Experimental Investigation for the Particle and Sample Size Effect on the Shear Strength Parameters of Tire Derived Aggregate (TDA)

by

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I dedicate my thesis to my whole family members; father, mother, brothers and especially for my beloved wife and best friend.

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ABSTRACT

Tire recycling and reuse in North America and worldwide have increased considerably, intending to reduce the harmful effects of scrap tires on the environment. Accordingly, the use of tire-derived aggregates (TDA) in civil engineering applications is on the rise at an unprecedented rate. TDA is often referred to as tire chips or tire shreds. In comparison to conventional backfill aggregates, TDA is an inexpensive, lightweight material that costs about 25% of the cost of conventional backfill. TDA has excellent geotechnical properties, maintains its structural integrity, and weighs 50–60% less than conventional earth fill. TDA has been successfully used in different civil engineering projects as a fill material in its pure state or mixed with soils in TDA-soil mixtures. Despite the superior geotechnical properties and successful applications of TDA, the size limitations between the available conventional laboratory testing equipment and the TDA particle sizes commonly used in practice are forcing the researchers and practitioners to conduct their tests on smaller TDA particle sizes rather than the actual sizes used in civil engineering applications. Moreover, several studies are conducted on TDA without due attention to the different sample sizes and their effect on the obtained results. So, the main focus of this research is to investigate the particle and sample size effects on the shear strength parameters of TDA using two commonly used test apparatuses, namely the direct shear and the triaxial.

Keywords: TDA, direct shear tests, triaxial tests, sample size effect, particle size effect, and shear strength parameters

LIST OF SYMBOLS AND ABBREVIATIONS USED

τ	Shear Stress
σ	Applied Normal Stress
φ'	Effective Angle of Internal Friction
c'	Effective Cohesion of Soil
γ	Unit Weight of Soil
E	Modulus of Elasticity
E_{50}	The Secant Modulus of Elasticity at 50%
G	Shear Modulus
G_{50}	The Secant Shear Modulus at 50%
μ	Poisson Ratio
Ø	Triaxial Cell Diameter
ε	Axial Strain
TDA	Tire Derived Aggregate
TDF	Tire Derived Fuel
TDP	Tire Derived Product

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CHAPTER 1 INTRODUCTION

1.1 General

Over 290 million tires are discarded each year in the United States and sent to stockpiles or landfills. This constitutes an environmental hazard by providing a breeding ground for mice, rats and insects. Besides, tires in stockpiles and landfills are considered a severe fire hazard because tires can catch fire easily and extinguishing a tire fire is difficult and may take months or even years (Cecich et al. 2016). Increased tire production worldwide has focused attention on the necessity for safe, sustainable disposal of scrap tires. Fortunately, 56% of the tires discarded in the USA are currently used as tire-derived fuel (TDF) by some factories. This reduces the burden of disposing of these tires. Around 7% of the scrap tires are used as retreads, and 24% are used in various civil engineering projects. Tire-derived aggregate (TDA) can be used for various purposes, including lightweight fill for road embankments, subgrade fill, engineered stress-reduction fill over pre-existing buried pipes or material for enhancing steep slopes along highways (Engstorm et al. 1994; Liu et al. 2000; Mahgoub and El Naggar. 2018)

Figure 1.1 Stockpiles of discarded tires in Western Victoria, Australia (Credits: United States Environmental Protection Agency

However, the statistics cited above are for the United States alone. In Alberta, Canada, more than five million scrap tires are disposed of each year, according to Alberta Recycling Management Authority (2013), and over 1 million scrap tires are generated in Nova Scotia yearly (Edinçliler et al., 2010). In addition, the number of scrap tires generated annually worldwide is increasing alarmingly and requires new solutions.

Further studies have determined that with the continued development of civil engineering applications, civil engineering projects have the potential to utilize large quantities of scrap tires. Moreover, the use of tire-derived aggregates in various projects has prompted more studies to evaluate the physical, chemical, mechanical, and shear strength properties of TDA so that they can be considered as a conventional construction material. The usage of TDA in civil engineering projects is due to its desirable geotechnical properties being light weight and free draining material and due to its excellent thermal properties.

Fortunately, TDA were used in several engineering projects as a pure material, TDA on its own, or mixed with different soil mixtures to enhance its properties. However, discarded tires in landfills or stockpiles cannot be used in civil engineering projects as they are, but they have to be shredded in smaller particle sizes. This process of shredding usually results in different ranges of particle sizes of shredded tires. Theses ranges were classified by ASTM D 6270 – 2008 into seven categories and one of the categories has two subcategories as shown in Table 1.1 below.

Table 1.1 ASTM D 6270 – 2008 classification of tire shreds

Category	**Subcategory**	**Size (mm)**
Powdered Rubber		<0.425 mm
Ground Rubber		0.425 – 2 mm
Granulated Rubber	-	0.425 – 12 mm
Tire Chips		12 – 50 mm
Tire Shreds		50 – 305 mm
Tire Derived Aggregate (TDA)	Type A - TDA	Around 75 – 100 mm with a maximum dimension 200 mm in any direction
	Type B - TDA	Around 150 – 305 mm maximum dimension 450 mm in any direction
Rough Shreds	-	Between 50 * 50 * 50 mm & 762 * 50 * 100 mm

In civil engineering projects, Tire shreds and TDA are used interchangeably with a difference in their particle size ranges as tire shreds ranges between 50 mm up to 305 mm and TDA is usually between 12 mm and up to 305 mm covering a higher range of particle sizes. This research will be focusing on Type A – TDA, with particle sizes ranging between 12 mm up to 100 mm.

The process of shredding tires to produce TDA is usually done by grinding, known as shredding, in which the tires are passed through shredders, in ambient temperatures, in order to be converted to smaller particles and if the resulted pieces need to be smaller in size they are passed through the shredder again till resulting in the desired particle size distribution. However, the grinding process could also be done in cryogenic temperatures in which tires are placed in liquid nitrogen, and their temperatures are brought down till they become a brittle material and then get crushed by mechanical hammers (Najim & Hall, 2010). The process of shredding tires often results in some protruding steel wires depending on how sharp the knives of the shredder are and these protruding steel wires were removed from all the sample, except for one sample, that were used in this research in order not puncture the triaxial member and this is considered one of the main difference between the TDA used in engineering projects, having protruding wires, and the TDA tested in laboratory testing.

In this research, the TDA used was brought from Halifax C&D Recycling Ltd and the shredding process of TDA was done by the conventional method of shredding tires, the tires through shredders in ambient temperatures till it reached the desirable particle size distribution between 12 mm up to 100 mm which is included in Type A – TDA from which six samples were made having a defined particle size distributions and a maximum particle size (D_{max}); 19.05, 38.1, 50.8, 76.2, 101.6 mm and a random sample having a D_{max} equal to 50.8 mm.

Figure 1.2 Halifax C&D Recycling Ltd shredded tires stockpiles

1.2 Research Objectives

The studies done on TDA to evaluate its shear strength parameters are relatively limited compared to conventional soils, and for geotechnical engineers to use TDA in civil engineering projects, more research should be achieved in order to cover all the aspects related to TDA. One of the main aspects that stands as a barrier between researchers and the TDA used in real projects is that TDA used in real projects is large compared to conventional soil testing equipment like direct shear and triaxial tests as the recommended ratio between the maximum particle size (D_{max}) and the width of the shear box (W) is 1/10 or smaller and 1/6 or smaller for the ratio between the maximum particle size (D_{max}) and the triaxial cell diameter. So, this thesis is mainly consisted of four phases of experimental work to reach the following objectives:

- Evaluating the particle size effect on the shear strength parameters of TDA using a large-scale Direct Shear testing apparatus.
- Evaluating the specimen (sample) size effect on the shear strength parameters of TDA using direct shear testing apparatus.
- Evaluating the particle size effect on the shear strength parameters of TDA using large-scale Triaxial testing apparatus.
- Evaluating the specimen (sample) size effect on the shear strength parameters of TDA using Triaxial testing apparatus.

1.3 Thesis Layout

This thesis mainly consists of seven chapters ordered in the following order:

- **Chapter 1** "Introduction" in which covered the research topic and the main objectives of this study.
- **Chapter 2** "Literature Review" which covers the previous work that was conducted on TDA to evaluate its properties and its shear strength parameters.
- **Chapter 3** "Evaluating the specimen (sample) size effect on the shear strength parameters of TDA using direct shear testing." This journal paper was submitted to the Transportation Research Board for publishing.
- **Chapter 4** "Evaluating the particle size effect on the shear strength parameters of TDA using a large-scale Direct Shear testing apparatus."
- **Chapter 5** "Evaluating the specimen (sample) size effect on the shear strength parameters of TDA using Triaxial testing apparatus."

- **Chapter 6** "Evaluating the particle size effect on the shear strength parameters of TDA using a large scale Triaxial testing apparatus."
- **Chapter 7 "**Conclusion and Recommendation" in which I will cover the conclusion that was derived from the experimental program that was done through the thesis and will introduce my recommendation for future work.

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CHAPTER 2 LITERATURE REVIEW

Several field and laboratory tests were conducted by researchers to determine the properties of TDA since the fourth quarter of the 20th century. This material has been used as a sustainable lightweight backfill material to reduce applied stresses for both short and long-term deformation. It also can be used as a vibration mitigating material that could be applied in rail lines projects, a material for enhancing steep slopes along highways and for landfills application instead of the conventional soils as in landfill gas collection trenches. However, as the usage of TDA is increasing rapidly, various laboratory tests are being conducted to evaluate the shear strength properties of the material and the compressibility of TDA and soil-TDA mixtures in order to be a more accepted construction material in the construction industry and to be used with confidence in several geotechnical applications that may utilize its useful characteristics.

The most common laboratory approaches are the direct shear and triaxial tests. The two tests, even for conventional materials, may result in different shear strength parameters for two main reasons. First, the Triaxial test has full control over the saturation and confinement pressure in contrast to the direct shear test in which such parameters can not be fully controlled. Second, the failure plane in the direct shear test might not happen on the weakest plane as the failure plan is forced to on mid, or around the mid, height of the sample being tested, while using triaxial test the failure is freerly allowed to happen at the weakest plane regardless of its orientation. However, the direct shear test is simpler, cheaper and faster than the triaxial test which makes it more favourable among geotechnical engineers.

Hence, this chapter will focus mainly on the researches and the studies that were conducted on TDA over the last few decads using the two afordmentioned test approcaches aiming to evaluate its properties and shear strength parameter. This chapter also discusses other tests pretained to TDA and their results to provide a full background survey of the studied material.

2.1 TDA Properties

2.1.1 Composition of Scrap Tires

Pehlken and Essadiqi (2005) reported the composition of the typical scrap tires generated from passenger and truck tires in North America, as shown in Table 2.1, as it is challenging to determine the composition of scrap tires as each tire factory has its composition criteria.

Table 2.1 Tires Composition in North America Reported by Pehlken and Essadiqi.

Composition	Passenger tire (% by weight)	Truck tire (% by weight)
Natural rubber	14	27
Synthetic rubber	27	14
Carbon black	28	28
Steel	14 - 15	14 - 15
Fibres, fillers, accelerators, etc.	16 - 17	16 - 17
Average total weight	New = 11 kg Scrap = 9 kg	New = 54 kg Scrap = 45 kg

2.1.2 Unit Weight

Several researchers studied the effect of compaction on the compacted unit weight of TDA, and it was found that compaction energy beyond 60% of the standard proctor will not affect the compacted unit weight significantly as the main effect of compaction on TDA is a more or less to arrange and orient the TDA chips evenly which is usually achieved with the 60% compaction energy. It was also observed that the water content would not affect the compacted unit weight (Humphrey et al. 1992; Ahmed. 1993; Humphrey et al. 1993; Moo-Young et al. 2003). On the other hand, the compacted density was affected by the compaction method and compaction conditions. However, Ahmed (1993) reported that the vibratory method of compaction was found to be inefficient for TDA unlike the conventional soils. Geosyntec Consultants (2018) reported a range of unit weights of TDA under four different scenarios; no compaction, light compaction, compaction done in laboratory and compaction done in field. The ranges of unit weight were reported below in Table 2.2.

Table 2.2 Unit Weight of TDA reported by Geosyntec Consultants in 2008

Compaction Type	**Unit Weight (kN/m^3)**
No Compaction	3.4 – 4.9
Light Compaction	3.4 – 4.9
Laboratory Compaction	5 – 6.9
Field Compaction	6.1 – 9.1

2.1.3 TDA Compressibility

Since the TDA is a highly compressible material, the failure of a TDA layer may be define (i.e., governed) by the settelemnt of the layer rather than its strength, as was reported by Bosscher et al. (1997) among others. Understanding the compressibility behaviour of TDA will help in forecasting the settlement that would occur during construction and after the construction and this will help in determining the in-situ unit weight of TDA. Due to the high compressibility of TDA used in this study, we had to increase the height of the upper half of the shear box by installing a 50 mm extension, so when the sample is compressed the failure plane will occur around mid-height of the sample being sheared. Understanding the compressibility of TDA also helped in determining the height of the extension to be added to the shear box as we found that the average compressibility of TDA samples under 200 kPa normal stress was around 30%, which constitute around 50 mm from the actual height of the shear box.

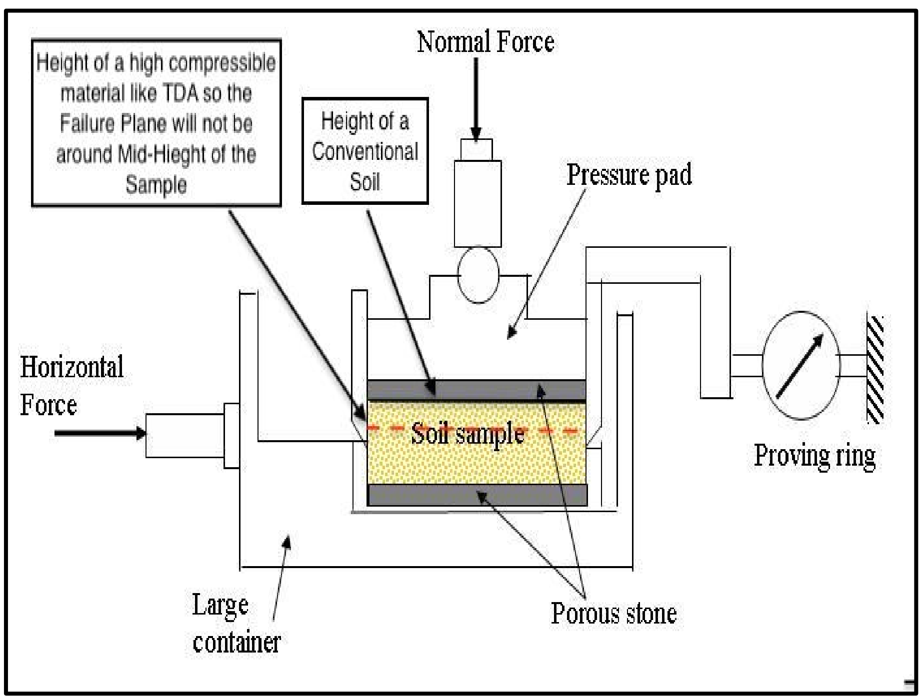

Figure 2.1 Direct Shear Apparatus Schematic

The compressibility of TDA was reported by Humphrey in 1992 for three TDA samples with maximum particle sizes of 50, 50 and 25 mm, respectively. The first sample was compacted while the latter two were in a loose state. A compression mold with a diameter of 254 mm and a height of 247 mm was used in the test with applied normal stress 200 kPa. The compressibility of the samples was reported to be 33-37%, 52% and 45%, respectively. In the same year, Humerphy et al. studied the compressibility of two compacted TDA samples with maximum particle size; 75 mm and 50 mm. The compression mold used had a diameter of 305 mm and a height of 318 mm. The compressibility was reported to be 38-41% and 40-43%, respectively, under 200 and 460 kPa normal stress.

Edil and Bosscher in 1992 also reported the compressibility of a compacted TDA sample with a maximum particle size of 75 mm to be 36% using a compaction mold of diameter 152 mm under normal stress of 690 kPa. Moreover, the compressibility of a TDA sample with a maximum particle size 38 mm was studied by Ahmed and Lovell in 1993 using a compaction mold of diameter 305 mm and a height of 317.5 mm and it was found that the compressibility of the compacted sample was 27% while for the loose one was 47%.

Two years later, Benda (1994) studied the compressibility of a TDA sample having a particle size distribution of 4.75 mm – 38 mm and it was found that the compressibility ranged between 27 – 32% under normal stress of 55 kPa. In 1997, Wu et al. (1997) conducted a series of triaxial tests using a triaxial cell of diameter 100 mm and a height of 200 mm for four TDA samples with maximum particle sizes of 38 mm 19 mm 9.5 mm and 2 mm, and the compressibility was found to be 27, 26.5, 31.6 – 25.4, and 27%, respectively, under a 55 kPa confining pressure. A year after, Reedy and Saichek (1998) used a compaction mold of diameter 360 mm and height of 300 mm to evaluate the compressibility of a TDA sample with a particle size range of 12 – 139 mm under three normal stresses; 32, 163 and 1005 and it was found that the compressibility of the TDA sample were 31, 50 and 65% respectively. Moo-Young in 2003 examined the compressibility of four TDA samples with a particle size distribution of; <50 mm, 50 – 100 mm, 100 – 200 mm and 200 – 300 mm under a normal stress of 110 kPa using a compaction mold of dimensions 610 mm by 610 mm and it was found that the compressibility of the samples was; 25, 35, 48 and 50% respectively.

To summarize, the compressibility of TDA is affected by the maximum particle size, either the sample being compacted or in a loose state and the normal stress applied. As the maximum particle size of the sample being tested increase the compressibility % increase and as the compaction energy applied to the sample before the test increase, the compressibility % decrease.

2.1.4 TDA Modulus of Elasticity (E)

The modulus of elasticity was reported by a number of researchers through conducting triaxial testing or by measuring the vertical compressibility (Meles, 2014). The modulus of elasticity was determined by Wu et al. in 1997 by conducting an extension test on a TDA sample and it was found that the modulus of Elasticity ranged between 450 up to 820 kPa. Two years earlier, Benda (1999) reported the Modulus of Elasticity to be ranging between 344 up to 820 kPa after conducting a series of triaxial testing with a confining pressure of 34 kPa up to 55 kPa. Yang et al. (2002) studied the variation of elastic modulus with confining pressure from several previous studies and reported an equation to correlate the initial tangent modulus of elasticity (E) with confining pressure (σ_3) as shown in equation (1).

$$E = 13.2 * (\sigma_3) - 0.0191\ (\sigma_3)^\wedge 2 \qquad \text{Equation 2.1}$$

2.1.5 TDA Poisson's ratio (μ)

The Poisson's ratio of TDA is determined by measuring the strain in triaxial test under vertical compression conditions or by measuring the vertical and horizontal stress under vertical loads as recommended by ASTM D 6270 (2008). It was reported by Humerphy and Sandford (1993) that the Poisson's ration varies between 0.2 and up to 0.32 for TDA samples depending on the maximum particle size and the TDA compositions. The equations used by Hurmphy and Sandford (1993) was reported by ASTM D 6270 (2008) as shown below.

$K_o = \sigma_h / \sigma_v$ Equation 1.2

$\mu = K_o / (1 + K_o)$ Equation 2.3

2.1.6 TDA Durability

Since the TDA composition is partially made of carbon so several researchers were worried about its durability specially when buried under deep depths in the ground as a backfill material and when exposed to different weather conditions to simulate the real situations that may occur with the presence of TDA in engineering projects. So, Chu (1998) done a long-term durability tests to study the durability of TDA by exposing a TDA sample to different weather condition for a year and a half. The Durability of TDA was measured according to its degradation. So, the particle size distribution was compared before and after exposing to different weather scenarios and it was found that the particle size distribution was almost the same which is considered a very good advantage for TDA. Another durability tests were conducted by AB-Malek and Stevensson (1986) studied the physical properties of a natural rubber sample submerged for a period of 42 years in a 24 m depth in sea water and it was found that the water absorption was only 4.7% and that there is no excessive deterioration for the rubber sample occurred after 42 years of submersion in sea water.

Summing up, TDA is a very durable material according the previous researches and no excessive deterioration occurs in a relatively sever conditions except for the corrosion of protruding steel wires that may extend to the steel wires inside the TDA which may decrease the strength parameters of TDA a little but not much. However, more researches should be conducted on this matter under different condition to confirm the high durability of TDA.

2.2 Laboratory Testing

2.2.1 Direct Shear Tests on Pure TDA

Direct shear test is one of the simplest tests to evaluate the shear strength parameters of TDA and soil-TDA mixtures. Due to its simplicity, its commonly used by testing laboratory and considered as the first option of soil testing compared to any other tests.

Humphrey and Sandford (1993) conducted several large-scale direct shear tests on different types and sizes of tire shreds (glass and steel belted). The direct shear tests were done using a shear box with dimensions 300 mm * 300 mm * 290 mm. Three normal stresses were applied in the direct shear box; 17, 34, and 68 kPa with a shearing rate of 7.6 mm/min. The internal friction angles for the tire shreds were ranging from 19° to 26° with a value of apparent cohesion ranging from 4.3 kPa to 11.5 kPa.

Foose et al. (1996) conducted a set of large-scale direct shear tests on TDA sample with particle size of 150 mm using a shear box of dimensions; 280 mm in diameter and 275 mm in height. The shearing rate was 1.3 mm/min under different normal stress ranging between

3 kPa to 120 kPa and the angle of internal friction was reported to be 30° and the cohesion was reported to be 3 kPa.

In 1997, Bernal et al. reported the angle of internal friction and the cohesion of a TDA sample with a maximum particle size of 50 mm to be 35° and the 0 kPa respectively after conducting a set of large-scale direct shear testing with a shear box of dimensions; 300 mm, 300 mm and 225 mm.

Moo-Young et al. (2003) conducted several direct shear tests using different sizes of tire shreds (smaller than 50 mm, 50-100 mm, 100-200 mm, and 200-300 mm). The results showed that the maximum friction angle was obtained for samples with 50 to 100 mm tire shreds with a friction angle of 32°.

Xiao et al. (2013) conducted a series of large scale direct shear testing to evaluate the shear strength parameters of TDA using a shear box of dimensions 800 mm, 790 mm and a height of 1220 mm and the TDA sample had a particle size range of 25 mm – 75 mm which is considered Type A – TDA. The sample was sheared at rate of 22 mm/min under three normal stress 24, 48 and 96 kPa. The tests resulted in 38.1° angle of internal friction and 14.3 kPa in cohesion.

Pando and Garcia (2011) reported the shear strength parameters of granulated rubber after summarizing the previous work done by several researchers and they found that the cohesion ranged between 0-11.4 kPa and the effective angle of internal friction to be 8.2 – 14.9 for several granulated rubber samples with maximum particle size 4.5 mm under various confining pressure.

Iranikhah and El Naggar (2018) reported that the angle of internal friction and cohesion of a TDA sample with a maximum particle size of 75 mm to be 23.9° and 18.2 kPa. These results were derived through conduction large scale direct shear tests on TDA sample using a shear box of dimension 305 mm, 305 mm and a height of 230 mm under three normal stresses; 50.1, 98.8, 196.4 kPa using a constant shearing rate of 0.5 mm/min.

2.2.2 Direct Shear Tests on TDA-Soil Mixtures

El Naggar et al. (2016) investigated the effect of TDA gradations on the shear strength parameters of sand-TDA mixtures. Several large-scale direct shear tests were conducted on three different TDA samples with maximum particle sizes; 0.3, 24, and 49 mm, respectively, mixed with sand using different amounts of TDA by volume; 15, 25, 50 and 100%. Three normal stresses were applied on the direct shear box; 50, 100, and 150 kPa under a constant shearing rate of 1 mm/min. The results indicated that the optimum TDA content in the sand mixture was 15% which resulted in the maximum shear strength among all other samples. Also, the results showed that the coarser the TDA content in the mixture, the higher the shear strength.

Iranikhah (2018) conducted an experimental investigation on the shear strength parameters and deformability behaviour of various soil types mixed with TDA by performing a large-scale direct shear testing on TDA-Soil mixtures. The TDA was mixed with clay, sand and gravel by volume and the shear box used had dimensions of 305 mm by 305 mm and a height of 230 mm. The shearing rate that was used in this research was 0.5 mm/min and the results showed that the addition of TDA to the sand and clay soil mixtures initially increased the shear resistance of the soil to a certain limit and then decreased. However, for the gravel-TDA mixture, the shear resistance of the gravel decreased by adding TDA content to the mixture.

A small-scale direct shear test was conducted by Gray and Ohashi (1983) to study the shear strength parameters of sand reinforced with fibers. The orientation of the fiber was predetermined with a size ranged from 20 to 250 mm. The applied normal pressure on the specimen upon shearing was up to 144 kPa. At 8% relative displacement, the failure was defined. In a dry condition, the shear strength of sand-fiber mixtures increased with an interface friction angle of 60º with respect to the shear surface.

Cetin et al. (2006) studied the shear strength parameters of tire-chips and cohesive clayey soil mixtures using direct shear tests. Two sizes of tire-chips were used with different percentages of the mixture according to soil weight content; 10, 20, 30, 40, and 50%. The results indicated changes, an increase then a decrease, in the shear strength parameters of the mixture based on the percentage of tire-chips content.

Akbulut et al. (2007) conducted several small-scale direct shear tests to evaluate the strength parameters of clayey soil mixed with synthetic fibers with a length range of 2 to 15 mm. The results showed that adding 2%, or less, of synthetic fiber with a length of 10 mm to the soil mixture increased the shear strength parameters while adding more than 2% decreased the strength properties of the mixture.

Xiao et al. (2013) conducted a series of large-scale shear tests using a shear box of dimensions 800 mm, 790 mm and a height of 1220 mm to investigate the shear strength parameters of large size TDA in contact with geosynthetic, sand, and concrete. In this study, TDA with type A was used. The results showed a cohesion with range of 5 to 14 kPa and friction angles of 19° to 39° for their different samples. The direct shear test of TDA-TDA sample reported the highest cohesion, while the highest friction angle was obtained for TDA-Sand sample.

Foose et al. (1996) performed several large-scale direct shear tests on sand-tire mixtures. Three of tire shreds were used in this study (smaller than 50 mm, 50 to 100 mm, and 100 to 150 mm). The applied normal stresses on the direct shear box were ranging from 3 to 120 kPa. The results showed that the maximum friction angle of the composition was 67° using larger size of tire shreds and 30% tire shred content of the whole mixture.

Using large scale direct shear tests, Tatlisoz et al. (1998) investigated the shear strength parameters of clean sand and sandy silt mixed with tire chips with shred lengths ranging from 30 to 110 mm. Low normal stresses were applied in this study all of them were less than 50 kPa. The results showed that adding 30% tire shreds to the sand increased the shear strength parameters of the mixture significantly. Adding more than 30% tire shreds to the sand reduced the shear strength parameters of the mixture.

2.2.3 Triaxial Tests on pure TDA

Triaxial test is more complicated than direct shear test because of the leaking, which might happen from the triaxial membrane due to the irregular shapes of TDA and the presence of protruding steel wires in TDA. However, triaxial tests is used by researchers to have a full control on the confining pressure and the saturation throughout the test plus they could simulate the real projects' soil conditions either consolidated or unconsolidated, drained or undrained and project that on the triaxial test they conduct.

Wu et al. (1997) used triaxial tests to determine the shear strength parameters of tire-chips with sizes ranging from 2 to 38 mm with different shapes; flat, granular, elongated and powder. The confining pressures used were ranging from 35 to 55 kPa. The results showed friction angles for the tire-chips ranging from 44 to 56°. Also, the results indicated a negligible cohesion when the confining pressure is below 40 kPa. While the cohesion increased a bit by increasing the confining pressure.

Ashari and El Naggar (2018) conducted several large scale triaxial testing of sustainable TDA backfilling. The TDA sample that was tested had a particle size range of 12 mm up to 63 mm. The triaxial cell diameter was of a diameter of 150 mm and a height of 300 mm. The shearing rate that was used was equal to 1 mm/min. The tests resulted in an angle of internal friction and cohesion equal to 25.5° and 23.5 kPa, respectively.

2.2.4 Triaxial Tests on TDA-Soil Mixtures

Ahmed (1993) conducted several large scale triaxial tests to study the shear strength behaviour of tire-chips and sand mixtures using a triaxial cell with diameter of 150 mm and a height of 300 mm. The confining pressure applied was ranging from 31 to 207 kPa and the results showed that using tire-chips content up to 38% of the sand mixture weight increased the shear strength parameters of the mixture.

Masad et al. (1996) conducted several series of triaxial tests to investigate the shear strength parameters of tires with no steel wires in the TDA-sand mixtures. The sample used had a diameter of 71 mm and a 147 mm height. The results showed that adding tire shreds to the sand mixture increased its compressibility and decreased the modulus of elasticity of the sand significantly. At higher confining pressure, the study reported that the modulus of elasticity of the tire/sand mixture increased.

To study the shear strength parameters of tire-chips mixed with sand, Lee et al. (1999) conducted several large scale triaxial tests using the vibration method for compaction. The confining pressures used were ranging from 28 up to 193 kPa. The results showed that adding tire-chips to the sand mixture increased its dilatant behaviour.

To investigate the engineering properties of shredded rubber tire-sand mixtures, a series of triaxial shear tests were conducted by Youwai & Bergado (2003). The study was performed using different ratios between rubber and sand. The results indicated that increasing the confining pressure increased the strength of the mixture linearly. On the other hand, increasing the sand content in the mixture led to varying the optimum friction angles between 30 to 34° without an increasing or a decreasing trend.

Zonberg et al. (2004) conducted 15 triaxial tests under consolidated drained conditions to evaluate the behaviour of tire shred-sand mixture. The results showed that pure tire shred specimens indicated a linear deviatoric stress vs strain behaviour. It also showed that specimens with lower than 35% of tire shred contents indicated a dilatant behaviour while samples with tire shred % higher than 35% exhibited a contractive behaviour.

To study the behaviour of tire-chips sand mixtures, Rao and Dutta (2006) performed several small scale triaxial tests using different tire-chips sizes; 10 mm by 10 mm, 20 mm by 20 mm, and 20 mm by 10 mm. The tire-chips were mixed with sand at the amounts of 0, 5, 10, 15, and 20% by weight. The confining pressures used in this study were ranging from 35 to 276 kPa. The results indicated that the friction angle and the cohesion increased by increasing the tire-chips content up to 20% which increased the compressibility behaviour of the mixture significantly.

2.2.3 Comparison between Direct Shear Test and Triaxial Test

While the findings of both tests are comparable, the limitations of the direct shear test are controlling the water pressure in the shear surface and the predefined failure plane, unlike the triaxial test where there is full control on the confining pressure and the saturation throughout the tests.

However, direct shear is simpler to carry on for testing in terms of the preparation and method (Saada & Townsend, 1981). Triaxial test is more complicated as the membranes are exposed to a potential puncture. For accuracy, the triaxial test is more accurate when it comes to study the stress and strain behaviour of the soil (Maccarini, 1993).

For TDA and TDA-soil mixtures, large-scale direct shear test results are more accurate than triaxial test results due to the large size of TDA mixture as triaxial test apparatus are not large enough for large TDA sizes and according to ASTM D 7181 (2011), the ratio between the maximum particle size to the cell diameter should be 1/6 or less (Foose et al. 1996). The results of the triaxial test for investigating the shear strength parameters of remolded and undisturbed soil was found to be higher than that of the direct shear test (Castellanos & Brandon 2013).

2.3 Other Laboratory Tests on TDA Mixtures

Different methods of investigations have been used by researchers to study the characteristics of TDA mixtures. Warith et al. (2004) carried on an investigation to study the effect of compressibility and hydraulic conductivity on two types of shredded tires from two different sources in landfill leachate collection system. The compression test results showed that the maximum normal strain of tire shreds is at the strains near 50%.

Warith & Rao (2006) were able to predict the initial thickness of the shredded tire layer using different one-dimensional compressibility and permeability tests for tire shreds landfill applications.

Lee & Roh (2007) studied the application of recycled tire-chips and expanded polystyrene as cushioning material using uniaxial compressive tests. The results found that the tire-chips can act a cushioning material to reduce the dynamic earth pressure which was developed due to the compaction of the backfill. The reduction percentage was about 70% from the dynamic horizontal earth pressure.

Kim & Kang (2011) conducted several unconfined compression tests on soil and rubber mixture to investigate the engineering properties of rubber added to lightweight soil. The results showed that the rubber content decreased the unconfined compressive strength of the mixture. Also, the results indicated that the rubber content exhibited the ductile behaviour in the mixture. In addition, the rubber content led to low unit weight of the mixture.

Ahn & Cheng (2014) conducted a full-scale shake table test to investigate the dynamic performance of TDA as a backfill material for retaining walls. They compared the results with the conventional backfill material. The results showed that TDA backfill reduced the dynamic pressure on the retaining wall when compared to the conventional material. The results showed a sustainable alternative for TDA usages as backfill material.

2.4 Field Research on TDA mixtures

Researchers conducted several field tests to investigate the compressibility of TDA and its potential usages as a sustainable embankment material. Eaton et al. (1994) reduced 25% of the frost penetration on a driving highway by using more than 20,000 waste tires with 51 mm size pieces to replace the cover soil layer from 305 to 610 mm.

Shalaby & Khan (2005) used tire shreds as embankment material on soft organic clay in Manitoba, Canada. The results of the field test showed that tire shreds can reduce the frost penetration due to its large voids and low water content compared to the clay. The results showed also that the tire shreds have a similar thermal profile to natural ground.

Meles et al. (2014) studied the compression behaviour of TDA by constructing an embankment test in Edmonton, AB, Canada. In this investigation, for sections of embankment was used (TDA/soil mixture, native soil, and 2 different types of TDA). The results showed that the performance of TDA soil mixture is equivalent to the control normal soil fill.

Yi et al. (2015) studied the effect of tire source, particle size, initial void ratio, and the testing method on the behaviour of two types of TDA using field and laboratory tests in both small- and large-scale compression tests in one dimension. For the field test a settlement plate and pressure cell was constructed to measure the compression behaviour of TDA. The embankment test used was two sections. The results showed that the average contact area ratio of TDA particles controls the elastic deformation of TDA. Also, the results indicated that the initial void ratio of TDA is the controlling parameter affecting the compressibility of TDA mixture.

Mahgoub & El Naggar (2019) investigated TDA as an engineering stress-reduction material over pre-existing buried pipes. The results of the experiment showed a significant reduction in the pipe’s stresses and the magnitude of transferred pressures by using a layer of TDA over the pipe compared to using conventional backfill material.

2.5 Thesis Research

As we see from the literature, there is a gap in testing pure TDA samples and what factors mainly affect the shear strength parameters of pure TDA. The reason behind this gap is that the TDA particles are considered relatively large compared to the conventional testing equipment that usually exist in laboratories and according to the ASTM there is some limitations for the ratio between the maximum particle size existed in the sample being tested to the diameter, or the length, of the testing equipment.

This research will try to identify the effect of two important factors which are; the particle size effect and the sample size effect on the shear strength parameters of TDA using series of direct shear and triaxial tests. This research is mainly divided into two categories, each category is divided into two subcategories. First category is mainly a series of direct shear tests to evaluate the shear strength parameters of TDA in which a large scale direct shear tests will be conducted to evaluate particle size effect on the shear strength parameters of six TDA samples having an increasing maximum particle size and then a series of direct shear tests will be conducted using four direct shear boxes on one sample of TDA to evaluate the effect of the sample size on the shear strength parameters of TDA. Moving on, to the second category of this thesis, a large scale triaxial testing was conducted on five TDA samples to evaluate the effect of the particle size on the shear strength parameters of TDA and then one sample will be tested using four triaxial cells each with a different diameter to evaluate the effect of the sample size on the shear strength parameters of TDA.

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CHAPTER 3 EFFECT OF SAMPLE SIZE ON TDA SHEAR STRENGTH PARAMETERS IN DIRECT SHEAR TESTS

Abstract

Tire-derived aggregate (TDA), a relatively new construction material, has been gaining acceptance as a backfill material for embankments, trenches, and earth-retaining structures due to its lightweight and excellent geotechnical properties. Type A TDA has a basic geometrical shape, with particles approximately 12 mm to 100 mm in size. Due to the simplicity and fairly accuracy of the direct shear test, most laboratories choose this test in preference to more complex tests. The shear strength parameters of materials with a large particle size are critical for geotechnical design.

However, TDA requires large-scale direct shear apparatus due to the consistently large size of its particles, and few facilities own this type of apparatus. Depending on the shear box dimensions, the aspect ratio of the particle size to the box dimensions may lead to variations in the shear strength results of the sample being evaluated. This research focuses on studying the effect of TDA sample size on the shear strength results of direct shear tests by using five different shear box sizes: (305 mm - 305 mm), (225 mm - 225 mm), (150 mm - 150 mm), (100 mm - 100 mm) and (60 mm - 60 mm). The findings show that the angle of internal friction increases slightly as the dimensions of the shear box decrease. It was found that the maximum variation in the angle of internal friction and the cohesion results of the different shear boxes was only 1.9° and 2.4 kPa, respectively. These differences should be taken into consideration when TDA shear test results are used in the geotechnical design. It is recommended that a shear box with an aspect ratio (W/D_{max}) greater than or equal to 4 should be used when evaluating the shear strength parameters of TDA.

Keywords: Tire-Derived Aggregates, TDA, Direct Shear Test, Shear Box, Shear Strength, Angle of Internal Friction (°) and Cohesion.

3.1 Introduction

Over 290 million tires are discarded each year in the United States and sent to stockpiles or landfills. This constitutes an environmental hazard by providing a breeding ground for mice, rats and insects. Besides, tires in stockpiles and landfills are considered a serious fire hazard because tires can catch fire easily and extinguishing a tire fire is difficult and may take months or even years (Cecich et al. 2016). Increased tire production worldwide has focused attention on the necessity for safe, sustainable disposal of scrap tires. Fortunately, 56% of the tires discarded in the USA are currently used as tire-derived fuel (TDF) by some factories. This reduces the burden of disposing of these tires. Around 7% of the scrap tires are used as retreads, and 24% are used in various civil engineering projects. Tire-derived aggregate (TDA) can be used for various purposes, including lightweight fill for road embankments, subgrade fill, around buried structures, or a material for enhancing steep slopes along highways (Engstorm et al. 1994; Liu et al. 2000; Mahgoub and El Naggar 2019).

However, the statistics cited above are for the United States alone. The number of scrap tires generated annually worldwide is increasing alarmingly and requires new solutions. Further studies have determined that with the continued development of civil engineering applications, civil engineering projects have the potential to utilize large quantities of scrap tires. Moreover, the use of tire-derived aggregates in various projects has prompted studies to evaluate the physical, chemical, mechanical, and shear strength properties of TDAs so that they can be considered as construction materials. TDA has two types; A and B. Type A is around 75 – 100 mm in size with a maximum particle dimension measured in any direction of 200 mm. However, Type B is around 150-305 mm in size, with a maximum particle dimension in any direction of 450 mm.

One of the tests performed to evaluate the shear strength parameters of TDA is the direct shear test, which is regarded by many laboratories as the primary test for soils, due to its simplicity and fairly accuracy. Direct shear tests have been performed for various types of soil with different specimen sizes, in boxes ranging in size from (60 mm × 60 mm) to more than (1000 mm × 1000 mm) for large-scale testing. The variation in shear box size, especially for samples with large particles, resulted in different findings for the same tested sample, so more researches were developed to study the effect of the scale factor on the shear strength parameters of the tested samples. One of the earliest researches that studied the effect of specimen size on the shear strength parameters of cohesionless soils was done by Parsons (1936). Three shear boxes of areas; 240 cm^2, 120 cm^2 and 36 cm^2 were used in the research to study the specimen size effect on the shear strength of Ottawa sand and crushed quartz. The normal loads that were applied to the samples ranged between 1.5 kPa up to 210 kPa. The results of the tests showed that there is a slight increase in the angle of internal friction as the shear box size decrease for both tested samples. Around 50 years later, Carroll (1979) conducted a series of static and cyclic direct shear tests using two circular shear boxes of diameters; 80 mm and 47.6 mm on two undisturbed clay samples brought from the Gulf of Alaska and the Gulf of Mexico. The static tests were performed with a constant sped rate of 0.013 mm/min while the cyclic tests were performed with a 0.1 Hz frequency, and a half period frequency of 10 seconds was maintained. The results showed that for the static tests, the smaller shear box resulted in a 10-15% higher shear strength than the larger shear box. While for the cyclic tests, the smaller shear box resulted in twice shear strength than the larger shear box.

These findings were supported by Cerato et al. (2006), who carried out a series of direct shear tests with three varying shear boxes sizes; 60mm, 101.6 mm and 304.8 mm. The tests were performed on five sand samples with different properties, each at three states (dense, medium, loose). The tests were performed with a constant shearing rate of 0.25 mm/min under five normal stresses ranging between 38 kPa – 150 kPa for the two smaller shear boxes while a range of 69 kPa – 207 kPa normal stresses were applied to the larger shear box. The results concluded that the angle of internal friction tended to increase as the sample size decreased. In addition, in a study of Isfahan clayey sand, Dadkhah et al. (2010) confirmed the trend of an increasing angle of internal friction with decreasing specimen size by performing a set of direct shear tests on 45 clayey sands with almost the same properties using three shear boxes; 300 mm, 100 mm and 60 mm. The tests were performed with a constant shearing rate of 1 mm/min and under three normal stresses ranging between 98 kPa – 294.2 kPa. The results of tests also showed that the cohesion increased with the increasing sample size for almost all the samples, and that angle of internal friction increases by increasing the density of the tested sample.

Furthermore, Mirzaeifar et al. (2013) conducted a series of direct shear tests with three shear boxes sizes; 60 × 60 mm, 100 × 100 mm and 300 x 300 mm on Firouzkooh sand in a pure state and reinforced by three geogrid materials. The tests were performed under a constant rate of 1 mm/min and three vertical pressures of 100 kPa, 200 kPa and 300 kPa. The tests confirmed the trend of the increasing angle of internal friction by decreasing the shear box size and this trend occurred while testing the sand in a pure state and when reinforced by geogrid materials. Recently, Shakri et al. (2017) studied the scale size effect on the shear strength of modified soft sand samples in which Pulverized fuel ash and cement were added to the soft sand to strengthen the soil mixture. A total of 40 samples were tested using two shear boxes of dimensions; 60 mm × 60 mm and 300 mm × 300 mm. The tests were conducted at a shearing rate of 0.85 mm/min for the small shear box, while a rate of 1 mm/min was used for the large shear box. The normal stresses applied to the samples ranged between 30 kPa – 120 kPa for the small shear box, while a range of 35 kPa – 138 kPa was applied to the large shear box. The results concluded that the peak shear strength decreases as the shear box size increases. Besides, Moayed et al. (2017) studied the specimen size effect on Firouzkooh sands with 0, 10, 20 and 30% silt percentages in the direct shear test. A total of four samples were tested in three shear boxes of dimensions; 60 mm × 60 mm, 100 mm × 100 mm and 300 mm × 300 mm. A range of 109 kPa – 436 kPa normal stresses were applied to the samples, and the tests were conducted with a fixed speed rate of 0.9 mm/min. This study concluded that the peak shear strength increases by decreasing the shear box size for all the tested samples, while the residual shear strength remained constant.

However, in contrast to the above findings, Palmeira and Milligan (1989) showed that for Leighton Buzzard sand samples, there was no significant variation in the angle of internal friction as the specimen size increased. The results were driven from a series of direct shear tests in which three shear boxes were used of dimensions; 1000 mm × 1000 mm × 1000 mm, 252 mm × 152 mm × 152 mm and 60 mm × 60 mm × 32 mm. The tests were performed on three Leighton Buzzard sand samples with maximum particle sizes of 2 mm, 1.2 and 0.6

mm with a shearing rate of 0.5 mm/min under constant vertical pressure of 30 kPa. The results concluded that the angle of internal friction is almost identical between the medium and the small shear boxes with a difference of 0.1 degrees and the difference between the large shear box and the smaller ones was around 0.7 degrees which do not constitute a significant difference in the shear strength of the Leighton Buzzard sand.

The above findings seem to be in agreement that the shear strength of the tested sample increases by decreasing the shear box size except that Palmeira (1989) showed that for the Leighton Buzzard sand there was no significant difference in the shear strength which may conclude that the effect of the specimen size on the shear strength depends on the type of sample tested. Table 3.1 summarizes the findings of previous studies conducted on the sample size effects for conventional soil materials.

It should be noted that all available studies considered only conventional soils and the sample size effect for TDA samples was not studied before. Therefore, the main focus of this research is to study the scale effect of the direct shear test in evaluating the shear strength parameters of TDA. Five square shear boxes; 305 mm × 305 mm, 225 mm × 225 mm, 150 mm × 150 mm, 100 mm × 100 mm and 60 mm × 60 mm were used to determine whether or not the sample size affects TDA shear strength parameters.

Table 3.1 Summary of the Literature review

Author/Date	Samples	Shear Box Size	Shearing Rate (mm/min)	Normal Stresses (kPa)	Conclusion
Parsons/1936	Ottawa sand & crushed quartz	Areas; 36, 120 & 240 cm^2	-	1.5 - 210 kPa	Angle of internal friction "slightly" increased by decreasing shear box size.
Carroll/1979	Clay samples	Diameters; 47.6 mm and 80 mm	0.013 mm/min	-	Shear strength increased by decreasing shear box size.
Cerato/2006	Sand samples	Square 60 mm & 101.6 mm & 304.8 mm	0.25 mm/min	38 - 207 kPa	Angle of internal friction increased by decreasing shear box size.
Dadkha/2010	Isfahan clayey sand	Square 60 mm & 100 mm & 300 mm	1 mm/min	98 - 294.2 kPa	Shear strength increased by decreasing shear box size.
Mirzaei/2013	Firouzkooh sand	Square 60 mm & 100 mm & 300 mm	1 mm/min	100 - 300 kPa	Angle of internal friction increases by decreasing shear box size.
Shakri/2017	Modified soft sand	Square 60 mm & 300 mm	0.85 – 1 mm/min	30 - 138 kPa	Peak shear strength increases by decreasing the shear box size.
Moayed/2017	Firouzkooh silty sand	Square 60 mm & 100 mm & 300 mm	0.9 mm/min	109 - 436 kPa	Peak shear strength increases by decreasing the shear box size while residual shear strength remains constant.
Palmeira/1989	Leighton Buzzard sand	Square 60 mm & 252 mm &1000 mm	0.5 mm/min	30 kPa	No significant difference

3.2 Direct Shear Test

Direct shear tests were performed on three types of apparatus: large-scale, medium-scale and small-scale direct shear machines. With the large-scale apparatus, tests were performed by using square shear boxes measuring 305 mm × 305 mm and 225 mm × 225 mm. While in the medium-scale apparatus, tests were performed using a 150 mm × 150 mm square shear box. Whereas, with the small-scale apparatus, tests were performed by using shear boxes measuring 100 mm × 100 mm and 60 mm × 60 mm. The height of the mold of the 305 mm shear box was modified to be 210 mm instead of 160 mm by installing a 50 mm extension on the shear box as shown in Figure (2.1), to accommodate the high compressibility of TDA, making the aspect ratio W/H = 1.45, where W is the width of the box and H is the total sample height. The shear boxes measuring 225 mm × 225 mm and 150 mm × 150 mm were also designed and constructed with a height of 210 mm, resulting in aspect ratios W/H of 1.07 and 0.71, respectively. Moreover, the height of the small-scale shear boxes was only 43 mm, resulting in aspect ratios W/H of 2.33 and 1.40, respectively. This information is summarized in Table 3.2 and illustrated in Figure (1). ASTM D3080 recommends that the minimum specimen width should be greater than ten times the maximum particle size. Furthermore, the minimum initial specimen thickness should not be less than six times the maximum particle diameter. However, it should be noted that these recommendations are mainly for conventional soils as ASTM D3080 was developed for testing of soils under

consolidated drained conditions not for TDA. The lower part of the shear boxes was the movable part, and it moves in the horizontal direction away from the machine via an electric motor and had a height of 80 mm in the large-scale and the medium-scale direct shear boxes and 18 mm in the two small-scale direct shear boxes.

Table 3.2 Shear boxes characteristics

Shear Box Dimensions						
		1	**2**	**3**	**4**	**5**
Length (L) (mm)	-	305	225	150	100	60
Width (W) (mm)	-	305	225	150	100	60
Height (H) (mm)	Lower part	80	80	80	18	18
	Upper part	130	130	130	25	25
Aspect ratio (W/H)	-	1.45	1.07	0.71	2.33	1.40
Aspect ratio (W/Dmax)	-	8	6	4	2.6	1.6

Each of the used direct shear apparatuses had 3 LVDTs (linear variable displacement transducers). One was connected to the load cell, to measure the shear force (kN). The second one barely touched the shear yoke and measured the vertical displacement (mm), while the third one barely touched the lower part of the shear box and measured the horizontal displacement (mm). The LVDTs were connected to a data acquisition system to record the data received from the LVDTs. The normal stresses, applied to the samples in the direct shear tests by means of a deadweight system, ranged from a minimum of 50.1 kPa up to 196.4 kPa.

Figure 3.1 Shear boxes and the TDA sample used in this research

3.3 TDA Sample Characteristics

The TDA sample used was obtained from Halifax C&D Recycling Ltd. The sample was referred to as 1.5-inch TDA, in accordance with the maximum particle size (D_{max}) in the sample. Sieve analysis was conducted on the sample following ASTM D6913-04 and the gradation curve obtained is shown in Figure (3.2). The unit weight of the tested TDA ranged between 6.3 kN/m^3 to 8.3 kN/$m^{3,}$ depending on the applied normal stress.

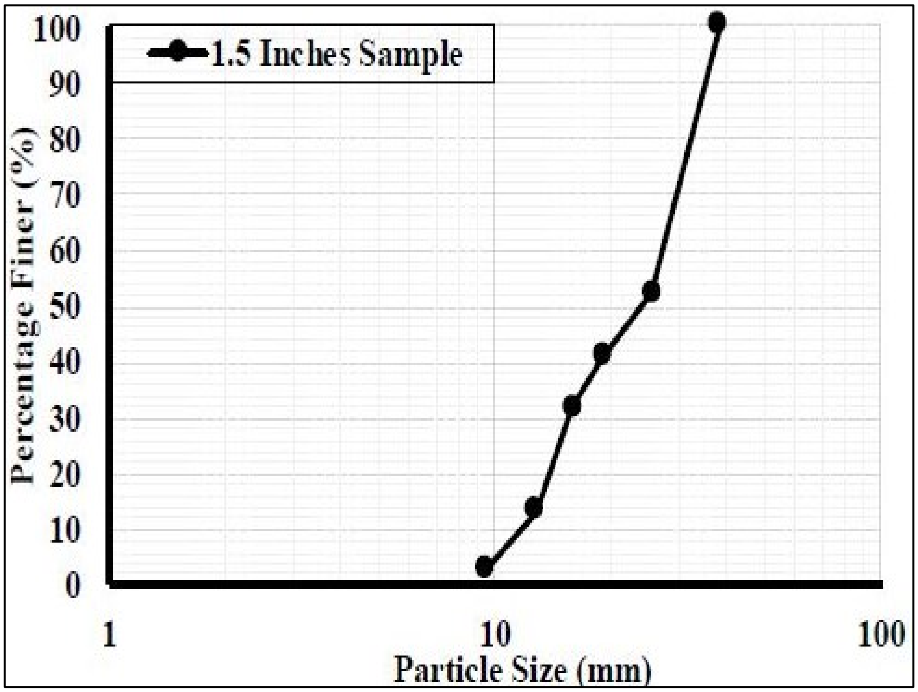

Figure 3.2 Gradation curve for the 1.5-inch TDA sample

As summarized in Table 3.3, the effective particle size (D_{10}) of the TDA sample was found to be 12 mm (0.47 inches), the average particle size (D_{50}) was 24.5 mm (0.96 inches), the coefficient of uniformity was 0.74, and the coefficient of curvature was 2.25.

Table 3.3 Shear box characteristics

	D10	D30	D50	D60	Coefficient of Curvature (C_c)	Coefficient of Uniformity (C_u)
(mm)	12	15.5	24.5	27		
(inches)	0.47	0.61	0.96	1.06	2.25	0.74

The coefficient of curvature (C_c) and coefficient of uniformity (C_u), respectively, were calculated as:

$$C_c = \frac{D_{60}}{D_{10}}, \text{ and } C_u = \frac{(D_{30})^2}{D_{10} * D_{60}}$$

3.4 Testing Procedures

The 1.5-inch TDA sample was tested in accordance with ASTM D3080 *Standard test method for direct shear test of soils under consolidated drained conditions*. First, the sample was prepared in accordance with ASTM D6913-04, and the gradation curve was obtained, as shown in Figure (3.2). The sample was then well mixed to prevent particle segregation. After that, the sample was divided into five parts, to form five layers. These were poured into the shear box layer by layer, with the proper compaction for each layer, for total compaction energy of 38,000 (Joules). Thus, the minimum required compaction energy was reached, which is 60% of the modified Proctor energy, according to ASTM D6270-08. The compaction was performed by using a modified Proctor hammer, following the procedures specified in ASTM D1557.

For the 305 mm shear box, 75 blows with the modified Proctor hammer were used to compact each layer, with a total of 375 blows for the whole sample. For the 225 mm shear box, 45 blows were used to compact each layer, with a total of 225 blows for the entire sample. Likewise, for the sample in the 150 mm shear box, 20 blows were used to compact each layer, with a total of 100 blows for the entire sample. In contrast, the samples in the 100 mm and 60 mm shear boxes were oriented by hand to ensure proper void filling and to prevent the sample from overflowing the shear box, since, at 43 mm, the height of the shear box was somewhat low relative to the sample size.

The TDA samples in the shear boxes measuring 305 mm, 100 mm and 60 mm were sheared under three applied normal stresses of 50.1 kPa, 98.8 kPa and 196.4 kPa. However, for the 225 mm shear box, the normal stresses applied were 87.9 kPa, 98.8 kPa and 196.4 kPa, because the hydraulic arm for this shear box could not apply normal stress less than 87.9 kPa. Moreover, the normal stresses applied to the150 mm shear box were 151 kPa, 175 kPa and 196.4 kPa. For all tests, actual in the box unit weight ranging between 6.3 – 8.3 kN/m^3 was maintained (the actual unit weight is that of the sample in the shear box after applying the respective normal stress).

The shearing rate was 0.5 mm/min for the large-scale and the medium scale direct shear tests and 1 mm/min for the small-scale direct shear tests. Low shearing rates were chosen to prevent an overestimation of the calculated shear stresses, and the samples were in a dry condition, so no accumulation of pore water pressure occurred. To the best of the authors' knowledge, the shearing rate used was lower than shearing rates used in the testing of TDA recorded in the literature (i.e., in Humphrey et al. 1993; Foose et al. 1996; Bernal et al. 1997; El Naggar et al. 2016; Xaio et al. 2013; and Sparks et al. 2019).

3.5 Results

3.5.1 Stress-Strain Curves

A total of 25 tests were performed to study the effect of the specimen size on the TDA shear strength results. Some of these tests were duplicated to verify the results. Since, the stress-strain curves did not show a clear peak for the considered shear strain range (i.e., around the 14% strain), The shear strength parameters were calculated at 10% of the horizontal strain percentage as recommended by ASTM D3080-11 and by Strenk et al. (2007) among several other researchers.

Figure (3.3) plots the shear stress (kPa) against the horizontal strain (%) for shear boxes having the same applied normal stress. It was observed that the shear stress at 10% horizontal strain was almost identical for the shear boxes measuring 300 mm and 100 mm (within 5%) and slightly higher in the 60 mm shear box (6% higher). The results obtained for the shear boxes measuring 225 mm and 150 mm are shown separately, in Figure (4), because the normal stresses applied to these shear boxes differed from those applied to the shear boxes previously discussed. Since the normal stresses 88 kPa and 98.8 kPa were very close, the stress-strain curves shown in Figure 3.4 (a) for these normal stresses are also very close. The same occurred in Figure 3.4 (b) for the normal stresses 175 kPa and the 196.4 kPa. Moreover, the graphs illustrate clearly that as the normal stress applied to the sample increased, the attained shear stress increased for all of the shear boxes.

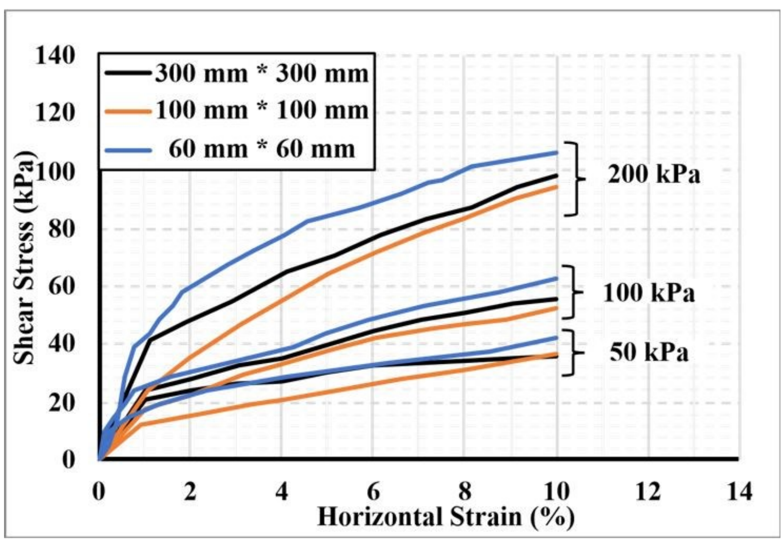

Figure 3.3 Shear stress (kPa) versus horizontal strain (%) for 305 mm, 100 mm and 60 mm shear boxes.

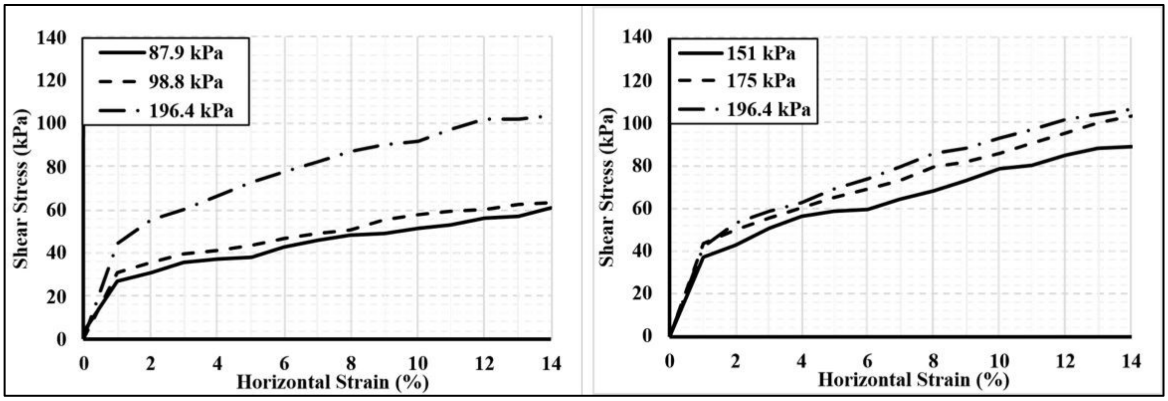

Figure 3.4 Shear stress (kPa) versus horizontal strain (%) for (a) the 225 mm shear box, and (b) the 150 mm shear box.

The shear stresses at 10% horizontal strain for the different normal stresses applied are summarized in Table 3.4 for ease of reference. These shear stresses were used to calculate the shear strength parameters of the TDA sample. Figure (3.5) shows the relationship between shear stress and normal stress for all the tests. Describing the mileage points based on linear equations made it possible to determine the shear strength parameters as shown in Table 3.4 below.

Table 3.4 Shear stresses, Angle of internal Friction and Cohesion for the Shear Boxes.

Shear Box	Normal Stress (kPa)	Shear Stress at 10% Horizontal Strain (kPa)	Angle of Internal Friction (°)	Cohesion
305 mm * 305 mm	50.1	36.6	22.018	16.4
	98.8	56.2		
	196.4	95.8		
225 mm * 225 mm	87.91	51.4	22.023	16.64
	98.8	57.5		
	196.4	96		
150 mm * 150 mm	151	75	22.12	14.04
	175	86		
	196.4	93.4		
100 mm * 100 mm	50.1	36.5	22.39	13.96
	98.8	51.8		
	196.4	95.8		
60 mm * 60 mm	50.1	38.4	23.86	16.08
	98.8	59.5		
	196.4	103		

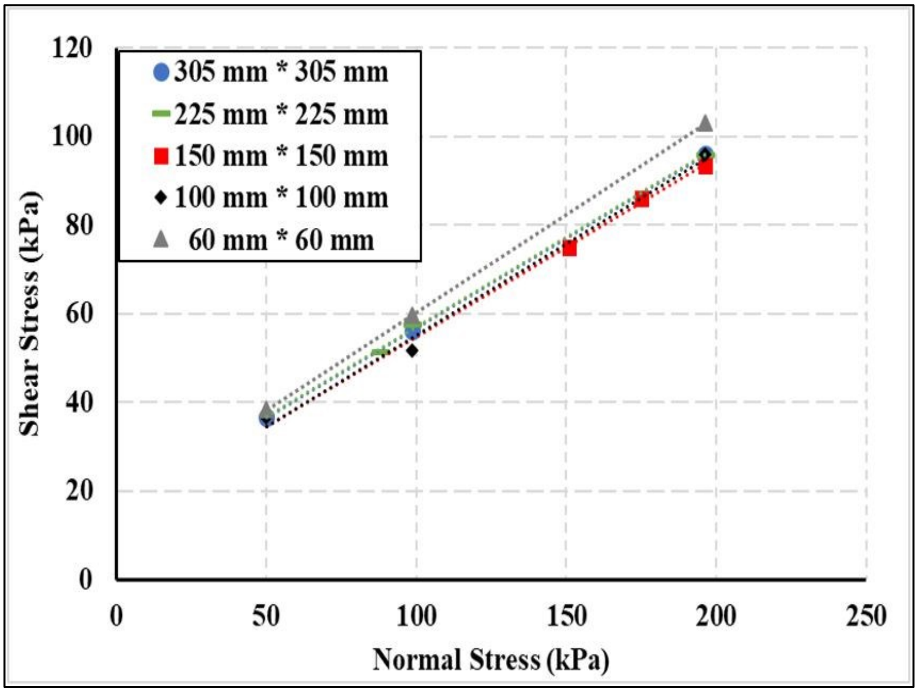

Figure 3.5 Shear stress versus normal stress for all the tests

3.5.2 Angle of Internal Friction and Cohesion

It was observed that the angle of internal friction exhibits a slight increase as the shear box size decreases, as shown in Figure 3.6. However, for the 60 mm shear box, the angle of internal friction showed a significant increase as shown in the figure. There was no increase in the angle of internal friction with the decrease in shear box size from 305 mm to 225 mm (i.e., for specimen width to maximum particle size, W/D_{max}, of 8 and 5.9 respectively). A negligible increase in the angle of internal friction of almost 0.1° occurred with the decrease in shear box size from 225 mm to 150 mm (i.e., for the W/D_{max}= 4 test). The angle of internal friction increased by only 0.3° with the decrease in shear box size from 150 mm to 100 mm (W/D_{max}= 2.6). Finally, there was a sizable increase of 1.5° in the angle of internal friction with a decrease in shear box size from 100 mm to 60 mm. On the other hand, the cohesion resulting from interlocking among the TDA particles was almost identical for the shear boxes measuring 305 mm, 225 mm and 60 mm. While it was less by only 2 kPa in the 150 mm and the 100 mm shear boxes, which are marginal. The average cohesion for all the mentioned shear boxes is around 16 kPa, which is practically small. So, the shear strength of TDA is primarily controlled by its angle of internal friction. Hence, based on the obtained results, it is recommended that a shear box with an aspect ratio (W/D_{max}) greater than or equal to 4 should be used when evaluating the shear strength parameters of TDA. If smaller box to be used, the differences in the strength parameters should be taken into consideration when TDA shear test results are used in the design.

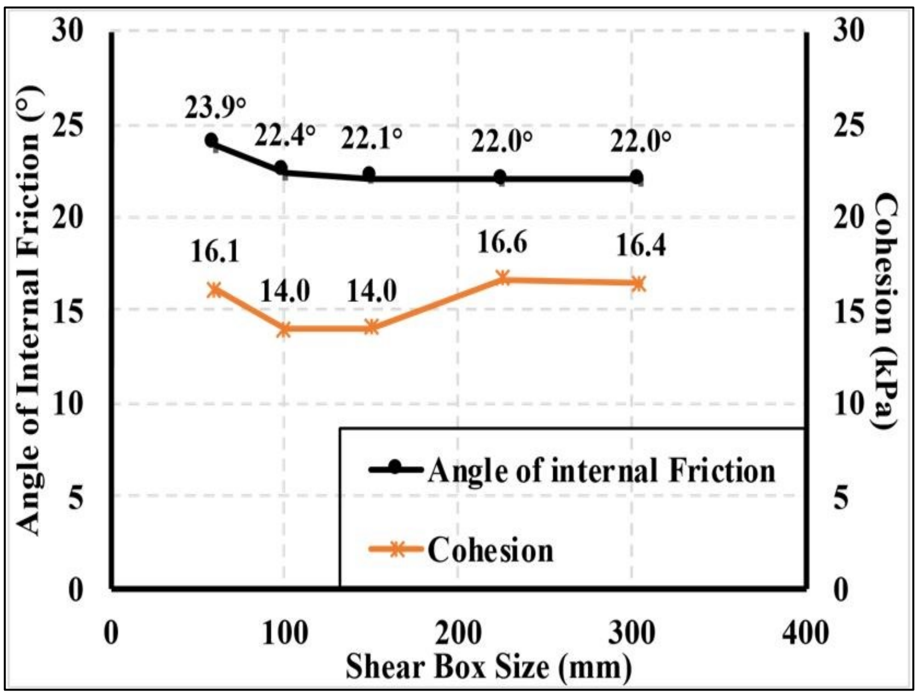

Figure 3.6 Angle of internal friction (°) versus shear box size (mm)

One of the previous studies conducted on a TDA sample having a maximum particle size of 1.5” inches, similar to the sample used in this study, was done by Humphrey et al. (1993) using a 286 mm square shear box in which the angle of the internal friction was reported to be 25. The difference between Humphery finding and the angle of internal friction reported in this research for the 305 mm shear box could be due to the difference in the dimensions of the two used shear boxes and that the TDA used in Humphrey was tested in its original state without removing the protruding wires so the interlocking between the particles as well as the extra friction between the protruding wires and the shear box walls resulted in a higher shear resistance.

3.5.3 Vertical Strain Behaviour

Moreover, as shown below in Table 3.5, for the shear boxes measuring 305 mm, 225 mm and 150 mm, the strain behaviour was contractive under all normal stresses applied to the sample. However, for the shear boxes measuring 100 mm and 60 mm, the strain behaviour was contractive-dilative. Due to the compressibility of the TDA particles and the presence of voids within the TDA sample, The TDA particles tend to fill these voids by being compressed and sliding on each other leading to a contractive strain behaviour in the first three shear boxes. However, the TDA particles in the smaller shear boxes are relatively large compared to the shear box size. So, the particles tend to slide on each other during shearing till no enough space is existing within the sample, so the particles start to push against the shear box top plate leading to a contractive-dilative behaviour.

Table 3.5 Strain behaviour under the normal stresses applied to the shear boxes

Shear Box	Normal Stress (kPa)	Unit Weight After Normal Stress is Applied (kN/m^3)	Strain Behaviour
305 mm * 305 mm	50.1	6.3	Contractive
	98.8	7.25	
	196.4	8.3	
225 mm * 225 mm	87.91	6.34	Contractive
	98.8	7.3	
	196.4	8.1	
150 mm * 150 mm	151	6.33	Contractive
	175	7.28	
	196.4	8.22	
100 mm * 100 mm	50.1	6.4	Contractive-Dilative
	98.8	7.34	
	196.4	8.25	
60 mm * 60 mm	50.1	6.3	Contractive-Dilative
	98.8	7.3	
	196.4	8.1	

3.6 Conclusion

To study the effect of sample size on the shear strength parameters of TDA, a nominal 1.5 inch TDA sample was tested by using five different shear boxes, in a total of 25 tests. In addition, some tests were duplicated to validate the results. From the test results, the following conclusions can be drawn:

(1) The angle of internal friction of TDA increases as the size of the shear box decreases while the cohesion did not show a definite trend.

(2) The increase in the TDA angle of internal friction observed for the small shear box (60 mm × 60 mm) could affect the design; thus, such results must be used with caution. Therefore, for evaluations of TDA shear strength, it is recommended to

use a direct shear box with an aspect ratio of shear box width to maximum particle size (W/D_{max}) of 4 or larger.

(3) The difference in cohesion among the different used shear box sizes was negligible, with a maximum variation of 2.4 kPa, which would not affect the design.

(4) The contractive-dilative strain behaviour observed in the two smaller shear boxes probably occurred due to the presence of large TDA particles that did not have enough space to be compressed. Because this behaviour contrasts with TDA behaviour in real site conditions, the contractive strain behaviour observed in the shear boxes measuring 305 mm, 225 mm and 150 mm could be a more reliable indicator to use when considering the settlement behaviour of TDA layers in engineering projects such as road subgrades and road embankments.

(5) ASTM D3080-90 recommends a W/D_{max} ratio greater than 6. This ratio should not be imposed for TDA since the results of the TDA tests showed that the same shear strength was obtained when using shear boxes with a W/D_{max} ratio as low as 4.

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CHAPTER 4 EFFECT OF PARTICLE SIZE ON TDA SHEAR STRENGTH PARAMETERS IN LARGE-SCALE DIRECT SHEAR TESTS

Abstract

The increase in the number of discarded tires every year is becoming a major issue all over the world. Tires stockpiles and landfills have become a critical issue as they are considered a fertile environment for the breeding of rats and insects, a real fire hazard that may take up to months to extinguish, and occupying a valuable large area of lands. One of the safest effective ways of recycling tires is that it gets used as backfilling material, among different usages, in civil engineering projects due to its low unit weight and specific gravity. However, to use any material in the construction industry, several material properties must be evaluated, including the shear strength parameters. The measured shear parameters are controlled by many factors. One main factor that is known to have a significant effect is the particle size. This paper focuses on evaluating the effect of the particle size on the shear strength parameters of six TDA samples having particle sizes range between (9.5 – 101.6 mm) using a large-scale direct shear machine with a square shear box of dimensions 305 mm by 305 mm and a height of 230 mm. The tests were conducted under three normal stresses; 50.1, 98.8 and 196.4 kPa using a constant shearing rate of 0.5 mm/min. The results of this study showed an increasing angle of internal friction as the maximum particle size increases. Moreover, the secant shear modulus also exhibited an increase by increasing the maximum particle size.

4.1 Introduction

The number of scrap tires generated every year all over the world is rapidly increasing. The reason behind this increase is that the number of vehicles is increasing, and the current technology is not targeting new means for recycling tires, but it is more into the development of renewable fuels. In 2015, Americans disposed around 250 million tires. In the same year, around 35 million scrap tires were discarded in Canada.

This increasing number of scrap tires is becoming a significant hazard for the environment as the primary means of getting rid of scrap tires is either by stockpiling or disposing them in landfills. These solutions possess serious hazards and are not environmentally acceptable as they are considered a fertile environment for insects and mosquitoes to breed and are prone to fire hazards as tires could catch fire easily, and it was noted that it is challenging to extinguish them (Cecich et al., 2016).

Fortunately, there are some methods for recycling scrap tires such as using them as Tire Derived Fuel (TDF) due to their high heat value, which is larger than the heat value of coal. Moreover, they could be used as ground rubbers for different applications as in children's playgrounds and gyms. Last but not least, they could be used in civil engineering projects as Tire Derived Aggregates (TDA) in which scrap tires are shredded into smaller pieces and used mainly as a light backfill material among other usages.

One of the main characterizations, which is essential for TDA adoption in civil engineering projects, is the geotechnical characterization. However, TDA particles are considered large in size compared to the available standard testing equipment, and practitioners are hence forced to test smaller TDA particle sizes not representative of the real sizes that are used in construction projects. Hence, the main focus of this research is to study the particle size effect on the shear strength parameters of TDA using a large-scale direct shear machine.

Several studies were done on granular and fine soils to study the effect of the particle size on the shear strength parameters.

For the granular materials, one of the earliest studies for the particle size effect for coarse-grained soils was done by Kim et al. (2014). The authors in this research investigated the shear strength parameters of coarse-grained soils for three samples with three different maximum particle sizes; 4.75 mm, 7.9 mm and 15.9 mm. The samples were tested in a pure state, supported with a soft geogrid, and supported with a stiff geogrid. The testing was done using a shear box with dimensions of 300 mm * 300 mm with a shear rate of 1 mm/min. The tests were performed under three normal stresses; 98 kPa, 196, kPa and 294 kPa. The results showed that the angle of internal friction increased from 40.56º for the 4.75 mm sample, up to 54.04º for the 15.9 mm sample.

Moreover, Islam et al. (2011) studied the effect of particle size on the shear strength parameters of sands. A series of direct shear tests was conducted on 10 samples in total. Eight samples with uniform particle sizes (0.075, 0.15, 0.212, 0.3, 0.6, 1.18, 1.72 and 2.76 mm) and two samples with graded particle sizes (0.075-1.18 mm and 0.075-2.36 mm). Tests were performed with a shear box with a diameter of 50.8 mm under a constant rate. The results showed that the angle of internal friction increased from 35.54º up to 42.24º for the samples with uniform particle sizes and for the two samples with graded particle sizes, the angle of internal friction increased from 41.18º to 41.83º.

Furthermore, Vangla and Latha (2015) conducted a series of direct shear tests to investigate the influence of the particle size on the shear strength of sands. The tests were conducted on three samples; fine, medium and coarse. The coarse sample had a maximum particle size of 4.75 mm. The medium sample had a maximum particle size of 2 mm, while the fine sample had a maximum particle size of 0.425 mm. The tests were conducted using a large-scale direct shear test with a shear box of dimensions 300 mm * 300 mm. The shearing rate was 1 mm/min under three normal stresses; 21 kPa, 37 kPa, 58 kPa. The results showed that the ultimate friction angle increased from 35.9º for the fine sand, up to 38.9º for the coarse sand.

As shown above detailed studies were conducted to study the particle size effect on the shear strength parameters of coarse and fine-grained soils, and it is noted that the shear resistance of the sample increase as the particle size increase. However, according to the author's knowledge, no studies were performed on TDA to study the effect of the particle size on the shear strength of TDA.

4.2 Experimental Setup and Material

4.2.1 Experimental Setup

Figure 4.1 shows the large-scale direct shear test setup with a sample size of 305 mm by 305 mm and a height of 230 mm that was used in this study. The height of the lower movable part of the shear box was 90 mm, and the height of the upper part was 140 mm.

This setup can shear a sample up to 50 mm horizontal displacement with a shearing rate ranging between 0.02 - 2 mm/min. The setup has a load cell and two linear variable displacement transducers (LVDTs), which were used to measure the shear force (kN), horizontal displacement (mm) and vertical displacement (mm). The load cell and the 2 LVDTs were connected to a data acquisition system to record the data from the test. The direct shear apparatus can apply normal stresses ranging between 50.1 – 293.2 kPa using a deadweight loading mechanism.

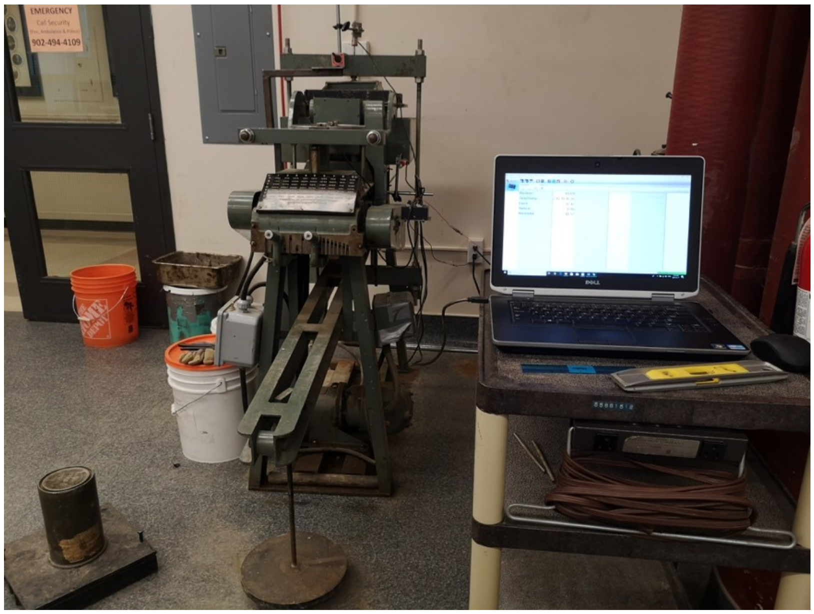

Figure 4.1 Large-scale direct shear apparatus.

4.2.2 Material

The TDA used in this research was shredded at Halifax C&D Recycling Ltd, shown in figure 4.2, using the conventional method of tires shredding by passing the tires through shredders under ambient temperature until reaching the desired particle size range. In this research, six samples having different maximum particle sizes (D_{max}); 19.05, 38.1, 50.8, 76.2, 101.6 mm and a random sample. The random sample is a random representative sample from the TDA brought from Halifax C&D Recycling Ltd, having a maximum particle size of 50.8 mm.

Figure 4.2 TDA from Halifax C&D Recycling Ltd.

Any protruding steel in the samples was removed entirely. So, the shear resistance resulting from these samples should be more conservative compared to the actual TDA used in civil engineering projects. However, the random sample was tested in its original state, having protruding steel. The samples were sieved following the procedures of ASTM C136/C136M – 14. All the samples had a particle size range starting from 9.5 mm and up to the maximum particle size (D_{max}) existing in the sample. Whereas the random sample had TDA particle sizes ranging between 9.5 – 50.8 mm, as shown below in Figure 4.3. Due to the particle size distribution for the six samples being tested, the samples fall under Type A – TDA.

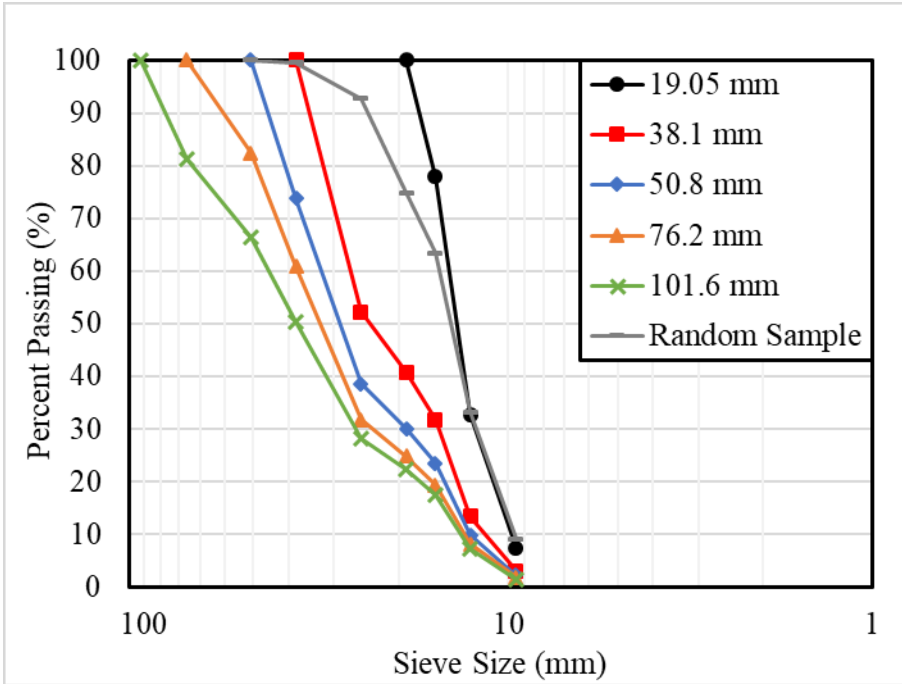

Figure 4.3 Particle size distribution of the tested samples.

The characteristics of the six samples are given below in Table 4.1. The samples had an increasing maximum particle size (D_{max}), which qualifies the samples for the study of the effect of the particle size effect on the shear strength parameters of TDA. The D_{50} for the 19.05 mm sample and the random samples was almost identical, while the maximum particle size (D_{max}) of the random sample was much higher than that of the 19.05 mm.

Table 4.1 Characteristics of The TDA used in the research

Characteristics	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Random Sample
D_{10} (mm)	9.5	12	12.8	13	15	9.5
D_{30} (mm)	12.4	16.5	19	25	27.5	12.4
D_{50} (mm)	14	25	29.5	33	39	15
D_{60} (mm)	15.5	27.5	33	39	45	16.5
D_{max} (mm)	19.05	38.1	50.8	76.2	101.6	50.8
Size Range (mm)	9.5 – **19.05**	9.5 – **38.1**	9.5 – **50.8**	9.5 – **76.2**	9.5 – **101.6**	9.5 – **50.8**
C_u	1.63	2.3	2.58	3	3	1.74
C_c	1.04	0.83	0.85	1.23	1.12	0.98

The coefficient of uniformity (C_u) was calculated as follows:

$$C_u = D_{60}/ D_{10} \quad [1]$$

While the coefficient of curvature (C_c) was calculated as follows:

$$C_c = D_{30}^2/(D_{60} * D_{10}) \quad [2]$$

4.3 Sample Preparation and Testing Scheme

4.3.1 Sample Preparation

Firstly, the samples were sieved following ASTM C136/C136M – 14. Then, the protruding steel was removed entirely. However, the random sample was tested in its original state having protruding steel to be able to compare the effect of the protruding steel on the shear resistance. After that, the retained particles on each sieve were mixed probably altogether to have less voids and to make sure that the failure plan inside the shear box is made of a representative portion of the sample.

Furthermore, proper compaction was applied to the samples with total compaction energy of 38,000 (Joules) to be within the range suggested by ASTM D6270-08 which stated that compaction energy higher than 60% of standard proctor energy will not affect the compacted unit weight of TDA significantly. Compaction was done using a modified proctor hammer following the procedures of ASTM D1557. To achieve the required compacted unit weight, TDA specimens were placed in five layers inside the shear box. Each layer was subjected to 75 blows till reaching the desired compacted unit weight, with a total of 375 blows for each sample.

4.3.2 Testing Scheme

A series of large-scale direct shear tests were performed in accordance with ASTM D3080/D3080M - 11 under strain-controlled conditions. The shear stress, horizontal displacement and vertical displacement were recorded up to 14% horizontal strain, and the angle of internal friction and cohesion were calculated at 10% relative lateral displacement as recommended by ASTM D3080. The samples were subjected to three normal stresses; 50.1 kPa, 98.8 kPa and 196.4 kPa. Normal stresses were selected based on real soil conditions, and they were applied using a deadweight loading mechanism.

The TDA specimens were sheared at a constant shearing rate of 0.5 mm/min. A low shearing rate was chosen to avoid overestimating the calculated shear resistance. The chosen shearing rate was less than that used in the literature according to the author's knowledge (Kim et al. 2014; Alias et al. 2014; Eslam et al. 2011; Vangla and Latha. 2015; Xaio et al. 2015; Humphrey et al. 1993; Foose et al. 1996; Bernal et al. 1997).

The density of the specimens before shearing, after applying the normal stresses, was calculated to assure that the tests were done under similar conditions, and it was summarized below in Table 4.2.

Table 4.2 Density before shearing (kN/m^3).

Maximum Particle Size (D_{max})	Density Before Shearing (kN/m^3)		
	50.1 (kPa)	98.8 (kPa)	196.4 (kPa)
19.05 mm	6.3	6.6	7.3
38.1 mm	6.3	6.7	7.3
50.8 mm	6.4	6.8	7.3
76.2 mm	6.3	6.7	7.4
101.6 mm	6.4	6.7	7.5
Random Sample	6.5	6.8	7.5

4.4 Results

4.4.1 Shear Strength

Figure (4.4) shows the shear stress-strain curves for the six TDA tested samples. It was found that the stress-strain curves are arranged in an increasing order depending on the increasing particle size, as shown in Figure 4.4.

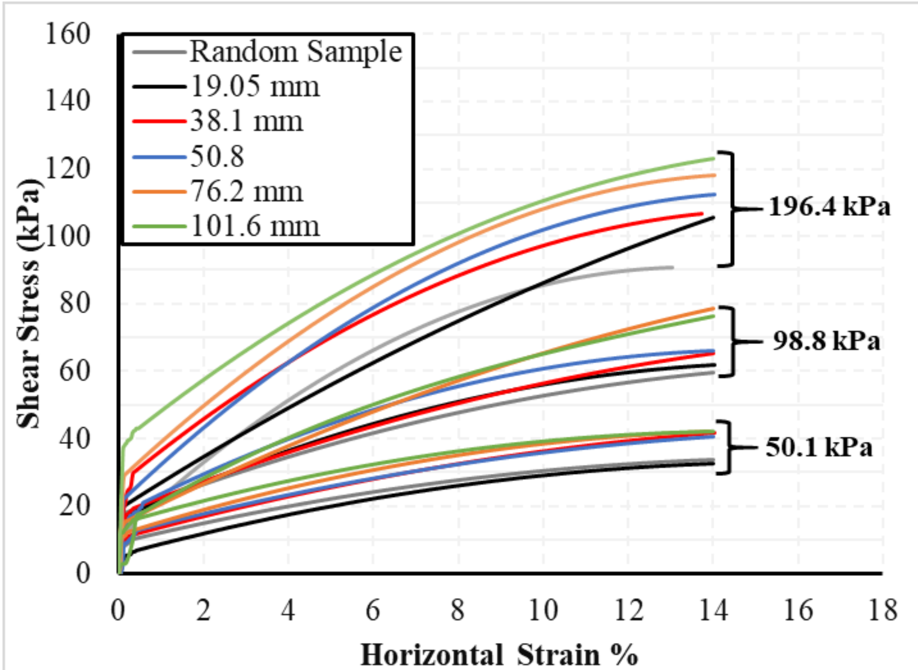

Figure 4.4 Shear Stress (kPa) Vs. Horizontal Strain (%)

The 19.05 mm sample showed the least shear stress-strain curve while the 101.6 mm sample showed the highest shear stress-strain curves under the three normal stresses. Since the average particle size (D_{50}) of the random sample and the 19.05 mm sample is very close, the two samples showed a close behaviour under the three normal stresses.

Generally, the curves showed a bi-linear behaviour with a very steep initial increase in shear stress. Then, the shear stress continued to increase with a lower slope up to 10% horizontal strain, after which most of the curves tending towards a residual.

The angle of internal friction and cohesion were defined using the Mohr-Coulomb failure criterion, and due to the absence of the peak, the failure was considered to be at 10% horizontal strain as recommended by ASTM D3080. Figure 4.6 shows Mohr-Coulomb failure envelopes for the six samples.

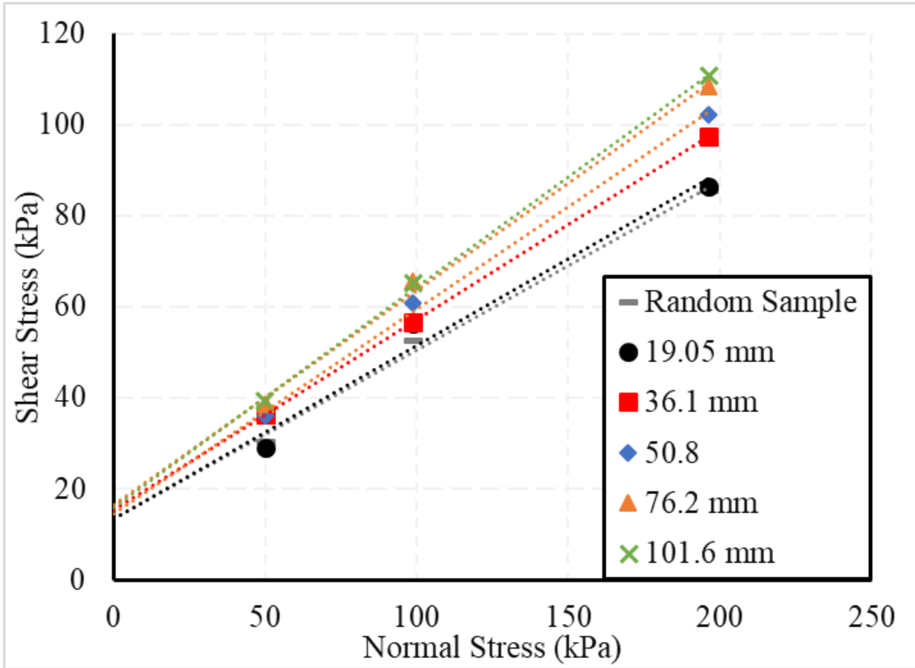

Figure 4.5 Mohr-Coulomb Failure Envelopes

From the failure envelopes above, the angle of internal friction and cohesion were calculated using the Mohr-Coulomb failure equation, as shown below in equation 4.

$\tau = c + \sigma \tan\varphi$ Equation 4

Where (τ) is the shear stress at 10% horizontal strain, (c) is the cohesion, which is the y-intercept, and (φ) is the angle of internal friction.

The angle of internal friction and cohesion were summarized in table 4.3 to ease their understanding. The Angle of internal friction showed an increase by increasing the maximum particle size, while the cohesion did not show a particular trend, neither increasing nor decreasing. However, the maximum cohesion difference is 3.1 kPa, which will not affect the geotechnical design, and the angle of internal friction will govern the shear resistance.

The random sample showed a slight increase in cohesion, compared to the 19.05 mm sample, and this could be attributed to the presence of protruding steel wires in the random sample that increases the interlocking between the particles of TDA.

Table 4.3 The Shear Strength Parameters

Sample (D_{max})	Angle of Internal Friction (°)	Cohesion (kPa)
101.6 mm	25.9	15.9
76.2 mm	25.2	16.5
50.8 mm	24.2	14.6
38.1 mm	22.7	15.3
19.05 mm	20.8	13.4
Random Sample	20.4	13.5

4.4.2 Secant Shear Modulus

The secant shear modulus (G_{50}) is a mechanical property that is used in this research to define how much shear force is required to cause deformation for TDA particles. The secant shear modulus (G_{50}) is calculated by dividing 50% of the shear stress at 10% strain by the corresponding shear strain, as shown in equation 4.3 below. The secant shear modulus for the six TDA samples tested is reported below as shown in Figure (4.5).

$$G_{50} = \frac{\tau_{50}}{\varepsilon}$$ Equation 4.3

Where (τ_{50}) is the shear stress at 10% strain and (ε) is the corresponding shear strain.

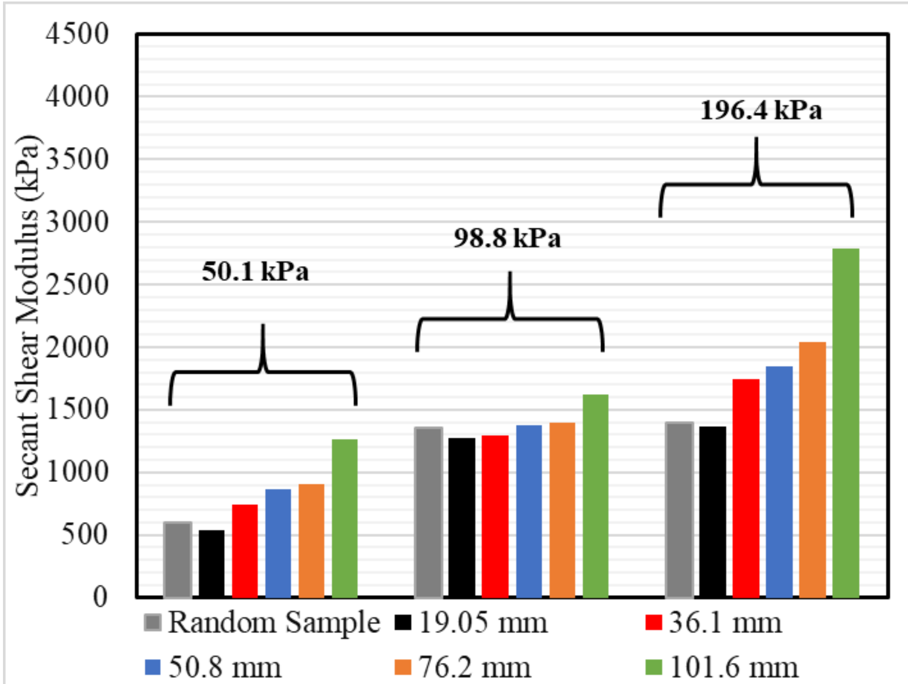

Figure 4.6 Secant Shear Modulus (kPa)

The secant shear modulus increases by increasing the maximum particle size as the 19.05 mm sample had a secant shear modulus ranging between 550 kPa - 1380 kPa. While the secant shear modulus for the 101.6 mm sample ranged between 1270 – 2800 kPa. In addition, the secant shear modulus was found to be stress depedent as it was found to increase as the applied normal stress increases. Compared to conventional soils, TDA has relatively low shear modulus, and this attributed due to TDA composition, which is mainly made of rubber.

Comparing the secant shear modulus in this study by the one reported by Iranikhah (2018) for a TDA sample with a maximum particle size of 75 mm that was obtained from Halifax C&D Recycling Ltd also. Iranikhah repoted the secant shear modulus to be within 700 - 1750 kPa, which is in agreement with the range of the secant shear modulus reported in this study and its close to the secant shear modulus of the 76.2 mm sample reported in this study which ranges between 870 to 2020 kPa. This decrease may be due to the difference in the gradation curves, compacted unit weight and void ratio. However, El Naggar et al. (2016) reported the secant shear modulus of three samples; dust, medium and coarse TDA to be around 400 kPa under 50 kPa normal stress and around 750 kPa under 100 kPa, which is expected to be less than the reported shear modulus in this study due to the difference in the particle sizes which was much smaller in El Naggar et al. (2016).

4.4.3 Strain Behaviour

The TDA samples exhibited contractive-dilative behaviour under all the applied normal stresses. Generally, a higher contraction followed by a less dilation occurs when the normal stress applied to the sample increase. Moreover, highly elastic material as TDA deforms for the following reasons: (1) Reorientation of the TDA particles, which is generally irrecoverable when unloaded; (2) Compression of the TDA particles, unlike conventional soils, and this is generally recoverable when unloaded. (3) Bending of TDA particles, unlike conventional soils, and this contributes to the majority of the compression that happens to the TDA when loaded.

Table 4.4 shows the maximum vertical deformation occurred for the six samples under the three normal stresses. The maximum difference in the vertical deformation that occurred for the sample increased by increasing the normal stress applied to the sample. Moreover, The presence of protruding steel in the random sample resulted in less deformation compared to the 19.05 mm as they have a close average particle size.

Table 4.4 Strain Behaviour for the TDA Samples

Sample (D_{max})	Maximum Vertical Deformation (mm)		
	50 (kPa)	100 (kPa)	200 (kPa)
101.6 mm	3.3	3.8	4.3
76.2 mm	2.4	3.3	3.4
50.8 mm	2.6	2.7	2.8
38.1 mm	3.2	3.6	3.9
19.05 mm	4.1	4.8	5.6
Random Sample	3.6	3.8	4.1
Maximum Difference (mm)	1.7	2.1	2.8

4.5 Conclusion

To study the particle size effect on the shear strength parameters of TDA, a series of large-scale direct shear tests were conducted on six different TDA samples using a shear box of dimensions; 305 mm * 305 mm * 230 mm. From the results of the tests, it could be observed that:

(1) The angle of internal friction of TDA increases by increasing the maximum particle size (D_{max}).

(2) The cohesion resulted from the interlocking between the TDA particles is not affected by the particle size as the cohesion increased then decreased by increasing the maximum particle size (the difference was less than 3 kPa).

(3) The average particle size (D_{50}) has a direct proportion with the angle of internal friction of TDA and this could be observed by comparing the results of the 19.05

mm sample and the random sample as they have a very close average particle size (D_{50}) and they resulted in a very close angle of internal friction while they have a different maximum particle size (D_{max}).

(4) The secant shear modulus of TDA increases by increasing the maximum particle size (D_{max}).

(5) The presence of protruding steel results in a less vertical deformation due to the excess interlocking between the sample particles.

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CHAPTER 5 EFFECT OF THE SAMPLE SIZE ON TDA SHEAR STRENGTH PARAMETERS IN TRIAXIAL TESTS

Abstract

The increasing interest in reusing scrap tires in civil engineering projects, got the attention of geotechnical engineers to conduct more researches regarding the geotechnical properties of TDA. Many factors control the value of the measured TDA shear strength parameters in the lab. One of these factors, which is know to have a determinantal effect, is the effect of the sample size on the shear strength parameters of TDA. Researches have studied the sample size effect for different kinds of natural soils using several testing equipment. However, for TDA there is a gap in studying the scale effect as the TDA particles are considered relatively large compared to the triaxial testing machines that usually exist in laboratories and according to ASTM the recommended ratio between the maximum particle size (D_{max}) for the sample being tested and the triaxial cell diameter should be 1/6 or smaller. However, for highly elastic materials as TDA, would that ratio be still valid, or the allowed ratio could be larger than 1/6. In this paper, a series of Triaxial tests were performed using four different triaxial cells with diameters of 50, 70, 100, and 150 mm. The tests were conducted on a TDA sample with a maximum particle size (D_{max}) of 25.4 mm under three confining pressures; 50, 100, and 200 kPa. The results showed that the scale effect on the shear strength parameters is negligible for samples with maximum particle size to triaxial cell diameter of 1/2.8. However, the elastic modulus (E) was found to increase slightly as the sample size decreases for all cells except for the 50 mm diameter cell which resulted in a difference that exceeded by 8%. Hence, it is recommended for triaxial testing of TDA to use a cell diameter, which is at least 2.8 times that of the maximum particle size.

5.1 Introduction

The usage of TDA in civil engineering projects started in the fourth quarter of the 20th century. TDA, at that time, was used as a backfill material for road embankments to allow construction over soft soils (Tatlisoz et al. 1998). Since that time, the research effort done on TDA to study its mechanical and geotechnical properties is rapidly increasing to extend the usage of TDA in different civil engineering applications. The research covered so many aspects of TDA like the shear strength parameters, durability, compaction energy, dry unit weight and compressibility. However, these aspects are affected by many factors like the particle size, shape, roughness, void ratio and dry unit weight of the sample being sheared. One of the main factors that affect the shear strength parameters of soil is the sample (specimen) size effect. The sample size effect for different soils was studied by many researchers using different testing equipment.

Palmeira and Milligan (1989) evaluated the specimen size effect on the shear strength parameters of sand. The tests were done on three sand samples with maximum particle sizes of 0.6 mm, 1.2 and 2 mm with a speed rate of 0.5 mm/min under a constant normal stress of 30 kPa. In this study, a series of direct shear tests using three shear boxes were used each with dimensions of; 60 mm × 60 mm × 32 mm, 252 mm × 152 mm × 152 mm and 1000 mm × 1000 mm × 1000 mm.This study showed that for the Leighton Buzzard sand samples, the specimen size has no significant effect on the shear strength parameters. . The results concluded that the angle of internal friction determined using the small shear box was 50.1°, and the medium shear box also showed an angle of internal friction equal to 50.2°, while the large shear box showed a slight increase in the angle of internal friction with a value of 49.4°. The maximum difference of the evaluated angle of internal friction was around 0.7°, which does not constitute a significant difference in the shear strength of the tested sand samples. Also, it should be noted that in Palmeira and Milligan (1989) work, the ratio between the maximum particle size and even the smallest box used was approximately 30 times which is way larger that what is suggested by the different standards for this test.

Cerato et al. (2006) conducted a series of direct shear tests using three square shear boxes; 60mm, 101.6 mm and 304.8 mm. In this study, five sand samples having a maximum particle sizes of 0.9, 1.7, 2, 5 and 5 mm were tested, each under three states; dense, medium and loose. The shearing rate used in this study was 0.25 mm/min, and the tests were conducted under five normal stresses ranging between 69 kPa – 207 kPa for the larger shear box and a range of 38 kPa – 150 kPa for the two smaller shear boxes. The results concluded that the friction angle decreased or remained constant with increasing the sample size depending on the sand type and the relative density of the sample being tested. Generally, for the coarse gravel samples, the closet in size to the particles being tested in this paper, the difference in the angle of friction was within only 2°.

A more recent research was done by Moayed et al. 2017 in which the effect of the specimen size on Firouzkooh sands shear strength was studied. The sand sample used had silt content of 0, 10, 20 and 30%. The samples were tested in three square shear boxes of dimensions; 60, 100 and 300 mm. The shearing rate was 0.9 mm/min, and the range of the normal stress applied to the samples was between 109 kPa – 436 kPa. This study concluded that the peak shear strength increases by decreasing the shear box size for all the tested samples as the angle of internal friction and cohesion for the sand sample with 0% silt content increased from 36.4° and 0.46 kPa when tested using the large shear box up to 41.6° and 19.79 kPa when tested using the small shear box. Moreover, the angle of internal friction and cohesion for the sand sample with 10% silt, increased from 34° and 0.02 kPa when tested using the large shear box up to 38.7° and 23.29 kPa when tested using the small shear box. In addition, the angle of internal friction and cohesion for the sand sample with 20% silt, increased from 32.9° and 0.03 kPa when tested using the large shear box up to 35.3° and 21.04 kPa when tested using the small shear box. Finally, the angle of internal friction and cohesion for the sand sample with 30% silt, increased from 31.7° and 0.05 kPa when tested using the large shear box up to 33.3° and 7.31 kPa when tested using the small shear box.

In the same year, Shakri et al. (2017) studied the scale size effect on the shear strength of modified soft sand samples in which Pulverized fuel ash and cement were added to the sand to strengthen the soil mixture. Two square shear boxes were used in this study having dimensions of 60 and 300 mm. The shearing rate was 1 mm/min for the 300 mm shear box, while the 60 mm shear box had a shearing rate of 0.85 mm/min. The normal stresses applied in the small shear box ranged between 30 kPa – 120 kPa, while a range of 35 kPa – 138 kPa was applied to the large shear box. The results showed that the peak shear strength increases as the shear box dimensions decrease. The sand sample with 4% cement content exhibited an increase in the shear strength from 80.93 kPa when tested using the large shear box, up to 82.2 kPa when tested using the small shear box. In addition, the sand sample with 8% cement content exhibited an increase in the shear strength from 88.97 kPa when tested using the large shear box, up to 90.85 kPa when tested using the small shear box. However, the sand sample with 12% cement content almost exhibited the same shear strength when evaluated using the two shear box with a maximum difference of 0.27 kPa. Finally, the sand sample with 16% cement content exhibited around 5.5 kPa increase in the shear resistance when evaluated using the small shear box.

Limited studies were done using triaxial tests to evaluate the sample size effect on the shear strength of soils. Scott (1987) conducted a series of drained triaxial compression tests on dense Leighton Buzzard sand samples with diameters of 38 mm and 100 mm. The samples were consolidated to have similar void ratios and confining pressures. The results of this study showed a higher peak strength and initial shear modulus in the large sample with a smaller post-peak shear strength at the end of the tests at around 15% strain.

Hu et al. (2011) investigated the sample size effect on the shear strength parameters of Loire river sand sample. In this study, three triaxial cells were used having a diameter of; 100, 500 and 1000 mm. The shearing rate of this study was kept between 1.67-2%/hr. The sand sample with a diameter of 100 mm showed an angle of internal friction of 39.6 degrees and the sand sample with 500 mm diameter showed a close angle of internal friction with a value of 39.5 degrees. However, the angle of internal friction decreased for the 1000 mm sample decreased to be 36.9 degrees. However, there was no clear trend for the obtained results with regards to the sample size effect.

Nabeshima et al. (1999) performed a series of triaxial tests to evaluate the scale effect on the shear resistance of clay samples. In this study, three triaxial cells were used, each with dimensions of; 22, 35, 50 mm in diameters and 44, 70, 100 mm in height, respectively. The tests were done under three confining pressures 50, 100 and 200 kPa in consolidated undrained conditions. The shearing rate applied to the samples was 0.05%/min to avoid any build up of the excess pore water pressure. The deviatoric stress vs. axial strain curves showed a minimal difference. However, the authors did not calculate the shear strength parameters, and the authors concluded that the specimen size did not affect the shear strength of the tested clay samples.

Kodaka et al. (2010) studied the effect of the specimen size on the shear strength parameters of sandy gravel soils using two triaxial cells. The smaller cell was 50 mm in diameter and 100 mm in height while the larger cell had a diameter of 300 mm and a height of 600 mm. The tests were done under both; drained and undrained conditions under three confining pressures; 50, 100 and 200 kPa. The shearing rate was 0.1%/min to avoid excess pore water pressure. The results showed that the friction angle increased by decreasing the sample size. A more recent study was done by Park and Jeong (2014) in which they conducted a series of triaxial tests to evaluate the shear resistance of loose and dense sand samples. In this study, two triaxial cells were used, having diameters of 50 and 100 mm and a height of 100 mm and 200 mm respectively. The tests were carried out under three confining pressures; 50, 100 and 200 kPa under drained conditions. For the loose sand sample, the drained angle of internal friction decreased from 32.9º to 32.4º. However, for the dense sand sample, the drained angle of internal friction decreased from 38.5º to 38.2º which is insignificant.

From the above, it could be shown that several studies were conducted to evaluate the specimen size effect on the shear strength parameters of different soils. However, according to the authors' knowledge, no studies were conducted on TDA to evaluate the sample size effect on its shear strength parameters. So, in this paper, a series of triaxial tests were conducted on a TDA sample using four triaxial cells, with different sizes, to evaluate the sample size effect on the measured TDA shear strength parameters.

5.2 Material

The TDA sample used in this paper was brought from Halifax C&D Recycling LTD. The sample has a particle size ranging between 9.5 mm and 25.4 mm. The sieve analysis was conducted following ASTM 6913-04, and the obtained gradation curve is shown below in Figure 5.1. The TDA sample used in this research complies with ASTM D6270-08 "Type A" TDA.

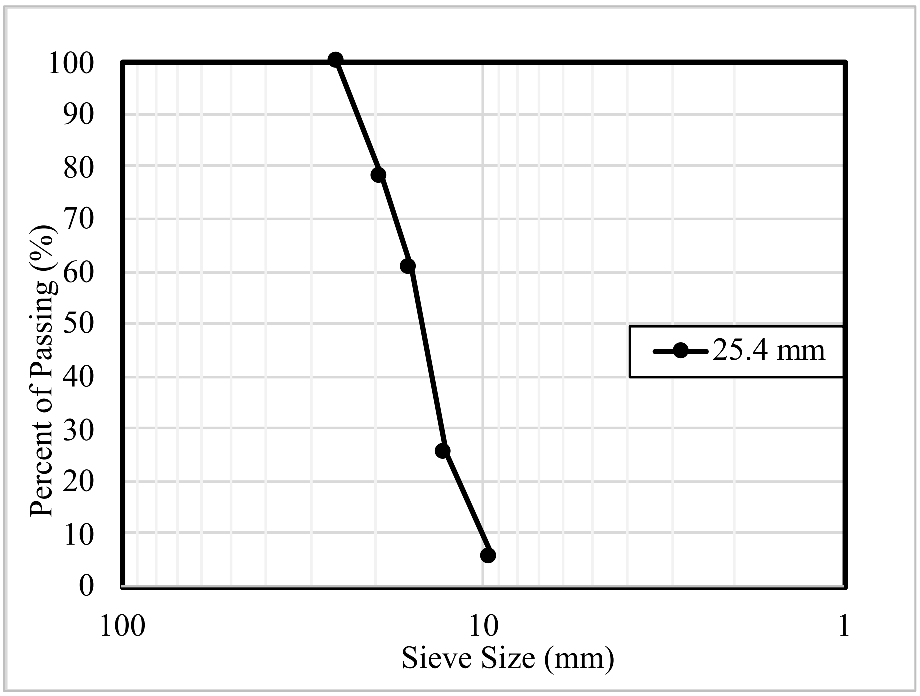

Figure 5.1 Gradation curve for the TDA sample

The protruding steel wires were removed from the sample to protect the triaxial membrane from puncturing. It is expected that removing the protruding steel wires from the TDA sample will lead to slightly less interlocking between the TDA particles so that the shear strength will be a little conservative than the shear strength of the TDA used in real projects. Moreover, the compacted unit weight of the sample was 6.6 ± 5% kN/m^3. The characteristics of the sample being tested are summarized in Table 5.1.

Table 5.1 Characteristics of the TDA sample

D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	Size Range (mm)	Coefficient of Curvature (C_c)	Coefficient of Uniformity (C_u)	Compacted Dry Unit Weight (kN/m^3)
10	13.5	15.5	16.5	9.5 – 25.4	1.65	1.1	6.6 ± 5%

The coefficient of uniformity (C_u) was calculated as follows:

$$C_u = D_{60}/ D_{10} \qquad [5.1]$$

While the coefficient of curvature (C_c) was calculated as follows:

$$C_c = D_{30}^2/(D_{60} * D_{10}) \qquad [5.2]$$

5.3 Triaxial Test Apparatus

Four triaxial cells were used in this research with dimensions (diameter by height) of 50 by 130 mm, 70 by 150 mm, 100 by 220 mm and 150 by 320 mm. The height to diameter ratio (H/ Ø) for all the samples was kept between 2 to 2.5, within the recommended range suggested by ASTM D7181-11. The axial loading was done using Instron 8501 hydraulic load frame. The shearing rate was 1 mm/min calculated in compliance with ASTM D7181-11 to allow the dissipation of any excess pore water pressure. The load and the axial displacement were recorded by an external load cell and a linear variable displacement transducers (LVDT) at a frequency of 20 Hz. Two GDS Advanced Pressure-Volume Controllers (ADVDPC) were used to control the volume change of the sample, and also to control the cell pressure and the back pressure during the shearing phase. Both controllers were kept at the same height and calibrated before each test. Figure 5.2 shows the two triaxial apparatus used in this research. The large triaxial cell was used to accommodate the

100 and 150 mm samples, whereas the small triaxial cell accommodated the smaller 50 and 70 mm samples.

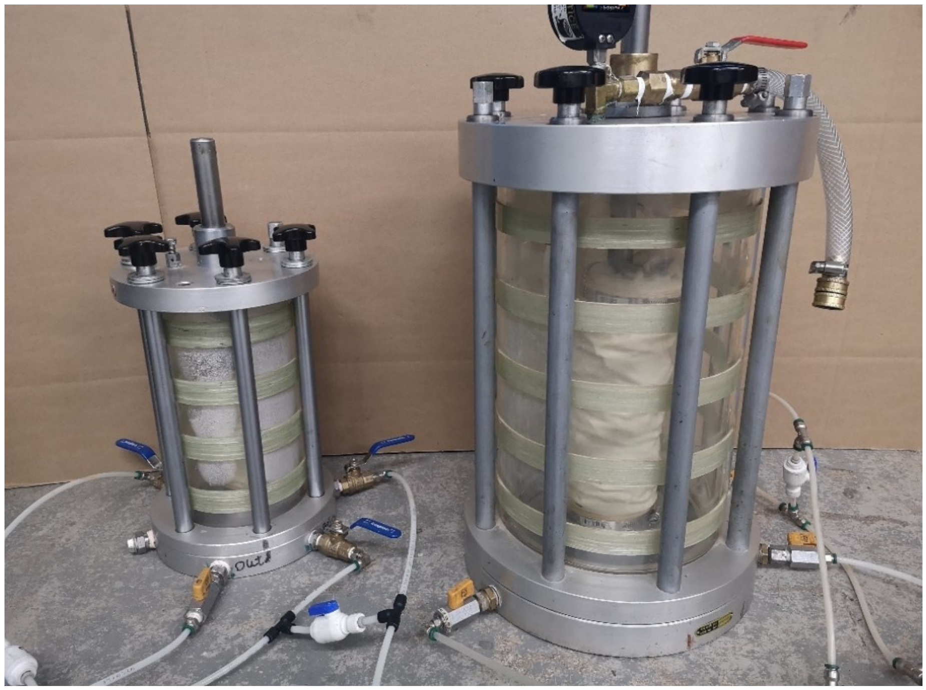

Figure 5.2 The Triaxial apparatus used in the study

The height of the shaft used in the test apparatuses was increased to accommodate the excessive consolidation that occurs to TDA due to the large voids that exist between the particles and also to allow reaching the targeted 20% strain regardless of the sample height. The connection between the shaft and specimen cap was a fixed connection so that the titling in the specimen cap will be minimal as recommended by ASTM D7181 – 11 as TDA has very random particle shapes, so it will be tough to level the surface of the sample without cap tilting. This kind of connection was modified after Baldi et al. (1988) by permission from ASTM International, and it was verified by some researchers such as Lade (2016).

5.4 Testing Scheme

5.4.1 Sample Preparation Stage

After conducting the sieve analysis and removing the protruding steel wires, the specimens were compacted using a modified proctor hammer for the larger compaction molds, while for the smaller compaction molds a steel rod was used to compact the sample. Extensive care was given to the membrane during compaction, and the compaction was done on five layers. Each layer was compacted till reaching the desired compacted unit weight of 6.6 ± 5% kN/m^3 following the procedures specified in ASTM D1557. According to ASTM D6270-08, compaction energy higher than 60% of the standard proctor will not affect the compacted unit weight of TDA significantly. So, the compaction energy used in this study was equal to or slightly higher than 60% of the standard proctor energy. The compaction was done on air-dried samples as researchers found that oven-dried TDA has slightly different physical properties and adding water content to the sample before compaction will not affect the compacted unit weight (Humphrey et al. 1992; Ahmed. 1993; Humphrey et al. 1993; Moo-Young et al. 2003).

The sample preparation was done in the following steps with extensive care given through the preparation to prevent the membrane from puncturing: (1) The split compaction mold was secured around the bottom and the top using hose clamps. (2) A relatively thick Humboldt member with a thickness of 0.635 mm was stretched around the split mold. (3) A bottom plate was secured to cover the bottom part of the mold. (4) Vacuum was applied between the membrane and the compaction mold so the membrane will fit tightly, and no wrinkles will exist in the membrane. (5) The sample was divided into five layers, and each layer was weighed and added to the mold. (6) Each layer was compacted until reaching the desired compacted dry unit weight. (7) The surface was leveled as much as possible. Then, (8) The porous stone was added to the top surface of the sample and the sample was inverted and centred over the bottom base of the triaxial covering the two water inlets of the bottom base of the triaxial. (9) The hose clamps were removed slowly to avoid disturbance to the sample, and the split mold was removed. (10) The porous stone and the specimen cap were added to the top surface of the sample after levelling it as possible. (11) One hose clamp was secured around the specimen cap and another one around the base of the triaxial. (12) Three readings of the initial sample height and diameter were recorded to calculate the initial volume of the specimen. (13) The shaft was connected to the specimen cap with grease on it, to minimize the friction, and the cylindrical triaxial cell was assembled and placed in the center of the load frame. (14) the loading frame was lowered to be barely touching the sample so that the uplift force, during saturation, will not push the shaft upward.

5.4.2 Saturation Stage

Water was pumped to the triaxial cell at a low pressure of 10 kPa to circulate through the whole triaxial cell, pipes and the two advance pressure-volume controllers while the drainage is kept open so the entrapped air will flow out of the system. This flushing process helped in minimizing the errors resulting from the compression of the entrapped air.

Then, back pressure is applied to the specimen so that the air voids inside the sample is filled with water and drive air into the solution so the entrapped air will be removed completely from the system. Due to the high drainage coefficient of TDA, the saturation is relatively simple and fast compared to conventional soils. The Skempton's pore water pressure parameter (B) was used to measure the degree of the sample saturation, and all the samples were saturated until reaching a minimum (B) value of 0.98.

5.4.3 Consolidation Stage

Similar to the saturation stage for the samples, the consolidation also is considered relatively fast. The consolidation stage is done by increasing the confining pressure while keeping the specimen pore pressure constant. Three confining pressures were used in this research; namely 50, 100 and 200 kPa. The volume of water driven out of the sample during the consolidation stage was measured using a plastic graduated measuring cylinder to be used in calculating the volume of the sample after consolidation.

5.4.4 Shearing Stage

To measure the shearing rate, the volumetric change was plotted against the logarithm of the time elapsed, and due to the high permeability of TDA, the calculated shearing rate was found to be higher than the rate that could be controlled by our volume pressure controllers. So, a rate of 1 mm/min was used for all samples. Axial strain up to 30% was achieved in the initial samples. However, under high strain levels, the samples were subjected to a severe potential of membrane puncturing, so a strain level of only 20% was chosen for the tests. The 20% strain is morethan sufficient since the TDA has no peak in its stress-strain curve, and according to ASTM D7181- 11, in the case of absence of maximum stress, the deviatoric stress at 15% should be considered as the maximum stress. However, several practitioners also considered the deviatoric stress at 10% strain as the maximum stress. In this paper, the shear strength parameters will be calculated at both10% and 15% strain.

Usually, TDA experiences a linear bulging after 10% strain due to the tilting of the specimen cap. However, using a fixed connection between the specimen cap and the shaft resulted in a right circular cylinder deformation as shown in Figure 5.3.

Figure 5.3 The sample deformation at 20% strain

5.4.5 Corrections

Triaxial tests have several sources of errors that need to be corrected for in order to obtain accurate results. Correction for the cross-sectional area during the shearing phase is considered the primary source of errors in triaxial tests. Several researchers studied the cross-sectional area correction factor were they recommended different correction equations to calculate the effective cross-sectional area as summarized in Table 5.2. However, in this research, a developed MATLAB model was done to get an exponential equation for the volumetric change from which the effective cross-sectional area and the volumetric strain were calculated for each of the conducted tests.

Table 5.2 Cross-sectional area correction equations reported by different researchers

Study	**Area Correction Equation**	**Deformation Shape**
La Rochelle et al. 1988	$A = A_o\,(1-\varepsilon_v)/(1-\varepsilon_a)$	Right Circular Cylinder
La Rochelle et al. 1988	$A = A_o \times \left[-0.25 + \sqrt{(25 - 20\varepsilon_a - 5{\varepsilon_a}^2)}/4\,(1-\varepsilon_a)\right]^2$	parabolic
Zhang and Garga 1997	$d_{max} = \frac{d_c}{4}\left[\left\{30\,\frac{(1-\varepsilon_v)}{(1-\varepsilon_a)}\right\} - 5\right]^{\frac{1}{2}} - 1$	parabolic

*where: A = corrected area of the specimen, A_o = initial area of the specimen, ε_v= volumetric strain of sample and ε_a = axial strain of sample.

5.5 Results

A total of 18 triaxial tests were conducted under consolidated drained conditions using three confining pressures; 50, 100, 200 kPa to resemble the stress levels expected in backfills, embankments and surrounding retaining walls. Four triaxial cells were used to evaluate the effect of the sample size on the shear strength parameters of one TDA sample, having a size range of 9.5 – 25.4 mm. six of the tests were used for the consistency and repeatability exercise.

5.5.1 Consistency and Repeatability of the Tests

The random nature of TDA arises some doubts regarding the repeatability and accuracy of the driven tests. So, the tests done using the 150 mm triaxial cell were duplicated under the three confining pressures to validate the repeatability and accuracy of the results. Figure 5.4 shows that the deviatoric stress-strain curves of the duplicated tests are in agreement, which proves the consistency and the accuracy of the results. The volumetric strain for the duplicated tests also showed an agreement between the results, as shown in Figure 5.5. The difference between the curves is minimal that could be neglected and will not make a significant difference in evaluating the shear strength parameters.

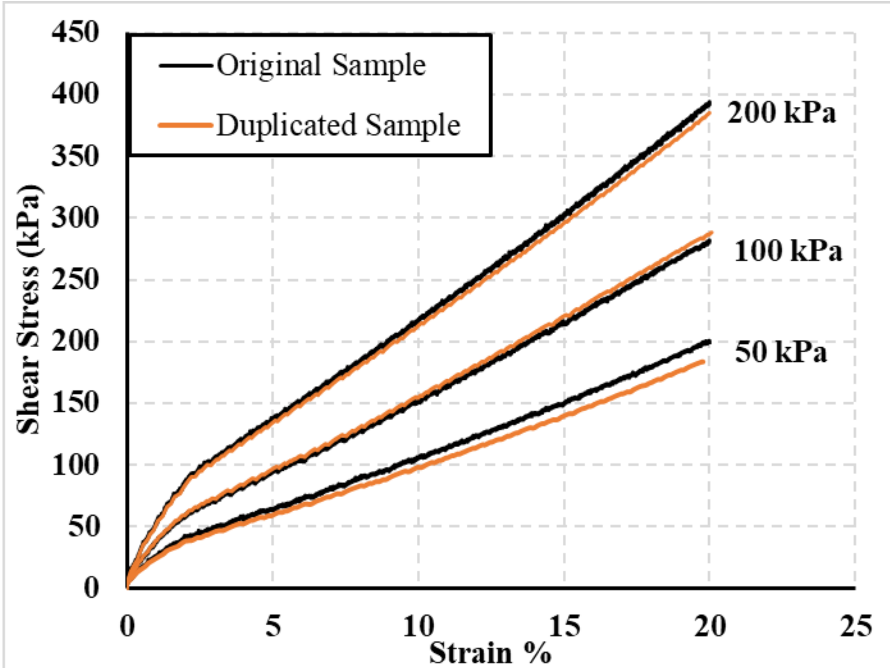

Figure 5.4 Deviatoric stress Vs. strain curves for the duplicated tests

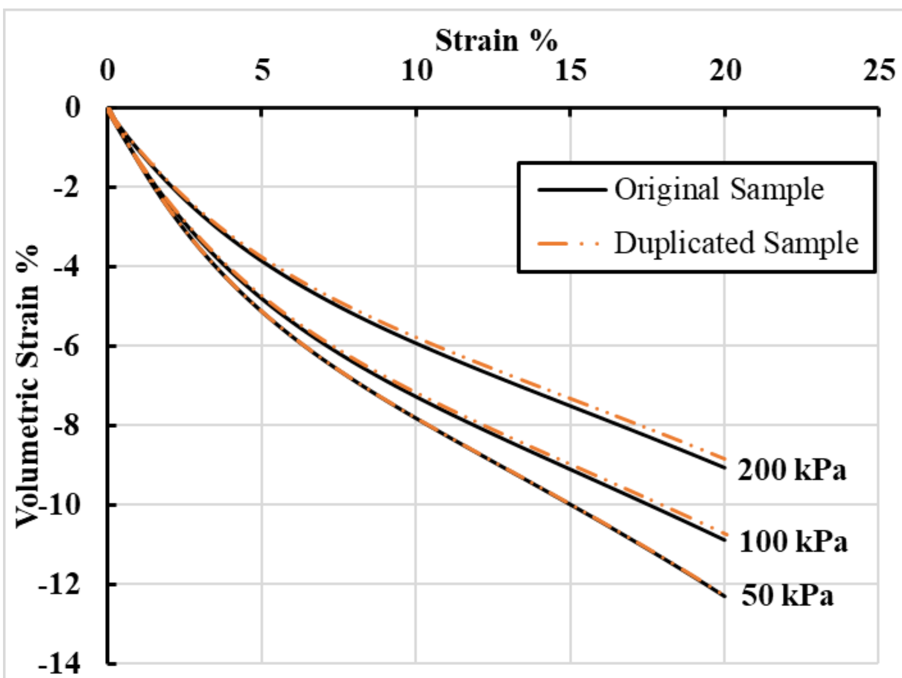

Figure 5.5 Volumetric strain Vs. strain % curves for the duplicated tests

5.5.2 Stress-Strain Curves

Figure 5.6 shows that the samples undergo a bilinear behaviour. After the initial steep increase in the deviatoric stress up to 3% strain, the samples showed a linearly increasing deviatoric stress with strain, which is confirming with the previous studies conducted by different researchers (Youwai and Bergado 2003; Masad et al. 1996; Lee et al. 1999 and Zornberg et al. 2004). These researchers reported a fairly linear behaviour for the tested TDA samples. The slight difference in the behaviour between this research and the previous studies may be attributed to the different particle size ranges used and the different compositions between the samples as the particle's composition depend on the TDA manufacturer. It may also be attributed to the different void ratios and unit weights of the samples being tested. However, with the random nature of TDA, the results of the different researchers and this research are in agreement.

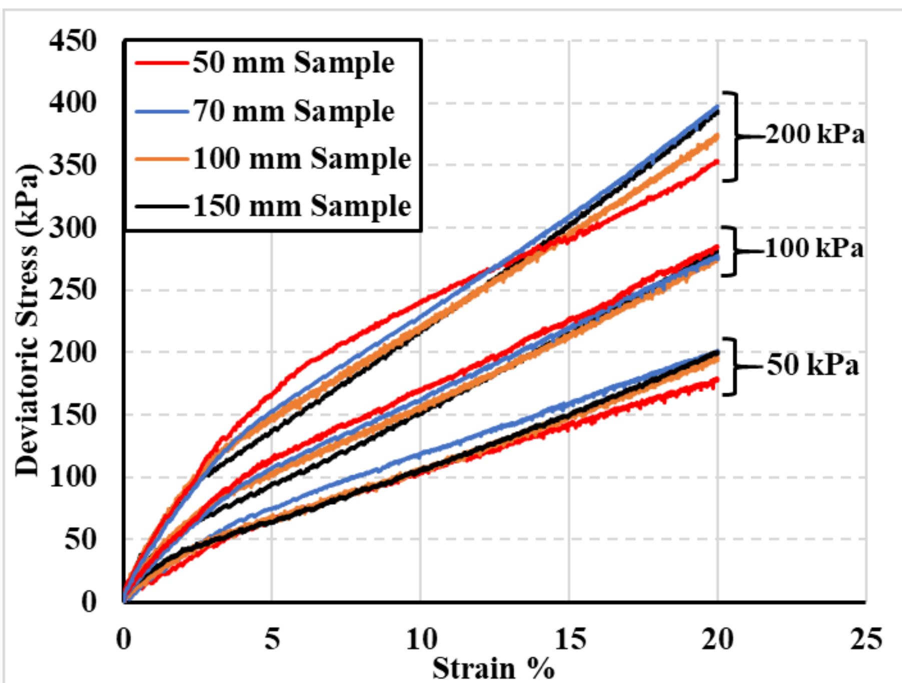

Figure 5.6 Deviatoric stress-strain curves for the tested samples

It is evident that the deviatoric stress-strain curve never reached a peak during the tests. According to ASTM D7181 – 11, in case of absence of maximum principal stress, the deviatoric stress at 15% strain should be considered as the maximum stress. Several researchers and practitioners are commonly considering the deviatoric stress at 10% strain as the maximum stress to be used in calculating the angle of internal friction and cohesion. The angle of internal friction and cohesion calculated by the Mohr-Coulomb failure criterion will be different depending on the maximum stress considered to be at which strain. In this study, the maximum stress is considered to be at 10% and 15% strain. The Mohr-Coulomb failure criterion, as shown below in equation 5.3, was used in calculating the angle of internal friction and cohesion for the tested sample.

$$\tau = c + \sigma \tan\varphi \qquad \text{Equation 2.3}$$

Where (τ) is the deviatoric stress at 10% and 15% strain, (c) is the cohesion, which is the y-intercept, and (φ) is the angle of internal friction.

Table 5.3 shows the reported angle of internal friction and cohesion in this research. It is clear that the calculated angle of internal friction for the TDA sample is almost constant when evaluated using different sample sizes. Also, the difference in cohesion exhibited between the sample sizes is negligible and will not affect the design parameters. The average angle of internal friction and cohesion reported in this research was 21.7° and 31.2 kPa, respectively, when considering the maximum stress to be at 15% and was 18.2° and 21.6 kPa, respectively, when considering the maximum stress to be at the 10% strain level. The reported friction angles are in agreement with the previous study conducted by Humphrey et al. (1993) as the repoted friction angles ranged between 19° to 25° for different TDA samples. While Zornberg et al. (2004) reported a friction angle of 21.4° for a TDA sample with a maximum particle size of 12.7 mm.

Table 5.3 Angle of internal friction (°) and Cohesion (kPa) for the tested sample

Triaxial Cell Diameter (D_{max})	**Strain 10%**		**Strain 15%**	
	Angle of Internal Friction (°)	**Cohesion (kPa)**	**Angle of Internal Friction (°)**	**Cohesion (kPa)**
50 mm	18.3	22.1	21.6	30.6
70 mm	18.2	22.4	21.6	31.1
100 mm	18.1	20.4	21.7	30.9
150 mm	18.3	21.6	21.8	30.9
Average	18.2	21.6	21.7	31.2

5.5.3 Volumetric Strain

The deformation that occurs for saturated soils is mainly due to the expulsion of the water from the voids within the sample, the reorientation between the soil particles to fill these voids and the deformation of the soils particles which is considered insignificant (Yi et al., 2015). However, for a highly elastic material like TDA, when the axial loading is applied, the TDA compresses due to: (1) reorientation of TDA particles within the sample, similar to conventional soil, and this is generally irrecoverable when unloaded; (2) The compression of the TDA particles, unlike to conventional soils, and this is generally recoverable when unloaded due to the perfect elastic behaviour of TDA which is mainly made of rubber with Poisson's ratio nearly equal to 0.5; (3) The bending of the TDA particles, unlike to conventional soils, and this contributes to the majority of the compression of the TDA samples and this also recoverable when unloaded (Meles, 2014). Figure 5.7 compares the volumetric strain that occurred for the samples under the three confining stresses. All the samples showed a volumetric contraction with a steady decrease in the volumetric change rate as the axial strain increase. The confining pressure was inversely proportional to the volumetric strain as the volumetric strain decreased when the confining pressure increased. This could be attributed to the presence of less voids inside the samples when the confining pressure increases and the steady decrease in the volumetric change rate with strain are due to the expulsion of the water out of the sample to the pressure controller to keep the confining pressure constant during the test. So, at low strains, samples have more voids filled with water, and during the shearing phase, these voids start to decrease, so the water coming out of the sample starts to decrease as well.

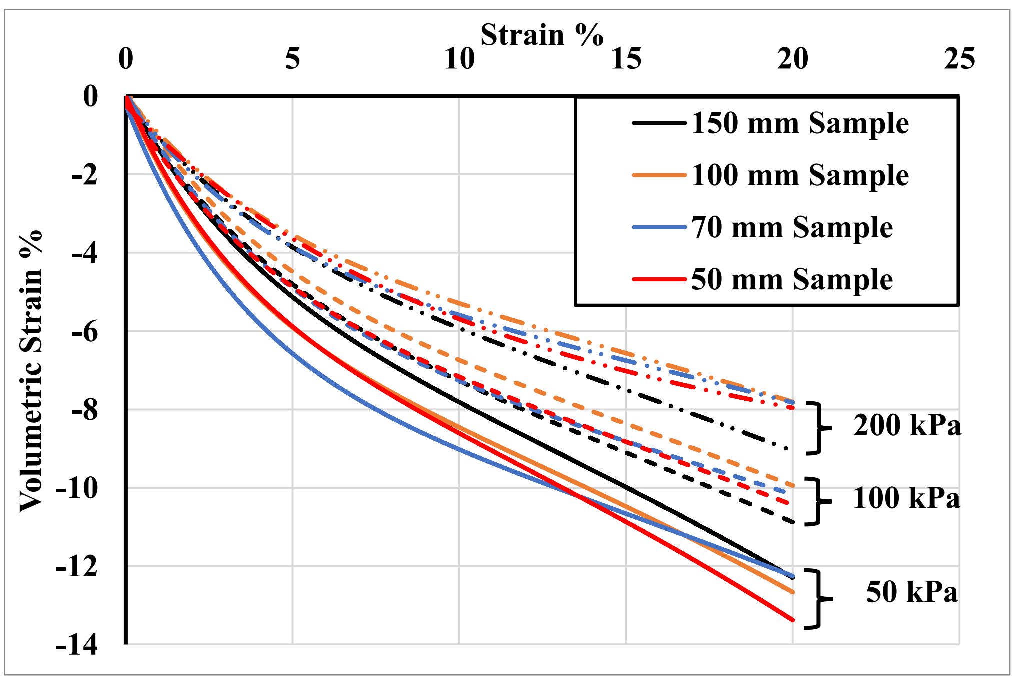

Figure 5.7 Volumetric strain for the tested samples

Comparing the volumetric strain of the samples conducted in this research to the previous work done by Youwai and Bergado in 2003 and Wu et al. 1997, it was observed that in this research the volumetric strain exhibited a steep initial contraction up to 5% strain then the contraction becomes almost linear unlike the fairly linear volumetric strain reported by Youwai and Bergado and Wu in their studies.

5.5.4 Stiffness

To study the effect of the sample size on the stiffness of the tested TDA sample, the values for the secant modulus E_{50} were calculated for each test and reported in Figure 5.8. The secant modulus of elasticity (E_{50}) was calculated using the following Equation:

$$E_{50} = \frac{\tau_{50}}{\varepsilon} \qquad \text{Equation 5.4}$$

Where (τ_{50}) is the deviatoric stress at 10% strain and (ε) is the corresponding axial strain.

Figure 5.8 showed a decreasing secant elastic modulus as the sample size increase. The decrease in the elastic modulus may be attributed to the freedom for the particles to reorient inside the sample. The ratio between the maximum particle size (D_{max}) and the triaxial cell diameters ranged between 1/6 – 1/2. So, with a fixed D_{max} and an increasing cell diameter, the particles will have more freedom to reorient within the sample while the sample is under axial loading. The reported elasticity modulus for the 150, 100 and 70 mm samples deviated within 3% around the average modulus which ranged between 1500 – 4000 kPa, when considering the maximum stress to be at 10%. However, the 50 mm sample showed a 8% increase from the average reported elastic modulus which would affect the geotechniocal designs. At 50 kPa normal stress, all the samples exhibited a close stiffness with a slight increase in the 70 mm sample. However, at 100 and 200 kPa normal stresses, the 150, 100 and 70 mm sample showed a close elastic modulus with a maximum difference around 3% while the 50 mm sample showed an 8% increase in the secant elastic modulus. This behaviour of decreasing elasticity modulus with an increasing sample size was reported by Omar 2013 when a loose sand sample was tested using 3 sample sizes; 38, 50 and 70 mm under both drained and undrained conditions.

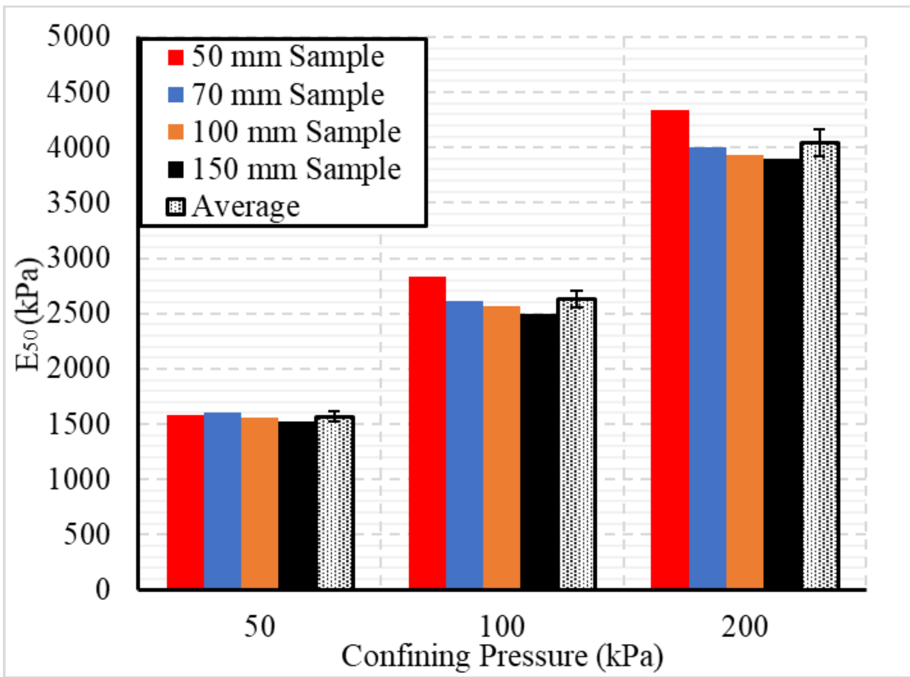

Figure 5.8 Secant elastic modulus for the tested sample at 10% strain.

Generally, the reported elasticity modulus in this study is within the range of the elasticity modulus of tires rubber reported by Beatty 1981, which ranged between 1200 – 5100 kPa, while higher than the range of the elasticity modulus reported by Wu et al. 1997 which ranged between 580 – 690 kPa for a TDA sample with maximum particle size of 38 mm under low confining pressures. This difference could be attributed due to: (1) the difference in the weight unit between the TDA samples used in Wu's study and this study as Wu reported the unit weight to be 6 kN/m^3 while the unit weight in this study is 6.6 kN/m^3. (2) The difference between the particle size distribution between the two samples. (3) TDA shows a significantly different behaviour in the deviatoric stress-strain curve and the volumetric strain under low confining pressures less than 25 kPa, as reported by Ashari (2018) and Lee et al. 1999.

5.6 Conclusion

The main objective of this study is to evaluate the sample size effect on the TDA shear strength parameters in triaxial tests. An experimental program of 18 consolidated drained triaxial tests was conducted on 4 sample sizes; 50, 70, 100 and 150 mm in diameter under three confining pressure; 50, 100 and 200 kPa. The results of the experimental program indicated that:

1- For the tested sample, the sample size has a negligible effect on the shear strength parameters.
2- The reported volumetric strain did not show a direct correlation, neither increasing or decreasing, with the sample size. However, the maximum volumetric strain difference between the four sample sizes is around 1.5%.
3- The secant elastic modulus for the 150, 100 and 70 mm samples was very close. However, 8% increase in the secant elastic modulus was observed for the 50 mm sample. Such an increase might affect the geotechnical design.
4- Based on this study, the recommended ratio between the maximum particle size (D_{max}) and the triaxial cell diameter to use when evaluating the shear strength parameters of TDA is 1/2.8 or smaller.

5- The 1/6 or smaller ratio recommended by ASTM D7181 -11 should be re-evaluated for testing a highly elastic material as TDA, and higher ratios up to 1/2.8 can be reasonably used without affecting the obtained strength parameters.

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CHAPTER 6 EFFECT OF THE PARTICLE SIZE ON TDA SHEAR STRENGTH PARAMETERS IN TRIAXIAL TESTS

Abstract

The increasing interest in reusing discarded tires in civil engineering projects, got the attention of geotechnical engineers to conduct more research regarding the geotechnical properties of TDA. Many factors control the measured geotechnical properties of TDA, and researchers cannot keep pace with evaluating those factors. One of the factors known to have a significant effect is the particle size effect on the shear strength parameters of TDA. Researches have studied the particle size effect for different kinds of soils using several testing equipments. However, for TDA there is a gap in studying the particle size effect as TDA particles are considered relatively large compared to the triaxial testing machines that usually exist in laboratories and according to ASTM the recommended ratio between the maximum particle size (D_{max}) for the sample being tested and the triaxial cell diameter (Ø) should be 1/6 or smaller. So, researchers are forced to evaluate TDA particles smaller than the actual TDA particle sizes used in civil engineering projects. However, as shown in the previous chapter that the sample size did not affect the shear strength parameters of TDA up to a ratio of 1/2.8 between the D_{max} and Ø. So, In this paper, a series of large-scale triaxial tests were performed using a 150 mm triaxial sample. Tests were conducted on five TDA samples with a maximum particle size (D_{max}); 19.05, 25.4, 38.1, 50.8 and 76.2 mm. The tests were done under consolidated drained conditions using three confining pressures; 50, 100, and 200 kPa. The results showed that the shear strength of TDA increase by increasing the maximum particle size while the cohesion did not show a specific trend.

Moreover, the samples exhibited an increase in the secant elastic modulus by increasing the particle size.

6.1 Introduction

In order for TDA to be used in civil engineering projects, its characterization must first be assessed in order to be used with confidence in its properties. The geotechnical characterization is one of the main characteristics which is essential for the adoption of the TDA in such an industry. However, TDA particles are considered relatively large compared to the standard testing equipment available, and therefore practitioners are forced to test smaller TDA particle sizes that are not representative of the actual sizes used in the different TDA applications. Hence, the main focus of this work is studying the effect of the particle size on the shear strength parameters of TDA.

One of the earliest studies for the particle size effect was done by Kirkpatric (1965) to study the effect of the particle size on the shear strength parameters of sand and glass beads. Five sand samples were tested, having increasing maximum particle size ranging between 0.39 mm and 2 mm. Besides, three glass beads sample with maximum particle sizes ranging between 0.3 mm and 0.58 mm. The results of this study showed that for the sand samples, the shear resistance slightly decreased with increasing the particle size. However, the glass beads samples showed an increasing shear resistance with increasing particle size.

Islam et al (2011) investigated the effect of particle size on the shear strength parameters of sands. Eight samples were tested having uniform particle sizes ranging between 0.075 mm and 2.76 mm. Besides, two samples having graded particle sizes (0.075-1.18 mm and 0.075-2.36 mm) were tested. Tests were performed with a circular shear box with a diameter of 50.8 mm under a constant rate. The results showed that the angle of internal friction increased from 35.54º up to 42.24º for the samples with uniform particle sizes and for the two samples with graded particle sizes, the angle of internal friction increased from 41.18º to 41.83º.

Kim et al (2014) investigated the shear strength parameters of 3 coarse grained soil samples having increasing maximum particle sizes; 4.75 mm, 7.9 mm and 15.9 mm. The samples were tested in a large scale 300 mm square shear box. The tests were performed under three confining pressure; 98, 196 and 294 kPa using a constant shear rate of 1 mm/min. The results showed that the angle of internal friction increased from 40.56º for the 4.75 mm sample, up to 54.04º for the 15.9 mm sample.

On the same year, Wang et al (2014) studied the particle size effect on the shear strength of accumulation soil was conducted by. In this study, ten accumulated soil samples were tested, five in a 500 mm square direct shear box and the other five in a triaxial testing machine having a 100 mm cell diameter and 200 mm height. The samples had an increasing average particle size (D_{50}) with a fixed maximum particle size (D_{max}). The shearing rate used in the study was 0.1mm/min at four confining pressures 100, 150, 200 and 250 kPa. Generally, the results showed that the shear resistance increased with increasing the average particle size of the sample being tested as the results from the direct shear tests indicated that the range of the angle of internal friction of the accumulation soil was 33.5–54.6º, while that reported from the triaxial tests indicate was 37.2–50.7º.

Moreover, Vangla and Latha (2015) investigated the particle size effect on three sand samples. The tested samples were fine, medium and coarse samples. The maximum particle size for the samples ranged between 0.425 mm and 4.75 mm. The tests were conducted using a large-scale direct shear test with a 300 mm square shear box of dimensions under three normal stresses; 21 kPa, 37 kPa, 58 kPa. The results showed that the ultimate friction angle increased from 35.9º for the fine sand, up to 38.9º for the coarse sand.

As seen above, limited studies on the impact of particle size on the shear strength parameters of different soils have been performed using triaxial tests, and according to the author's knowledge, no research was done on to study the particle size effect on the shear strength parameters of TDA.

6.2 Material

The samples tested in this research were shredded at Halifax C&D Recycling Ltd, using the conventional method of tires shredding by passing scrap tires through shredders under normal temperatures till reaching the targeted particle size range. In this study, five TDA samples having different maximum particle sizes (D_{max}); 19.05, 25.4, 38.1, 50.8 and 76.2 mm were tested.

Figure 6.1 TDA from Halifax C&D Recycling Ltd.

Any protruding steel wires from the TDA particles were removed entirely to protect the triaxial membrane from puncturing. So, the shear strength parameters, especially the cohesion, resulting from these samples is expected to be slightly conservative compared to the actual TDA used in civil engineering applications. The samples were sieved following the procedures of ASTM C136/C136M – 14. The TDA samples in this study were having a particle size range between 9.5 mm up to the maximum particle size (D_{max}) existing in each sample, as shown in the gradation curves in Figure 6.2. Besides, the samples were named according to their maximum particle sizes (D_{max}). The compacted unit weight of the samples was 6.6 ± 5% kN/m^3.

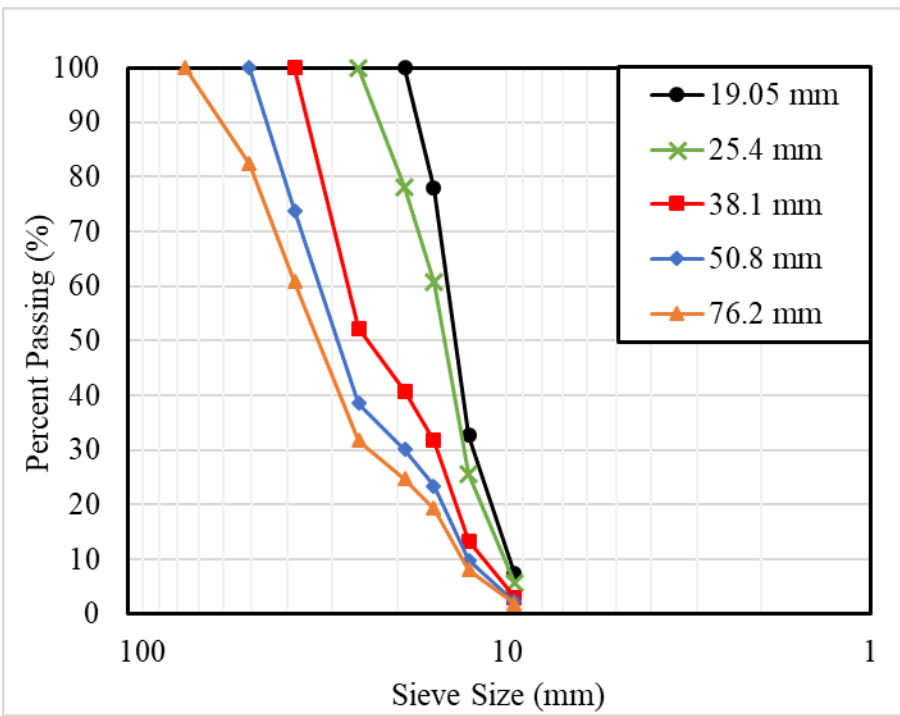

Figure 6.2 Gradation curves for the five samples.

The properties of the five samples were summarized in Table 6.1. The coefficient of uniformity increases as the maximum particle size increases, which means that the sample with larger particle sizes is covering more particle size range than the samples with smaller particle sizes.

The coefficient of uniformity (C_u) was calculated as follows:

$$C_u = D_{60}/\ D_{10} \qquad [1]$$

While the coefficient of curvature (C_c) was calculated as follows:

$$C_c = D_{30}^2/(D_{60} *\ D_{10}) \qquad [2]$$

Table 6.1 Characteristics of the TDA used in the research

Characteristics	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5
D_{10} (mm)	9.5	10	12	12.8	13
D_{30} (mm)	12.4	14	16.5	19	25
D_{50} (mm)	14	16	25	29.5	33
D_{60} (mm)	15.5	17	27.5	33	39
D_{max} (mm)	19.05	25.4	38.1	50.8	76.2
Size Range (mm)	9.5 – 19.05	9.5 – 25.4	9.5 – 38.1	9.5 – 50.8	9.5 – 76.2
C_u	1.63	1.7	2.3	2.58	3
C_c	1.04	1.15	0.83	0.85	1.23

6.3 Triaxial Test Apparatus

In total, 18 consolidated drained large scale triaxial tests were performed to assess the effect of the particle size on the shear resistance of TDA. The samples were tested using a triaxial cell with dimensions; 150 mm in diameter by 320 mm in height. The height of the sample to the cell diameter ratio (H/ Ø) is 2.1, which falls between the recommended range suggested by ASTM D7181-11. The axial loading was done using Instron 8501 hydraulic load frame. A 1 mm/min shearing rate was used in this study that was calculated in compliance with ASTM D7181-11 to allow the dissipation of any excess pore water pressure. An external load cell was used to record the axial load. Moreover, a linear variable displacement transducer (LVDT) was used to record the axial displacement. Two GDS Advanced Pressure-Volume Controllers (ADVDPC) were used to record the volume change of the sample and control the pressure during the shearing phase. The two pressure-volume controllers were kept at the same height and calibrated before each test to minimize the errors. Figure 6.3 shows the triaxial apparatus used in this research.

Figure 6.3 The Triaxial testing setup

The height of the shaft used in the triaxial apparatus was increased to accommodate the excessive consolidation that occurs to the TDA samples due to the presence of large voids between the TDA particles and also to allow reaching the targeted 20% strain level. The connection between the piston and specimen cap was a rigid connection so that the titling in the specimen cap will be minimal as recommended by ASTM D7181 – 11. Choosing a rigid connection between the shaft and the specimen cap is recommended when testing a highly elastic material as TDA as TDA particles have very random shapes that will be too tough to level the surface of the sample without cap tilting. This kind of connection was modified after Baldi et al. (1988) by permission from ASTM International, and it was verified by some researchers as Lade (2016).

6.4 Testing Scheme

6.4.1 Sample Preparation Stage

The TDA samples were checked for any protruding steel wires to avoid the puncture of the triaxial membrane. The specimens were compacted using a modified proctor hammer. Extensive care was given to the membrane during compaction to avoid membrane puncturing, and the compaction was done on five layers. According to ASTM D6270-08, compaction energy higher than 60% of the standard proctor will not affect the compacted unit weight of TDA significantly. So, compaction energy equal to, or slightly higher than, 60% of the standard proctor was applied to each sample. Researchers found that oven-dried TDA has different physical properties and adding water to the sample will not affect the compacted unit weight. So, compaction was done air-dried samples (Humphrey et al. 1992; Ahmed. 1993; Humphrey et al. 1993; Moo-Young et al. 2003).

The sample preparation was done in the following steps. First, the split mold was secured around the bottom and the top using hose clamps and a relatively thick Humboldt member was stretched around the split mold. Then, vacuum was applied between the membrane and the compaction mold so the membrane will be stretched. After that, the sample was divided into five portions and each portion was weighed and added to the mold so that the compaction will be applied on five layers till reaching the targeted compacted unit weight. Next, the surface was leveled and a porous stone was added to the top of the sample and the sample was inverted and centred over the base of the triaxial covering the two water inlets. The specimen cap and a porous stone were added to the top surface of the sample after levelling it as possible. In order to ensure the isolation between the cell pressure and the backpressure, two hose clamps were tightly secured around the specimen cap and the triaxial bottom plate. After that, the sample height and diameter were measure three times to calculate the initial volume of the specimen. Then, the shaft was connected to the specimen cap with grease on it, to minimize the friction, and the cylindrical triaxial cell was assembled and placed in the center of the load frame. Finally, the loading frame was lowered to be barely touching the sample so that the uplift force, during saturation, will not push the shaft upward.

6.4.2 Saturation Stage

The triaxial was loaded up with water, at a low pressure of 10 kPa, to circulate the water through the entire triaxial cell and the two pressure-volume controllers while the drainage was kept open so the entangled air will stream out of the system. This flushing procedure minimized the errors that may occur due to the compression of the entangled air voids. At that point, back pressure is applied to the sample so the air voids inside the sample are loaded up with water and entrapped air will be removed from the entire system.

The saturation process is a function of time and pressure. However, due to the high permeability and drainage coefficient of TDA, the saturation phase is relatively simple and fast compared to natural soils. The Skempton's pore water pressure parameter (B) was used to measure the degree of the sample saturation, and all the samples were saturated until reaching a minimum (B) value of 0.98.

5.3.3 Consolidation Stage

The consolidation stage is achieved by increasing the confining pressure while keeping the pore pressure of the sample constant, and it is also considered to be relatively fast. Three confining pressures were used in the research; 50, 100 and 200 kPa. The volume of water driven out of the sample during the consolidation stage was measured using a plastic graduated measuring cylinder, and it was observed that a significant contraction occurred to the samples during the consolidation stage, so the height of the shaft had to be increased to reach the desirable strain level.

6.4.4 Shearing Stage

To measure the shearing rate, the volumetric change was plotted against the logarithm of the time elapsed. However, the high permeability of TDA resulted in a shearing rate higher than the rate that could be controlled by our volume pressure controllers. So, a lower rate of 1 mm/min was used for all the samples.

In the initial tests, a 30% strain level was achieved. However, the samples were subjected to a severe potential of membrane puncturing, so a 20% strain level was chosen for the tests which is sufficient since the TDA is an elastic material with no peak in its stress-strain curve, and according to ASTM D7181- 11, in the absence of a maximum stress, the deviatoric stress at 15% should be considered as the maximum stress.

Usually, TDA experiences a linear bulging after 10% strain due to the tilting of the specimen cap. However, using a fixed connection between the specimen cap and the shaft resulted in a right circular cylinder deformation as shown in Figure (6.4).

Figure 6.4 The sample deformation at 20% Strain

6.4.5 Corrections

Triaxial tests have several sources of errors that need to be corrected for in order to have more accurate results. Correction for the cross-sectional area during the consolidation and shearing phases is considered the primary source of errors in triaxial tests. Several researchers studied the cross-sectional area correction factor, were they recommended different correction equations to get the effective cross-sectional area as summarized in Table 6.2.

However, in this research, an advanced MATLAB model was done to get an exponential equation for the volumetric change from which the effective cross-sectional area and the volumetric strain were calculated. These correction factors were applied to the results before evaluating the shear strength parameters.

Table 6.2 Cross-sectional area correction equations reported by different researchers

Study	Area Correction Equation	Deformation Shape
La Rochelle et al. 1988	$A = A_o\,(1 - \varepsilon_v)/(1 - \varepsilon_a)$	Right Circular Cylinder
La Rochelle et al. 1988	$A = A_o \times \left[-0.25 + \sqrt{(25 - 20\varepsilon_a - 5{\varepsilon_a}^2)}/4\,(1 - \varepsilon_a)\right]^2$	parabolic
Zhang and Garga 1997	$d_{max} = \frac{d_c}{4}\left[\left\{30\,\frac{(1-\varepsilon_v)}{(1-\varepsilon_a)}\right\} - 5\right]^{\frac{1}{2}} - 1$	parabolic

*where: A = corrected area of the specimen, A_o = initial area of the specimen, ε_v= volumetric strain of sample and ε_a = axial strain of sample.

6.5 Results

A total of 18 triaxial tests were conducted under consolidated drained conditions using three confining pressures; 50, 100, 200 kPa to resemble the stress levels expected in backfills, embankments and surrounding retaining walls. A total of five samples were tested, having an increasing maximum particle size (D_{max}) ranging between 19.05 – 76.2 mm. All the samples had a diameter of 150 mm and a height of 320 mm.

6.5.1 Consistency and Repeatability of the Tests

The random nature of TDA arises some doubts regarding the repeatability and accuracy of the driven tests. So, the 25.4 mm sample was duplicated under the three confining pressures to validate the repeatability and accuracy of the results. Figure 6.5 shows that the deviatoric stress-strain curves of the duplicated tests are in agreement, which proves the consistency and the accuracy of the results. The volumetric strain for the duplicated tests also showed an agreement between the results, as shown in Figure 6.6. The difference between the curves is minimal that could be neglected and will not make a significant difference in evaluating the shear strength parameters.

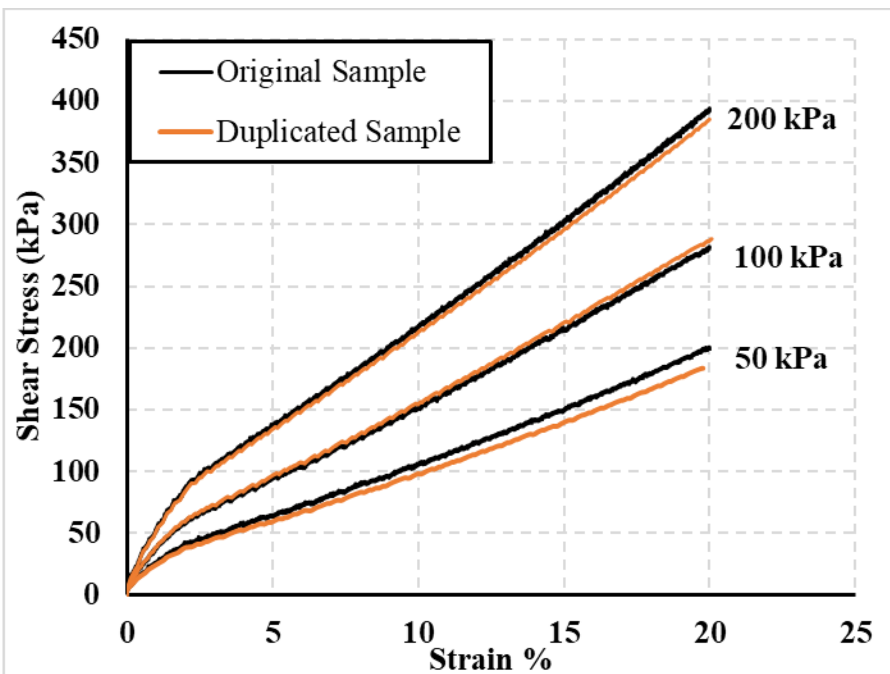

Figure 6.5 Deviatoric stress vs. strain curves for the duplicated tests

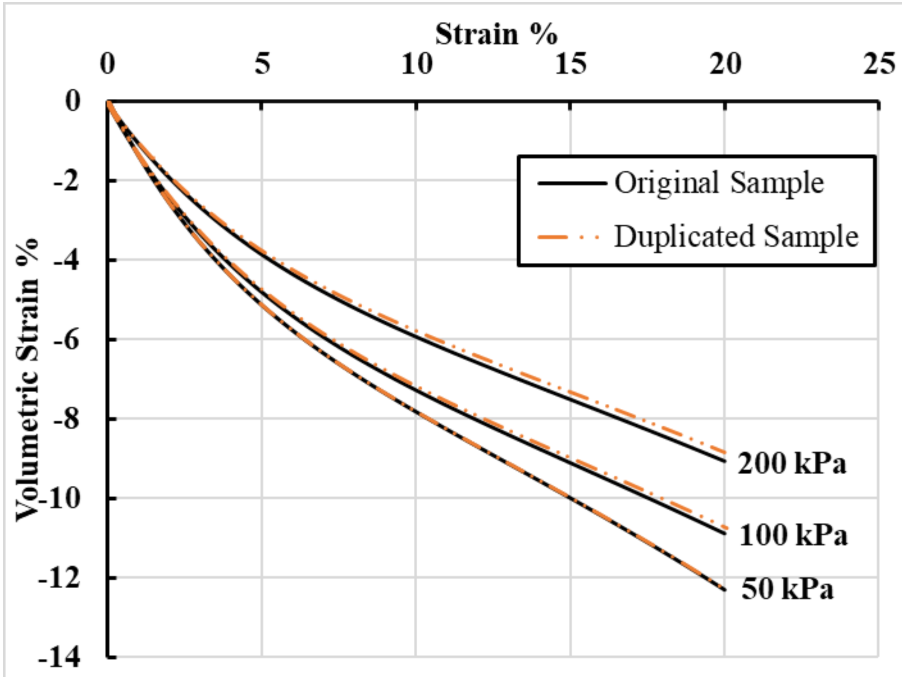

Figure 6.6 Volumetric strain Vs. strain % curves for the duplicated tests

6.5.2 Stress-Strain Curves

Figure 6.7 shows that all the samples exhibited a bilinear stress-strain behaviour with a close initial stiffness for the 19.05, 25.4 and 38.1 mm samples and a higher stiffness for the 50.8 and 76.2 mm samples. The samples undergo an initial steep increase in the deviatoric stress up to 2% strain, followed by a linearly increasing deviatoric stress up to 20% strain level. The deviatoric stress-strain curves of this study are in agreement with the previous studies conducted by Youwai and Bergado 2003, Masad et al. 1996, Lee et al. 1999 and Zornberg 2004. These researchers reported a fairly linear deviatoric stress-strain curves. The slight difference in the results between this study and the previous studies may be attributed to: (1) The different maximum particle size used. (2) Different samples gradation curves. (3) Different TDA composition depending on the TDA source (4) Most importantly, the random nature of TDA.

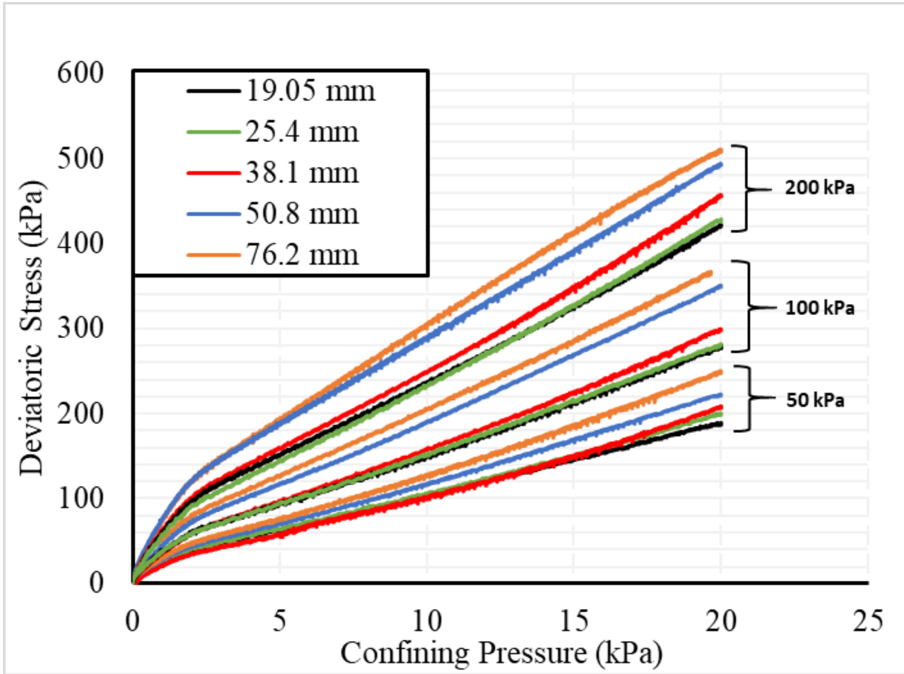

Figure 6.7 Deviatoric stress-strain curves for the five samples

TDA samples do not reach a peak in its deviatoric stress-strain curves, and this phenomenon is clearly observed in figure 6.7. However, ASTM D7181 – 11 recommended considering the deviatoric stress at 15% to be the maximum stress when no peak is observed in the stress-strain curve. Several practitioners used the deviatoric stress at 10% strain as the maximum stress for TDA to be used as in evaluating the shear strength parameters. In this study, shear strength parameters were calculated at both 10% and 15% strain levels. Mohr-Coulomb failure criterion was used in evaluating the shear strength parameters for the five tested samples. The angle of internal friction and cohesion were evaluated using the following equation.

$$\tau = c + \sigma \tan\varphi \qquad \text{Equation 6.3}$$

Where (τ) is the deviatoric stress at 10% and 15% strain levels, (c) is the cohesion, which is the y-intercept, and (φ) is the angle of internal friction.

Table 6.3 The shear strength parameters for the five sample

Sample (D_{max})	Strain 10%		Strain 15%	
	Angle of Internal Friction (°)	**Cohesion (kPa)**	**Angle of Internal Friction (°)**	**Cohesion (kPa)**
19.05 mm	17.8	21.6	21.3	30.5
25.4 mm	18.3	21.6	21.5	29
38.1 mm	19.2	18.4	23.3	28
50.8 mm	21.4	20.5	24.8	30.6
76.2 mm	21.8	23.4	25.6	32

Table 6.3 shows that the angle of internal friction increased by increasing the maximum particle size (D_{max}). However, cohesion exhibited a decrease followed by an increase as the maximum particle size (D_{max}) increase. Moreover, Considering the deviatoric stress at 10% strain as the maximum stress results in a more conservative shear strength parameters.

To simplify the understanding of the results, the results were plotted in columns, as shown below in Figure 6.8. The maximum difference in the angle of internal friction and cohesion between the samples is 4° and 5 kPa, respectively, when considering the maximum stress to be at 10% strain. While the difference becomes 4.3° and 4 kPa, respectively, when considering the maximum stress to be at 15% strain.

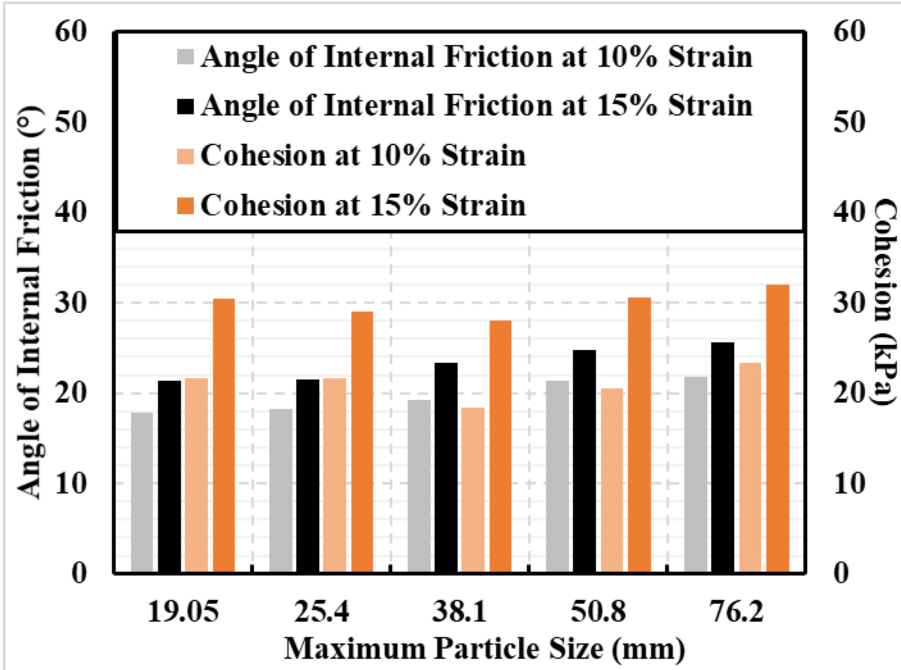

Figure 6.8 Angle of internal friction and cohesion for the five samples

6.5.3 Volumetric Strain

The deformation that happens for saturated nature soils is mainly due to the expulsion of water from the samples voids, the reorientation of the soil particles and the deformation of the soil particles, which is almost negligible (Yi et al., 2015). However, highly elastic material as TDA deforms for the following reasons: (1) Reorientation of the TDA particles, which is generally irrecoverable when unloaded; (2) Compression of the TDA particles, unlike conventional soils, and this is generally recoverable when unloaded. (3) Bending of TDA particles, unlike conventional soils, and this contributes to the majority of the compression that happens to the TDA when loaded (Meles, 2014).

Figures 6.9.a, 6.9.b and 6.9.c show the volumetric strain that occurred to the five samples under the three confining pressures. The samples showed a steep volumetric contraction followed by a steady decrease in the rate of volumetric change as the strain increases. The maximum particle size (D_{max}) did not show a correlation with the volumetric strain % as under the 50 kPa confining pressure, the volumetric strain % decreased by increasing the maximum particle size, however, under the 100 and 200 kPa confining pressures, there was no correlation between the maximum particle size and the confining pressures, as shown in the following figures.

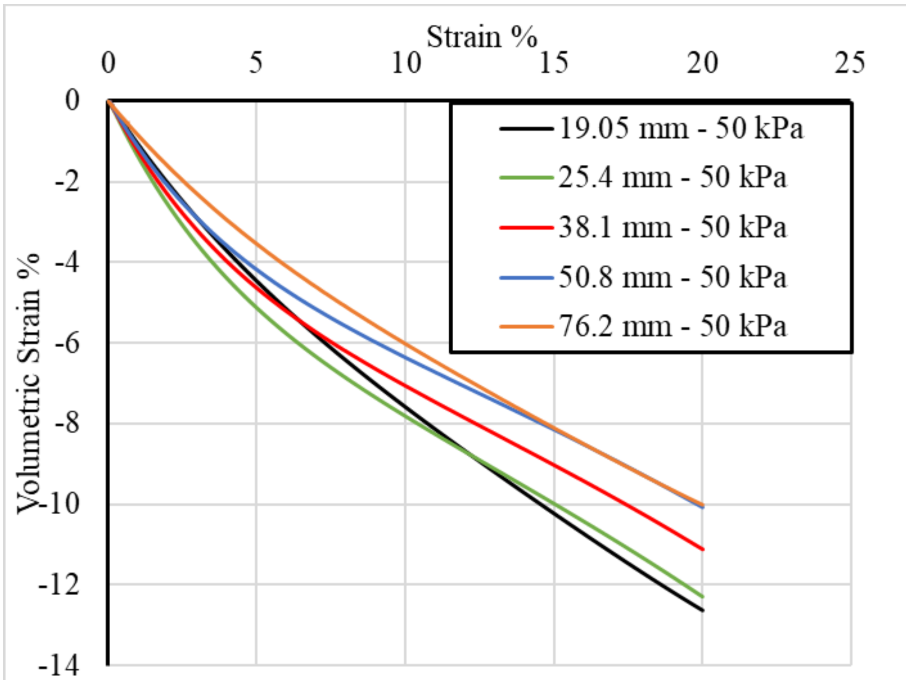

Figure 6.9.a Volumetric strain % for the samples under 50 kPa confining pressure

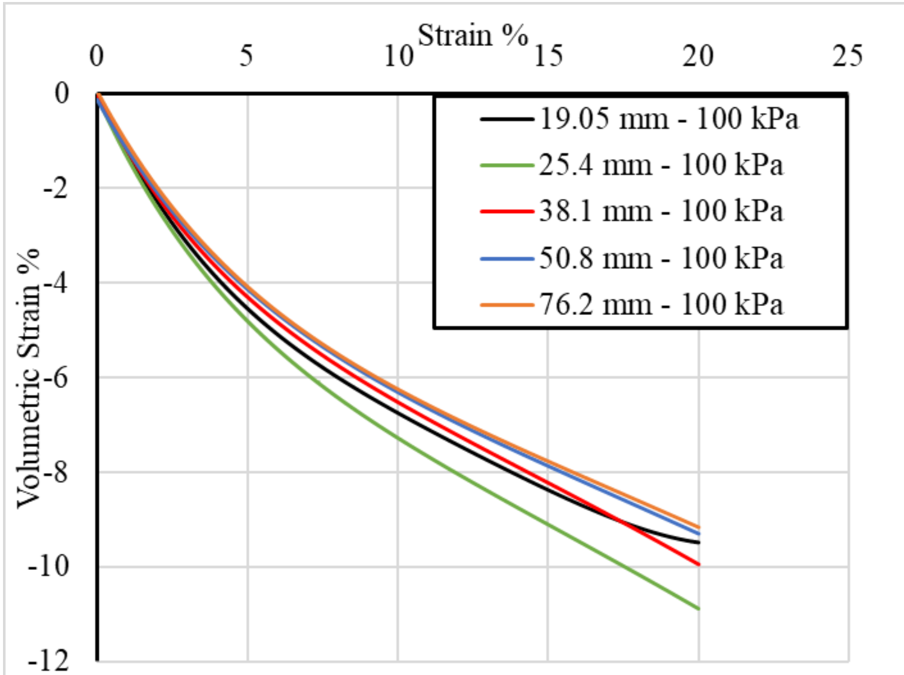

Figure 6.9.b Volumetric strain % for the samples under 100 kPa confining pressure

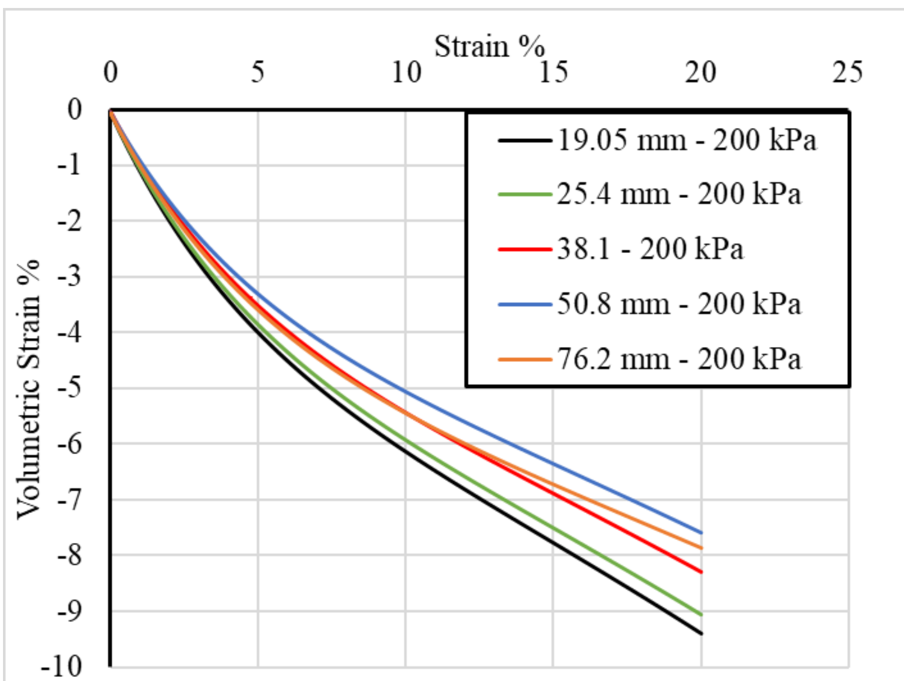

Figure 6.9.c Volumetric strain % for the samples under 200 kPa confining pressure

The confining pressure showed an inversely proportional correlation with the volumetric strain as the volumetric strain decreased when the confining pressure increased. The samples showed a volumetric strain % between 10 – 12.5% under the 50 kPa confining pressure. However, this range decreased to be 9 – 10.8% under 100 kPa confining pressure, and the range decreased more under the 200 kPa to be 7.5 – 9.25%. This behaviour could be attributed due to the presence of fewer voids within the samples when the confining pressure increases.

6.5.4 Stiffness

The effect of the particle size on the stiffness of the five samples was evaluated by calculating the secant elastic modulus (E_{50}) as reported in Figure 6.10. Generally, the elastic modulus reported in this study is in agreement with the elastic modulus of tires rubber reported by Beatty 1981 that ranged between 1200 – 5100 kPa. The secant elastic modulus (E_{50}) was calculated using the following equation:

$$E_{50} = \frac{\tau_{50}}{\varepsilon} \qquad \text{Equation 6.4}$$

Where (τ_{50}) is the deviatoric stress at 10% and (ε) is the corresponding axial strain.

Figures 6.10.a shows that the secant elastic modulus increased by increasing the particle size. In addition, the fact that the elastic modulus increases by increasing the maximum particle size is attributed to the less freedom the particles with larger size have to reorient within the sample as the maximum particle size (D_{max}) is increasing while the triaxial cell diameter was kept constant. It could also be attributed to the presence of less steel wires in the smaller particles, unlike the large particles, which usually contain much higher steel wires content.

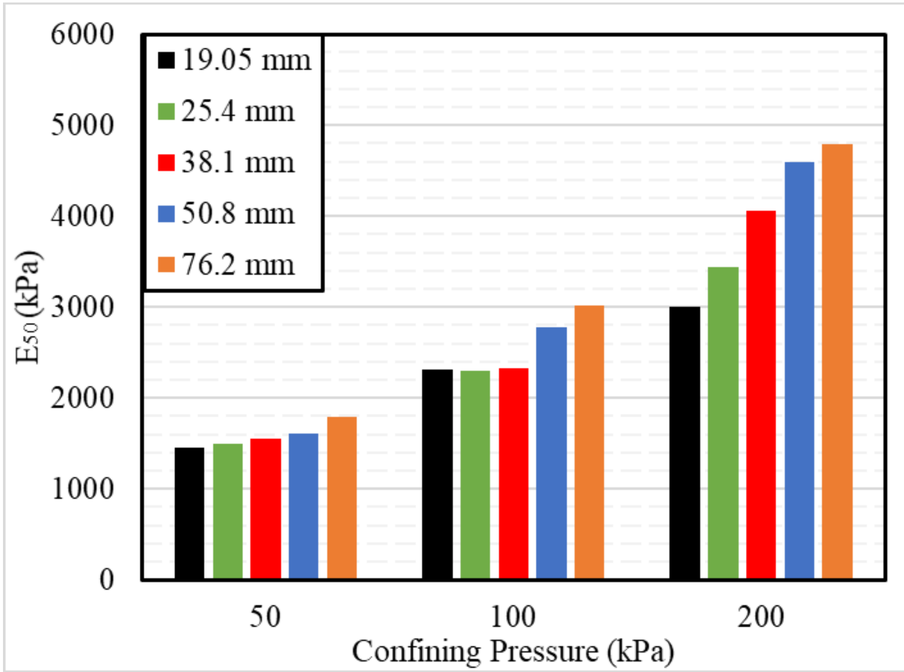

Figure 6.10 The secant elastic modulus at 10% strain

6.6 Conclusion

This research is mainly about evaluating the particle size effect on the shear strength parameters of TDA. Five samples with an increasing particle size were tested using a large scale triaxial with dimensions of; 150 mm in diameter and 320 mm in height. From this study, it could be concluded that:

1- The angle of internal friction of TDA increases by increasing the maximum particle size (D_{max}).

2- The cohesion of TDA did not show a defined correlation with the particle size as the cohesion exhibited a decrease followed by an increase by increasing the particle size.

3- The secant shear modulus of TDA increases by increasing the maximum particle size (Dmax).

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CHAPTER 7   CONCLUSION

7.1 Summary

This thesis addressed the sample and particle size effect on the shear strength parameters of TDA using triaxial and direct shear tests. A total of 66 tests were conducted to reach the outcomes of this research. The present thesis was divided into four main phases.

The first phase (*chapter three*) addressed the **sample size effect** on the shear strength parameters of TDA using **direct shear tests**. In this chapter, five shear boxes were used to evaluate the sample size effect on a TDA sample. For each sample size, three normal stresses were applied, with a total of 15 tests for this phase.

The second phase of this thesis (*chapter four*) addressed the **particle size effect** on the shear strength parameters of TDA using **large-scale direct shear tests**. In this chapter, six TDA samples, having an increasing maximum particle size, were tested under three normal stresses using a square shear box of dimensions; 300 mm by 300 mm by 230 mm with a total of 18 tests for this phase.

The third phase of this study (*chapter five*) addressed the **sample size effect** on the shear strength parameters of TDA using **triaxial tests**. In this chapter, four triaxial sample sizes with diameters of; 50, 70, 100 and 150 mm were used to evaluate the sample size effect on a TDA sample at three confining pressures with a total of 15 tests for this phase.

Finally, The fourth phase of this study (*chapter six*) addressed the **particle size effect** on the shear strength parameters of TDA using **large-scale triaxial tests**. In this chapter, five TDA samples, having an increasing maximum particle size, were tested under three confining pressures using a large scale triaxial cell with a diameter of 150 mm and a height of 320 mm. This phase of my thesis had a total of 18 large-scale triaxial tests.

7.2 Findings of this Research

7.2.1 Sample Size Effect – Direct Shear Tests

1- The sample size has no effect on the shear strength parameters of TDA as the angle of internal friction remained almost constant as the size of the shear box increased. The angle of internal friction for the TDA sample ranged between 22 – 22.4° when evaluated using direct shear boxes with an aspect ratio between the shear box width and maximum particle size (W/Dmax) equal to 4 or larger.

2- No correlation was observed between the cohesion and the shear box size. However, the maximum difference between the cohesion reported for each shear box, around 2.4 kPa, is negligible and would not affect the geotechnical designs.

3- Shear boxes with a (W/D_{max}) aspect ratio of 4 or larger should be used when evaluating the shear strength parameters of TDA.

4- The ratio recommended by ASTM D3080-90 for the (W/D_{max}) should not be imposed for TDA since the results of the TDA tests using direct shear tests showed that the same shear strength was obtained when using shear boxes with a W/D_{max} ratio as low as 4.

7.2.2 Particle Size Effect – Direct Shear Tests

5- The angle of internal friction of TDA increases as the maximum particle size increases. The angle of internal friction for the six TDA samples ranged between 20.4 – 25.9° when evaluated using a large scale direct shear box with dimensions of 300 mm by 300 mm by 230 mm.

6- No correlation was observed between the cohesion and the particle size. However, the maximum difference between the cohesion reported for the TDA samples, around 3.1 kPa, is negligible and would not affect the geotechnical designs significantly.

7- The secant shear modulus (G_{50}) of TDA, evaluated using a large scale direct shear box, increases by increasing the maximum particle size (D_{max}). Moreover, the shear modulus for the tested samples ranged between 453 – 2513 kPa.

7.2.3 Sample Size Effect – Triaxial Tests

8- The sample size has no effect on the shear strength parameters of TDA as the angle of internal friction of TDA remained constant as the size of the triaxial samples increases. The angle of internal friction for the TDA sample ranged between 18.2 – 18.3° when evaluated using triaxial cells with aspect ratios between the maximum particle size and triaxial cell equal to 1/2.8 or smaller.

9- No correlation was observed between the cohesion and the triaxial sample size. However, the maximum difference between the cohesion reported for the triaxial sample sizes, around 3 kPa, is negligible and will not affect the geotechnical designs.

10- Triaxial samples with an aspect ratio between the maximum particle size Dmax and the triaxial cell diameter (D_{max}/Ø) of 1/2 or larger can be used when evaluating the shear strength parameters of TDA.

11- The (D_{max}/Ø) ratio recommended by ASTM D7181 - 11 should not be imposed for TDA since the results of the TDA tests using triaxial tests showed that the same shear strength was obtained when using triaxial samples with a (D_{max}/Ø) ratio as low as 1/2.

12- The sample size has almost a negligible effect on the volumetric strain as the TDA sample evaluated using different triaxial sample sizes exhibited very close volumetric strains curves.

13- The secant elastic modulus (E_{50}) of TDA, evaluated using triaxial tests, increases by decreasing the sample size. Moreover, the elastic modulus for the tested sample sizes ranged between 1500 – 4000 kPa.

7.2.4 Particle Size Effect – Triaxial Tests

14- The angle of internal friction of TDA increases as the maximum particle size of the sample increases. The angle of internal friction for the five TDA samples ranged between 17.8 – 21.8° when evaluated using a large scale triaxial apparatus having a diameter of 150 mm and a height of 320 mm.

15- No correlation was observed between the cohesion and the particle size. The maximum difference between the cohesion reported for the TDA samples was around 5 kPa.

16- The secant elastic modulus (E_{50}) of TDA, evaluated using a large scale triaxial apparatus, increases by increasing the maximum particle size (Dmax). Moreover, the elastic modulus for the tested samples ranged between 1450 – 4800 kPa.

17- No correlation was observed between the particle size and the volumetric strain when evaluated in a large scale triaxial apparatus.

7.3 Recommendations

The following suggestions are recommended for further investigation in order to have more accurate and reliable geotechnical properties for TDA to broad its usage in civil engineering applications.

1- Studying the sample and particle size effect on the shear strength parameters of TDA under consolidated undrained conditions.

2- Developing larger direct shear boxes and triaxial cells based on the ratios recommended in this study to accommodate the testing of larger TDA particle sizes (Type B TDA).

3- Testing larger TDA particle sizes (Type B TDA) that are commonly used in civil engineering applications and evaluate its characteristics, advantages and disadvantage over Type-A TDA.

4- Studying the behaviour of TDA when subjected to higher normal stresses above 300 kPa in direct shear tests and confining pressure above 300 kPa in triaxial tests.

5- Studying the long term performance of TDA in civil engineering applications. This includes the changes in shear resistance over time, long term compression or dilation, and the change in the physical and chemical properties of TDA over time.

6- Developing a numerical model that can generate the stress-strain curves with only two controlling variables; confining pressure and maximum particle size.

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