of tire shred size, confining pressure, and tire shred–sand mixing ratio on the pullout resistance of geogrid embedded in tire shred–sand mixtures. In addition, the optimum mixing ratio for three sizes of shredded tires—9.5 mm in nominal size, 50–100 mm in length, and 100–200 mm in length—were determined from compaction tests performed on mixtures with varying mixing ratios of shredded tires and sand. Since minimal segregation of mixture components is required for proper performance of the composite material, mixing ratios that lead to minimal segregation of the two materials are also proposed.

## 2 Test Materials

### 2.1 Ottawa Sand

Commercially available ASTM graded sand (unground silica) manufactured by US Silica Company, Ottawa, IL, was used in the preparation of the tire shred–sand mixtures. This sand conforms to ASTM C778 (ASTM 2006) (“Standard Specification for Standard Sand”) and is commercially known as Ottawa sand. Figure 1 shows its grain size distribution. The specific gravity of Ottawa sand is 2.65.

### 2.2 Tire Shreds

Figure 2 shows the three different sizes of tire shreds that were used in the laboratory tests (tire chips 9.5 mm in nominal size, tire shreds 50–100 mm in length, and tire shreds 100–200 mm in length). The tire shreds are produced and supplied by Entech Co.

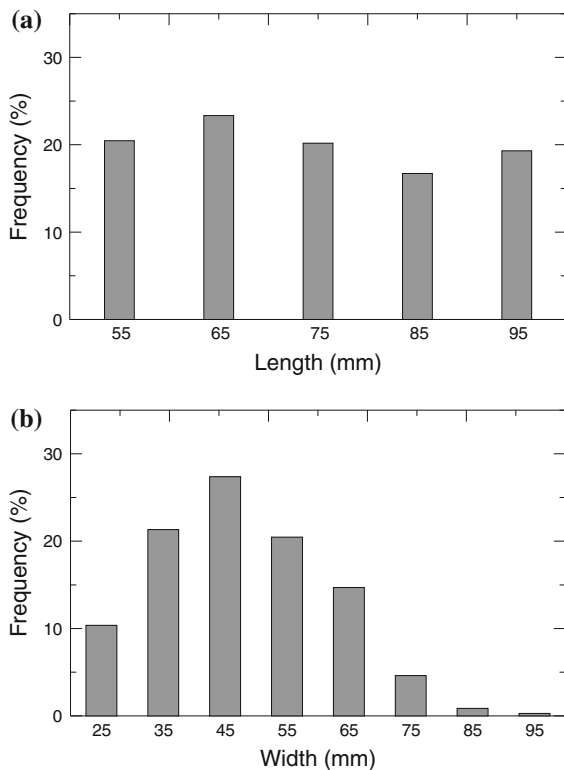


**Fig. 2** Tire shred sizes considered in the study: **a** tire chips 9.5 mm in nominal size, **b** tire shreds 50-to-100 mm in length, and **c** tire shreds 100-to-200 mm in length

located in White Pigeon, Michigan. Tire chips (9.5 mm in nominal size) provided by the supplier needed no further processing in the laboratory, whereas shredded tire pieces had to be cut to required tire shred sizes. For the geometric characterization of the tire shreds, measurements were made using a ruler on randomly selected tire shreds. The largest distance between any two points of the shred is taken as its length (Drescher et al. 1999). Figures 3 and 4 show the distributions of length and width of tire shreds with lengths ranging from 50–100 to 100–200 mm, respectively. The average lengths, widths, and thicknesses for these two size ranges of 50–100 and 100–200 mm are 76, 49, and 10 mm, and 137, 65, and 11 mm, respectively. An important property indicative of the shape of tire shreds is the aspect ratio, defined as the

length-to-width ratio. The average aspect ratios are 1.6 and 2.2 for the tire shred size ranges of 50-to-100 and 100-to-200 mm, respectively. The larger tire shreds are elongated and flat, while the smaller tire chips are equidimensional (cubical) in shape and have no metallic wire or fabric reinforcements present. In the case of the 50-to-100-mm-long tire shreds and 100-to-200-mm-long tire shreds, reinforcement in the form of fine metallic wires and fabric protruded from the shredded tire pieces.

The specific gravity  $G_{TS}$  of the tire chips and tire shreds was determined in accordance with ASTM C127 (ASTM 2007) [“Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate”]. Table 1 shows the average  $G_{TS}$  values obtained for the tire shreds

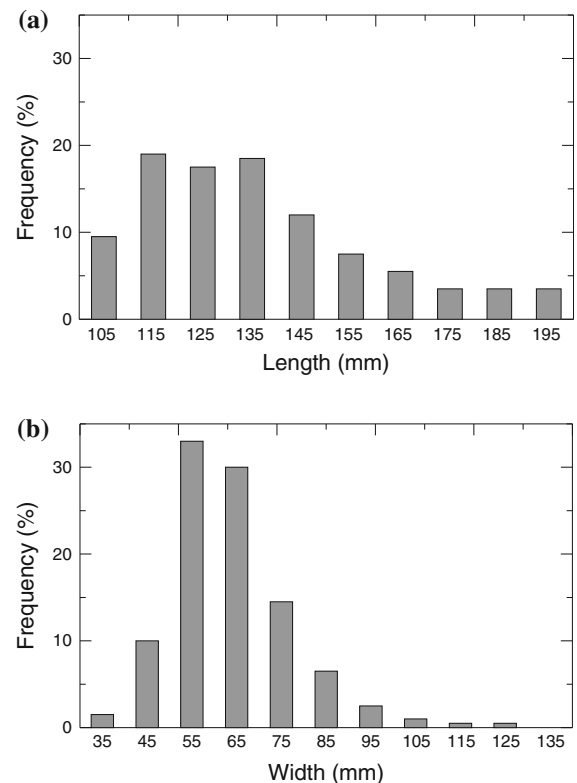


**Fig. 3** Geometry of tire shreds of 50–100 mm in length. **a** Distribution according to length. **b** Distribution according to width

considered in this study. The specific gravity values of tires shreds are greater than those of tire chips due to the presence of steel wires.

### 2.3 Geogrid

A commercially available uniaxial geogrid made of high-density polyethylene (HDPE) with a tensile strength of 52 kN/m at 5 % strain was used in the pullout tests (geogrid type: UX 1500 MSE manufactured by Tensar). The UX 1500 MSE geogrid has a relatively large aperture size (17 mm × 445 mm in size, refer to Fig. 5); this is the reason it was selected, as it can allow large tire shreds to penetrate its openings and thus provide additional resistance to pullout. Table 2 summarizes the geogrid properties. The average dimensions of the geogrid specimen used for the tests are 0.96 m × 0.31 m (length × width).



**Fig. 4** Geometry of tire shreds of 100–200 mm in length. **a** Distribution according to length. **b** Distribution according to width

**Table 1** Specific gravity of tire shreds

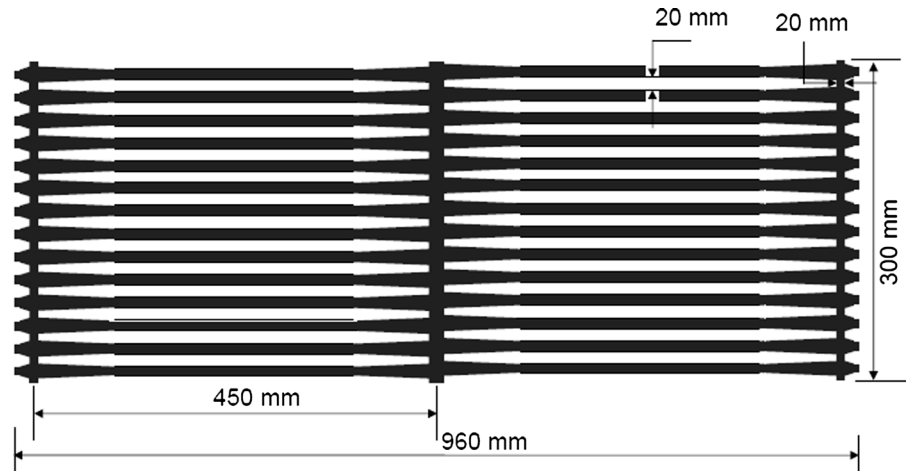
Size of shredded tires	Specific gravity ( $G_{TS}$ )
9.5-mm	1.16
50–100 mm in length	1.26
100–200 mm in length	1.24

## 3 Compaction and Segregation Studies on Tire Shred–Sand Mixtures

### 3.1 Compaction of the Tire Shred–Sand Mixtures

A series of compaction tests using a mold 270 mm in diameter and 232 mm in height was performed to determine the optimum mixing ratio of the tire shred and sand mixtures considered in this study. Using the standard Proctor compaction effort (600 kN m/m<sup>3</sup>), the mixtures of air-dried tire shreds and Ottawa sand were compacted in the mold using a rammer (mass = 9.21 kg

**Fig. 5** Geogrid specimen



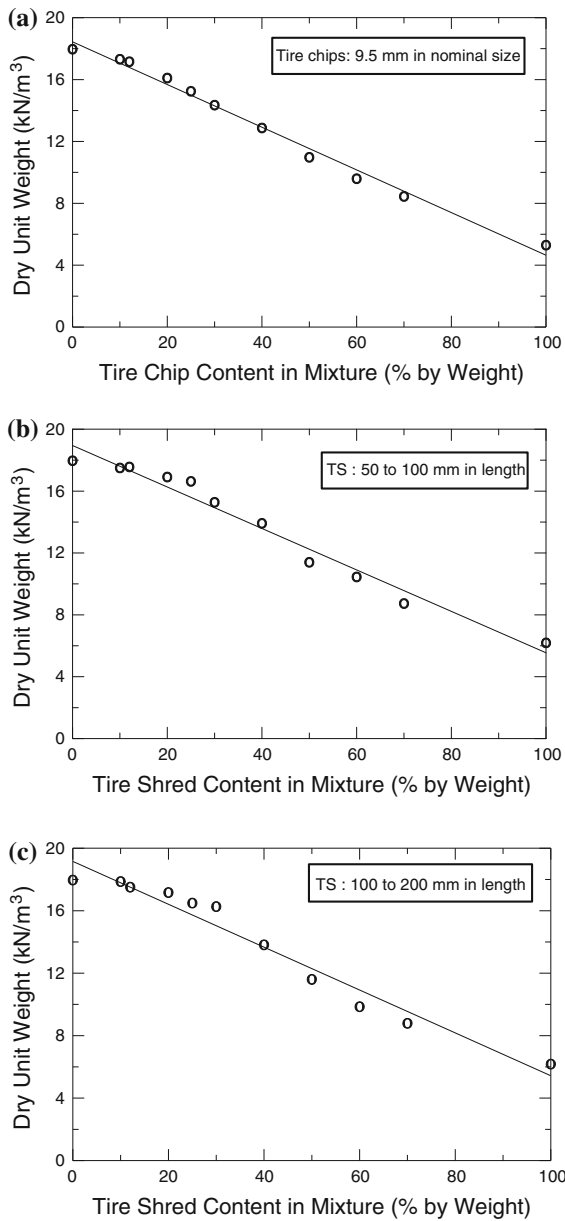
**Table 2** Properties of the geogrid used (UX 1500 MSE, Tensar)

Property	Unit	Machine direction (MD) value
True initial modulus	kN/m	1,580
Tensile strength at 5 % strain	kN/m	52
Long-term allowable load in sands, silts and clay	kN/m	45.2
Long-term allowable load in well graded sands	kN/m	43.9
Long-term allowable load in aggregate	kN/m	43.1
Junction strength	kN/m	105

and drop height = 0.4 m) in three layers with 72, 72 and 73 blows, respectively. The mixtures were prepared at various mixing ratios using tire shreds of three different sizes (tire chips 9.5 mm in nominal size, tire shreds 50–100 mm in length, and tire shreds 100–200 mm in length) and Ottawa sand. The compacted unit weight of each mixture was then determined. The tire shred content of the tire shred–sand mixtures was varied from 0 to 100 % (i.e., from pure sand to pure tire shreds). The ratio of the diameter of the mold to the average size of the tire shreds with length 100-to-200 mm is of the order of two and hence size effects may be present for this tire shred size range. However, size effects for the other two tire shred sizes used in the study (9.5 and 50-to-100 mm length) is small. The compacted unit weight of the mixtures of tire shreds and sand decreased linearly with increasing tire shred content (Fig. 6); this is expected due

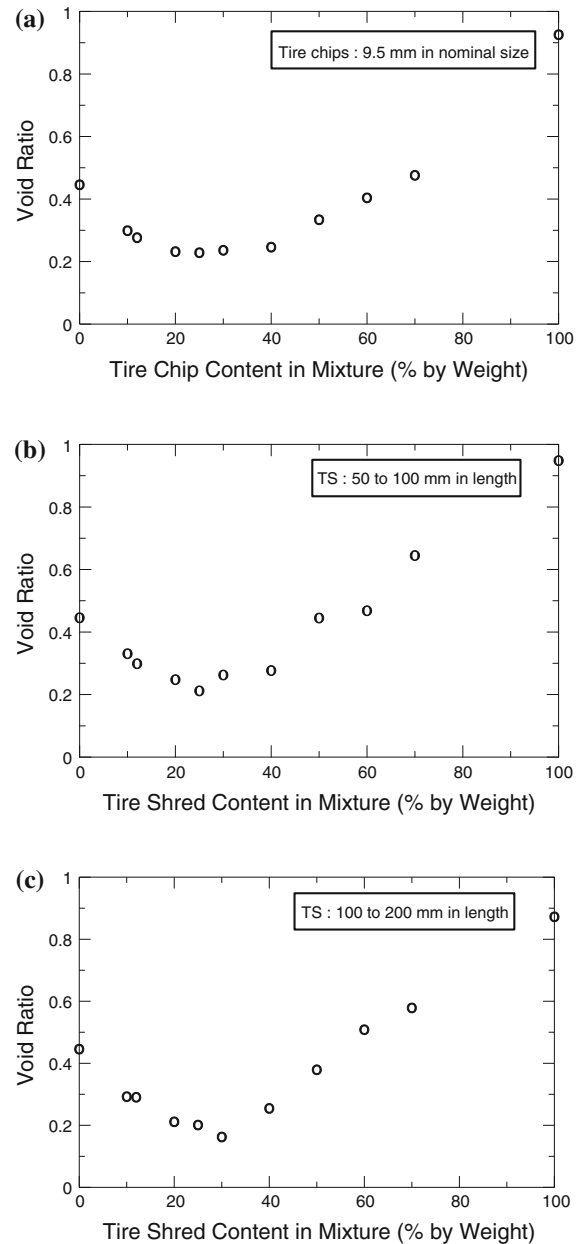
to the lower specific gravity of the tire shreds compared to that of sand (refer Table 1).

For each compacted mixture, the void ratio of the mixture was calculated from the measured unit weight, weight of tire shreds and sand, and known specific gravity of tire shreds and sand. The void ratios of the compacted tire shred–sand mixtures were plotted as a function of the tire shred content of the mixtures (see Fig. 7). The compacted mixtures consisting only of tire shreds had void ratios of 0.92, 0.95 and 0.87 for shredded tire sizes of 9.5, 50–100 and 100–200 mm, respectively. Once sand particles are added to a given volume of tire chips or shreds, the void ratio of the mixture of the two materials decreases since the sand particles fill the existing voids in the mixture. A minimum void ratio of the mixture is reached when the existing volume of voids between the shreds are filled with sand particles. When all voids between the tire shreds are filled with sand particles, any further addition of sand will increase both the overall volume of the mixture and its minimum void ratio. Hence, the curve of the void ratio of the compacted mixtures versus the percentage of tire shred content has a minimum at shredded tire contents (by weight) equal to 25 % for tire chips 9.5-mm in nominal size, 25 % for tire shreds 50–100 mm in length, and 30 % for tire shreds 100–200 mm in length (Fig. 7). Yoon et al. (2006) reported similar findings for mixtures prepared with sand and 38-to-76 mm long tire shreds. The void ratios corresponding to the optimum mixing ratios are 0.23, 0.21, and 0.16 for shredded tire sizes of 9.5, 50–100 and 100–200 mm, respectively. This mixing ratio at which the minimum void ratio of the mixture



**Fig. 6** Unit weight of shredded tires and Ottawa sand mixtures with different shredded tire contents. **a** Tire chips (9.5-mm nominal size). **b** Tire shreds (50–100 mm in length). **c** Tire shreds (100–200 mm in length)

of the two materials (shreds and sand) is observed is defined as the optimum mixing ratio. The void ratio of the mixtures at the optimum mixing ratio is smaller than the void ratio for the compacted sand only. Table 3 provides the minimum void ratio values



**Fig. 7** Total void ratios of compacted shredded tire–sand mixtures as a function of the shredded tire content by weight. **a** Tire chips (9.5 mm in nominal size). **b** Tire shreds (50–100 mm in length). **c** Tire shreds (100–200 mm in length)

$e_{min,ts}$ ,  $e_{min,sand}$ , and  $e_{min,mix}$  of the compacted samples consisting of tire shreds only, sand only, and mixtures, respectively. The optimum mixing ratio of tire shreds and sand is given both by weight and volume proportions.



**Table 3** Summary of compaction tests results

Size of shredded tires	$\gamma_{d,mixture}$ with optimum mixing ratio (kN/m <sup>3</sup> )	$e_{min,ts}$	$e_{min,sand}$	$e_{min,mix}$	$e_{g,mix}$	Optimum mixing ratio of shredded tires/sand (by weight)	Optimum mixing ratio of shredded tires/sand (by volume)
9.5 mm nominal size	15.2	0.92	0.45	0.23	1.99	25/75	46/54
50–100 mm in length	16.6	0.95	0.45	0.21	1.98	25/75	42/58
100–200 mm in length	16.3	0.87	0.45	0.16	1.49	30/70	49/51

For mixtures with binary packing, the granular (or skeleton) void ratio (Salgado et al. 2000; Thevanayagam et al. 2002; Carraro et al. 2003) determines which component of the mixture dominates the response. The granular void ratio of the tire shred–sand mixture  $e_{g,mix}$  is calculated by assuming that the volume of sand is an added volume of voids. The granular void ratio  $e_{g,mix}$  can be obtained from the expression

$$e_{g,mix} = \frac{V_V + V_S}{V_{TS}} \quad (1)$$

where  $V_V$  is the volume of voids,  $V_S$  is the volume of sand, and  $V_{TS}$  is the volume of tire shreds.

The matrix of finer particles dominates if it, on average, floats (separates) the larger particles. This happens when  $e_{g,mix} > e_{max,CF}$ , where  $e_{max,CF}$  is the maximum void ratio of the coarser fraction (in this case, the tire shreds). Table 3 shows  $e_{g,mix}$  for the mixtures in the present testing program.

### 3.2 Segregation of the Tire Shred–Sand Mixtures

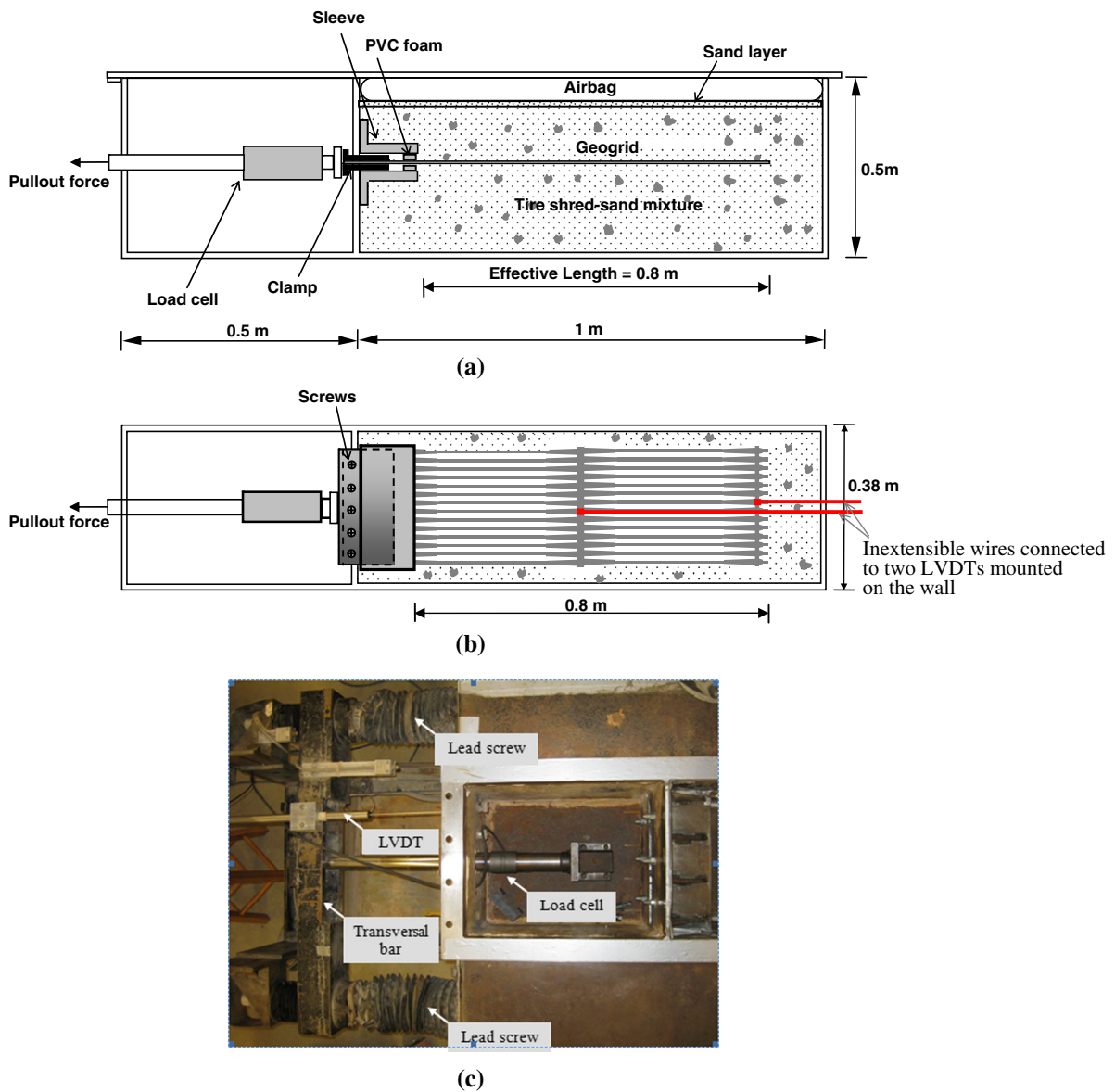
Segregation has been one of the main concerns regarding use of tire shred–sand mixtures as fill or backfill materials. The amount of segregation was quantified during compaction studies performed in the laboratory. After compaction of each mixture, segregation of the tire shreds in the compacted samples was evaluated by determining the tire shred–sand ratios at three different layers in these samples. Segregation was found to be negligible for mixtures with low tire shred content (less than 30 % by weight). However, for mixtures with tire shred content greater than 30 %, segregation was found to be pronounced. This happens because the voids between the tire shreds are very large compared with the size of the sand grains and, therefore, during compaction using an impact-type

rammer, the sand grains easily settle down through these voids within the tire shred matrix in the case of mixtures with high tire shred contents. For the optimum tire shred mixing ratios determined in the previous section, little or no segregation was observed.

## 4 Interaction of Geogrid and Tire Shred–Sand Mixtures

The pullout testing program was undertaken to evaluate the pullout response of the UX 1500 MSE uniaxial geogrid embedded in the tire shred–sand mixtures for various testing conditions. The parameters considered in this study were: (1) various tire shreds sizes (tire chips 9.5 mm in nominal size, tire shreds 50–100 mm in length and tire shreds 100–200 mm in length), (2) various tire shred–sand mixing ratios (0, 12, 25 and 100 % of tire shreds in the mixtures by weight; the entire range of mixing ratios, from pure sand to pure tire shreds, was investigated) and (3) various confining pressures (40, 70, and 100 kPa).

For the mix with 25/75 proportion by weight of tire shreds to sand,  $e_{g,mix}$  can be calculated from the compacted unit weights of the mixtures (Fig. 6) and is found to be equal to about two for all the three tire shred sizes. The unit weight of tire shreds alone in an uncompacted state was determined by knowing the weight of tire shreds filling a known volume of a container and was found to be equal to 4.9 kN/m<sup>3</sup>. The maximum void ratio of tire shreds alone,  $e_{max,ts}$ , was then calculated from the uncompacted unit weight and found to be equal to about 1.4. As  $e_{g,mix}$  is greater than  $e_{max,ts}$ , the tire shreds will be floating in sand matrix for all the mixtures considered in the study, which means that mechanical behavior is significantly influenced by the behavior of the sand itself.



**Fig. 8** Pullout box details: **a** Schematic of a cross-sectional view, **b** schematic of plan-view of the box, and **c** instrumentation on pullout machine showing load cell and LVDT

#### 4.1 Pullout Test Set-Up

The main components of the pullout testing system are: (1) pullout box, (2) shearing system, (3) geogrid clamping system, (4) airbag for application of the confining pressure, (5) monitoring system, and (6) data acquisition system. Figure 8a, b show a schematic diagram of the cross-sectional and plan views of the pullout box. The pullout box consists of the tire shred-sand mixture chamber and the load-cell chamber.

Samples are prepared in the tire shred-sand-mixture chamber with inner dimensions of  $1.0 \text{ m} \times 0.38 \text{ m} \times 0.47 \text{ m}$  (length  $\times$  width  $\times$  height). A sleeve was fitted at the front face of the pullout box to transfer the point of application of the pullout load beyond the rigid front wall. To minimize the friction between the sample and side walls of the pullout box, smooth vinyl sheets were placed along the side walls of the box. The pullout load was applied using two stepper motors. The pullout rate was taken as  $1 \text{ mm/min}$  in this study. During the geogrid

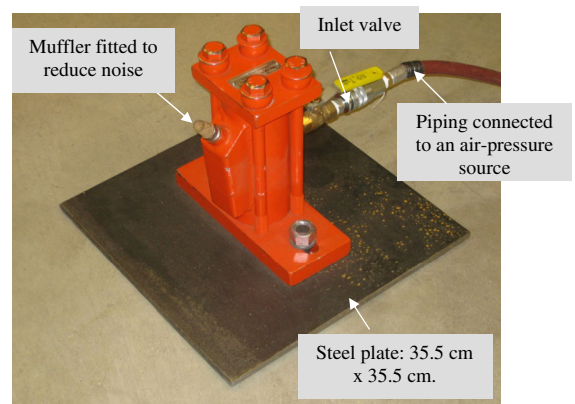


pullout tests, the front-end displacement of the geogrid was monitored using an LVDT, while the pullout force was monitored using a load cell attached to the loading system (Fig. 8c). Displacements of the middle and the end nodes of the geogrid were also monitored by connecting inextensible wires at the middle and at the end of the geogrid to LVDTs mounted outside the pullout box. These inextensible wires were encased in stiff plastic tubes to reduce the resistance offered to their movement during pullout. All the LVDTs were calibrated before performing the pullout tests.

Studies in the literature indicate that minimization of boundary effects requires a minimum sample size of 8–12 times the particle size (Indraratna et al. 1993). In the present study, the ratio of the width of the pullout box to the size of tire chips is about 40 and hence box boundary effects on samples prepared with tire chip–sand mixtures are negligible. During preparation of samples with tire shred–sand mixtures, tire shreds in the mixture can be oriented in any direction. Depending on its orientation, the ratio of the width of pullout box to the average size of tire shred measured along width of the box will vary. This ratio will be a minimum when the longer axis of tire shred is oriented parallel to the width of the box and will be a maximum when oriented perpendicular to the width of the box. Considering the average tire shred size, this ratio was found to lie between 6 and 10, and 3 and 10 for 50-to-100 and 100-to-200 mm long tire shreds, respectively. This indicates that the boundary effects may be present for 100-to-200 mm long tires shreds when they are aligned along the width direction. However, it was observed during sample preparation that there was a tendency, perhaps because constraint was less along the length of the box, for tire shreds to align in larger numbers along the longer dimension of the box. Based on these considerations, boundary effects on samples prepared using 50-to-100 and 100-to-200 mm tire shred sizes can be considered to be small.

#### 4.2 Compaction Procedure

The samples were compacted using a pneumatically operated impact-piston type compactor, as shown in Fig. 9. This type of compactor was found to impart high impact, linear force with no high-frequency vibration involved and to efficiently transfer energy to the sample. A square steel plate (35.5 cm in length  $\times$  35.5 cm in width  $\times$  0.95 cm in thickness)



**Fig. 9** An impact piston-type compactor bolted to a steel plate (compactor model: 50-2LS-EM, manufactured by VIBCO)

was attached to the bottom of the compactor to facilitate compaction of the samples inside the pullout box. The compactor was connected to a pressure source by a pressure line. Each lift of the tire shred–sand mixture was compacted by traversing the compactor along the length of the box for a period of five minutes. Further details of the compactor and the compaction procedure can be found in Balunaini and Prezzi (2010).

#### 4.3 Sample Preparation

The tire shred–sand mixture was compacted in four 10-cm-thick layers inside the pullout box. For each layer, the required quantities of tire shreds and Ottawa sand were first mixed thoroughly in a container before placement and compaction within the pullout box. No moisture was added during preparation of the mixtures. After compaction of the second layer, the geogrid was fixed to the loading system through a clamping system. The clamping system consisted of L-shaped upper and lower clamps (see Fig. 10); the geogrid was tightly bolted between these clamps. Each geogrid sample consisted of thirteen longitudinal ribs and two transverse ribs and was 300–320 mm in width and 960 mm in length. The effective embedment length of the geogrid within the tire shred–sand mixture samples was equal to 0.8 m. A PVC foam (used to seal wide gaps) was used to seal the remaining gap between the sleeves in order to minimize leakage of sand during compaction of the final two lifts of the mixture and testing. After compaction of the final layer, the unit weight of the mixture was calculated from the weight of the mixture added to the tire shred–sand-mixture



**Fig. 10** L-shaped geogrid clamps

chamber and the volume of the sample. Table 4 summarizes the test conditions and unit weights of the samples prepared in the pullout box. For a given mixing ratio of tire shreds and sand, the compacted unit weights of samples prepared for testing at three different confining pressures (40, 70 and 100 kPa) were quite similar. A maximum difference of  $1.0 \text{ kN/m}^3$  was observed in the unit weight values of the samples tested (the average unit weight values for the samples are reported in Table 4). Table 4 also shows the sand-matrix unit weight defined as the ratio of the weight of the sand to the volume of the sand matrix (volume of sand matrix = the total volume occupied by the mixture minus the volume occupied by the tire shreds). This ratio is an indicator of the relative packing of the sand particles within the matrix.

To complete the preparation of the sample, a thin sand layer was placed on top of the compacted tire shred–sand mixture to prevent the exposed steel wires of the tire shreds from damaging the airbag during its inflation to apply the desired confining pressure. Then, the flexible-rubber airbag was placed on top of the thin sand layer, and a steel plate was bolted on the pullout box. The airbag was inflated against the steel plate. The air pressure was applied through the regulator from a central laboratory air-pressure system.

## 5 Pullout Test Results and Analysis

### 5.1 Geogrid Pullout Resistance

FHWA guidelines recommend that the pullout load corresponding to a maximum rear-end displacement

of 15 mm of the specimen be used to select the pullout resistance of extensible reinforcements, if the maximum value for the pullout resistance or rupture of the specimen does not occur first. In the present study, geogrid rupture was not observed in any of the pullout tests: the maximum pullout load developed in the geogrid subjected to the confining pressures (40–100 kPa) considered in this study was much less than the ultimate tensile strength of the geogrid. In addition, no maximum (peak) pullout load was observed. The soil-to-reinforcement relative movement depends on the extensibility of the reinforcement material, the soil type, and confining pressure (Elias et al. 2001). For the tire shred–sand mixtures (12/88 and 25/75 mixes, by weight of tire shreds-to-sand), when the geogrid rear-end displacement was 15 mm, the geogrid front-end displacement ranged from 40 to 60 mm. Therefore, the pullout resistances of the geogrid placed in the samples tested under various test conditions (given in Table 4) were determined from the pullout load corresponding to a geogrid front-end displacement of 50 mm.

The pullout resistance of the reinforcement is predominantly due to frictional resistance, with passive resistance against transverse members due to wedging of the tire shred–sand mixture inside the geogrid apertures occurring only for the two transverse ribs present within the geogrid embedment length equal to 0.8 m (refer Fig. 8b). For the confining pressures considered in the study, the failure mechanism was governed by slippage of the reinforcement, and no tensile failure (breakage) of the reinforcement was observed in any of the pullout tests performed.

### 5.2 Effect of Confining Pressure

Figures 11, 12, 13 and 14 show the pullout load versus frontal displacement response of the UX 1500 MSE geogrid embedded in Ottawa sand and tire shred–sand mixtures. The initial shear stiffness of the geogrid–sand interface is greater than that of the geogrid–mixture interface. When a geogrid is placed in samples prepared with sand only, the pullout load increases continuously and then levels off at geogrid front-end displacements equal to about 25, 45 and 70 mm for confining pressures of 40, 70 and 100 kPa, respectively. However, for tire shred–sand mixtures, the pullout load increases continuously with displacement and does not reach a constant value within the

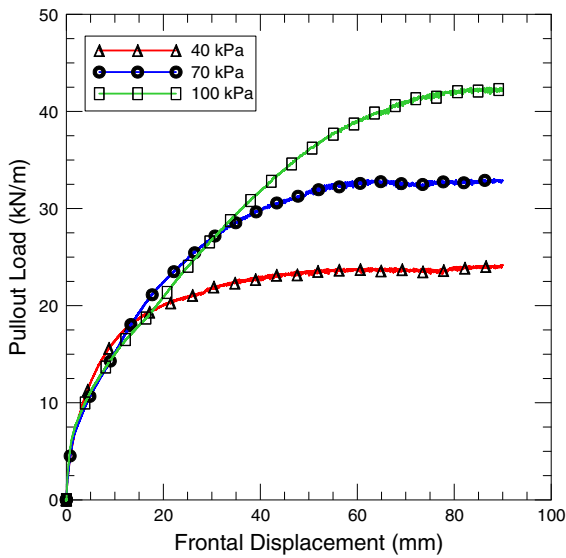
**Table 4** Summary of pullout tests and compacted unit weights achieved in the box

Size of shredded tires	Tire shred-sand ratio (by weight)	Confining pressure (kPa)	Maximum unit weight of mixture (kN/m <sup>3</sup> ) Yoon (2006)	Unit weight (kN/m <sup>3</sup> )	Relative compaction (%)	Sand-matrix unit weight (kN/m <sup>3</sup> )
Ottawa sand	0/100	40	18.0	17.4	96.7	17.4
		70				
		100				
9.5 mm in nominal size	12/88	40	17.2	15.9	92.2	17.2
		70				
		100				
	25/75	40	15.2	14.6	96.1	16.1
		70				
		100				
	100/0	40	5.3	5.1	96.2	–
		70				
		100				
50–100 mm in length	12/88	40	17.6	16.3	92.6	17.1
		70				
		100				
	25/75	40	16.6	14.7	88.6	15.7
		70				
		100				
	100/0	40	6.2	5.0	80.6	–
		70				
		100				
100–200 mm in length	12/88	40	17.5	15.3	87.4	16.0
		70				
		100				
	25/75	40	16.3	14.6	89.6	15.5
		70				
		100				
	100/0	40	6.3	5.7	90.4	–
		70				
		100				

maximum front-end displacement (equal to 90 mm) possible with the equipment used in this study. This indicates that the interface shear stress versus displacement response for a geogrid in a tire shred–sand mixture is more ductile than for a geogrid in sand.

Figure 15 shows that the pullout resistances increase with increasing confining pressures. For samples prepared with tire shred–sand mixtures, as the tire shred content in the mixture decreases from 100 to 25 % and then to 12 % (by weight), the geogrid pullout resistance envelope (the geogrid pullout

resistance plotted as a function of confining pressure) approaches that of the sample prepared with sand only. A comparison of the pullout resistances of geogrid placed in mixtures prepared with tire chips and tire shreds sizes of 50–100 mm and 100–200 m shows that the pullout resistance envelope of geogrid placed in tire chip–sand mixtures is closer to that of the envelope for sand only (Fig. 15a). Consider, for example, the samples prepared with the 25/75 mix subjected to a confining pressure of 70 kPa. The pullout resistance of the geogrid in tire chip–sand mixture is 84 % of that



**Fig. 11** Pullout force versus frontal displacement (Ottawa sand)

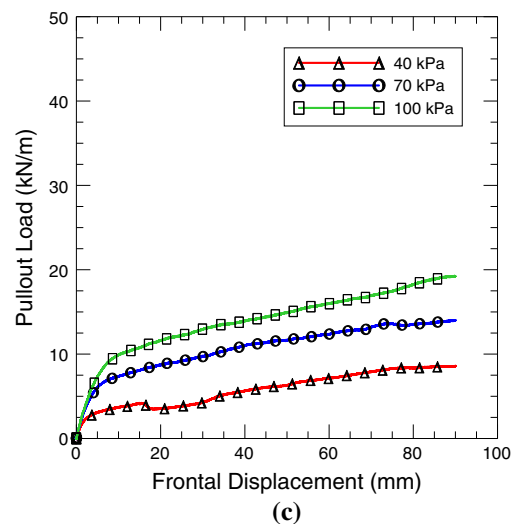
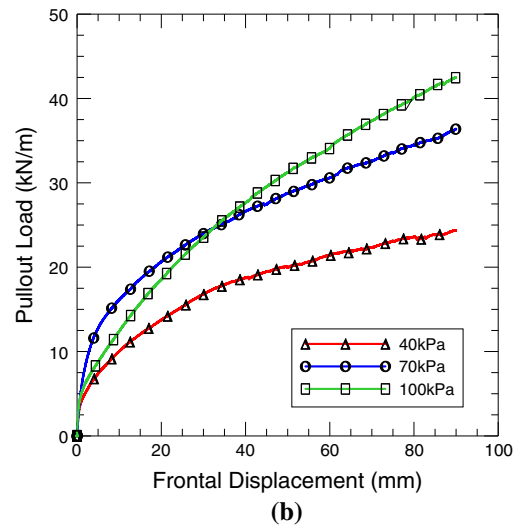
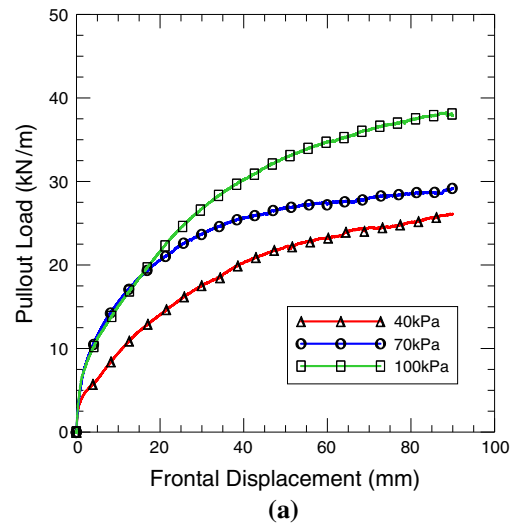
placed in sand only, whereas it is 75 and 66 % of that placed in sand only for mixtures prepared with 50–100 and 100–200 mm tire shred sizes, respectively.

Youwai et al. (2004) and Tanchaisawat et al. (2010) performed pullout tests on PVC-coated hexagonal-wire mesh and two types of geogrids embedded in various tire shred–sand mixing ratios (0, 30, 40, 50, and 100 %, by weight of tire shred content in the mixture). They also observed that the pullout resistance envelope of reinforcement embedded in tire shred–sand mixtures falls within the pullout resistance envelopes of reinforcement embedded in samples prepared with sand only and tire shreds only.

### 5.3 Effect of Tire Shred Size

Figure 16 compares the pullout resistances of samples prepared with different sizes of shredded tires. The sizes of shredded tires considered in this study were 9.5 mm in nominal size, 50-to-100 mm in length, and 100-to-200 mm in length. The results shown in Fig. 16 are for the average values of the length ranges, i.e., 75 and 150 mm for the 50–100 mm and 100–200 length size ranges, respectively.

The effect of size of tire shred on the pullout resistance of the geogrid tested was not significant for



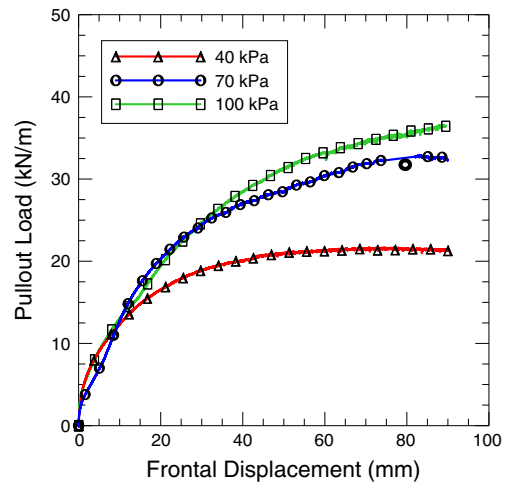
**Fig. 12** Pullout force versus frontal displacement (mixtures of sand and tire chips 9.5 mm nominal size). **a** Mixtures with 12 % tire chips by weight. **b** Mixtures with 25 % tire chips by weight. **c** Mixtures with 100 % tire chips by weight

**Fig. 13** Pullout force versus frontal displacement (mixtures of sand and tire shreds 50–100 mm in length). **a** Mixtures with 12 % tire shreds by weight. **b** Mixtures with 25 % tire shreds by weight. **c** Mixtures with 100 % tire shreds by weight

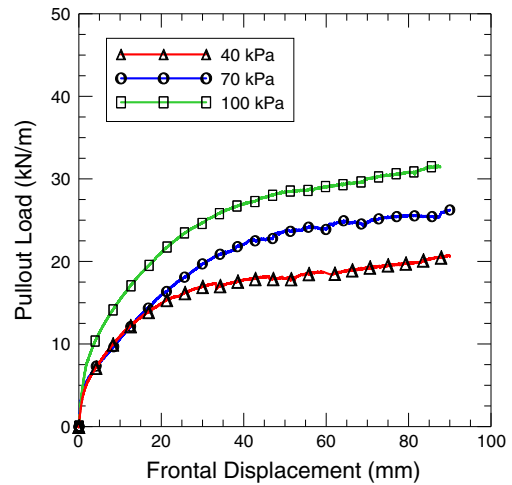
mixtures prepared either at low or high tire shred contents (12/88 or 100/0 mixtures by weight of tire shreds to sand) (see Fig. 16a, c) indicating that: (1) for the 12/88 mix, the pullout behavior of geogrid is controlled by the predominant component in the mixture (sand); and (2) for the 100/0 mix, the pullout resistance is independent of the size of the tire shreds. However, the size of the tire shreds had an effect on the pullout resistance for the 25/75 (by weight of tire shreds to sand) mixture, as shown in Fig. 16b. For the 25/75 mix, the geogrid pullout resistance decreases with increasing tire shred size. There might be two reasons for this: (1) higher sand-matrix unit weights were achieved for mixtures prepared with 9.5 mm tire chips and 50–100 mm tire shreds because compaction was more effective in mixtures with 9.5 mm tire chips and 50–100 mm tire shreds than that for mixtures with 100–200 mm tire shred size (see Table 4); and (2) higher passive resistance may have developed as a result of interlocking of the smaller tire chips and 50–100 mm tire shreds within and around the geogrid openings (9.5-mm-size tire chips and 50–100 mm tire shreds can much more easily wedge against the apertures of the geogrid than larger tire shreds). The geogrid openings were 17 mm × 445 mm in size, and hence the smaller size tire shreds present in the mixtures may have been able to more effectively wedge against the transverse ribs of the geogrid.

### 5.4 Effect of Tire Shred–Sand Mixing Ratio

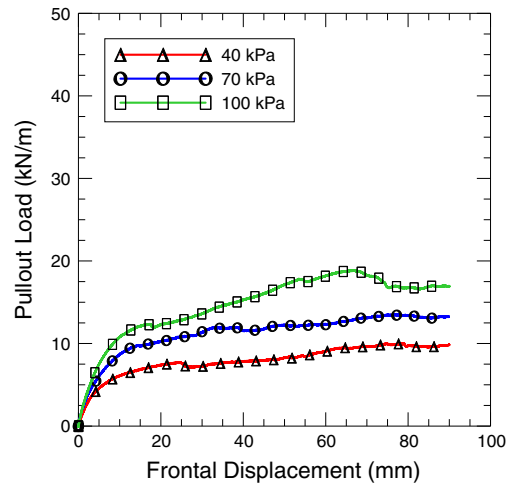
Figure 17 shows the pullout resistance of geogrids embedded in samples prepared with various tire shred-to-sand mixing ratios and subjected to three different confining pressures. The pullout resistance was greatest for geogrid embedded in samples prepared with sand only and lowest for those embedded in samples prepared with tire shreds only. The pullout resistance of geogrid increases with decreasing tire shred content (increasing sand content) in the mixtures. For



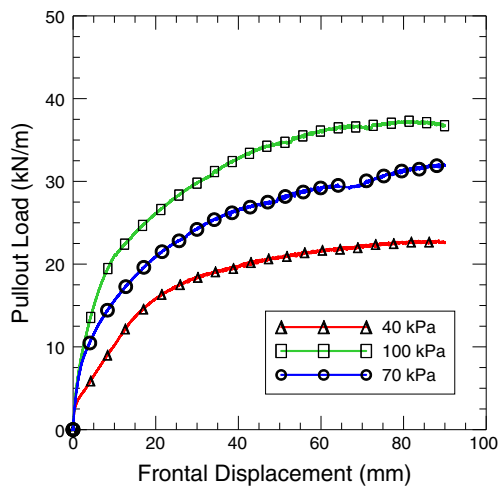
(a)



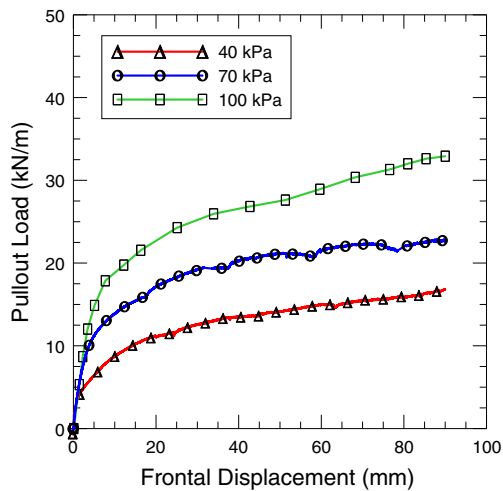
(b)



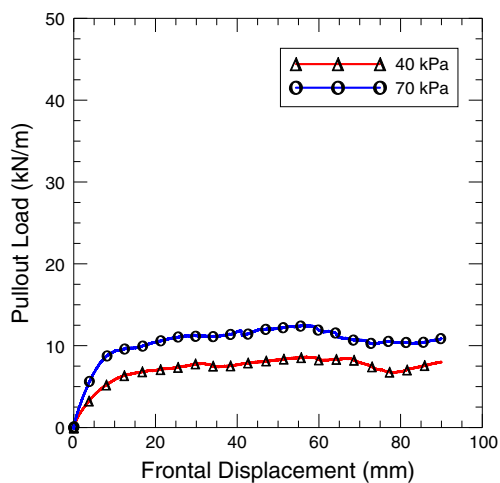
(c)



(a)



(b)



(c)

◀ **Fig. 14** Pullout force versus frontal displacement (mixtures of sand and tire shreds 100–200 mm in length). **a** Mixtures with 12 % tire shreds by weight. **b** Mixtures with 25 % tire shreds by weight. **c** Mixtures with 100 % tire shreds by weight

example, at a confining pressure of 70 kPa and for tire shreds 50-to-100 mm in length, the pullout resistance of geogrids placed in 25/75 and 12/88 mixtures (by weight of tire shreds to sand) was 1.94 and 2.32 times that of the pullout resistance of geogrid embedded in samples prepared with tire shreds only. This is due to the fact that sand particles fill the voids between the tire shreds, contributing to the increased geogrid pullout resistance.

Youwai et al. (2004) and Tanchaisawat et al. (2010) reported end-of-test pullout resistance values of 22–53 kN/m for hexagonal wire reinforcement (aperture size = 80 mm × 100 mm) and 25–75 kN/m for geogrid reinforcements (aperture sizes = 15 mm × 15 mm and 25 mm × 30 mm) embedded in 30/70 mixtures (by weight of tire shreds to sand) and subjected to confining pressures up to 100 kPa. The tire shred size considered in their study ranged from 5 to 80 mm. For similar test conditions, the pullout resistance of the geogrid tested in the present study was lower (20–30 kN/m), possibly due to differences in aperture configuration (size = 17 mm × 445 mm) and pullout resistance definition (end-of-test vs. front-end displacement equal to 50 mm).

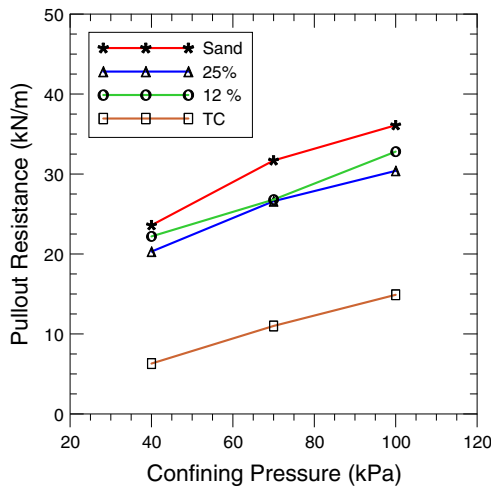
## 6 Geogrid Pullout Resistance Factors

In the design of MSE structures, it is essential to estimate the pullout resistance factor  $F^*$  between the reinforcement and the backfill material. For a known value of  $F^*$ , the pullout resistance of the reinforcement per unit width can be estimated using (Elias et al. 2001):

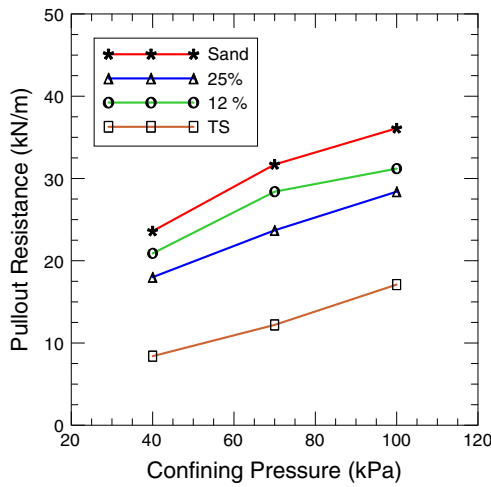
$$P_r = F^* \alpha \sigma'_v L_e C \quad (2)$$

where  $P_r$  is the pullout resistance of the reinforcement,  $F^*$  is the pullout resistance factor,  $\alpha$  is a correction factor to account for nonlinear shear stress mobilized along the embedded length of the reinforcement,  $\sigma'_v$  is the vertical effective stress at the reinforcement-soil interface,  $L_e$  is the embedded length of the reinforcement in the resisting zone, and  $C$  is the effective unit perimeter of the reinforcement. The correction factor

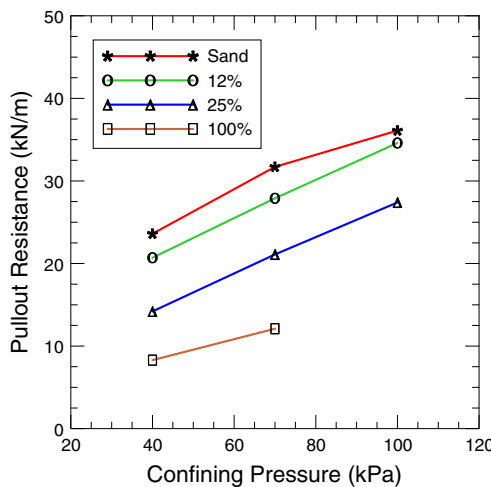




(a)



(b)



(c)

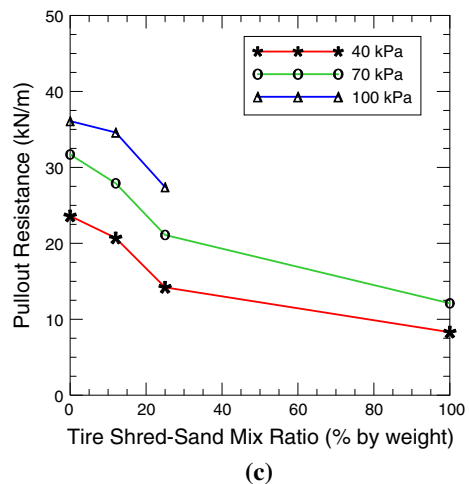
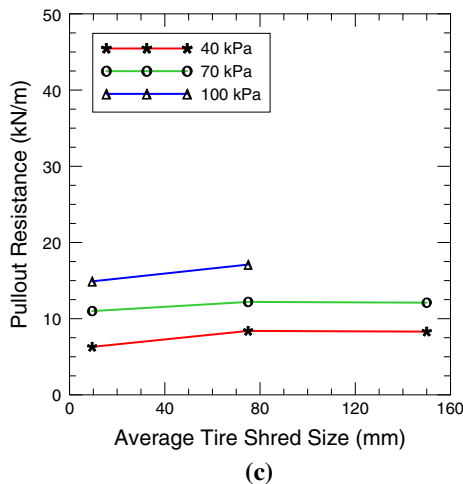
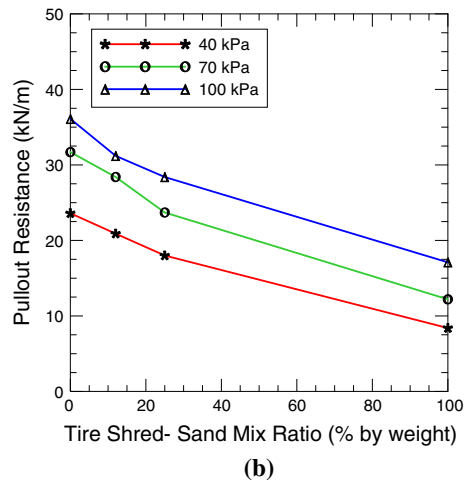
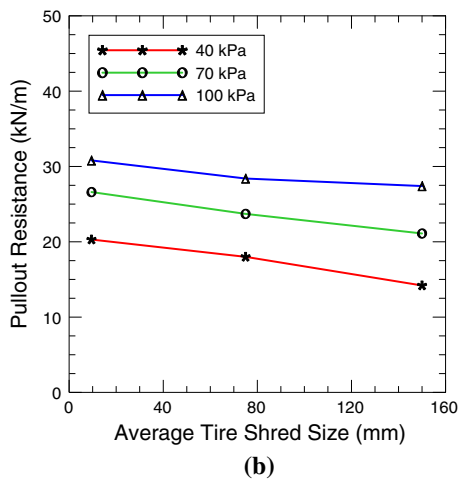
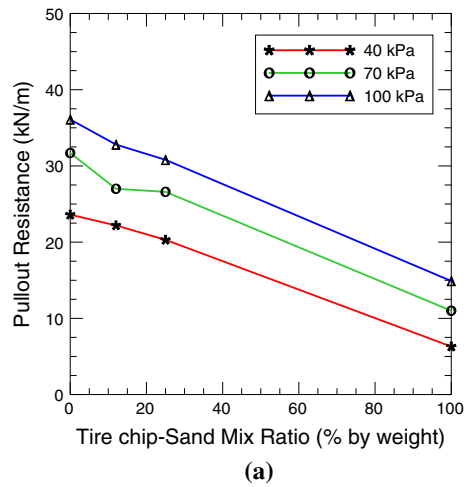
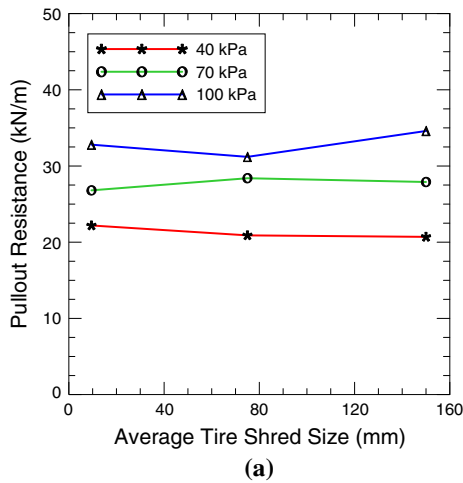
◀ **Fig. 15** Geogrid pullout resistance of mixtures prepared with various mixing ratios and confining stresses. **a** Tire chips. **b** Tire shreds 50–100 mm in length. **c** Tire shreds 100–200 mm in length

$\alpha$  varies from 0.6 to 1.0 for extensible reinforcements. Elias et al. (2001) recommended using a value equal to 0.8 for geogrids. Table 5 provides the pullout resistances and the pullout resistance factors  $F^*$  for geogrid embedded in sand only ( $F^* = 0.3$  to  $0.49$ ) and tire shred–sand mixtures ( $F^* = 0.12$  to  $0.44$ ) for all the tests performed in this study.

### 7 Summary and Conclusions

This paper present the results of large-scale pullout tests performed to evaluate the pullout response of geogrid embedded in tire shred–sand mixtures. The following summarizes the main components of and the conclusions drawn from the testing program:

1. The optimum mixing ratio of a given tire shred–sand mixture, which can be obtained from the results of compaction tests, is the mixing ratio at which addition of more sand to the mixture leads to an increase in the total void ratio of the mixture. The optimum mixing ratio for the mixtures considered in this study ranged from 25 to 30 % (by weight) (42 to 49 % by volume) of tire shreds in the mixture.
2. Pullout tests were performed for various tire shred–sand mixtures prepared at various mixing ratios (0, 12, 25 and 100 %). The mixtures consisted of shredded tires (9.5 mm in nominal size, 50–100 mm in length and 100–200 mm in length) and Ottawa sand. The pullout tests were performed for three different confining pressures (40, 70 and 100 kPa). Based on the test results, the effects of confining pressure, tire shred size, and mixing ratio are: (1) the pullout resistance of geogrid decreases with increasing tire shred content (decreasing sand content) in the mixtures, (2) the pullout resistance of the geogrid embedded in the sample prepared using only tire shreds was significantly lower (by a factor greater than 50 %) than for sand only, (3) the size of the tire shreds did not affect the geogrid pullout resistance at either low or high tire-shred contents (12 or



**Fig. 16** Geogrid pullout resistance versus shredded tire size of tire shred–sand mixtures. **a** 12 % shredded tire mixture (by weight). **b** 25 % shredded tire mixture (by weight). **c** 100 % shredded tire mixture (by weight)

**Fig. 17** Geogrid pullout resistance versus tire shred–sand mixing ratio. **a** Tire chips (9.5 mm in size). **b** Tire shreds (50–100 mm in length). **c** Tire shreds (100–200 mm in length)

**Table 5** Summary of geogrid pullout resistances

Size of shredded tires	Tire shred:sand ratio (by weight)	Confining pressure (kPa)	Pullout resistance <sup>a</sup> (kN/m)	Pullout resistance factor
Ottawa sand	0/100	40	23.6	0.49
		70	31.7	0.38
		100	36.1	0.30
9.5 mm nominal size	12/88	40	22.2	0.46
		70	26.8	0.32
		100	32.8	0.27
	25/75	40	20.3	0.42
		70	26.6	0.32
		100	30.4	0.25
	100/0	40	6.3	0.13
		70	11.0	0.13
		100	14.9	0.12
50–100 mm in length	12/88	40	20.9	0.44
		70	28.4	0.34
		100	31.2	0.26
	25/75	40	18.0	0.38
		70	23.7	0.28
		100	28.4	0.24
	100/0	40	8.4	0.18
		70	12.2	0.15
		100	17.1	0.14
100–200 mm in length	12/88	40	20.7	0.43
		70	27.9	0.33
		100	34.6	0.29
	25/75	40	14.2	0.30
		70	21.1	0.25
		100	27.4	0.23
	100/0	40	8.3	0.17
		70	12.1	0.14
		100	<sup>b</sup>	<sup>b</sup>

<sup>a</sup> Pullout resistance is taken as the pullout load corresponding to geogrid front-end displacement of 50 mm

<sup>b</sup> Pullout test for geogrid placed in only tires (100–200 mm in length) and at confining pressure of 100 kPa was not performed due to significant compression of the sample which could damage the rubber air bag during its inflation

100 %, by weight of tire shreds); however, for mixtures with 25 % tire shred content by weight, greater pullout resistance was observed for geogrids embedded in tire chip–sand mixtures than in tire shred–sand mixtures. For instance, when the samples were subjected to a confining pressure of 40 kPa, the pullout resistance of geogrid placed in tire chip–sand mixtures was 11 and 30 % higher than for tire shred–sand mixtures prepared

with tire shred sizes of 50-to-100 and 100-to-200 mm, respectively.

- Pullout resistance factors needed for the design of geogrid-reinforced earth structures with tire shred–sand mixtures as the backfill material were proposed based on the results of tests performed in this study. The pullout resistance factors of geogrid placed in sand only ranged from 0.30 to 0.49, whereas, for tire shred–sand mixtures, this

factor ranged from 0.26 to 0.46, 0.23–0.42, and 0.12–0.18 for the 12/88, 25/75 and 100/0 mix, respectively.

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