Effect of Tire-Derived Aggregate (TDA) Content On the Shear Strength Parameters of Gravel-TDA Mixtures

Ali Iranikhah, Hany El Naggar
Department of Civil and Resource Engineering,
Dalhousie University, Halifax, Nova Scotia, Canada

ABSTRACT

The principal objective of this research was to investigate the shear strength parameters of different mixtures of gravel-tire derived aggregates (TDA) for use in civil engineering applications. Also, volumetric change data were obtained to find the deformability and compressibility behavior of the mixtures. The tests were performed using a large-scale direct shear box apparatus. First, gravel was tested alone. Then, TDA was mixed with gravel in random orientations from 0 to 100% by weight. In total, eight samples (GT0, GT5, GT10, GT20, GT25, GT40, GT50, and GT100) were prepared and tested at three normal stresses (50.1, 98.8 and 196.4 kPa). Then, Mohr-Coulomb failure envelopes were drawn for all specimens, and the angle of internal friction and cohesion were determined. The results were compared to find the optimum TDA content and stress-strain behavior of the mixtures. It was observed that mixing TDA content up to 25% by weight with gravel did not change the shear strength of the mixtures significantly, and the internal friction angle was reduced slightly from 44 to 42º (about 5% reduction). However, the apparent cohesion had a sharp decrease from 25 to 15 kPa (about 67% reduction). By mixing more than 25% TDA content with the gravel, the internal friction angle dropped sharply from 42 to 30º (about 40% reduction). Moreover, it was observed that the increase in TDA content reduced the density and increased the compressibility behavior of the mixtures. Likewise, the addition of TDA content increased the mixtures ultimate strain allowing to accommodate greater strain before failure.

RÉSUMÉ

L'étude des paramètres de résistance au cisaillement de nombreux mélanges d'agrégat dérivés de pneus (TDA) était l'objectif principal de ce travail de recherche pour les différentes applications en génie civil. De plus, les données de changement volumétrique ont été obtenues pour se renseigner sur la déformabilité et la compressibilité de ces mélanges. Les essais ont été réalisé à la grande boîte de cisaillement directe. Au préalable, le test a été réalisé sur le gravier, puis sur le mélange du TDA avec du gravier orienté aléatoirement de 0 à 100% en poids. En total, neuf le échantillons (GT0, GT5, GT10, GT20, GT25, GT40, GT50 et GT100) ont été réalisés et testés à trois contraintes normales (50.1, 98.8 et 196.4 kPa). Ensuite, les enveloppes de rupture de Mohr-Coloumb ont été dessinées pour déterminer l'angle de frottement interne et la cohésion pour tous les mélanges. Les résultats ont été comparés pour trouver la teneur optimale en TDA ainsi que le comportement contrainte-déformation des mélanges. Il a été observé que le mélange de TDA jusqu'à 25% en poids avec du gravier ne change pas significativement la résistance au cisaillement du gravier et que l'angle de frottement interne diminue légèrement de 44 à 42º (réduction d'environ 5%). Cependant, la cohésion apparente diminue fortement de 25 à 15 kPa (réduction d'environ 67%). Ensuite, en mélangeant plus de 25% de TDA avec le gravier, l'angle de frottement interne se réduit brusquement de 42 à 30º (réduction d'environ 40%). Par ailleurs, il a été observé que l'augmentation de la teneur en TDA réduit la densité et augmente la compressibilité du mélange. De plus, l'addition de TDA augmente le durcissement du mélange et l'échantillon subit une déformation plus élevée sans être défaillant.

1 INTRODUCTION

The growth of tire production in the world requires us to pay more attention to their safe and sustainable disposal after they are discarded. Since used tires are bulky, they occupy huge spaces in landfills, causing many problems. For instance, during rainy seasons, tire stockpiles collect a lot of rainwater. This water usually hosts many insects such as mosquitoes that can transfer dangerous diseases like encephalitis to humans. Also, there is a potential risk of fire from stockpiled tires (Cecich et al. 2016). Over 500 million scrap tires are stockpiled in the United States, while about 28 million are annually stockpiled in Canada (Edinçliler et al., 2010). In the US, only about 22% of the discarded tires are recycled and reused in different applications, and the rest end up in landfills and illegal dumps (Cecich et al. 2016).

Two most common products of used tires are tire-derived fuel (TDF) and tire-derived aggregate (TDA). TDA is produced from discarded tires by shredding them into small pieces and then commonly used in civil engineering applications. Some countries like Canada and US promote the use of TDA in civil engineering applications. In Canada, all provinces with tire recycling programs are banning disposal of discarded tires in landfills. For example, 6.3 million scrap tires were recovered from landfills in Nova Scotia (Pehlken and Essadiqi 2005).

Tire shreds are named based on their size and shredding techniques. Tire particles with sizes ranging from 50 to 305 mm are named tire shreds and from 12 to 50 mm are called tire chips. These two sizes are known as tire-derived aggregate (TDA). Tire particles less than 12 mm is called granular or crumb rubber (Strenk et al. 2007).

TDA and soil-TDA mixtures can be used as lightweight embankment fill, retaining wall backfill, drainage layers for landfills, roads, among several other civil engineering applications. Up to three-meter-thick fill of TDA material can be used without experiencing any internal heating problem (ASTM D6270-17 2017). According to Xiao et al. (2012) and Ahn and Cheng (2014), TDA shows a softer response than conventional aggregates to dynamic earthquake pressures and tolerates larger residual deformations without significant failure.

When tire sherds are mixed with soil, their weakness regarding high compressibility and deformability, as well as self-heating problem is reduced (Jamshidi Chenari et al. 2017).

El Naggar et al. (2016) conducted a series of large-scale direct shear box test (box dimension: 430 mm ^{x} 280 mm, and height: 230 mm) to find the effect of gradation of TDA on shear strength properties of sand-TDA mixtures. Three sizes of TDA (dust, medium and coarse) were chosen, and then TDA with different gradation was mixed with sand at 15, 25, 50 and 100 % by volume. Each composition was tested at maximum dry density under three normal stress levels (50, 100, 150 kPa). El Naggar et al., (2016) found that the additional TDA in the sand leads to the early start of nonlinearity behavior of the mixture. Also, they found that 15 % TDA content (25% dust, 25% medium and 50% coarse) or (100% coarse) performs better in terms of shear strength than other sand-TDA compositions and that the 15% TDA content increases the internal friction angle by a range of 3-6.5º. In addition, they noted that sand-TDA mixtures show strain-hardening behavior and by applying more confining pressure, the stiffness of the mixture increases.

Another study was performed by Akbulut et al. (2007) to find the strength and dynamic behavior of the clayey soil mixed with randomly oriented scrap tire or synthetic fibers. They used a small-scale shear box (ring diameter: 60 mm and height: 35 mm) and noticed that adding waste tires to clayey soil enhances the shear strength properties of the soil. Tire shred length and content were found to be the main factors influencing the shear strength of the mixture. Akbulut et al., (2007) also observed that adding 2% tire shred with 10 mm length to the soil results in the highest shear strength among the mixtures.

Tatlisoz et al. (1998) conducted a series of large-scale direct shear box test (ring diameter: 280 mm and height: 300 mm) to find the mechanical properties of clean sand and silty sand mixed with tire chips ranging from 30-110 mm. They applied three normal stresses under 50 kPa and observed that 30% TDA content by volume is the optimum percentage of the mixtures. Moreover, adding more than 30% TDA content reduces the shear strength properties of the mixtures. They mentioned that this reduction is due to the separation of the TDA from the soil which leads to a weaker soil-TDA composition.

Wu et al. (1997) carried out triaxial tests on soil samples containing tire shred under 40 mm length and recorded the internal friction angle of 40º for tire chips.

Foose et al., (1996) carried out a series of large-scale direct shear test (ring diameter: 279 mm, and height: 275 mm) to find the effect of normal stress, sand matrix unit weight, shred content, length, and orientation in sand-TDA mixtures. Also, they used a theoretical model based on Maher & Gray, (1991) to predict the behavior of the mixtures at different TDA content. Foose et al., (1996) used three size groups of TDA (<5 cm, 5-10 cm, and 10-15 cm) and mixed each of them with sand at different percentages by volume. They applied normal stresses ranging from 7 to 70 kPa to each sample while shearing at a rate of 0.13 cm/min. They found that shred content, density, and normal stress are the key factors affecting the shear strength behavior of the sample. They also observed that the addition of TDA to sand increases the internal friction angle up to 67º and that the compaction level effects the stress-strain behavior. Their results indicate the internal friction angle of 30º and cohesion of 3 kPa for tire shred only. Also, the parametric study verified the results of the internal friction angle by only 2º difference in most cases.

Humphrey and Sandford (1993) conducted a series of large-scale direct shear tests on tire chips from three different suppliers. They measured an effective internal friction angle ranging from 19 to 25º and cohesion between 4.3 and 11.5 kPa.

Another study was conducted by Ahmed (1993) to determine the strength and compressibility behaviors of rubber-sand mixtures. He reported that with chip/mix ratio of 38% or less, the rubber-sand mixture shows low compressibility and dry density while high strength and drainage behavior.

The effect of tire shred and fiber reinforcement on the shear strength properties and stress-strain behavior of reinforced sand was studied by Gray and Ohashi (1983). They conducted a theoretical prediction and small-scale direct shear test and found that factors influencing the shear strength are: concentration and area ratio of fiber (upper limit 1.7% across the shear plane) and the fiber orientation (upper limit 60º with respect to the shear surface). Also, they noted that the compaction level does not affect the shear strength of reinforced sand.

Environmental impact of TDA on groundwater quality was studied by Humphrey et al. (1997). They conducted two field trial using control wells study to find the effect of the TDA on the level of natural substances in groundwater like aluminum and zinc. Except for higher concentration of Manganese (Mn) and iron (Fe) leached from TDA to water, no other increase was observed to affect the secondary drinking water standard.

All above research confirm that TDA can be a great replacement for conventional aggregates. On one hand, it improves the shear strength behavior of the soil. On the other hand, it is a sustainable and environmentally friendly solution to getting rid of the huge stockpile of discarded tires.

Several studies have been carried out in the past to find the effect of TDA on the shear strength behavior of fine-grained soils. However, limited studies have been conducted on gravel-TDA mixtures. Therefore, this experimental work was carried out to find the effect of randomly oriented TDA on the shear strength and geotechnical behavior of gravelly soils.

The primary objective of this study was to investigate the shear strength properties and deformation behavior of the randomly oriented TDA mixed with gravel and find the optimum TDA content. Also, volumetric change data were obtained to determine the effect of TDA content on the compressibility behavior of gravel-TDA mixtures. Another objective was to analyze the stress-strain behavior of the mixtures at different strain and confining pressures. Hence, a series of large-scale direct shear box tests were performed on gravel-TDA mixtures.

2 MATERIALS

In this study, TDA as a recycled aggregate was replaced with gravel at different percentages by weight. Physical Characteristics of the TDA and gravel are described below.

2.1 TDA

Tire-derived aggregates (TDA) are pieces of shredded tires and mostly consist of synthetic rubber combined with steel belts. They are classified as type A with a maximum dimension of 200 mm in any direction and type B with a maximum dimension of 450 mm in any direction or 300 mm for at least 90% of the sample by weight (ASTM D6270-17 2017). The TDA sample used in this study were type A and were shredded and processed by Halifax C&D recycling Ltd located in Enfield, Nova Scotia (see Figure 1). Since the shear box width was limited to 305 mm, particles larger than 75 mm were removed from the sample. Therefore, the maximum particle size was limited to one-fourth of the shear box length to eliminate boundary and size effects (Humphrey and Sandford 1993). Due to TDA particles were flat and elongated, their length was measured using a ruler. Also, according to El Naggar et al. (2016), particle size characterization of TDA makes them unsuitable for sieve analysis.

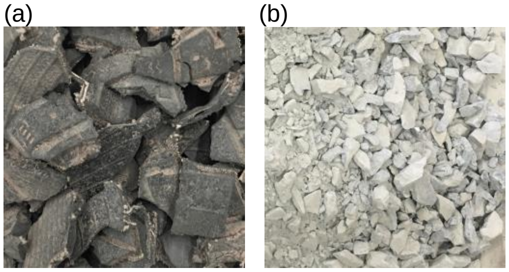


Figure 1. Picture of the aggregates: (a) TDA; (b) Gravel

A TDA sample was randomly selected and measured in all directions. Figure 2 shows the histogram of the TDA for length ranging from 0-10 mm, 10-20 mm, 20-30 mm, 30-40 mm, 40-50 mm, 50-60 mm, 60-70 mm and 70-75 mm. The aspect ratio (length/width) which is one of the main physical properties of TDA was measured 2.8 for the range of the TDA sample. Also, the whole sample had an average thickness of about 8.9 mm. The dry unit weight of the TDA was measured in accordance with standard test method ASTM D698 (2016). According to Humphrey and Sandford (1993), the compaction energy has a negligible effect on the density of the TDA, and hence they used 60% of standard proctor energy. Similarly, water content of TDA has a negligible effect on its dry density, and therefore the compaction test for TDA was performed on the air-dry sample (Cecich et al. 2016; ASTM D6270-17 2017). Table 1 shows the physical properties of the TDA. According to ASTM D6270-17 (2017), in order to maximize the rubber-to-rubber contact, the amount of exposed steel belts needs to be limited. Hence, in this study, the exposed wires were removed with a scissor.

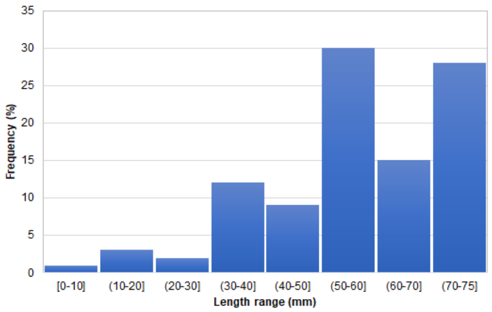


Figure 2. Histogram of the TDA size

Table 1. Characteristic of the TDA

Characteristics	Value
Optimum water content, ω (%)	0
Maximum dry density, γ_{m} $(\mathrm{kg}/\mathrm{m}^3)$	723
Average thickness (mm)	8.9
Average Aspect ratio	2.8

2.2 Gravel

A relatively uniform gravel was taken from a local supplier for use in this study (see Figure 1). Grain size analysis was performed according to (ASTM D422 2007). Figure 3 shows the gradation curve for the gravel. Also, laboratory compaction test with standard effort (ASTM D698 2016) was performed to measure the maximum dry density and optimum water content of the sample. Table 2 presents the physical properties of the gravel. According to the unified soil classification system (ASTM D2487-11 2011), it was classified as well-graded gravel with sand.

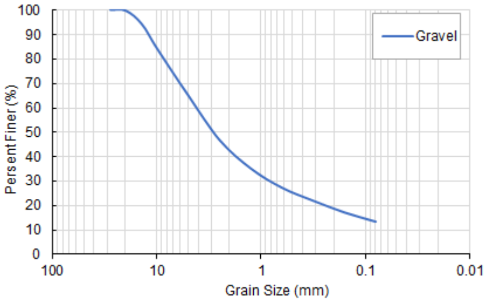


Figure 3. Gradation curves of the gravel

Table 2. Characteristic of the gravel

Characteristics of gravel	Value
D_{10} (mm)[1]	0.07
D_{30} (mm)[1]	0.80
D_{50} (mm)[1]	3.00
D_{60} (mm)[1]	4.50
Coefficient of uniformity, C_u[2]	64.29
Coefficient of curvature, C_C[2]	2.03
Optimum water content, ω (%)	7.50
Maximum dry density, γ_m (kg / m^3)	1954

[1] D_{10} , D_{30}, D_{50} and D_{60} are the diameter of the aggregates at where the sample is finer than 10, 30, 50 and 60% respectively

[2] $C_u = \frac{D_{60}}{D_{10}} \cdot C_C = \frac{D_{30}^2}{D_{10} * D_{60}}$

3 METHODOLOGY

In this study, a large-scale direct shear box apparatus was used to investigate the shear strength properties of the considered gravel-TDA mixtures. Since in a field condition, tire shreds are mainly mixed with soil in random orientation, hence in this study, the effect of orientation was not considered. Also, the mixtures were compacted with maximum standard effort. The tests were conducted on the mixtures with different TDA content by weight at different confining pressures. At first, tests were started by finding the shear strength properties of the gravel alone and then TDA was replaced with the gravel in the mixtures from 0 to 100% by weight. Table 3 lists all the samples by name, particle content and dry unit weight.

Table 3. Mixture properties

Mixture	TDA % (by weight)	Gravel % (by weight)	Dry Unit Weight, γ ($^{kN}/_{m^3}$)
GT0	0	100	17.4
GT05	5	95	17.2
GT10	10	90	16.1
GT20	20	80	14.2
GT25	25	75	13.1
GT40	40	60	9.8
GT50	50	50	9.0
GT100	100	0	6.4

4 EXPERIMENTAL SETUP AND PROCEDURES

A large-scale direct shear apparatus with a square mold was used to conduct shear tests on gravel-TDA mixtures. The device was customized to accommodate a high compressibility of the TDA and gravel-TDA samples. The tests were performed according to the standard test procedure in ASTM D3080 (2012). Figure 4 shows the large-scale direct shear box apparatus used in this study. The apparatus consists of 305 mm square box (nominal dimension) made from steel 9-mm thick. According to ASTM D3080 (2012), the maximum particle size of aggregates needs to be ten times smaller than the length of the shear box to eliminate boundary effects. Humphrey and Sandford (1993) suggested that for larger particles like TDA, tests can be performed with particles that are four times smaller than the shear box length and therefore boundary effect will be insignificant. The largest particle size in this study was 75 mm, and it was adequate. The lower half of the box was 90-mm high and was seated on a movable base. The upper half of the box was 80-mm high. An extension was made and mounted on top of the upper half with 50-mm high, and therefore the final height of the box reached 220 mm to accommodate the large compressibility of the TDA and gravel-TDA mixtures. The upper half of the box was fixed while the lower half was able to move with an electric motor. A load cell with an LVDT was mounted to measure the shear force. Also, two LVDTs were installed to monitor the horizontal and vertical displacements of the box during shearing; One, on top of the box contacting a steel plate over the sample to measure the vertical deformation and the other one was installed horizontally contacting the lower half to measure the lateral displacement. In addition, all LVDTs were connected to a data acquisition system (CAMPBELL SCIENTIFIC CR200 Series), and data were collected and monitored using a personal computer. All tests were performed in a strain-controlled condition while the shear force, horizontal displacement and vertical deformation were recorded up to a total displacement of 43 mm or strain of about 14%, at a shearing rate of 0.5 mm/min.

Figure 4. The large-scale direct shear box apparatus

5 ANALYSIS AND DISCUSSION OF THE RESULTS

Shear stress was calculated by dividing shear force by the horizontal cross-section area of the box (930.25 cm^2) and the shear strain was calculated by dividing the horizontal displacement by the length of the box (30.5 cm). According to Strenk et al. (2007), TDA is a strain-hardening material, and hence shear strength must be taken at 10% lateral displacement. Foose et al. (1996) chose shear stress at 9% strain when no peak shear stress was observed during the test. They noted that 9% strain is an optimum point where the greatest shear strength is achieved. In this study, failure was taken at peak shear stress. If no peak shear stress was obtained up to 14% strain (4.27-cm lateral displacement), 10% horizontal strain was taken as the shear stress at failure (ASTM D3080 2012)

Figure 5 to Figure 7 illustrate the variation of shear stress with horizontal strain for gravel-TDA mixtures at three confining pressures (50.1, 98.8 and 196.4 kPa). As shown in Figure 5 and Figure 6, the shear stress reached the peak and then dropped to a residual level for 100% gravel (GT0). By adding more TDA content to the gravel, the peak shear stress shifted to the right and decreased. Then for mixtures containing more than 40% TDA content by weight, no peak shear stress was obtained up to 14% horizontal strain. A similar observation was seen at 196.4 kPa confining pressure; however, at 196.4 kPa confinement, by adding more than 20% TDA content by weight to gravel, no peak shear stress was gained up to 14% strain. Hence, the addition of TDA content to gravel increases the deformability behavior of the mixtures to a higher strain before experiencing any failure. In other words, the mixtures show strain-hardening behavior without no pronounced peak stress on the stress-strain curves.

As indicated before, confining pressure is an important factor affecting the shear strength behavior of the mixtures. It was observed that at higher confining pressure, the mixtures experienced higher shear stress.

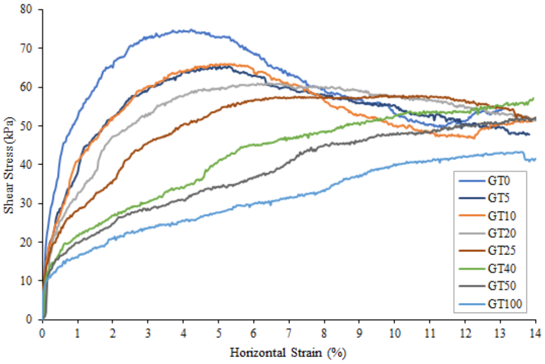


Figure 5. Shear stress vs. Horizontal strain graph for gravel-TDA mixtures at 50.1 kPa confining pressure

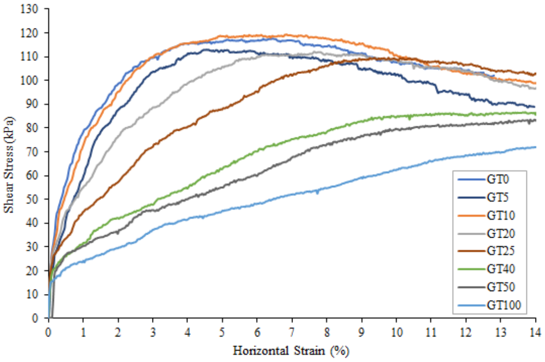


Figure 6. Shear stress vs. Horizontal strain graph for gravel-TDA mixtures at 98.8 kPa confining pressure

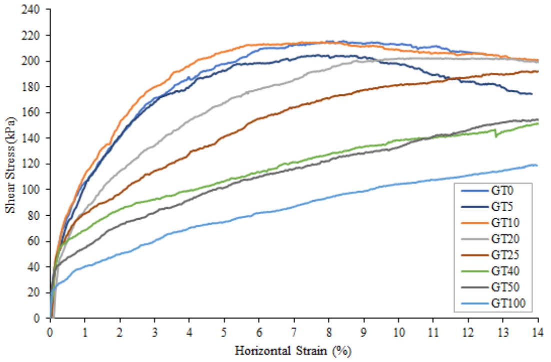


Figure 7. Shear stress vs. Horizontal strain graph for gravel-TDA mixtures at 196.4 kPa confining pressure

Figure 8 to Figure 10 show vertical deformation versus horizontal displacement curve for gravel-TDA mixtures. It is seen that samples were initially compressed and then dilated upon shearing. At 50.1 and 98.8 kPa confining pressure, the amount of condensing was not considerable for samples containing lower TDA content; however, their dilation was significant upon shearing. The addition of TDA content to the mixture increased the compressibility behavior of the mixtures. The amount of compression was insignificant when the TDA content of the mixture was 25% or less. When the TDA content increased more than 25%, the mixture experienced a greater contraction upon shearing

These observations are supported by Ghazavi (2004) who performed shear box test, and Lee et al. (1999), who conducted a series of triaxial test on sand-rubber mixtures. They noticed that TDA-soil mixtures initially got smaller and then begun to dilate.

It should be noted that the amount of confining pressure influenced the vertical deformation of the mixtures. As shown in Figure 8 to Figure 10, the compressibility behavior of the mixture increased at higher confining pressure.

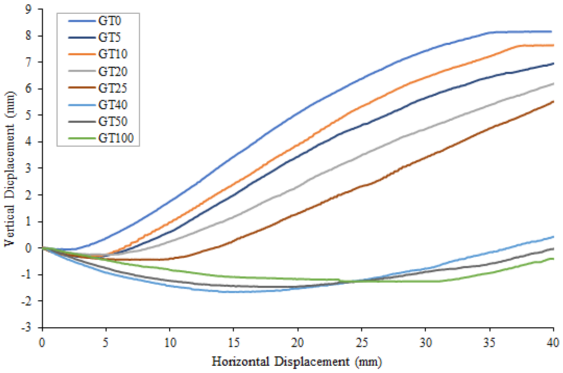


Figure 8. Vertical vs. Horizontal displacement graph for gravel-TDA mixtures at 50.1 kPa confining pressure

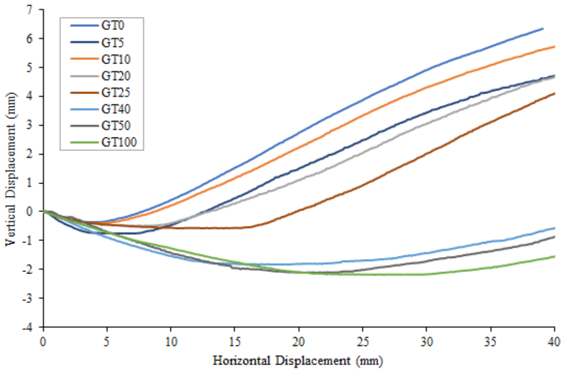


Figure 9. Vertical vs. Horizontal displacement graph for gravel-TDA mixtures at 98.8 kPa confining pressure

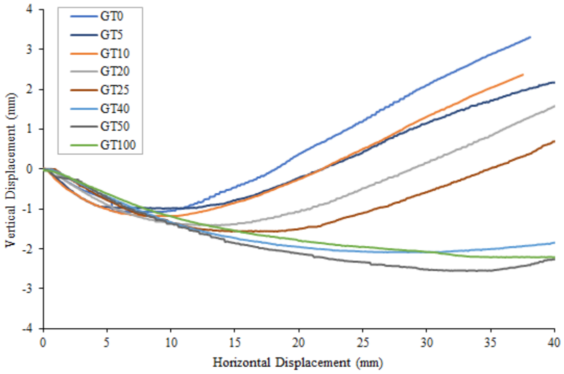


Figure 10. Vertical vs. Horizontal displacement graph for gravel-TDA mixtures at 196.4 kPa confining pressure.

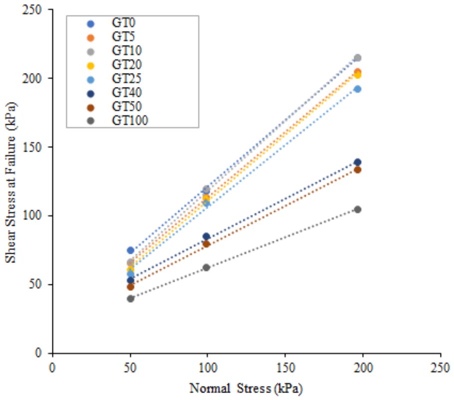


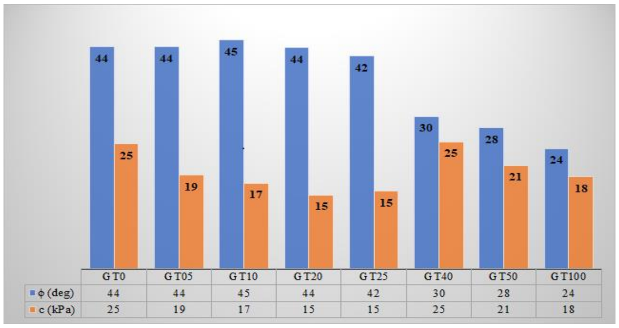
Figure 11. Mohr-Coloumb failure envelope for gravel-TDA mixtures

To draw failure envelopes, each mixture was tested at three confining pressure (50.1, 98.8, and 196.4 kPa) and shear stress at failure was determined. Figure 11 illustrates the failure envelopes for gravel-TDA mixtures. It is seen that by increasing the TDA content in the mixtures, the slope of the line, which represents the internal friction angle, decreased. Also, the Y-intercepts were all greater than zero representing the apparent cohesion. According to Ghazavi (2004), the apparent cohesion results from penetration of TDA into the soil. Furthermore, Strenk et al. (2007) noticed that confining pressure enhances the interlocking effect between soil and TDA particles and increases the apparent cohesion.

As shown in Figure 11, the variation of shear stress with confining pressure was linear for gravel-TDA mixtures. This finding contradicts the results of Foose et al. (1996), Gray and Ohashi (1983), Maher and Gray (1991) at which the failure envelope for sand-tire shred mixtures is none linear. However, it is worth to mention that they conducted their tests mainly at low confining pressures.

5.1 Summary of the results

Figure 12 shows a summary of all gravel-TDA mixtures. It is seen that by adding TDA content up to 25% by weight to the gravel, the angle of internal friction did not change significantly and reduced about 5% only. However, apparent cohesion had a sharp decrease. It seems that, in the mixtures containing less than 25 % TDA content, the gravel particles were more dominant in the shear zone. Hence, the shear failure is similar to 100% gravel sample. Likewise, adding TDA content up to 25% increases the penetration of gravel particles into the TDA which decreases the apparent cohesion. Moreover, it was observed that increasing the percentage of the TDA in the sample reduced the dry unit weight of the mixtures. Therefore, gravel-TDA mixtures can be used as a lightweight material in civil engineering application. Also, due to the higher compressibility behavior of the gravel-TDA mixtures, their density changes significantly under different confining pressure. Hence, the design value for the dry unit weight needs to be taken based on the confining pressure applied to the soil-TDA mixture and overlying materials (Strenk et al. 2007). It should be noted that the internal friction angle of 24° and apparent cohesion of 18 kPa was observed for the TDA only.



	GT0	GT05	GT10	GT20	GT25	GT40	GT50	GT100
■ ϕ (deg)	44	44	45	44	42	30	28	24
■ c (kPa)	25	19	17	15	15	25	21	18

Figure 12. Summary of the results for gravel-TDA mixtures

6 REPEATABILITY

Some tests were randomly repeated three times to ensure the repeatability and accuracy of the results and to find any factor that may change and affect the consistency of the results.

7 CONCLUSION

A series of large-scale direct shear box tests were conducted on different gravel-TDA mixtures. TDA was replaced with gravel in all mixtures from 0 to 100% by weight. Shear strength parameters were calculated using Mohr-Coulomb failure criteria. It was obtained that the addition of 25% TDA by weight does not change the angle of internal friction significantly; however, cohesion tends to decrease sharply. Mixing more than 25% TDA with gravel decreases the friction angle sharply while increases the cohesion. Also, it was seen that mixing TDA with gravel reduces the dry unit weight of the sample.

According to this study, using gravel-TDA mixtures up to 25% by weight is quite promising and needs to be promoted in civil engineering applications. Using TDA creates a lightweight and cheap alternative, while helps to solve several environmental problems.

Further studies are needed to assess the feasibility of mixing TDA with gravel in the field and find the shear strength of the mixture in real condition. Also, the economic aspects of using gravel-TDA mixtures in civil engineering projects need to be highlighted to practicing engineers to promote its use.

8 ACKNOWLEDGMENT

The authors acknowledge the financial support provided by the Natural Sciences and Engineering Council of Canada (NSERC), and the generosity of our research collaborator Halifax C&D Recycling Limited for the donation of all the TDA materials used in this project. Also, our appreciation is extended to Divert NS who partially funded this research.

9 REFERENCES

Ahmed, Imtiaz. 1993. *Laboratory Study on Properties of Rubber-Soils*. http://docs.lib.purdue.edu/jtrp/1069.

Ahn, Il Sang, and Lijuan Cheng. 2014. "Tire Derived Aggregate for Retaining Wall Backfill under Earthquake Loading." *Construction and Building Materials* 57: 105–16.

Akbulut, Suat, Seracettin Arasan, and Ekrem Kalkan. 2007. "Modification of Clayey Soils Using Scrap Tire Rubber and Synthetic Fibers." *Applied Clay Science* 38(1–2): 23–32.

ASTM D2487-11. 2011. "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." *Annual Book of ASTM Standards*: 1–12.

ASTM D3080. 2012. "Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained." *Annual Book of ASTM Standards*: 1–9.

ASTM D422. 2007. "Standard Test Method for Particle-Size Analysis of Soils: ASTM D 422." *Annual Book of ASTM Standards* 63: 1–8.

ASTM D6270-17. 2017. "Standard Practice for Use of Scrap Tires in Civil Engineering Applications." *Annual Book of ASTM Standards* (Reapproved): 1–21.

ASTM D698. 2016. "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort." *Annual Book of ASTM Standards*: 1–13.

Cecich, Venessa et al. 2016. "Use of Shredded Tires As Lightweight Backfill MATERIAL FOR RETAINING STRUCTURES." *Waste Management & Research* 14: 433–51.

Edinçliler, Ayşe, Gökhan Baykal, and Altug Saygili. 2010. "Influence of Different Processing Techniques on the Mechanical Properties of Used Tires in Embankment Construction." *Waste Management* 30(6): 1073–80.

Foose, Gary J., Craig H. Benson, and Peter J. Bosscher. 1996. "Sand Reinforced with Shredded Waste Tires." *Journal of Geotechnical Engineering* 122(9): 760–67.

Ghazavi, M. 2004. "Shear Strength Characteristics of Sand Mixed with Granular Rubber." *Geotechnical and Geological Engineering* 22: 401–16.

Gray, Donald H., and Harukazu Ohashi. 1983. "Mechanics of Fiber Reinforcement in Sand." *Journal of Geotechnical Engineering* 109(3): 335–53.

Humphrey, Dana N., Lynn E. Katz, and Michael Blumenthal. 1997. "WATER QUALITY EFFECTS OF TIRE CHIP FILLS PLACED ABOVE THE GROUNDWATER TABLE." *Testing soil mixed with waste or recycled materials, ASTM STP 1275*: 299–313.

Humphrey, Dana N., and Thomas C. Sandford. 1993. "Tire Chips as Lightweight Subgrade Fill and Retaining Wall Backfill." *Symposium on Recovery and Effective Reuse of Discarded Materials and By- products for Construction of Highway Facilities* (207): 20.

Jamshidi Chenari, Reza, Behzad Fatahi, Mohammad Ali Akhavan Maroufi, and Reza Alaie. 2017. "An Experimental and Numerical Investigation into the Compressibility and Settlement of Sand Mixed with TDA." *Geotechnical and Geological Engineering* 35(5): 2401–20.

Lee, J. H., R. Salgado, A. Bernal, and C. W. Lovell. 1999. "SHREDDED TIRES AND RUBBER-SAND AS LIGHTWEIGHT BACKFILL By." *Journal of Geotechnical and Geoenvironmental Engineering* 125(2): 132–41.

Maher, Mohamad H., and Donald H. Gray. 1991. "STATIC RESPONSE OF SANDS REINFORCED WITH RANDOMLY DISTRIBUTED FIBERS." *Journal of Geotechnical Engineering* 116(11): 1661–77.

El Naggar, Hany, Pendar Soleimani, and Amirnezam Fakhroo. 2016. "Strength and Stiffness Properties of Green Lightweight Fill Mixtures." *Geotechnical and Geological Engineering* 34(3): 867–76.

Pehlken, Alexandra, and Elhachmi Essadiqi. 2005. "Scrap Tire Recycling in Canada." *CANMET Materials Technology Laboratory* 8.

Strenk, Patrick M. et al. 2007. "Variability and Scale-Dependency of Tire-Derived Aggregate." *Journal of Materials in Civil Engineering* 19(3): 233–41.

Tatlisoz, Nilay, Tuncer B. Edil, and Craig H. Benson. 1998. "Interaction between Reinforcing Geosynthetics and Soil-Tire Chip Mixtures." *Journal of Geotechnical and Geoenvironmental Engineering* 124(11): 1109–19.

Wu, Wei Y., Christopher C. Benda, and Robert F. Cauley.

1997. “Triaxial Determination of Shear Strength of Tire Chips.” *Journal of Geotechnical and Geoenvironmental Engineering* 123(5): 479–82.

Xiao, Ming, Jan Bowen, Mathew Graham, and Jesus Larralde. 2012. “Comparison of Seismic Responses of Geosynthetically Reinforced Walls with Tire-Derived Aggregates and Granular Backfills.” *Journal of Materials in Civil Engineering* 24(11): 1368–77.