Experimental Investigation on the Shear Strength Parameters and Deformability Behavior of Various Soil Types Mixed with Tire-Derived Aggregate

by

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I dedicate this thesis to my beloved wife and parents for all their support and encouragement throughout my years of study.

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ABSTRACT

Stockpiles of waste tires have become a serious environmental problem in Canada and worldwide. According to the Rubber Association of Canada, approximately 28 million scrap tires are generated annually in Canada, including 940,000 in Nova Scotia (Pehlken and Essadiqi 2005). The use of tire-derived aggregate (TDA) in civil engineering applications has been studied for many years. Using TDA alone has a self-ignition and high compressibility problem. Mixing TDA content with soil has great potential as a light filling material. Several studies have been carried out in the past to investigate the effect of TDA content mainly smaller than 20 mm in length on the shear strength behavior of a single type of soil especially sandy soil. However, limited studies have been conducted on TDA alone larger than 20 mm in length or the TDA content mixed with various soil types. Hence, to cover the limitations of previous studies, a series of large-scale direct shear box (305 mm × 305 mm × 220 mm) tests were performed on TDA alone with sizes up to 75 mm in length, and mixed with various soil types. Three types of soil including gravelly soil (coarse grain), sandy soil (medium grain), and clayey soil (fine grain) were selected to mix with the TDA content. First, the physical properties of the soils and TDA were determined. Next, TDA content was added to each soil type from 0 to 100% by weight, and each mixture was compacted using standard proctor energy. Then, the direct shear tests were conducted on the mixtures at the confining pressures of 50.1, 98.8 and 196.4 kPa. Test results showed that the addition of TDA content to the soils considerably decreases the dry unit weight of the mixtures. Also, adding TDA content to the gravel reduces the shear resistance of the mixtures upon shearing at all the confining pressures. However, the addition of TDA content up to 10% by weight to the clay and sand increases the shear resistance of the mixtures upon shearing significantly. It was found that except for the clay alone, adding more than 25% TDA content to the soils increases the compressibility behavior of the mixtures significantly. Test results also indicate that the addition of up to 25% TDA content by weight to the gravel and sand does not change the angle of internal friction considerably. However, adding up to 10% TDA content by weight to the clay increases the internal friction angle, from 18.8 to 32.3º. The addition of TDA content to the soils also contributes to a strain-hardening behavior in the mixtures. Also, adding TDA content to the mixtures decreases the normalized lateral earth pressure at-rest.

LIST OF ABBREVIATIONS AND SYMBOLS USED

c = cohesion intercept

γ_d = dry unit weight

ω = optimum water content

φ = angle of internal friction

ε = shear strain

τ = shear stress

G = shear modulus

TDA = tire-derived aggregate

TDF = tire-derived fuel

kPa = kilo pascal

MPa = mega pascal

LSDS = large-scale direct shear

SSDS = small-scale direct shear

LST = large-scale triaxial

SST = small-scale triaxial

CD = consolidated drained

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CHAPTER 1: INTRODUCTION

1.1 Background and Statement of the Problem

Growing populations are generating significant amounts of discarded tires every year. Disposing of the waste tires in landfills contributes to serious environmental problems, and it is crucial to find an environmentally-friendly solution for disposal. Since scrap tires are bulky, they occupy considerable space in landfills. In addition, stockpiled tires collect rainwater during rainy seasons. This water frequently hosts many insects, including mosquitoes, that can transfer dangerous diseases such as encephalitis to humans. Moreover, there is a potential risk of fire from stockpiled tires (Cecich et al. 2016). Over 500 million scrap tires are stockpiled in the United States annually (Edinçliler et al. 2010). Only about 22% of them are recycled and reused in various applications, and the rest of them end up in landfills and illegal dumps (Cecich et al. 2016). According to the Rubber Association of Canada, approximately 28 million scrap tires are generated in Canada each year, which is almost one tire per person (Pehlken and Essadiqi 2005). Figure 1.1 shows a stockpile of scrap tires.

Figure 1.1 A stockpile of scrap tires ("The Spruce" n.d.)

Fortunately, some countries such as Canada and the USA are currently implementing an active tire recycling program. To impose the program, an environmental fee is applied to the purchase of brand-new tires, and then the money collected is used to divert scrap tires from landfills. For example, according to Pehlken and Essadiqi (2005), the province of Nova Scotia, Canada, has succeeded in diverting 6.3 million scrap tires from landfills (a recovery rate of 86%).

1.2 Reuse of Scrap Tires

A scrap tire is made of a combination of synthetic rubber, fibers and steel cords. Steel and fiber cords reinforce the rubber, and a steel belt extends below the tread. Figure 1.2 illustrates the composition of a passenger car tire, and Table 1.1 lists the typical materials used in the passenger and truck tires.

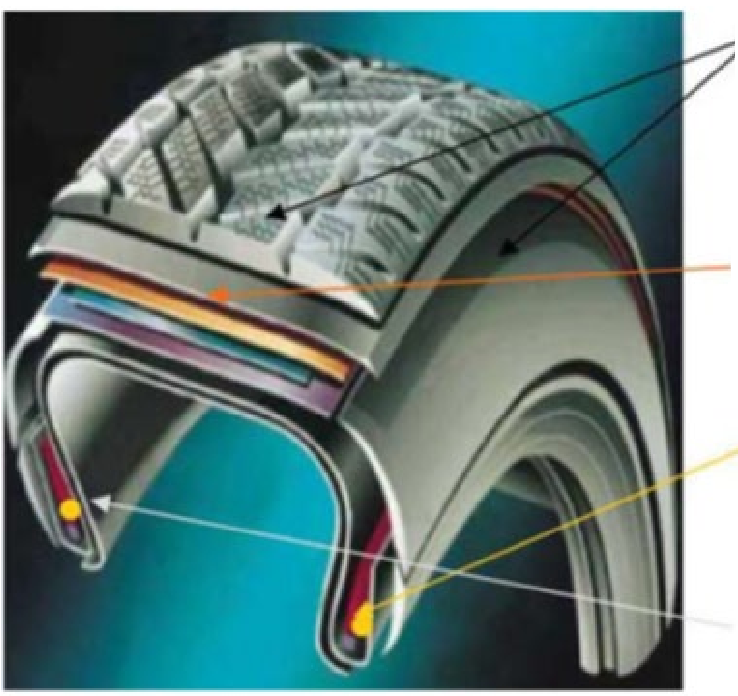


Figure 1.2 The components of a car tire (Micelli et al. 2015)

Table 1.1 Typical composition of a tire (Pehlken and Essadiqi 2005)

Material	Passenger Tire	Truck Tire
Natural rubber	14%	27%
Synthetic rubber	27%	14%
Carbon black	28%	28%
Steel	14-15%	14-15%
Fiber	16-17%	16-17%
Average Weight	New 11 kg, Scrap 9 kg	New 54 kg Scrap 45 kg

Scrap tires can be used in the form of a whole tire or tire shreds in various applications. Shredding the scrap tires is performed by a tire shredder with specific blades in reclining facilities. Figure 1.3 shows tire shredding blades.

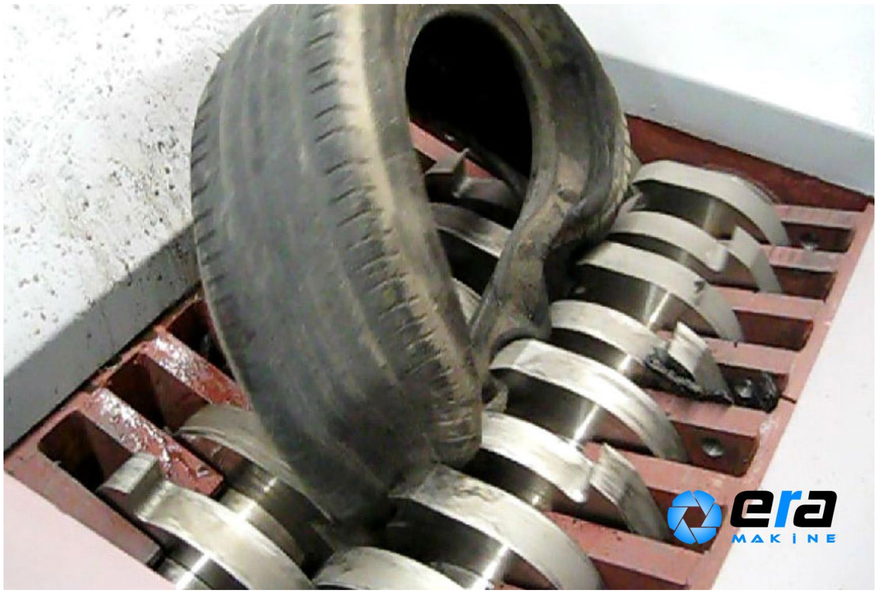


Figure 1.3 Tire shredding blades ("Era Makine" n.d.)

Tire shreds are categorized based on their size and shredding techniques. According to Strenk et al. (2007), particle sizes ranging from 50 to 305 mm are referred to as tire shreds, while those from 12 to 50 mm are called tire chips. These two sizes are commonly known as tire-derived aggregates (TDA). Also, particles less than 12 mm in size are referred to as granular or crumb rubber. Smaller tire shreds require higher processing and shredding time, and therefore, their production cost is higher than other alternatives. Table 1.2 lists the cost of processing and shredding of scrap tires based on their size. As shown in the table, reducing the tire shred size leads to higher processing cost.

Table 1.2 Tire shredding costs (Pehlken and Essadiqi 2005)

size	cost per ton	Process Rate (ton/hour)
5 cm	$12	10-12
< 5 cm	$31	7
< 1.25 cm	$31 – $68	2-3

Based on ASTM D6270 (2017), tire shreds are classified into two types. Type A is referred to the tire shreds with a maximum dimension of 200 mm in any direction, and those with a maximum dimension of 450 mm in any direction, or 300 mm for at least 90% of the sample by weight are classified as type B.

According to the Rubber Association of Canada, approximately 240,000 tons of scrap tires were recovered from landfills, and shredded in recycling facilities in Canada in 2003. More than 40% of them were shredded up to the size of rubber crumb. Rubber crumb is used in various applications including plastic products, industrial wheels, and asphalt (Pehlken and Essadiqi

2005). The use of rubber crumb in the products contributes to some technical advantages such as high durability and elasticity, and thermal and acoustic insulation (Pehlken and Essadiqi 2005).

Two other products of scrap tires are tire-derived fuel (TDF) and tire-derived aggregate (TDA). TDF consists of whole or shredded tires and is used as a substitute fuel in cement kilns and paper mills industries. Roughly 20% of scrap tires are used as TDF, and about 13% of them are used as TDA in Canada (Pehlken and Essadiqi 2005). TDA and soil-TDA mixtures have been used for many years in geotechnical engineering applications. They can be used as a lightweight embankment fill or retaining wall backfill, or as drainage layers for landfill, roads, and several other civil engineering applications. Pure TDA fills up to three meters in thickness can be used without resulting in internal heating problems (ASTM D6270 2017). Also, according to Xiao et al. (2012), and Ahn and Cheng (2014), TDA fills exhibit a softer response than conventional aggregates to dynamic earthquake pressures, and tolerates larger residual deformations without failure.

1.3 Objectives of Present Research

Mixing soil with TDA content has great potential as a light filling material which reduces the TDA's self-ignition problem and provides lower compressibility behavior (Jamshidi Chenari et al. 2017). Previous researchers have primarily focused on the shear strength behavior of TDA content with sizes smaller than 20 mm in length mixed with a single type of soil mainly sandy soil. In contrast, limited studies have been conducted on clayey and gravelly soils mixed with TDA content with sizes larger than 20 mm.

Therefore, the primary objective of this study was to investigate the shear strength behavior of TDA content with length up to 75 mm mixed with various soil types. Also, the effect of TDA content on the compressibility behavior of the mixtures was determined. Another objective was to find the effect of various confining pressures on the shear strength and compressibility behavior of the soil-TDA mixtures. Also, the effect of TDA content on the shear strength parameters of the mixtures including the angle of internal friction and cohesion were determined.

To address the objectives, three types of soil including gravelly soil (coarse grain), sandy soil (medium grain), and clayey soil (fine grain) were selected, and mixed with the TDA content at various percentages ranging from 0 to 100% by weight. Then, a series of large-scale direct shear box (305 mm × 305 mm × 220 mm) tests were performed at confining pressures of 50.1, 98.8, and 196.4 kPa.

1.4 Thesis Outline

This thesis comprises five chapters. Chapter 1 identifies scrap tires as a problem and explains the consequences of disposing of waste tires in landfills. It then introduces alternatives for reusing the discarded tires in various applications. Finally, the objectives of this study about the shear strength behavior of soil-TDA mixtures are introduced. Chapter 2 reviews previous laboratory studies on TDA and soil-TDA mixtures including direct shear testing and triaxial compression methods. Then, it compares direct shear testing and triaxial compression methods performed on various soil and soil-TDA mixtures. Chapter 3 presents the physical properties of the materials used in this study. Then, the preparation of the mixtures based on the mixing ratio is explained. Finally, the procedure for performing the large-scale direct shear tests is explained. Chapter 4 describes the results of the tests for the considered mixtures. First, it presents the variation of dry unit weight with TDA content for the mixtures. Then, it compares the variation of shear stress with shear strain for the mixtures. Based on the failure criteria, Mohr-Coulomb envelopes are then demonstrated. Next, the vertical deformation of the mixtures upon shearing is evaluated. Then, the shear strength parameters of the mixtures obtained from the direct shear tests are presented, and a comparison is made between the shear strength parameters of the mixtures. The strain compatibility for the TDA content is then discussed. Finlay normalized lateral earth pressure at-rest condition is determined for the mixtures. Chapter 5 contains the summary of the findings of this research and proposes future areas of research.

CHAPTER 2: LITERATURE REVIEW

The previous research utilized different experimental approaches including direct shear test and triaxial compression method to evaluate the shear strength properties and compressibility behavior of TDA and soil-TDA mixtures. In a triaxial compression test, there is full control on confinement and saturation, and the failure progresses in a natural plane. However, in the direct shear test, there is no control over pore water pressure in the shear surface, and the failure plane occurs in the predetermined horizontal direction which may not be the weakest plane. On the other hand, the simplicity of performing direct shear test compared to triaxial compression method has made it more versatile amongst geotechnical designers.

In this chapter, first, previous studies on shear strength behavior of TDA and soil-TDA mixtures obtained from the direct shear test is presented. Then, previous research on the shear strength behavior of TDA and soil-TDA mixtures attained from triaxial compression method is described. Finally, a comparison is made between the direct shear test versus triaxial compression method to find the advantages and disadvantages of each testing method.

2.1 Direct Shear Test

Gray and Ohashi (1983) conducted a serious of small-scale direct shear tests (specimen diameter: 62.5 mm) to find the shear strength properties of sand reinforced with fibers in a predetermined orientation. Fiber sizes ranged from 20 to 250 mm. They performed the tests in a dry condition and applied confining pressures of up to 144 kPa to the specimens upon shearing. In their study, failure was defined as 8% relative lateral displacement. They noted that the compaction energy has a negligible impact on the shear strength of sand-fiber mixtures and the shear strength of the mixtures is mainly influenced by fiber concentrations across failure plane and fiber orientations. They concluded that the shear strength of sand-fiber mixtures increases up to a maximum fiber concentration of 1.67% across the shear plane with an upper limit of 60º with respect to the shear surface.

Humphrey and Sandford (1993) conducted a series of large-scale direct shear box tests (box dimensions: 305 mm ×305 mm × 228 mm) on tire shreds from three different suppliers. One supplier's tire shreds were glass belted ranging from 13 to 38 mm in size. The other suppliers' tire shreds were composed of steel and glass belted between 13 to 76 mm in size. Humphrey and Sandford (1993) compacted the tire shreds using 60% of standard proctor energy at three layers in the shear box. Also, they applied confining pressures of 17, 34, and 68 kPa to the specimens upon shearing at a shear rate of 7.6 mm/min. Failure was defined at a peak or in the absence of a peak at 10% relative lateral displacement. They measured internal friction angles ranging from 19 to 25° and cohesion intercepts between 7.7 and 11.5 kPa for the tire shreds.

Foose et al. (1996) carried out a series of large-scale direct shear tests (specimen diameter: 279 mm and height: 314 mm) on sand-tire shred mixtures. They wanted to find the effects of normal stress, sand matrix unit weight, shred content, length, and orientation in the shear strength behavior of sand-TDA mixtures. They also used a theoretical model based on Maher and Gray (1991) to predict the shear strength of the mixtures at various TDA content. Foose et al. (1996) used three TDA sizes (<5 cm, 5 to 10 cm, and 10 to 15 cm), and mixed each of them with sand at the amount of 10, 20 and 30% by volume. In their study, the vibration method with the dry condition was used to compact the mixtures. They also applied normal stresses ranging from 3 to 120 kPa to each sample upon shearing at a shear rate of 0.13 cm/min. Failure was defined at a peak and in the absence of a peak at 9% relative horizontal displacement. They found that tire shred content, sand matrix unit weight, and normal stress are the main factors affecting the shear strength behavior of the mixtures. They also observed that the addition of tire shred content with 15 cm length at the amount of 30% by weight to the sand enhances the internal friction angle of the mixture by up to 67°. The results showed an internal friction angle of 30° and cohesion of 3 kPa for pure tire shreds regardless of length. The parametric study results of the angle of internal friction also verified the experimental results with only 2° difference in most cases.

Tatlisoz et al. (1998) conducted a series of large-scale direct shear tests (specimen diameter: 280 mm and height: 300 mm) on clean sand and sandy silt mixed with tire chips to determine the shear strength properties of the mixtures. Tire shreds length ranged from 30 to 110 mm and were mixed with the soils at the amount of 10 to 100% by volume. The mixtures were compacted at three layers with 44 blows each, and the optimum water content of 2% only added to the sand. They applied three normal stresses less than 50 kPa upon shearing at a shear rate of 0.4 mm/min. Failure was defined at a peak or in the absence of a peak at 60 mm horizontal displacement. They reported that the addition of 30% tire shreds content by volume to the sand increases the shear strength of the mixtures significantly, while adding more than that then reduces the shear strength. They mentioned that the addition of more than 30% tire shreds content to the sand contributes to the segregation between soil and tire shred particles, and therefore a weak soil-TDA mixture in terms of shear strength properties is created. It should be noted that according to Tatlisoz et al. (1998), no significant increase was observed from the addition of tire shred content to the silty sand.

Another study was performed by Akbulut et al. (2007) to investigate the shear strength behavior of clayey soil mixed with randomly oriented scrap tire rubber or synthetic fibers ranging from 2 to 15 mm in length. They used a small-scale direct shear ring (ring diameter: 60 mm and height: 35 mm). Mixtures were compacted in the ring using standard proctor energy. Akbulut et al. (2007) found that adding waste tire rubber to clayey soil enhances the shear strength properties of the soil. The length and content of tire rubber fibers were found to be the main factors influencing the shear strength of the mixture. Akbulut et al. (2007) observed that adding 2% tire rubber fibers with a length of 10 mm to the soil increases the shear strength of the mixture, while at a higher shred content then decreases.

El Naggar et al. (2016) conducted a series of large-scale direct shear box tests (box dimensions: 430 mm × 280 mm, with a height of 230 mm) to study the effect of TDA gradations on the shear strength properties of sand-TDA mixtures. Three TDA sizes (0.3, 23.5, and 48.5 mm) were selected and mixed with the sand in the amounts of 15, 25, 50 and 100% by volume. Each composition was compacted using standard proctor energy at five layers with 25 blows each. They also applied three normal stresses of 50, 100, and 150 kPa upon shearing. El Naggar et al. (2016) found that a composition with 15% TDA content (25% with 0.3 mm in length, 25% with 23.5 mm in length, and 50% with 48.5 mm in length) by volume results in a higher shear strength than other sand-TDA compositions. They also recorded an increase of 3 to 6.5° for the angle of internal friction of the mixtures compared to sand alone. The also noted that the addition of TDA content to the sand leads to a strain-hardening behavior in the mixture.

2.2 Triaxial Compression Test

A serious of large-scale triaxial compression tests (specimen diameter: 152.4 mm) were carried out by Imtiaz Ahmed (1993) to find the shear strength behavior of tire chips and tire chips-sand mixtures. He compacted the tire chips using various compaction energy method (modified, standard, and 50% standard), and applied confining pressures ranging from 31.02 to 206.8 kPa to the specimens. Ahmed (1993) determined the shear strength of the mixtures at 5,10, 15, and 20% axial strains, and found that the addition of tire chips content up to 38% by weight to the sand reduces the dry unit weight while increases the shear strength of the mixture. He reported angle of internal frictions ranging from 25.46 to 38.1° and cohesion intercepts between 36.4 to 49.99 kPa for the mixing ratio of 38% at various axial strains of 5 to 20%.

Masad et al. (1996) conducted a series of triaxial compression tests (specimen diameter: 71.1 mm) on tire shreds, sand, and their mixtures. The maximum size of the tire shreds used was 4.75 mm. He found that the addition of tire shreds to sand increases the compressibility behavior and reduces the density of the mixture. They also noted that the modulus of elasticity of the tire shred-sand mixture was significantly lower than sand alone. However, at a higher confining pressure, the resilient modulus of the mixture was higher than sand alone. They concluded that the tire shred-sand mixtures can be used as a lightweight material beneath other conventional soils, and can exhibit a high resilient modulus due to the confinement. Masad et al. (1996) also observed a strain-hardening behavior for pure tire chips and determined angle of internal frictions and cohesions at three axial strains. (Angles of internal friction of 6, 11, and 15°, and cohesion of 70, 71, and 82 kPa were found at 10, 15, and 20% axial strain, respectively).

Wu et al. (1997) carried out a series of small-scale triaxial compression tests (specimen diameter: 100 mm) with a constant stress path method on five tire chips products with various sizes and shapes. The tire chips sizes ranged from 2 to 38 mm in length, and the shapes were flat, granular, elongated, and powder. They conducted the tests at confining pressures ranging from 34.5 to 55 kPa and observed that the shear strength was fully mobilized at more than 5% axial strain. Wu et al. (1997) recorded the angle of internal frictions for the tire chips ranging from 44 to 56° at various axial strains. The largest interparticle friction angle recorded for flat tire chips with a length of 38 mm. They also noted that the cohesion intercept was negligible due the low confining pressures ranging from 34.5 to 55 kPa.

Lee et al. (1999) performed a serious of large-scale triaxial compression tests (specimen diameter: 150 mm and height: 300 mm) to find the shear strength behavior of tire chips mixed sand. They removed exposed steel belts from the tire chips and limited the size of the tire chips to 30 mm. Also, the vibration method was used to compact the mixtures. Tests were performed in a consolidated drained condition and confining pressures ranging from 28 to 193 kPa applied to the specimens. Also, the rate of loading was considered at 1% axial strain/min. Their test results showed that the relationship between deviatoric stress and axial strain is almost linear up to 25% strain. A similar observation was made for volumetric change versus strain. Lee et al. (1999) also noted that the addition of tire chips to the sand increases the dilatant behavior of the mixture.

Shear strength properties of tire shreds mixed with sand were studied by Youwai and Bergado (2003) using a series of triaxial compression tests (specimen diameter: 100 mm and height: 200 mm). They selected mixing ratios of 0:100, 50:50, 60:40, 70:30, 20:80 and 100:0 by weight, and the maximum tire shred size was limited to 16 mm. To compact the mixtures, the optimum water content of 7.5% was considered for the sand, while no water was added to the tire shreds. Each mixture was compacted in five layers with 21 to 25 blows each. Also, the vibration method was considered to reach the maximum density. The triaxial tests were conducted in a consolidated drained condition, and confining pressures of 50, 100, and 200 kPa was applied to the specimens. Failure was defined at 25% axial strain, and the loading rate was selected at 0.19 axial stain/min. Youwai and Bergado (2003) found that the addition of tire chips to the sand contributes to a mixture with both dilation and compression characteristics. Also, for more mixtures containing more than 70% tire shreds, the amount of deformation is significant. They also developed a constitutive model within a critical state framework to predict the stress versus strain behavior of tire shred-sand mixtures. They noted that due to the high deformability of the mixtures upon axial load, such a model should be considered both elastic and plastic. The results of the constitutive model confirmed the laboratory results with minor differences. Youwai and Bergado (2003) also found that the addition of tire shreds up to 70% by weight to the sand reduces the internal friction angle from 34 to 30°.

Zornberg et al. (2004) performed a serious of large-scale triaxial compression tests (specimen diameter: 153 mm and height: 305 mm) to find the shear strength behavior of pure tire shreds and sand-tire shreds mixtures. Tire shreds had a maximum length of 102 mm and were mixed with the sand at the amount of 0 to 100% by weight. Steel belts were removed from the edges of the tire shreds to eliminate membrane puncture. The tamping method was used to compact the tire shreds only, and for the mixtures of sand-tire shreds, vibration method in dry condition was considered. Tests were performed in a consolidated drained condition and confining pressures ranging from 48.3 to 207 kPa were applied to the specimens upon axial loading. A loading rate of 0.5% axial strain/min was considered, and the failure was defined at a peak and in the absence of a peak at 15% axial strain. Zornberg et al. (2004) found that tire shred content and aspect ratio were the main factors affecting the shear stress versus strain behavior of the mixtures. They noted that an increase in aspect ratio enhances the shear strength of the mixtures. They also found that adding up to 35% tire shreds to the sand increases the shear strength of the mixtures, while more than that then reduces the shear strength. Zornberg et al. (2004) also found that adding tire shred content to the sand results in a mixture without being failed up to 15% axial strain. Their results also show that compaction energy has a negligible impact on the shear strength properties of the mixtures. Zornberg (2004) recorded an angle of internal friction of 26.5° and cohesion of zero for the pure tire shreds.

Rao and Dutta (2006) conducted a serious of small-scale triaxial compression tests (specimen diameter: 100 mm and height: 200 mm) on mixtures of sand-tire chips. The Tire chips sizes were 10 mm × 10 mm, 20 mm × 20 mm, and 20 mm × 10 mm and they were mixed with the sand at the amount of 0, 5, 10, 15, and 20% by weight. The tire chips were distributed randomly in the soil. Compaction tests were performed using standard proctor energy in three layers with 56 blows each. Triaxial compression tests were performed in a consolidated drained condition and confining pressures ranging from 34.5 to 276 kPa were applied upon axial loading. Rao and Dutta (2006) noted that increasing the tire chips content from 0 to 20% by weight enhances the angle of internal friction slightly from 38 to 40.1°, and the cohesion intercept also increases from 0 to 18.4 kPa. They reported that adding 20% tire chips to the sand contributes to a mixture with the same behavior of a sand-gravel mixture. They also noted that the addition of tire chips content to the sand increases the compressibility behavior of the mixture.

Table 2.1 summarizes previous research including direct shear test and triaxial compression method on the shear strength behavior of TDA and soil-TDA mixtures. Most studies confirm that the addition of TDA content within a limit to soil enhances the shear strength properties of the mixture while reduces the dry unit weight. Therefore, soil-TDA mixtures can be used as a lightweight alternative in geotechnical engineering applications including highway embankment fill or retaining wall backfill. Reusing of the scrap tire in geotechnical engineering applications is a promising practice that helps the environment by removing the stockpiled tires from landfills.

Table 2.1 Reviews of past studies on TDA and soil-TDA mixtures

Ref.	Materials	Tire shred size (mm)	Test conditions	γ_d (kN/m^3)	c (kPa)	φ (º)	Optimum TDA content
Gray and Ohashi (1983)	sand mixed with natural and synthetic fibers in a predetermined orientation (max =22 fiber)	20 - 250	SSDS[1] (diameter: 62.5 mm) strain rate: - confining pressures: <144 kPa compaction: - optimum water content: - dry condition strain controlled failure: 8% strain	-	-	sand: a) dense: 39 b) loose: 31	fiber concentration of 1.67% in the shear plane
Humphrey and Sandford (1993)	TDA alone from three different suppliers	a) glass belted (13 - 38) b) composed of steel and glass belted (13 - 76)	LSDS[2] (305 mm x 305 mm x 228 mm) strain rate: 7.6 mm/min confining pressures: 17, 34, and 68 kPa compaction: 3 layers with 60% of standard proctor energy optimum water content: - dry condition failure: peak or 10% strain	TDA: 6.06 - 6.3	TDA: 7.7 - 11.5	TDA: 19 - 25	-
Foose et al. (1996)	mixtures of sand and shredded tire in random and vertical orientation (shred content: 10 and 30% by vol.)	< 50 50 - 100 100 - 150	LSDS (diameter: 279 mm, height: 314 mm) strain rate: 0.13 cm/min confining pressures: <80 kPa compaction: vibration optimum water content: - dry condition failure: peak or 2.5 cm (9% strain)	sand: a) dense: 17.7 b) loose: 15.5 sand-tire shred mixtures: 14.7 -16.8 (for 30% tire shred content: 16.8)	tire shred: 3	tire shred: 30 sand: a) dense: 34 b) loose: 25 sand-tire shred mixture (mixing ratio: 30%): 67	30% tire shreds (15-cm length)

Ref.	Materials	Tire shred size (mm)	Test conditions	γ_d (kN/m^3)	c (kPa)	φ (º)	Optimum TDA content
Tatlisoz et al. (1997)	clean sand and sandy silt mixed with tire chips (TDA content: 0, 10, 20, 30, 100% by vol.)	30 - 110	LSDS (diameter: 280 mm, height: 300 mm) strain rate: 0.4 mm/min confining pressures: <50 kPa compaction: standard proctor + vibration: 3 layers- each 44 blows optimum water content: a) sand: 2% b) sandy silt and tire chips: - failure: peak or 60 mm displacement	tire chips: 5.9 sand: a) loose: 14.7 b) dense: 16.8 sandy silt: 18.3 mixtures: a) sand-tire chips: 13.3 - 15.6 b) sandy silt-tire chips: 16.3 - 17.6	tire chips: 0 sand: 2 sandy silt: 11 mixtures: a) sand-tire chips: 2 b) sandy silt-tire chips: 8 - 39	tire chips: 30 sand: 34 sandy silty: 30 mixtures: a) sand-tire chips: 46 - 52 b) sandy silt-tire chips: 53 - 55	30% tire chips in sand-tire chips mixture
Akbulut et al. (2007)	clayey soil-Tire rubber fiber mixtures	2 - 5 5 - 10 10 - 15	SSDS (diameter: 60 mm, length: 35 mm) strain rate: - confining pressures: - compaction: standard proctor optimum water content: - failure: -	tire rubber fiber: 11.31 - 11.75	219 (for 30-mm length of fiber)	clay-TDA mixtures: 17 - 36	2% fiber with 10-mm length
El Naggar et al. (2016)	various size of TDA mixed with sand (TDA content: 0, 15, 25, 50, 100% by vol.) 29 samples	dust: 0.3 medium: 23.5 coarse: 48.5	LSDS (430 mm × 280 mm × 230 mm) strain rate: - confining pressures: 50, 100, and 150 kPa compaction: standard proctor (5 layers-each 25 blows) optimum water content: - failure: -	TDA: 3.32 - 6.93 sand: 18.25 sand-TDA mixtures: 10.79 - 16.55	-	TDA: 17.5 - 27.5 sand: 36.5 sand-TDA mixtures: 27.5 - 45	15% TDA

Ref.	Materials	Tire shred size (mm)	Test conditions	γ_d (kN/m^3)	c (kPa)	φ (º)	Optimum TDA content
Imtiaz Ahmed (1993)	tire chips-sand mixtures and tire chips-Crosby till mixtures (0 - 66.54% by weight)	12.7 and 25.4	LST[3] (diameter: 152.4 mm) CD[4] condition strain rate: - confining pressures: 31.02 - 206.8 kPa compaction: a) tire chips: proctor (modified, standard, 50% standard) b) tire chips-sand: vibration optimum water content: - failure= 5, 10, 15, and 20% of axial strain	TDA: 6.13-6.87 sand: 18.18 sand-TDA mixtures (mixing ratio:38%): 13.95	TDA: @5%ε_v: 13.38 - 17.10 @10%ε_v: 22.13 - 24.61 @15%ε_v: 27.44 - 32.96 @20%ε_v: 33.23 - 39.16 sand: 0 rubber-sand mixture (mixing ratio=38%): @5%ε_v: 49.99 @10%ε_v: 43.3 @15%ε_v: 36.4	TDA: @5%ε_v: 6.89 - 9.79 @10%ε_v: 11.24 - 14.63 @15%ε_v: 15.88 - 20.3 @20%ε_v: 20.46 - 25.32 sand: 41.42 rubber-sand mixture (mixing ratio=38%): @5%ε_v: 25.46 @10%ε_v: 34.54 @15%ε_v: 38.1	38% TDA content in sand-TDA mixture
Wu et al. (1997)	five tire chips products	2 - 38 (powder granular elongated flat)	SST[5] (diameter: 100 mm, height: 200 mm) CD condition strain rate: 4.23×10^{-6} - 8.47×10^{-6} m/s confining pressures: 34.5 - 55 kPa compaction: - optimum water content: - *constant σ_1 stress path method failure: peak	tire chips: 4.9 - 5.9	tire chips: 0	tire chips: 44 - 56	-
Lee et al. (1999)	rubber-sand mixture with 40% tire chips by weight	< 30 (with no exposed steel belting)	LST (diameter: 150 mm, height: 300 mm) CD condition strain rate: 1%εv /min confining pressures: 28, 97, and 193 kPa compaction: vibration optimum water content: - failure: -	sand: 18.2 tire chips: 6.3 tire chips-sand mixture: 12.5	-	-	-

Ref.	Materials	Tire shred size (mm)	Test conditions	γ_d (kN/m^3)	c (kPa)	φ (º)	Optimum TDA content
Youwai and Bergado (2003)	mixtures of shredded rubber tires and sand (mixing ratio: 0,20,30,40,50% by weight	< 16	LST (diameter: 100 mm and height: 200 mm) CD condition strain rate: 0.19%εv/min confining pressures: 50, 100, and 200 kPa compaction: 5 layers-each 21 to 25 blows + vibration optimum water content: a) sand: 7.5% b) shredded rubber: - *strain controlled failure: peak or 25% axial strain	shredded tire: 6.72 - 7.37 sand: 17.35 - 17.52 sand-tire shred mixtures: 12.42 - 15.23	-	sand-tire shred mixtures: 30 - 34	70% tire shreds
Zornberg et al. (2004)	tire shred-sand mixtures (tire shred content: 0, 5, 10, 15, 20, 30,38.3, 60, 100% by weight)	length: < 102 aspect ratio: 1, 2, 4, and 8	LST (diameter: 153 mm, height: 305 mm) CD[4] condition strain rate: 0.5%εv /min confining pressures: 48.3, 103.5, and 207 kPa compaction: a) tire shreds: tamping b) sand and mixtures: vibration optimum water content for compaction: - dry condition *steel belts were removed to eliminate puncture failure: peak or 15% axial strain	sand: a) (Dr = 55%): 15.64 b) (Dr = 75%): 16.21 tire shred: 6.3	tire shred (L = 50.8 mm): 22.8 sand a) (Dr = 55%): 7.8 b) (Dr = 75%): 3.8 tire shred-sand mixtures: 7 - 60	tire shred (L=50.8 mm): a) with cohesion: 21.4 b) (no cohesion): 26.5 sand a) (Dr = 55%): 36.8 b) (Dr = 75%): 41 sand-tire shred mixtures: 34.4 - 37.2	35% tire shreds

Ref.	Materials	Tire shred size (mm)	Test conditions	γ_d (kN/m^3)	c (kPa)	φ (º)	Optimum TDA content
Rao and Dutta (2006)	sand mixed with tire chips (0, 5, 10, 15 and 20% by weight)	10 × 10 20 × 20 20 × 10	SST (diameter: 100 mm, height: 200 mm) CD condition strain rate: - confining pressures: 34.5 - 276 kPa compaction: 3 layers- each 56 blows optimum water content: - *distribution of tire chips: random failure: peak	Tire chips: - sand: 14.89 ± 0.27	sand: 0 sand-tire chips mixture: 13.3 - 18.4	sand: 38 sand-tire chips mixtures: 39.9 - 40.1	20% tire chips

[1] SSDS: Small-Scale Direct Shear

[2] LSDS: Large-Scale Direct Shear

[3] LST: Large-Scale Triaxial

[4] CD: Consolidated Drained

[5] SST: Small-Scale Triaxial

2.3 Comparison of Direct Shear and Triaxial Compression Methods

Direct shear testing and triaxial compression method have been widely used for many years to find the shear strength behavior of soil. Both approaches contribute to comparable results regarding shear strength parameters of soil (cohesion intercept and angle of internal friction). Most studied have been mainly focused on conventional soils for the comparison. However, there are limited studies that have compared the testing methods for TDA and soil-TDA mixtures.

Maccarini (1993) conducted a series of triaxial compression and direct shear tests on residual soil. He found that the shear strength parameters of the soil obtained from both testing methods are comparable. However, he noted that the triaxial compression test is more accurate than the direct shear test in terms of evaluating the stress path and shear stress versus strain behavior of the soil.

Similar findings were obtained in another study performed by Saada and Townsend (1981). They evaluated direct shear and triaxial compression tests to find the limitations of each testing method. They found that the shear strength properties of soil obtained from both testing methods are similar. Saada and Townsend (1981) mentioned that the simplicity of the direct shear test has made it more popular than triaxial method amongst geotechnical designers. Also, direct shear test results have been successfully used for many years in geotechnical engineering applications. However, a triaxial compression test is more difficult to perform and needs more considerations regarding the membrane penetration and consolidation procedure. Saada and Townsend (1981) suggested that while the direct shear test is more versatile between practitioners, the accumulation of many data with the testing procedure makes it inappropriate for evaluation of stress path.

Castellanos and Brandon (2013) conducted a series of direct shear and triaxial compression tests on remolded and undisturbed soils ranging from low to high plasticity. They found that because remolded soils are more homogeneous and isotropic, their shear strength properties are similar in both testing methods. However, undisturbed samples have a preferred particle orientation and may exhibit higher shear strength in the triaxial compression test.

Finally, according to Foose et al. (1996), the shear strength parameters of TDA and soil-TDA mixtures obtained from a direct shear test is more accurate than a triaxial compression test. They noted that two factors affect the triaxial compression test results. First, according to ASTM D7181 (2011), , the largest particle size must be six times smaller than the specimen diameter in a triaxial compression test. Most common triaxial apparatuses are not relatively large-enough to accommodate the TDA size. Also, due to sharp edges and metals projecting from tire shreds, membrane punctures may happen during the testing procedure. Hence, it is necessary to use a thicker membrane to prevent the puncture. However, the use of the thicker membrane influences the stiffness of the sample and leads to some error in the results.

CHAPTER 3: MATERIALS AND METHODS

This chapter contains three sections. In the first section, the physical properties of the materials used in this study are evaluated. To determine the properties of the materials, particle-size analyses of the TDA and soils used in this study were performed. Hydrometer analysis was also conducted on the clayey soil to find the size of a portion passing the No. 200 sieve. In addition, to find the optimum water content and dry unit weight, laboratory compaction tests using standard proctor energy were performed on the materials. Atterberg limit test was also conducted on the clayey soil to find the plasticity index.

In the second section, the preparation of the mixtures in various mixing ratios is described in detail. Finlay, in the last section, to determine the shear strength behavior of the TDA and soil-TDA mixtures, a direct shear testing procedure using a large-scale direct shear apparatus with a square box (305 mm × 305 mm × 220 mm) is described. In other words, the last two sections involve the preparation and compaction of the mixtures into the shear box; then, performing the direct shear tests on the mixtures and recording the data.

3.1 Materials Used

3.1.1 Tire-Derived Aggregate (TDA)

The TDA sample used in this study was type A, and was shredded and processed by Halifax C&D Recycling Ltd., located in Enfield, Nova Scotia. Figure 3.1 shows the picture of the TDA sample used in this study. Because the TDA particles were mostly flat and elongated, a sieve analysis was not feasible (El Naggar et al. 2016; Foose et al. 1996). Instead, a histogram analysis was performed to find the particle-size distribution of the TDA. To conduct the histogram analysis, a TDA sample was randomly selected, and the particles were measured in all directions using a ruler. Figure 3.2 shows the histogram of the initial TDA sample.

Figure 3.1 Photograph of the TDA sample used in this study

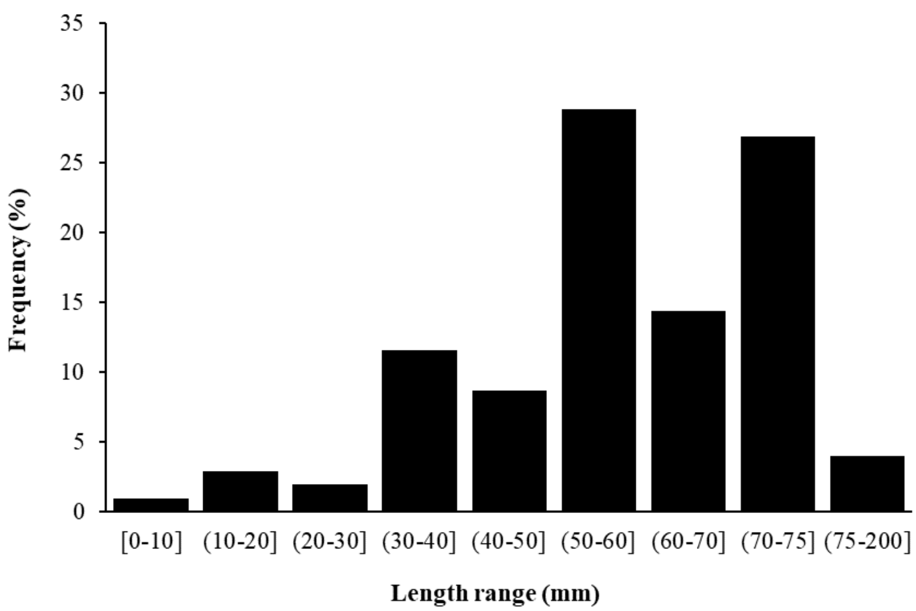


Figure 3.2 Histogram of the initial TDA sample

According to ASTM D3080 (2012), the maximum particle size of aggregates must be ten times smaller than the length of the shear box, to eliminate boundary effects. However, Humphrey and Sandford (1993) have suggested that for larger particles such as TDA, a direct shear test can be performed with particles that are four times smaller than the length of the shear box. Their test results showed that the boundary effect is minimized in this case, and the particles are sheared in the box with a minimal external effect. In addition, according to Foose et al. (1996), the use of tire shreds with a maximum length less than half the diameter of a direct shear ring reduces the boundary effect during shearing. Since the length of the shear box used in this study was limited to 305 mm, TDA particles larger than 75 mm in length were removed from the sample (3.9% of the sample). Therefore, the maximum particle-size was limited to one-fourth of the shear box length to eliminate boundary and size effects (Humphrey sand Sandford 1993). Figure 3.3 shows the histogram of the TDA sample after removal of the particles larger than 75 mm in length. As shown in the figure, the TDA particle sizes ranges from 0-10 mm, 10-20 mm, 20-30 mm, 30-40 mm, 40-50 mm, 50-60 mm, 60-70 mm, and 70-75 mm.

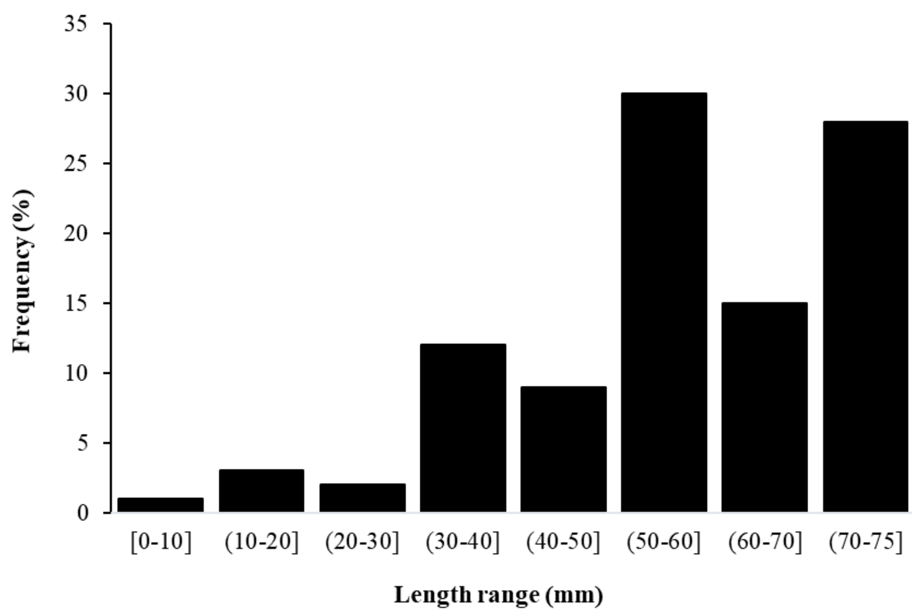


Figure 3.3 Histogram of the TDA particles used in this study

The TDA sample had the average aspect ratio (length/width) of 2.8, and the average thickness of 8.9 mm. The dry unit weight (γ_d) of the TDA sample was determined in accordance with the standard test method described in ASTM D698 (2012). It should be noted that due to the TDA particles were flexible; the compaction energy had a negligible effect on its dry unit weight. Therefore, according to Humphrey and Sandford (1993), 60% of the standard Proctor energy was applied to the specimen.

Similarly, because the addition of water content to the TDA sample did not change the dry unit weight at all, the compaction test was performed on an air-dried sample (Cecich et al. 2016; ASTM D6270 2017). Table 3.1 shows the physical properties of the TDA sample used in the shear box tests.

According to ASTM D6270 (2017), to use TDA particles effectively, rubber-to-rubber contact needs to be maximized by reducing the number of exposed steel belts. In this study, the exposed wires were therefore removed from the edges of the TDA particles using a pair of scissors.

Table 3.1 Characteristics of the TDA used in this study

Characteristics	Value
Size range (mm)	10 - 75
Average thickness (mm)	8.9
Average Aspect ratio	2.8
optimum water content (%)	-
dry unit weight, γ_d (kN/m^3)	7.1

3.1.2 Gravelly Soil

A relatively uniform gravelly soil was obtained from a local supplier used in this study. The particle-size analysis of the soil was performed in accordance with ASTM D422 (2007). Figure 3.4 shows the particle-size distribution of the gravelly soil.

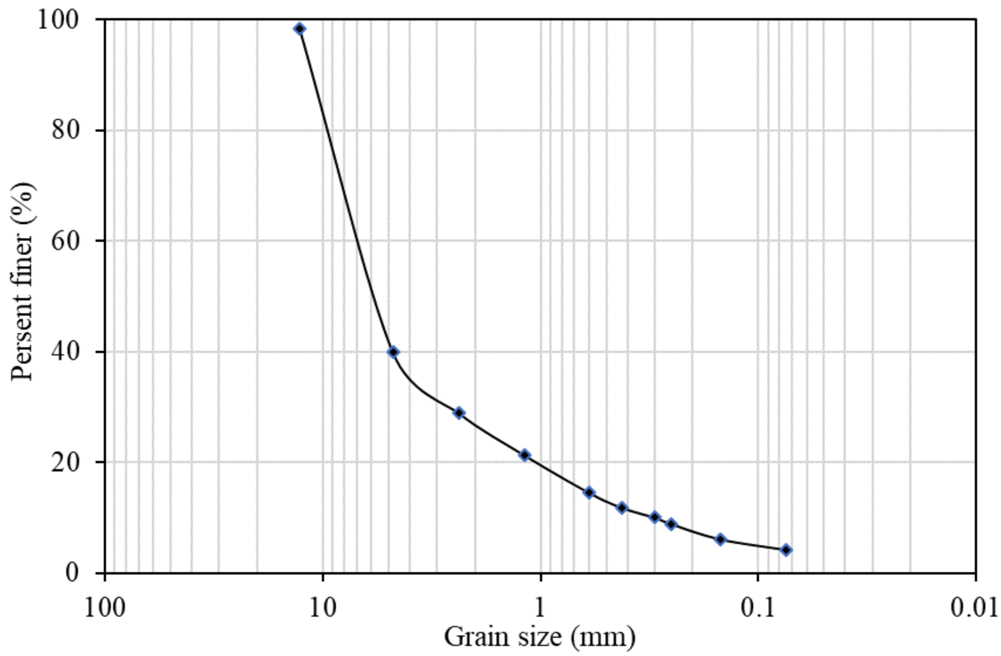


Figure 3.4 particle-size distribution of the gravelly soil used in this study

In addition, to find the dry unit weight and optimum water content (ω) of the soil sample, a laboratory compaction test using standard proctor energy was performed according to ASTM D698 (2012). Table 3.2 lists the physical characteristic of the gravelly soil. The soil had a coefficient of uniformity of 23.33 and a coefficient of curvature of 2.74. In accordance with the unified soil classification system (ASTM D2487 2011), the soil was classified as well-graded gravel with sand.

Table 3.2 Characteristics of the gravelly soil used in this study

Characteristics	Value
D_{10} (mm)[1]	0.30
D_{30} (mm)[1]	2.40
D_{50} (mm)[1]	5.90
D_{60} (mm)[1]	7.00
Coefficient of uniformity, C_u[2]	23.33
Coefficient of curvature, C_C[2]	2.74
Optimum water content, ω (%)	7.50
dry unit weight, γ_d (kN/m^3)	19.2

[1]D_{10} , D_{30}, D_{50} and D_{60} represent the diameter of the aggregate when the sample is finer than 10, 30, 50 and 60%, respectively.

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

3.1.3 Sandy Soil

A relatively uniform sandy soil obtained from Dalhousie University geotechnical laboratory was used in this study. The particle-size distribution of the soil was determined in accordance with ASTM D422 (2007). Figure 3.5 illustrates the particle-size distribution of the sandy soil. In addition, to find the dry unit weight and optimum water content of the soil, a laboratory compaction test using standard proctor energy was performed in accordance with ASTM D698 (2016). Table 3.3 summarizes the physical characteristics of the sandy soil. The soil had a coefficient of uniformity of 3.33 and a coefficient of curvature of 0.92. By following the unified soil classification system procedure (ASTM D2487, 2011), the soil was classified as poorly graded sand.

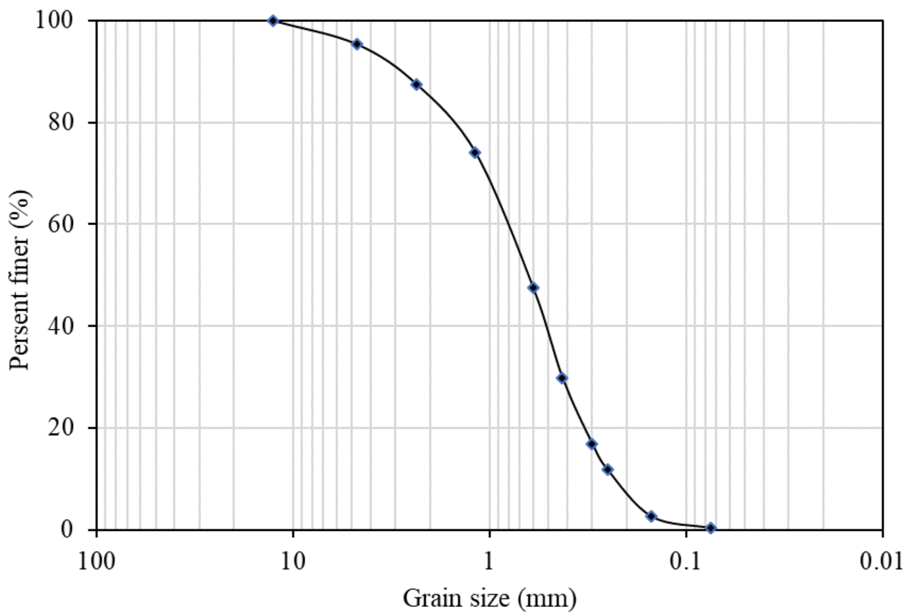


Figure 3.5 Particle-size distribution of the sandy soil used in this study

Table 3.3 Characteristics of the sandy soil used in this study

Characteristics	Value
D_{10} (mm)	0.24
D_{30} (mm)	0.42
D_{50} (mm)	0.65
D_{60} (mm)	0.80
Coefficient of uniformity, C_u	3.33
Coefficient of curvature, C_C	0.92
Optimum water content, ω (%)	13
dry unit weight, γ_d (kN/m^3)	16.8

3.1.4 Clayey Soil

The clayey soil was supplied from Enfield, Nova Scotia to use in this study. The soil sample had a clayey-rock characteristic in a natural condition. Therefore, it was first dried at 110º for 24 hours, and then was smashed into finest pieces before being used in this study. The particle-size analysis was performed in accordance with ASTM D422 (2007).

It should be noted that sieve analysis was performed to find the distribution of the particles greater than 75 µm (retained on the No. 200 sieve). In contrast, hydrometer analysis was conducted to find the distribution of the particles smaller than 75 µm (passed the No. 200). Figure 3.6 depicts the particle-size distribution of the clayey soil. In addition, dry unit weight and optimum water content of the soil were determined using standard proctor energy method described by ASTM D698 (2012). To find the plasticity index of the clayey soil, Atterberg limit test was also performed according to the standard test method described by ASTM D4318 (2017).

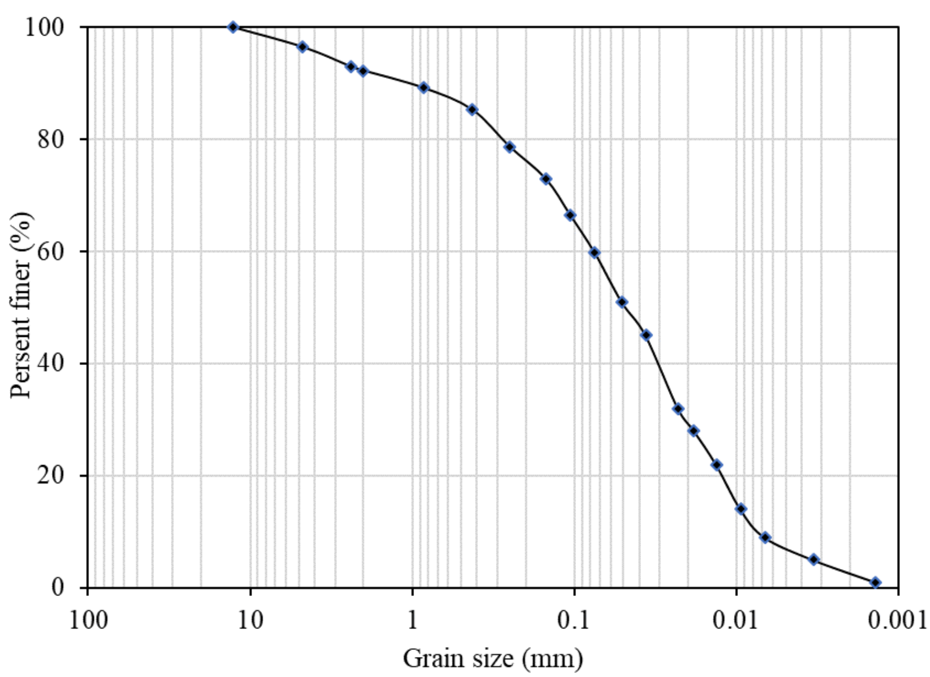


Figure 3.6 Particle-size distribution of the clayey soil used in this study

Table 3.4 presents the physical characteristics of the clayey soil used in this study. In accordance with the unified soil classification system (ASTM D2487 2011), the soil was classified as sandy lean clay.

Table 3.4 Characteristics of the clayey soil used in this study

Characteristics	Value
Liquid Limit, LL	25.2
Plastic Limit, PL	15.9
Plasticity Index, PI	9.3
Optimum water content, ω (%)	14
dry unit weight, γ_d (kN/m^3)	18.4

3.2 Preparation of the Mixtures

In this section, the preparation of the mixtures for use in the large-scale direct shear test is explained. As indicated before, three types of soil were selected to mix with the TDA particles in this study. Before mixing the soil samples with the TDA content, they were dried in an oven for 24 hours at 110º C and then smashed if needed. The TDA sample was dried at room temperature for 72 hours. Following the drying of the materials, the required percentages of each soil and TDA content were measured carefully based on their mixing ratio. Also, the optimum water content of each soil was measured and added to each soil. Then, the materials were transferred into a tray where they were mixed carefully until a consistent mixture was obtained. As indicated before, the water content for compaction of the TDA particles was found to be zero, and hence no water was added to the TDA particles.

The mixed materials were then poured gently into the shear box in five layers using a shovel. At each step, the mixture on the tray was mixed thoroughly before being poured into the shear box. Special care and continuous observations were made to prevent any inconsistency in the mixtures. Therefore, the segregation between the soil and TDA particles did not occur during the sample preparation and transferring into the shear box. It should be noted that segregation is likely to occur in mixtures with higher percentages of TDA content. When segregation occurs, the soil settles beneath the TDA particles, and the mixture loses its consistency. Edil and Bosscher (1994) conducted a series of triaxial tests on mixtures of sand and tire chips. They found that with a tire chips content greater than 30% by volume, segregation increased between the sand and tire chips particles. Bosscher et al. (1992) likewise conducted a field study, where they observed that segregation occurs in mixtures containing more than 50% TDA content by volume.

Table 3.5 to 3.7 presents the percentages of the TDA content by weight for each mixture from 0 to 100%. In the table, the first letter in the first column indicates the soil type (G for the gravel, S for the sand, and C for the clay) and the second letter shows the TDA content following by its ratio in the mixture by weight. It should be noted that the percentage of the TDA content by weight was defined as the ratio of the weight of the TDA content to the total weight of the soil-TDA mixture.

Table 3.5 Properties of the gravel-TDA mixtures

Mixture	TDA % (by weight)	Gravel % (by weight)	γ_d (kN/m^3)
GT0	0	100	18.5
GT10	10	90	17.1
GT20	20	80	15.0
GT25	25	75	13.8
GT40	40	60	10.3
GT50	50	50	9.5
GT100	100	0	6.9

Table 3.6 Properties of the sand-TDA mixtures

Mixture	TDA % (by weight)	Sand % (by weight)	γ_d (kN/m^3)
ST0	0	100	16.6
ST10	10	90	15.7
ST25	25	75	13.9
ST50	50	50	10.8
ST100	100	0	6.9

Table 3.7 Properties of the clay-TDA mixtures

Mixture	TDA % (by weight)	Clay% (by weight)	γ_d (kN/m^3)
CT0	0	100	18.0
CT10	10	90	16.5
CT25	25	75	13.7
CT50	50	50	9.7
CT100	100	0	6.9

3.3 Direct Shear Testing Procedure

Following the preparation of the mixtures in the shear box, a serious of large-scale direct shear tests were performed on each mixture. The direct shear tests were carried out according to the standard test procedure described by ASTM D3080 (2012).

Figure 3.7 shows the large-scale direct shear box apparatus with a square box (305 mm × 305 mm × 220 mm) used in this study. As shown in the figure, the device consists of a 305 mm square box (nominal dimensions) made of steel with a thickness of 9 mm. The lower half of the box was 90 mm high and was seated on a movable base. The upper half of the box was 80 mm high. To accommodate the large compressibility of the TDA sample and soil-TDA mixtures while being sheared, the apparatus was customized, and an extension with a height of 50 mm was made and mounted on top of the upper half of the shear box. Thus, the total height of the shear box reached 220-mm.

To shear the mixtures in the box, the upper half of the box was fixed, while the lower half

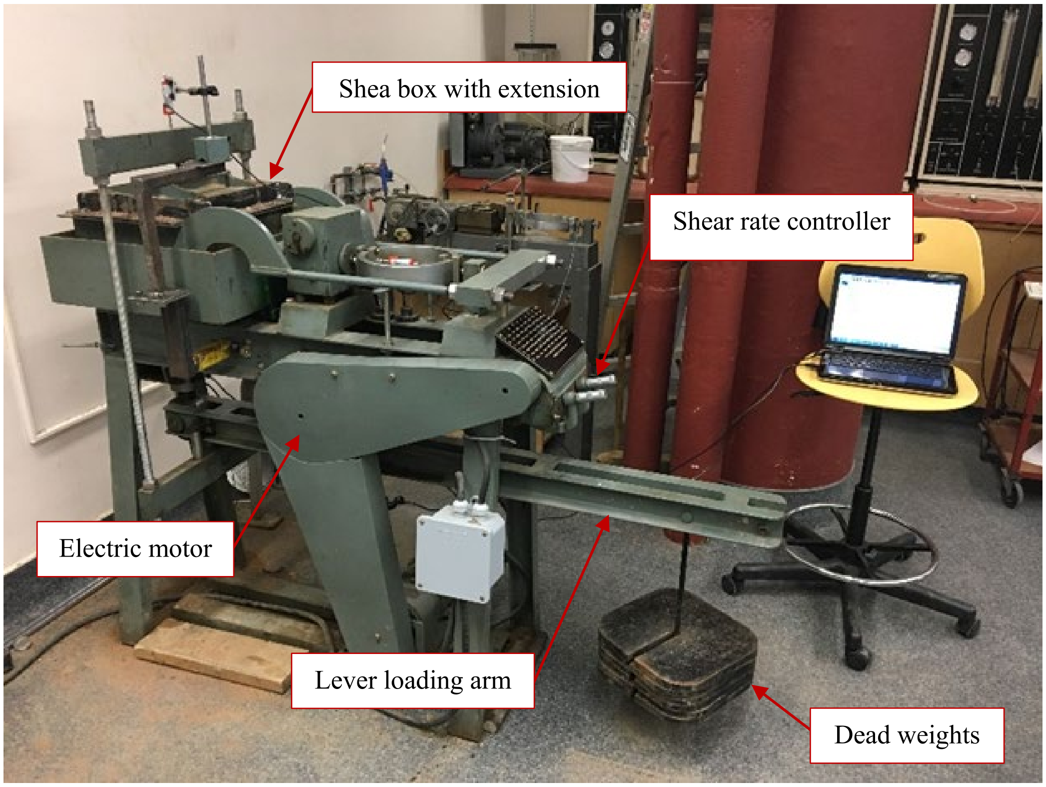


Figure 3.7 The large-scale direct shear apparatus with a square box

was able to move by the power of an electric motor at a controlled rate. Therefore, the specimen could be sheared near a single shear plane in the middle of the shear box. As shown in the previous picture, the confining pressures were applied to the specimens by dead weights and were transferred to the top of the specimens from a lever loading arm. It should be noted that, before positioning the loading arm, a steel plate cap was placed on top of the specimen, and then the confining pressure was applied to the specimen.

A load cell with a linear variable displacement transducer (LVDT) was mounted to measure the shear force. In addition, two LVDTs were installed to monitor the horizontal and vertical displacement of the mixture during shearing. One was installed above the box, contacting a steel plate over the sample to measure the vertical deformation. The other was installed horizontally, contacting the lower half of the box, to measure the lateral displacement. All LVDTs were also connected to a data acquisition system (CAMPBELL SCIENTIFIC CR200 Series), and data were recorded and monitored with the aid of a computer. Figure 3.8 shows the location of the LVDTs.

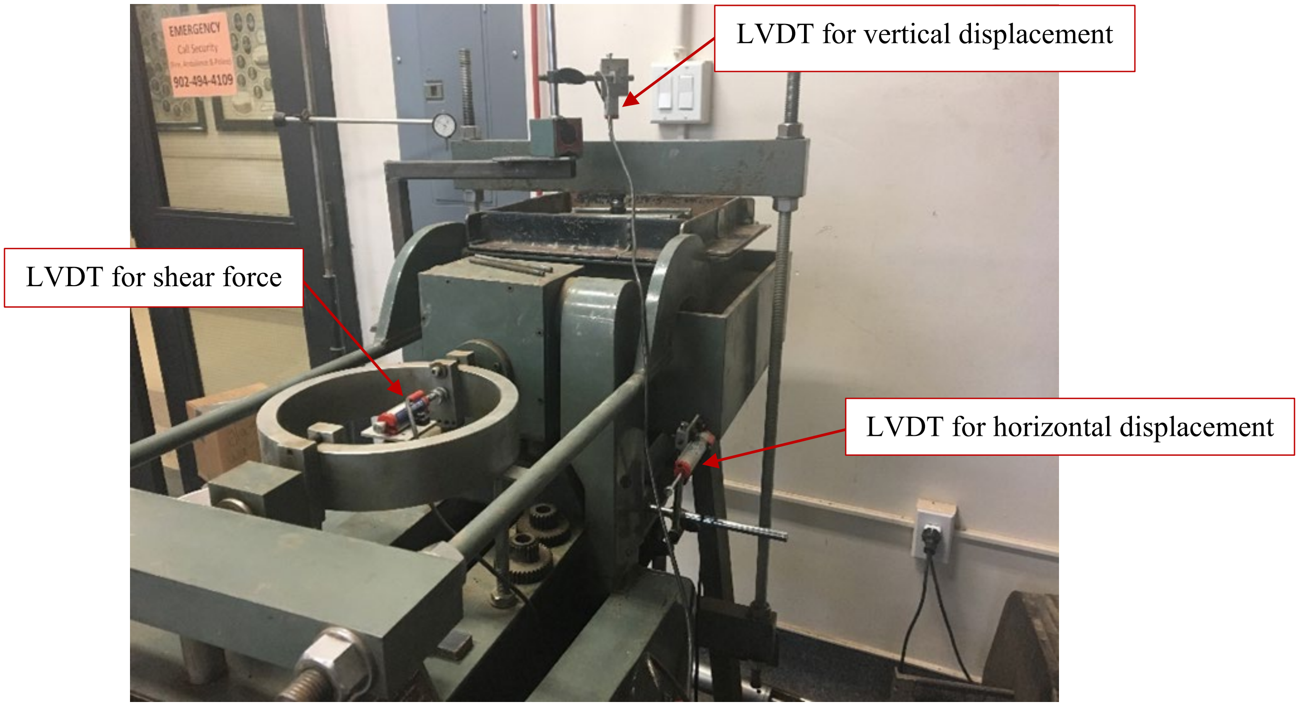


Figure 3.8 Location of the LVDTs

In this study, TDA content and confining pressures were the primary variables considered, and the direct shear tests were conducted on the mixtures with various TDA content and confining pressures (50.1, 98.8, and 196.4 kPa).

Some studies in the past considered the effect of TDA orientation on the shear strength behavior of the soil-TDA mixture. Since under field conditions, tire shreds are usually mixed with soil in a random orientation, the effect of TDA orientation was not considered in this study.

The mixtures were tested at a relatively high confining pressures ranging from 50.1 to 196.4 kPa. It should be noted that, at a lower confining pressure, the shear stress cannot mobilize completely through the shear plane, and this may result in some slip and pull-out effects during shearing. In other words, it influences the shear strength behavior of the mixtures and contributes to an apparent friction angle (Gray and Ohashi 1983).

All tests were performed in a strain-controlled condition at a constant shear rate. While the tests were running, the shear force, horizontal displacement and vertical deformation were recorded up to a total relative lateral displacement of 14%. Then, at 14% relative lateral displacement, the tests were terminated, and all the data were collected. It should be noted that the shear rate of a clayey soil needs to be slow enough to prevent excess pore water pressure in the specimen and allow the dissipation of pore water pressure while being sheared. Hence, it may take several days to perform a direct shear test on clayey soil. However, according to Bowles (1982), a shear rate of 1.2 to 1.3 mm/min gives a close approximation for drained shear strength of a clayey soil obtained from a direct shear test. Therefore, the shear rate was taken at a low rate of 0.5 mm/min in this study.

As mentioned earlier, the shear force was applied by an electric motor and was recorded during shearing the samples using LVDT. After the shear tests were terminated, the shear stress was calculated by dividing the shear force by the horizontal cross-sectional area of the box (930.25 cm^2). Then, the shear strength of the mixtures was defined at a peak shear stress. If there was no peak shear stress up to 14% relative lateral displacement, the shear stress at 10% relative lateral displacement was taken as the shear strength of the mixtures (ASTM D3080 2012).

It should be noted that some tests were repeated twice to ensure that the test procedure used in the study was accurate, and the results were indicative. The repeated tests showed similar results which confirmed the accuracy and repeatability of the tests.

CHAPTER 4: RESULTS AND DISCUSSIONS

In this chapter, first, the variation of the dry unit weight of the mixtures with TDA content is presented. Next, the shear stress versus shear strain results obtained from the large-scale direct shear tests for the mixtures are discussed. The Mohr-Coulomb failure envelopes are then drawn to find the shear strength parameters of the soil-TDA mixtures. The vertical deformation of the mixtures upon shearing are then evaluated. Next, a comparison between the shear strength parameters of the gravel-TDA, sand-TDA, and clay-TDA is made. Also, the behavior of the pure TDA upon shearing at various shear strain is discussed. Finally, the effect of TDA content on the normalized lateral earth pressure at-rest condition is presented.

4.1 Dry Unit Weight of the Mixtures

Figure 4.1 to 4.3 illustrate the variation of dry unit weight with TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures used in the large-scale direct shear tests. In the figures, for comparison purpose, the TDA content ranges from 0%, corresponding to soil alone, to 100%, which means TDA alone. It is seen that the addition of TDA content to the soils considerably reduced the dry unit weight of the mixtures. It should be noted that the reduction in the dry unit weight of the mixtures results from the low dry unit weight of the TDA (7.1 kN/m^3) which is less than two times of the conventional soils used in this study.

The reduction of dry unit weight is beneficial when designing a retaining wall, and the lateral earth pressure needs to be minimized. Also, when the soil beneath a fill is weak, the use of a light soil mixture contributes to overcoming the weakness. Hence, the soil-TDA mixtures can be a lightweight alternative in geotechnical applications.

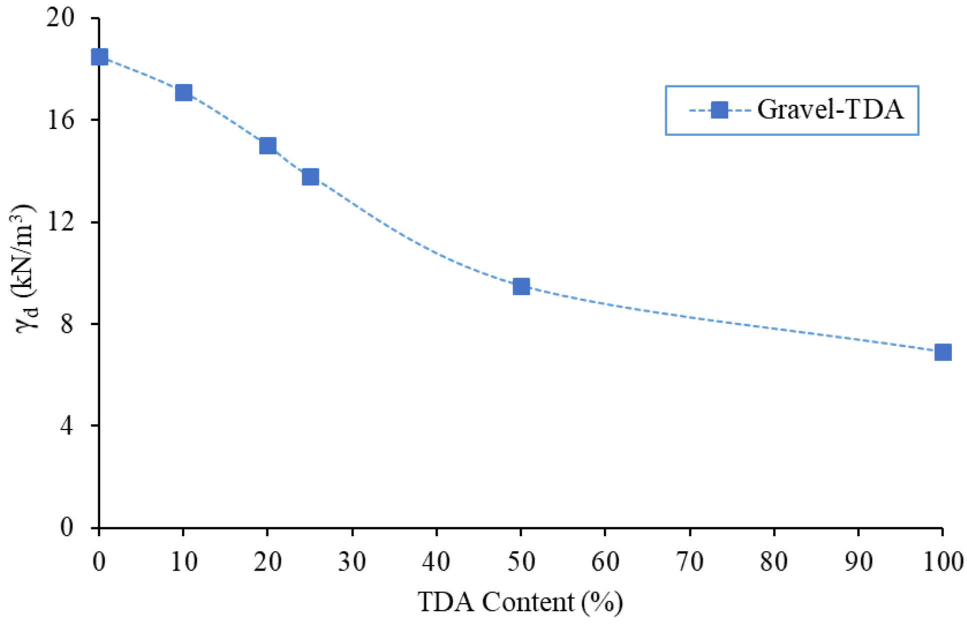


Figure 4.1 Dry unit weight vs. TDA content for the gravel-TDA mixtures

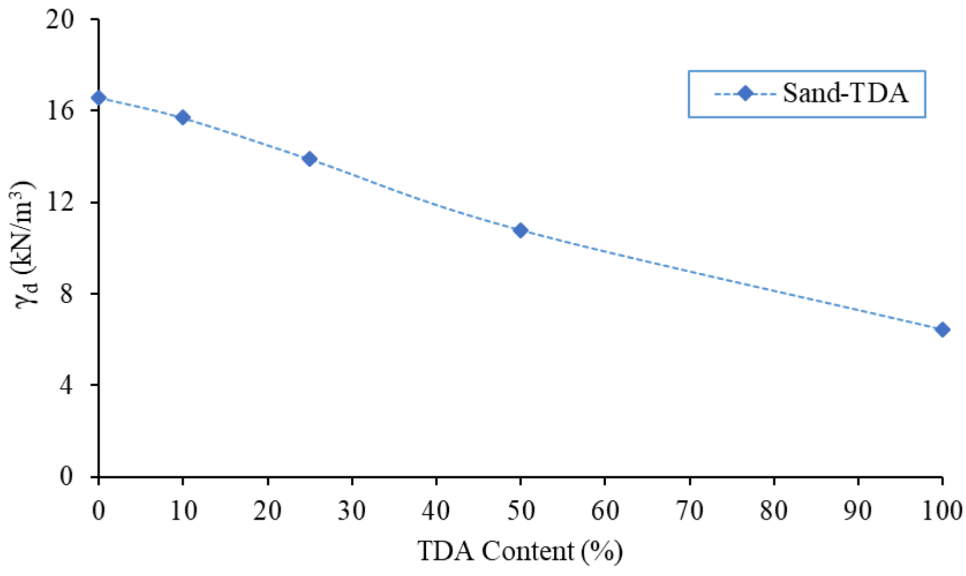


Figure 4.2 Dry unit weight vs. TDA content for the sand-TDA mixtures

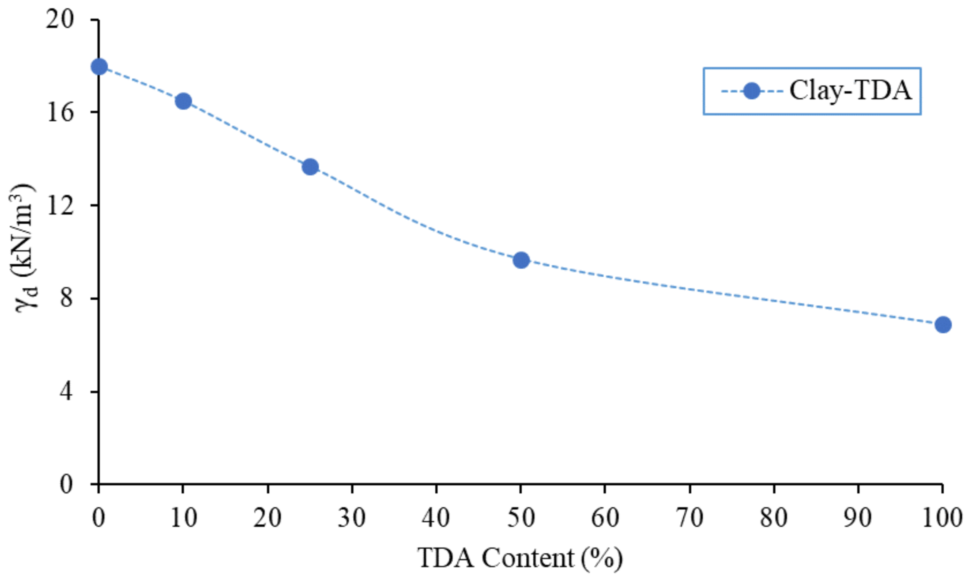


Figure 4.3 Dry unit weight vs. TDA content for the clay-TDA mixtures

4.2 Shear Stress vs. Shear Strain Behavior

4.2.1 Gravel-TDA Mixtures

For all the gravel-TDA mixtures, direct shear tests were conducted at the three confining pressures of 50.1, 98.8, and 196.4 kPa. Figure 4.4 illustrates the variation of shear stress with shear strain for the gravel-TDA mixtures at 50.1 kPa confining pressure. As shown in the figure, for 100% gravel (GT0) a clear peak shear stress was observed, representing the shear strength of the sample. Then, the addition of TDA content to the gravel decreased the shear resistance of the mixtures upon shearing at 50.1 kPa confining pressure.

It should be noted that the addition of TDA content up to 25% by weight to the gravel decreased the peak shear resistance gradually at a higher shear strain. Then, for mixtures containing more than 25% TDA content, no peak shear stress was exhibited up to 24% shear strain. In other words, mixtures containing more than 25% TDA content showed a strain-hardening behavior, and did not fail up to 24% shear strain.

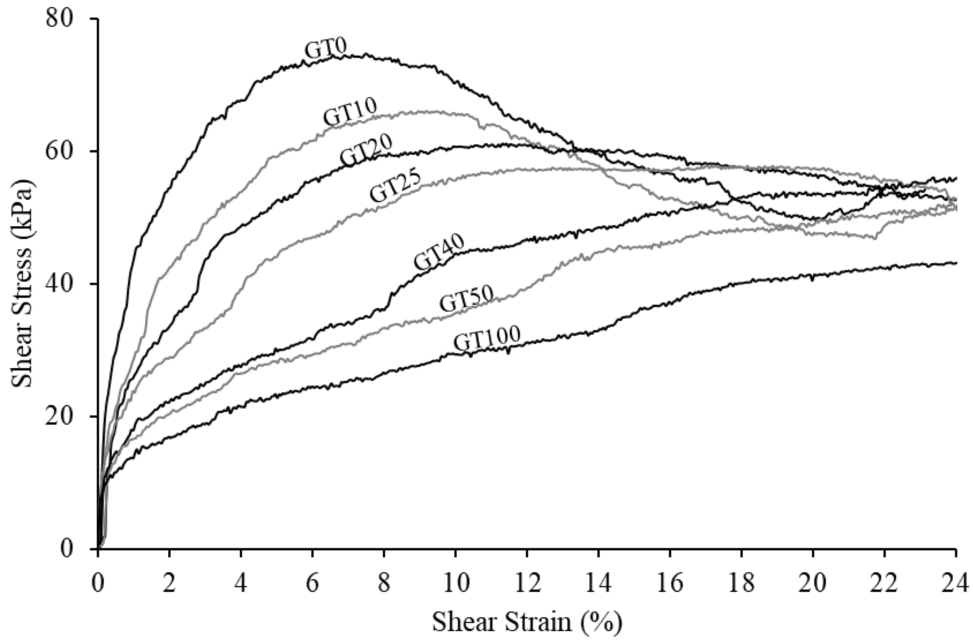


Figure 4.4 Shear stress vs. Shear Strain for the gravel-TDA mixtures at 50.1 kPa confining pressure

Figure 4.5 and 4.6 illustrate the variation of shear stress with shear strain for the gravel-TDA mixtures at 98.8 and 196.4 kPa confining pressures. As shown in the figures, a peak shear stress was observed upon shearing for 100% gravel at 98.8 and 196.4 kPa confining pressures. Then, the addition of TDA content to the gravel decreased the shear resistance of the mixtures at the considered confining pressures. It should be noted the reduction in the shear resistance up to 10% TDA content was not significant at 98.8 and 196.4 kPa confining pressures. Also, as shown in the figures, the addition of TDA content up to 25% at 98.8 confining pressure and up to 20% at 196.4 kPa confinement decreased the peak shear resistance of the mixtures at a higher shear strain. Then, for mixtures containing more than 25% TDA content at 98.8 kPa confining pressure, and more than 20% TDA content at 196.4 kPa confinement, no peak shear resistance was expedited up to 24% shear strain. In other words, mixtures containing more than 25% TDA content at 98.8 kPa confining pressure and more than 20% TDA content at 196.4 kPa confinement showed a strain-hardening behavior and did not fail up to 24% strain.

Finally, a comparison of the results of shear stress versus shear strain at the considered confining pressures showed that increasing the confining pressure from 50.1 to 196.4 kPa enhanced the shear resistance of the mixtures with the same amount of TDA content.

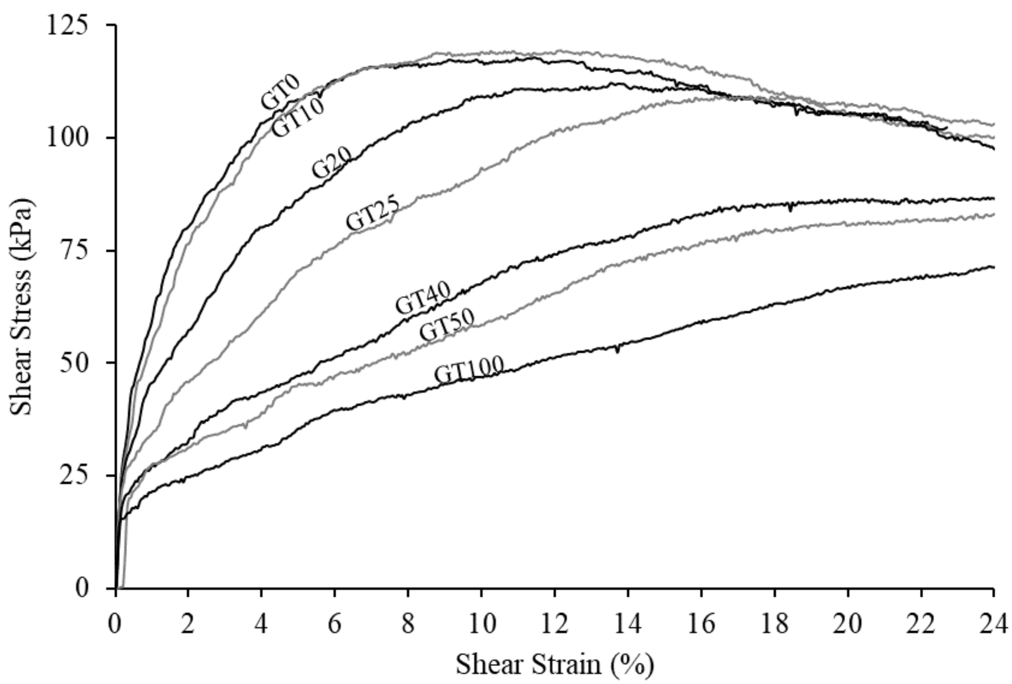


Figure 4.5 Shear stress vs. Shear Strain for the gravel-TDA mixtures at 98.8 kPa confining pressure

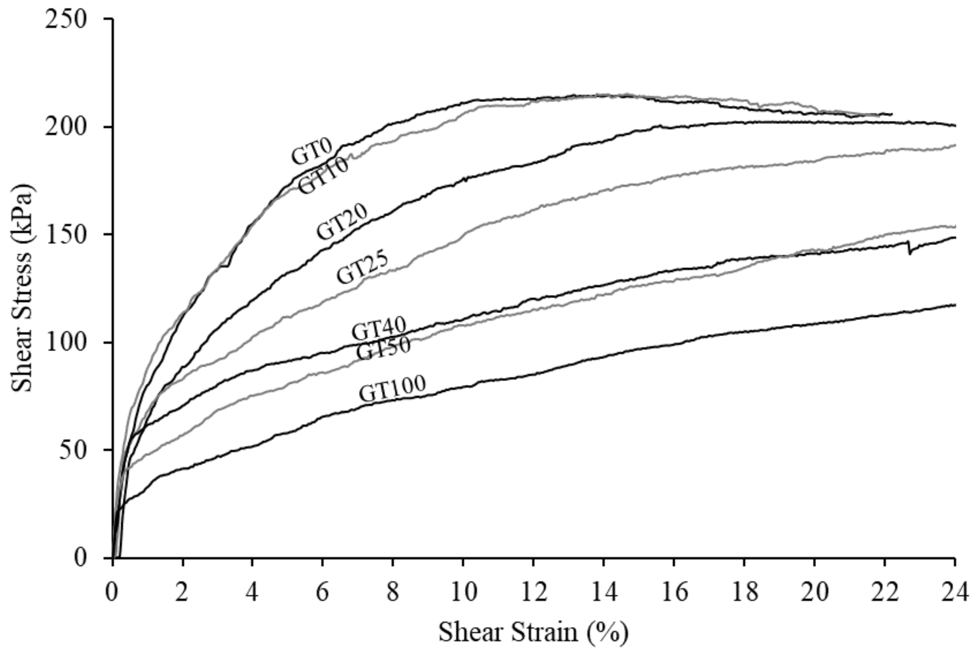


Figure 4.6 Shear stress vs. Shear Strain for the gravel-TDA mixtures at 196.4 kPa confining pressure

4.2.2 Sand-TDA Mixtures

For all the sand-TDA mixtures, direct shear tests were conducted at the three confining pressures of 50.1, 98.8, and 196.4 kPa. Figure 4.7 depicts the variation of shear stress with shear strain for the sand-TDA mixtures at 50.1 kPa confining pressure. As shown in the figure, for 100% sand (ST0), a clear peak shear stress was observed, demonstrating the shear strength of the sample. Then, the addition of up to 10% TDA content by weight to the sand increased the peak shear stress at a similar shear strain. Increasing the TDA content from 10 to 25%, again increased the peak shear stress at a higher shear strain. In contrast, for mixtures containing more than 25% TDA content, the shear resistance decreased. It should be noted that except for the pure TDA (ST100), all the sand-TDA mixtures reached their peak shear stress at 50.1 kPa confining pressure.

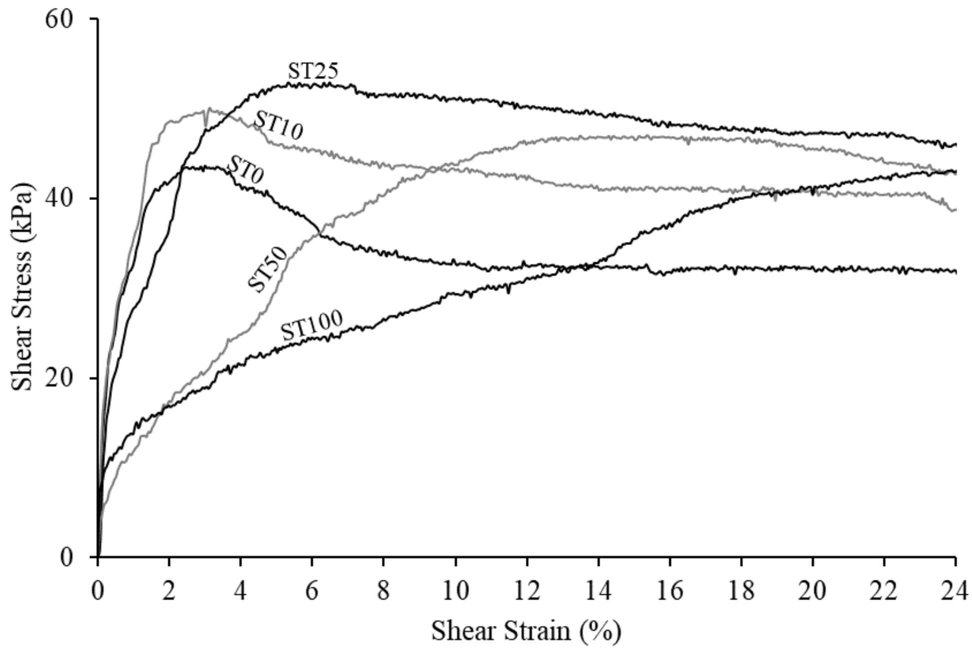


Figure 4.7 Shear Stress vs. Shear Strain for the sand-TDA mixtures at 50.1 kPa confining pressure

Figure 4.8 and 4.9 illustrate the variation of shear stress with shear strain for the sand-TDA mixtures at 98.8 and 196.4 kPa confining pressures. Similar observations were made at 98.8 and 196.4 kPa confining pressures. However, unlike the situation with the confining pressure of 50.1 kPa, increasing the TDA content from 10 to 25% by weight did not significantly change the peak shear resistance of the mixtures. However, the peak shear resistance of ST25 was observed at a higher shear strain compared to ST10. Then, for mixtures containing more than 25% TDA content, no peak shear stress was exhibited up to 24% shear strain at the considered confining pressures. In other words, mixtures containing more than 25% TDA content showed a strain-hardening behavior and did not fail up to 24% shear strain.

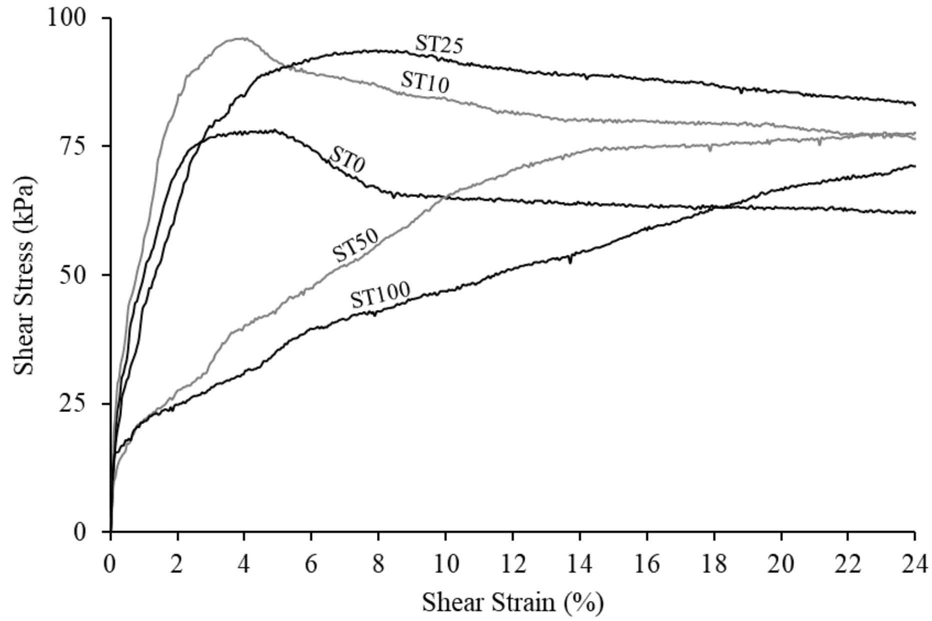


Figure 4.8 Shear Stress vs. Shear Strain for the sand-TDA mixtures at 98.8 kPa confining pressure

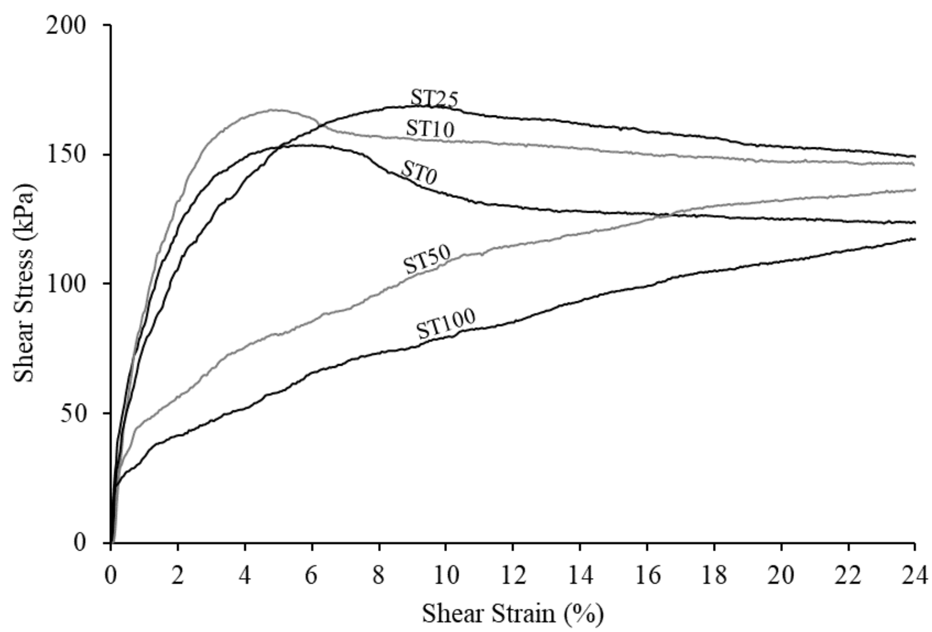


Figure 4.9 Shear Stress vs. Shear Strain for the sand-TDA mixtures at 196.4 kPa confining pressure

Finally, a comparison of the results of shear stress versus shear strain at the considered confining pressures showed that increasing the confining pressure from 50.1 to 196.4 kPa enhanced the shear resistance of the mixtures with the same amount of TDA content.

4.2.3 Clay-TDA Mixtures

For all the clay-TDA mixtures, the direct shear tests were conducted at the three confining pressures of 50.1, 98.8, and 196.4 kPa. Figure 4.10 illustrates the variation of shear stress with shear strain for the clay-TDA mixtures at 50.1 kPa confining pressure. As shown in the figure, for 100% clay (CT0) a peak shear stress was observed, representing the shear strength of the sample. Then, adding up to 10% TDA content by weight to the clay increased the peak shear stress significantly at a higher strain.

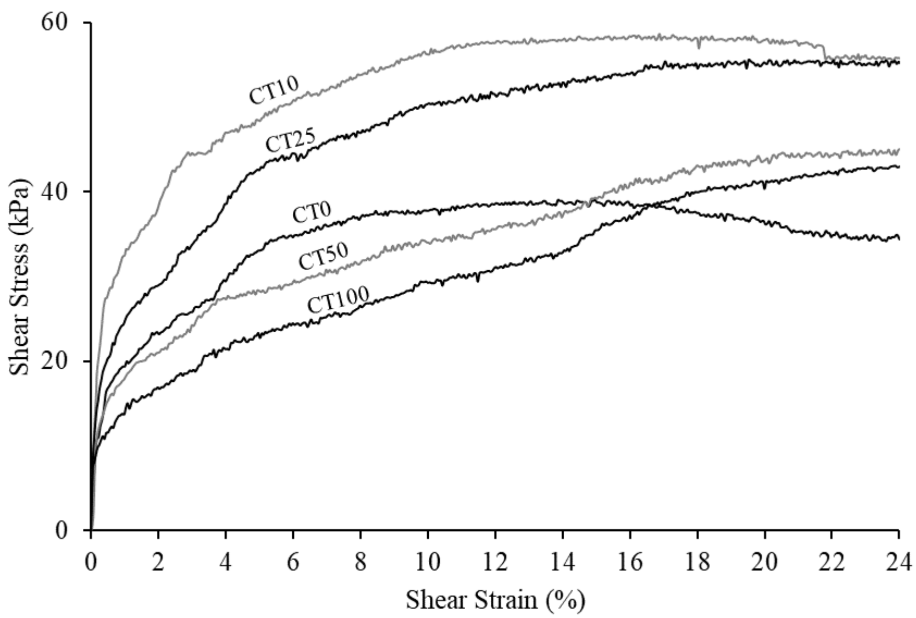


Figure 4.10 Shear stress vs. Shear Strain for the clay-TDA mixtures at 50.1 kPa confining pressure

However, the addition of more than 10% TDA content then decreased the shear resistance of the mixture without being failed up to 24% shear strain. It was also found that, although increasing TDA content from 10 to 25% decreased the shear resistance of the mixture, it was still higher than clay alone (CT0).

Similar observations were made for mixtures upon shearing at 98.8 and 196.4 kPa confining pressures; however, no peak shear stress was exhibited up to 24% shear strain by any of the samples (see Figure 4.11 and 4.12). It should be noted that considering the failure at 10% relative lateral displacement for mixtures with no peak shear stress, the highest shear resistance and the lowest shear resistance were observed for CT10 and clay alone (CT0) amongst the mixtures at all the confining pressures, respectively.

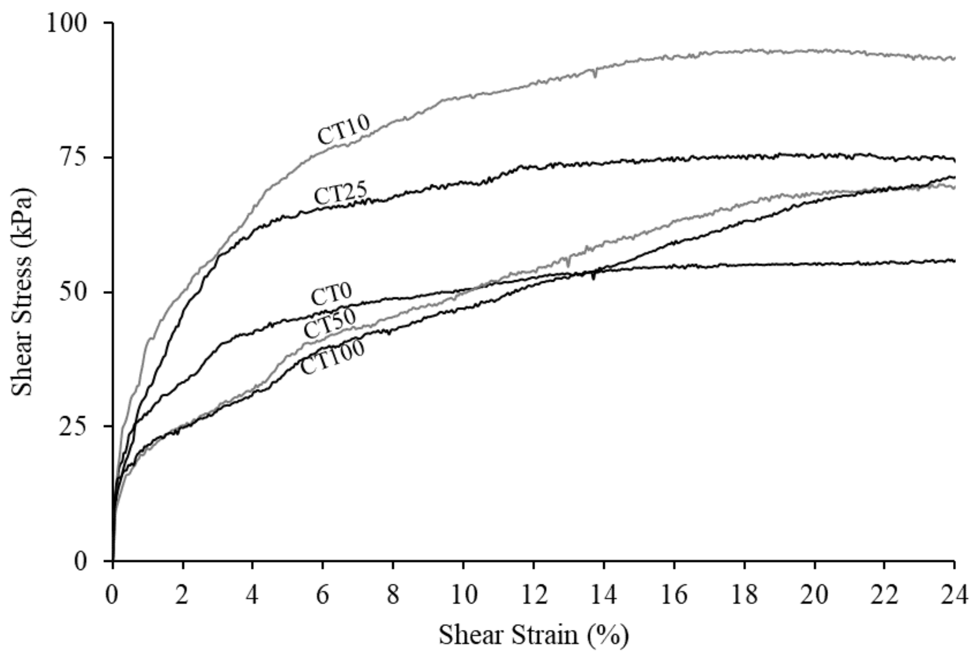


Figure 4.11 Shear stress vs. Shear Strain for the clay-TDA mixtures at 98.8 kPa confining pressure

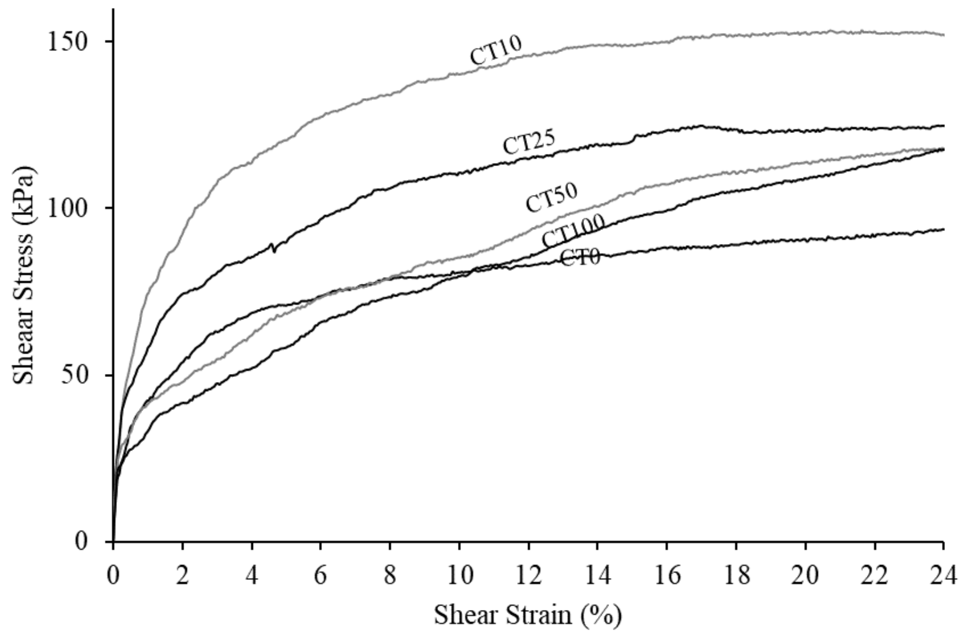


Figure 4.12 Shear stress vs. Shear Strain for the clay-TDA mixtures at 196.4 kPa confining pressure

Finally, a comparison of the results of shear stress versus shear strain at the considered confining pressures showed that increasing the confining pressure from 50.1 to 196.4 kPa enhanced the shear resistance of the mixtures with the same amount of TDA content.

4.3 Mohr-Coulomb Failure Criterion for the Mixtures

The Mohr-Coulomb failure criterion was used to find the angle of internal friction and cohesion for the soil-TDA mixtures used in this study. As explained before, each specimen was tested at the three normal stresses of 50.1, 98.8 and 196.4 kPa. Failure was defined at a peak and, in the absence of a peak, at 10% relative lateral displacement.

The Mohr-Coulomb failure envelope is defined as a linear relationship between normal stress and the corresponding shear strength. The slope of the line represents the angle of internal friction and the interception of the line with Y-axis shows the cohesion. Equation 4.1 expresses the Mohr-Coulomb failure law (DAS 2014):

$$\tau = c + \sigma \tan \varphi \qquad (4.1)$$

where τ is shear stress at failure, c is cohesion intercept and φ is the angle of internal friction. By referring the shear stress versus relative lateral displacement behavior of the mixtures obtained from the direct shear tests, the Mohr-Coulomb failure envelopes for the mixtures were drawn. Then, the shear strength parameters of the mixtures (angle of internal friction and cohesion) were determined from the failure envelopes. Figure 4.13 to 4.15 show the variation of shear strength with confining pressure (Mohr-Coulomb failure envelopes) for the gravel-TDA, sand-TDA, and clay-TDA mixtures.

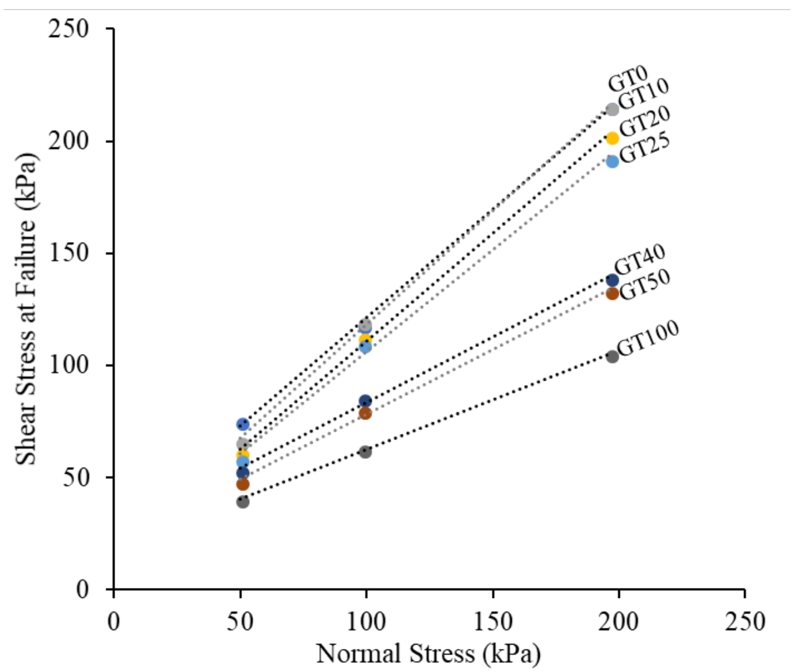


Figure 4.13 Failure envelope for the gravel-TDA mixtures

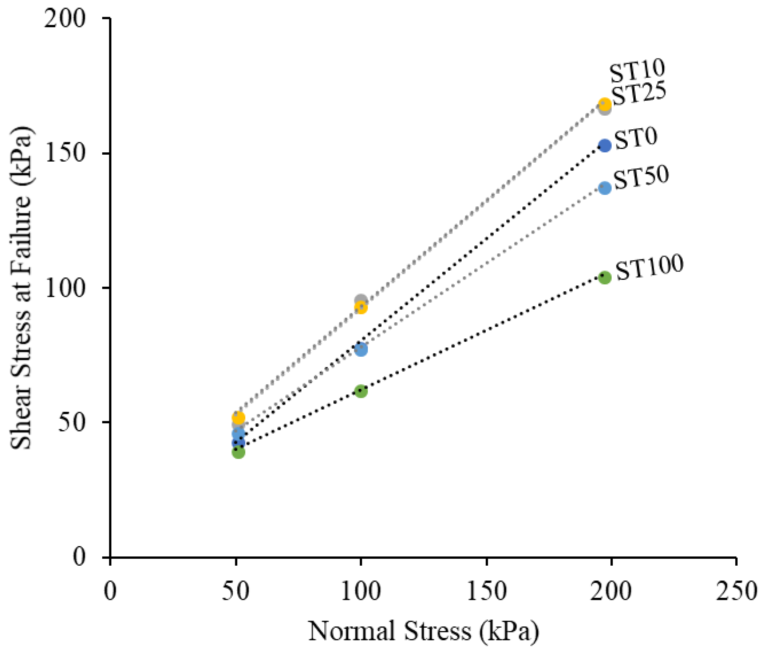


Figure 4.14 Failure envelope for the sand-TDA mixtures

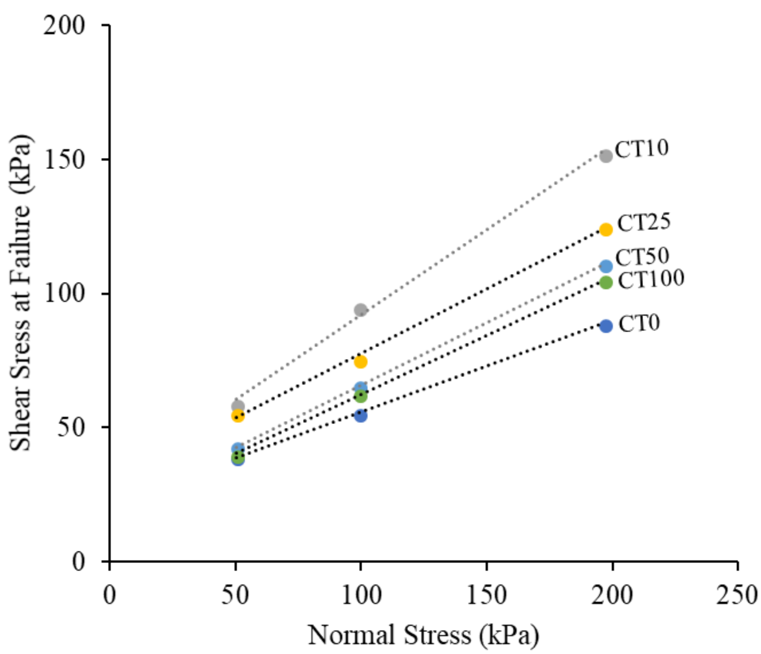


Figure 4.15 Failure envelope for the clay-TDA mixtures

A summary of the shear strength parameters (φ and c) of the gravel-TDA, sand-TDA, and clay-TDA mixtures obtained from the failure envelopes will be presented later in sections 4.5 to 4.6.

4.4 Vertical Deformation vs. Shear Strain Behavior

4.4.1 Gravel-TDA Mixtures

Figure 4.16 to 4.18 show the variation of vertical deformation with shear strain for the gravel-TDA mixtures at the three confining pressures of 50.1, 98.8, and 196.4 kPa. It was observed that mixtures containing up to 25% TDA content were initially compressed, and then dilated upon shearing. For 100% gravel (GT0), the compression was negligible at 50.1 kPa confining pressure, and the specimen was mainly dilated upon shearing. However, mixtures containing more than 25% TDA content were mainly compressed upon shearing at all the confining pressures.

It should be noted that for mixtures containing up to 25% TDA content, the dilation increased upon shearing at a lower TDA content, and the maximum dilation occurred for 100% gravel (GT0). In contrast, for mixtures containing more than 25% TDA content, the compression was increased at a higher TDA content, and the maximum compression was obtained for the pure TDA (GT100).

In general, mixing TDA content with the gravel increased the compressibility behavior of the mixtures upon shearing. The figures also indicate that the dilation behavior of the mixtures were decreased at a higher confining pressure. Also, for mixtures containing more than 25% TDA content, increasing the confining pressure from 98.8 to 196.4 kPa did not considerably change the compressibility behavior of the mixtures upon shearing.

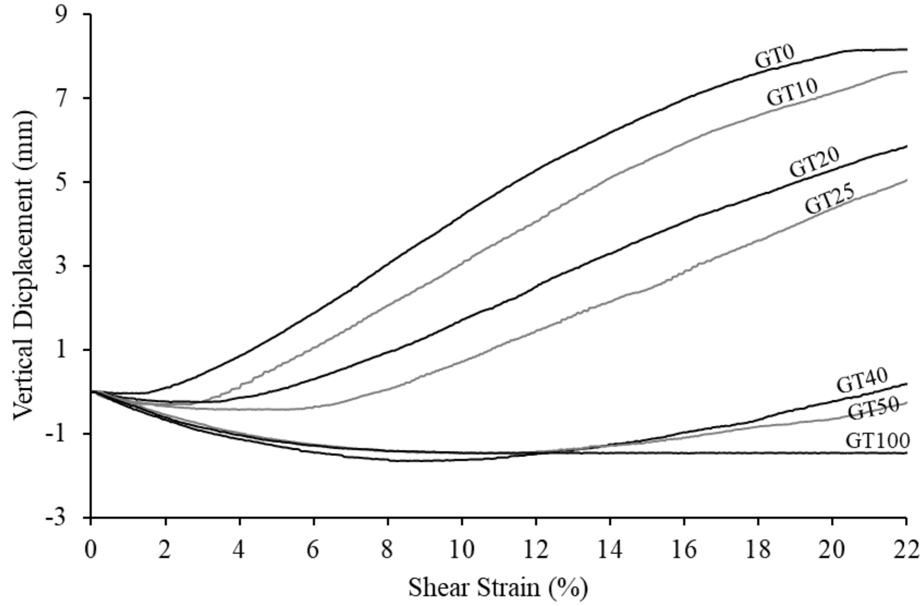


Figure 4.16 Vertical displacement vs. Shear Strain for the gravel-TDA mixtures at 50.1 kPa confining pressure

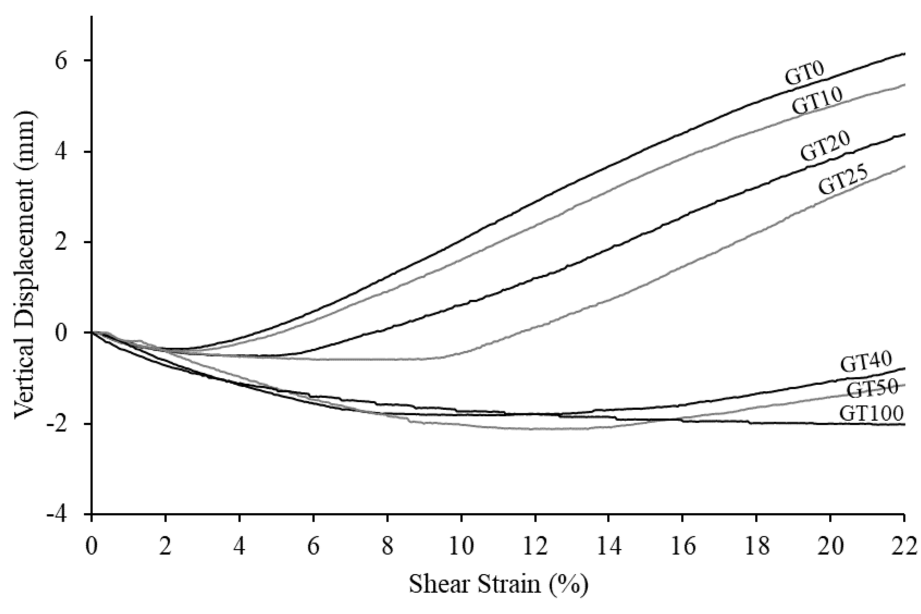


Figure 4.17 Vertical displacement vs. Shear Strain for the gravel-TDA mixtures at 98.8 kPa confining pressure

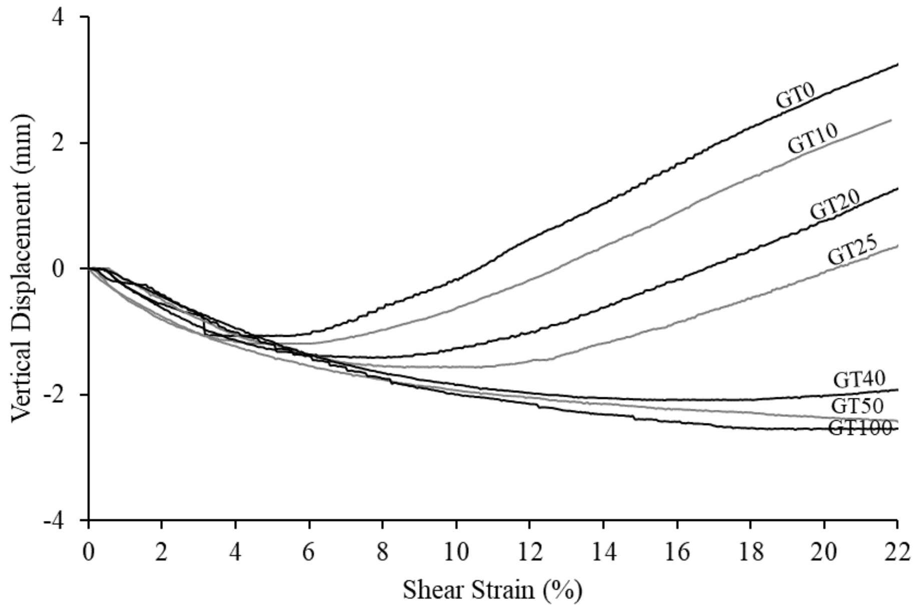


Figure 4.18 Vertical displacement vs. Shear Strain for the gravel-TDA mixtures at 196.4 kPa confining pressure

4.4.2 Sand-TDA Mixtures

Figure 4.19 to 4.21 illustrate the variation of vertical deformation with shear strain for the sand-TDA mixtures at 50.1, 98.8, and 196.4 kPa confining pressures. It was observed that mixtures containing up 25% TDA content were initially compressed, and then dilated upon shearing at all the confining pressures. For 100% sand (ST0), the dilation upon shearing was not significant at all the confining pressures, and the sample returned to its almost initial height after compression. In contrast, mixtures containing more than 25% TDA content were mainly compressed upon shearing. It should be noted that mixtures with TDA content of 10 and 25% had a similar dilation upon shearing at 98.8 and 196.4 confining pressures. However, mixtures with TDA content of 50 and 100% had a similar compression behavior upon shearing at the confining pressures.

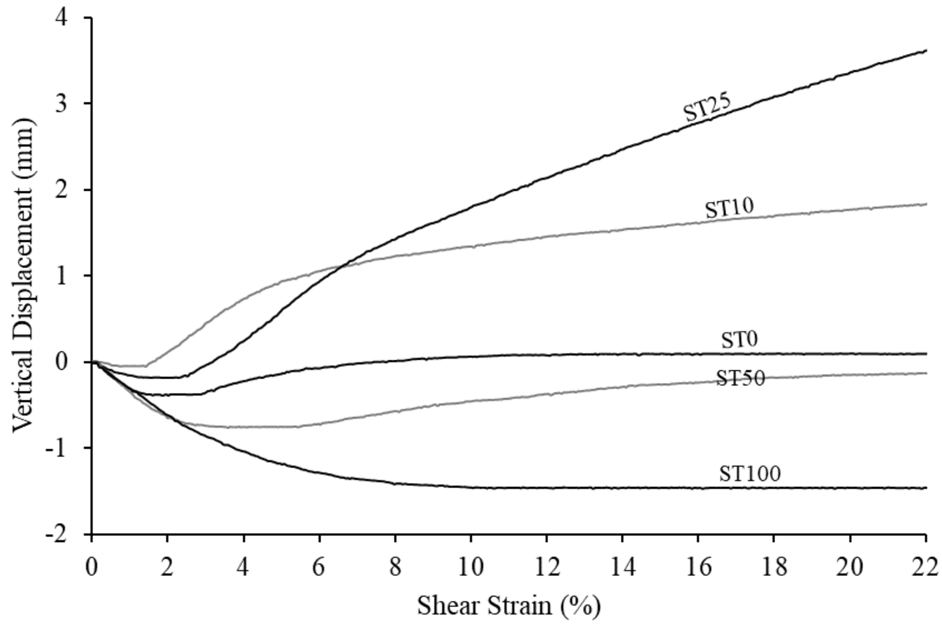


Figure 4.19 Vertical displacement vs. Shear Strain for the sand-TDA mixtures at 50.1 kPa confining pressure

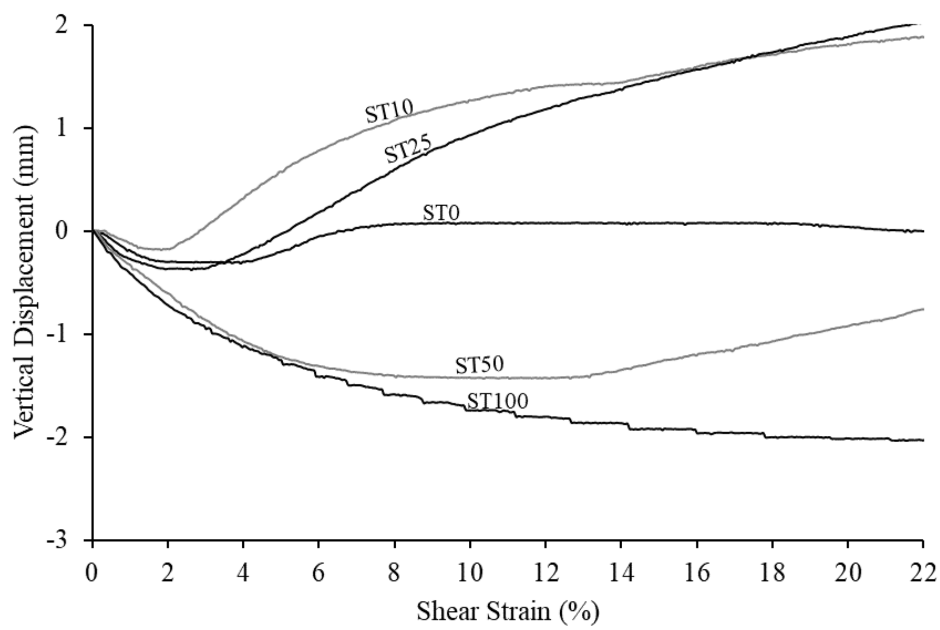


Figure 4.20 Vertical displacement vs. Shear Strain for the sand-TDA mixtures at 98.8 kPa confining pressure

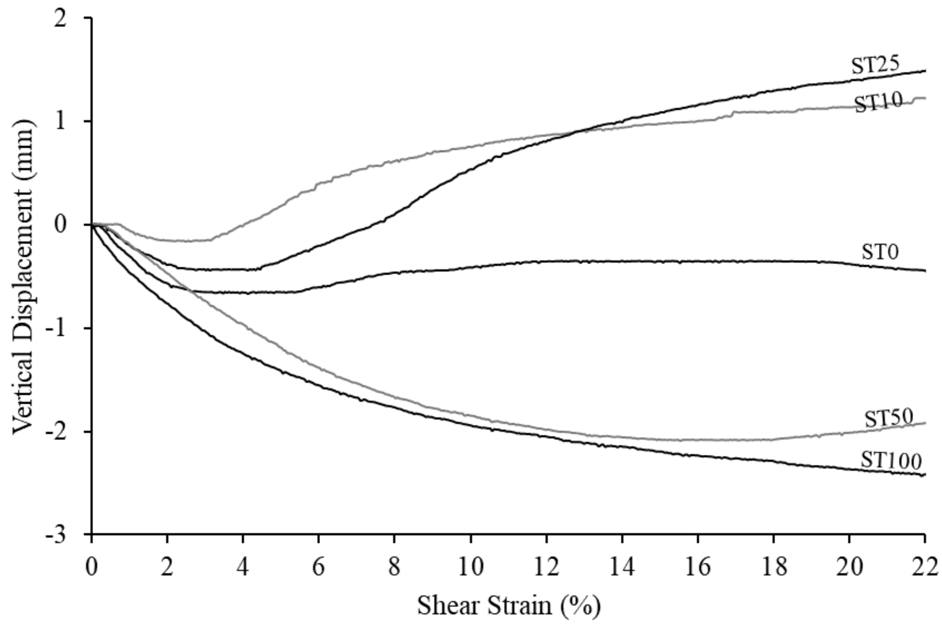


Figure 4.21 Vertical displacement vs. Shear Strain for the sand-TDA mixtures at 196.4 kPa confining pressure

In general, mixing TDA content with the sand increased the compressibility behavior of the mixtures upon shearing. The figures also indicate that the dilation behavior of the mixtures was decreased at a higher confining pressure.

4.4.3 *Clay-TDA Mixtures*

Figure 4.22 to 4.24 illustrate the variation of vertical deformation with shear strain for the clay-TDA mixtures at 50.1, 98.8, and 196.4 kPa confining pressures. As shown in Figure 4.22, except for the pure TDA (CT100), all other mixtures were initially compressed and then dilated upon shearing at 50.1 kPa confining pressure. However, CT100 was only compressed upon shearing at 50.1 kPa confining pressure. For 100% clay (CT0), the amount of dilation upon shearing was insignificant at 50.1 kPa confining pressure, and the specimen returned to its initial height after compression. The addition of TDA content increased the compressibility behavior of the mixtures upon shearing at 50.1 kPa confining pressure, and the greatest compression was observed for the pure TDA (CT100). It should be noted that mixtures containing up to 10% TDA content had a similar compression upon shearing. However, the dilatation of the mixture with 10% TDA content (CT10) was greater than clay alone (CT0).

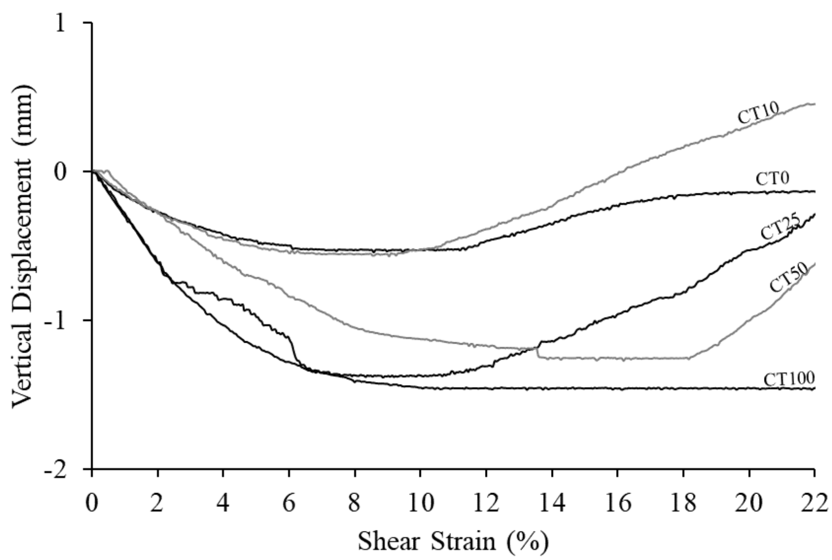


Figure 4.22 Vertical displacement vs. Shear Strain for the clay-TDA mixtures at 50.1 kPa confining pressure

As shown in Figure 4.23 and 4.24, all mixtures were only compressed upon shearing at 98.8 and 196.4 kPa confining pressures. It should be noted that the addition of TDA content up to 10% to the clay decreased the compressibility behavior of the mixture upon shearing significantly. Then, adding more than 10% TDA content increased the compressibility behavior of the mixtures again. However, it was still lower than clay alone, and the highest compression upon shearing was observed for 100% clay (CT0) at 98.8 and 196.4 kPa confinements. The figures also indicate that the compression behavior of the mixtures increased at a higher confining pressure.

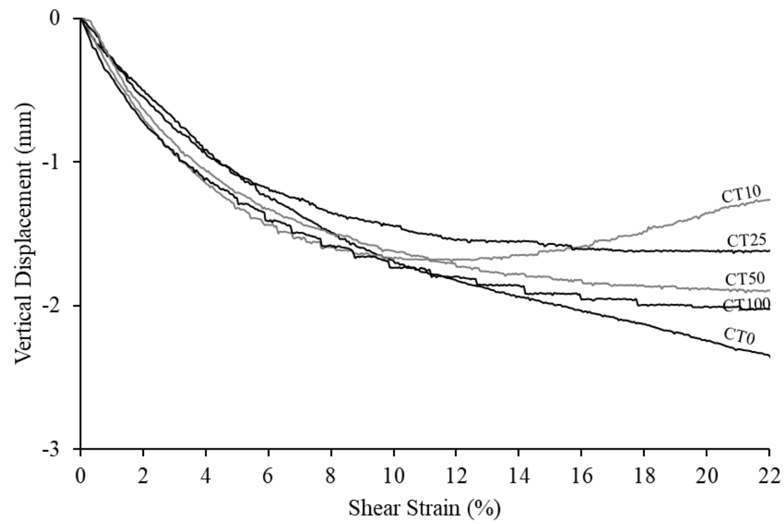


Figure 4.23 Vertical displacement vs. Shear Strain for the clay-TDA mixtures at 98.8 kPa confining pressure

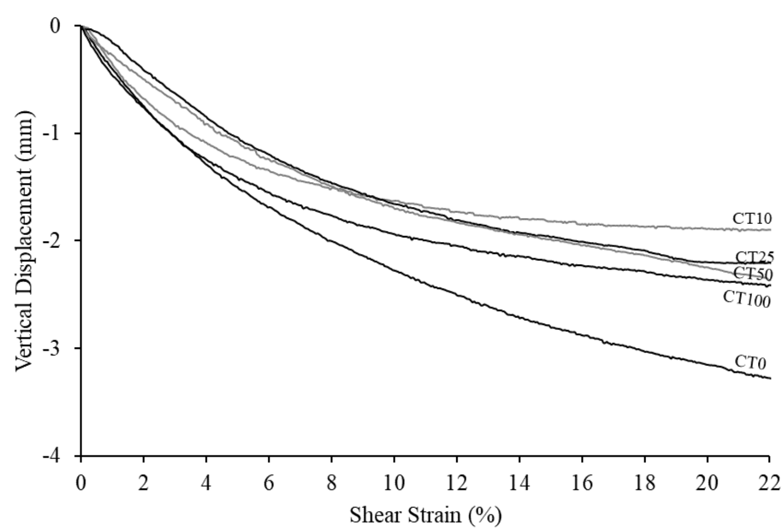


Figure 4.24 Vertical displacement vs. Shear Strain for the clay-TDA mixtures at 196.4 kPa confining pressure

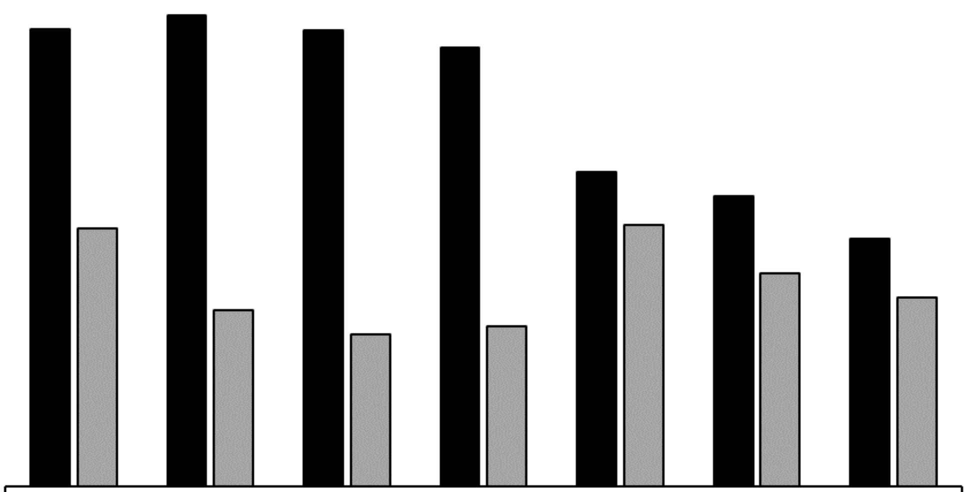
4.5 Shear Strength Parameters of the Gravel-TDA Mixtures

4.5.1 Angle of Internal Friction and Cohesion

Figure 4.25 shows the variation of the angle of internal friction and cohesion with TDA content for the gravel-TDA mixtures. As shown in the figure, the addition of up to 10% TDA content by weight to the gravel increased the angle of internal friction slightly, from 44 to 45.4º. The addition of a further amount of TDA content up to 25% by weight then reduced the angle of internal friction from 45.4 to 42.2°. In general, for mixtures with up to 25% TDA content, the angle of internal friction did not change significantly. It may be argued that for these mixtures, the gravel was the dominant particle in the shear plane, and controlled the shear strength behavior of the mixtures. Increasing TDA content from 25 to 40% by weight to the gravel sharply reduced the angle of internal friction, from 42.2 to 30.2° (a reduction of about 40%). Then, adding more than 40% TDA content to the gravel reduced the angle of internal friction again.

For all the gravel-TDA mixtures, a cohesion intercept was observed in the failure envelope. It may be argued that applying the high confining pressures ranging from 50.1 to 196.4 kPa to the specimens upon shearing resulted in the apparent cohesion for the gravel-TDA mixtures. It should be noted that at a lower confining pressure, the shear stress cannot mobilize completely through the shear plane, and this may result in some slip and pull-out effects during shearing. In other words, confining pressures of lower than 50 kPa influences the shear strength properties of the mixtures, and contributes to the apparent friction angle (Gray and Ohashi 1983). Therefore, to avoid the apparent friction angle, the confining pressures of 50.1, 98.8 and 196.4 kPa were considered in this study.

It was observed that the addition of up to 20% TDA content to the gravel reduced the apparent cohesion from 24.8 to 14.7 kPa, and then, a further amount of TDA content up 25% did not change the cohesion significantly. An explanation is due to the high flexibility of the TDA particles, adding up to 25% TDA content to the gravel increased the mobilization of shear stress in the shear plane, and therefore decreased the apparent cohesion. Then, increasing TDA content from 25 to 40% enhanced the apparent cohesion from 15.4 to 25.2 kPa. It may be argued that the mixtures containing more than 25% TDA content had a strain-hardening behavior, and their shear strengths parameters were obtained at 10% relative horizontal displacement. Therefore, a larger deformation for failure increased the appetent cohesion. Then, adding more than 40% TDA content again decreased the cohesion due to the easier mobilization of shear stress at the considered confining pressures.



	GT0	GT10	GT20	GT25	GT40	GT50	GT100
■ ϕ (deg)	44.0	45.4	43.9	42.2	30.2	28.0	23.9
□ c (kPa)	24.8	17.0	14.7	15.4	25.2	20.6	18.2

Figure 4.25 Summary of the shear strength parameters of the gravel-TDA mixtures

4.5.2 Shear Modulus

Shear modulus is a mechanical parameter used in analyzing the behavior of material while being sheared. Equation 4.2 is used to calculate the shear modulus (Jia 2018):

$$G = \frac{\tau}{\varepsilon} \qquad (4.2)$$

where G is shear modulus, τ is shear stress, and ε is shear strain. By using equation 4.2 and referring to the shear stress versus shear strain behavior of the soil-TDA mixtures, shear modulus can be determined. To compare the shear modulus of the mixtures used in this study, secant shear modulus (G_{50}) was defined as 50% of the shear strength divided by the corresponding shear strain.

Figure 4.26 illustrates the variation of secant shear modulus with TDA content for the gravel-TDA compositions at 50.1, 98.8, and 196.4 kPa confining pressures.

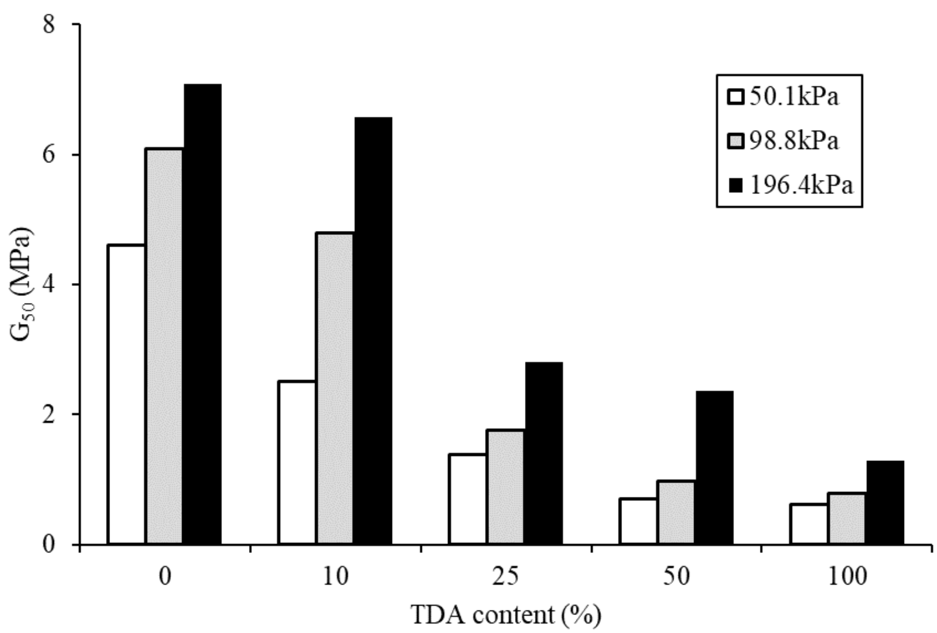


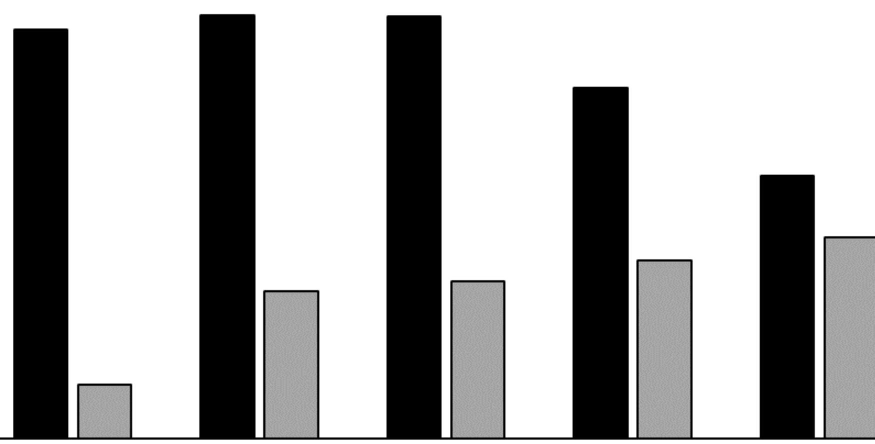
Figure 4.26 Variation of secant shear modulus with TDA content for the gravel-TDA mixtures

It is seen that the addition of TDA content to the gravel decreased secant shear modulus at all the confining pressures. It should be noted that the decrease in the shear modulus was not significant up to 10% TDA content by weight at 196.4 kPa confining pressure. Also, it is evident from the picture that for mixtures containing the same amount of TDA content, increasing the confining pressure from 50.1 to 196.4 kPa enhanced the secant shear modulus considerably.

4.6 Shear Strenght Parameters of the Sand-TDA Mixtures

4.6.1 Angle of Internal Friction and Cohesion

Figure 4.27 shows the variation of the angle of internal friction and cohesion with TDA content for the sand-TDA mixtures.



	ST0	ST10	ST25	ST50	ST100
■ ϕ (deg)	37.1	38.4	38.3	31.8	23.9
□ c (kPa)	4.8	13.4	14.3	16.2	18.2

Figure 4.27 Summary of the shear strength parameters of the sand-TDA mixtures

As shown in the figure, the addition of up to 10% TDA content by weight to the sand increased the angle of internal friction slightly from 37.1 to 38.4 º (by about 4% increase). In general, the addition of up to 25% TDA content by weight to the sand did not change the angle of internal friction significantly. It may be argued that up to 25% TDA content, the sand was the dominant particle in the shear plane, and controlled the shear strength behavior of the mixtures. Then, increasing the TDA content from 25 to 50% sharply reduced the angle of internal friction, from 38.3 to 31.8° (a reduction of about 20%). The reduction was continued up to the 100% TDA content.

For all the sand-TDA mixtures, a cohesion intercept was observed in the failure envelope. It may be argued that applying the high confining pressures ranging from 50.1 to 196.4 kPa to the specimens upon shearing resulted in the apparent cohesion. It was also observed that increasing TDA content from 0 to 100% enhanced the apparent cohesion gradually. An explanation is due to the TDA particles were coarser than sand grains, they decreased the mobilization of the shear stress in the shear plane upon shearing for all the considered confining pressures, and therefore the apparent cohesion was increased. In addition, mixtures containing more than 25% TDA content had a strain-hardening behavior, and their shear strengths parameters were obtained at 10% relative horizontal displacement. Therefore, a larger deformation for failure increased the apparent cohesion.

4.6.2 Shear Modulus

Figure 4.28 illustrates the variation of secant shear stiffness with TDA content for the considered sand-TDA mixtures at 50.1, 98.8, and 196.4 kPa confining pressures. It is seen that the addition of TDA content up to 10% by weight to the sand did not affect the secant shear modulus significantly. However, the addition of more than 10% TDA content by weight to the sand sharply decreased the secant shear modulus at all the confining pressures. Also, it is evident from the picture that, for mixtures containing the same amount of TDA content, increasing the confining pressure from 50.1 to 196.4 kPa enhanced the secant shear modulus considerably.

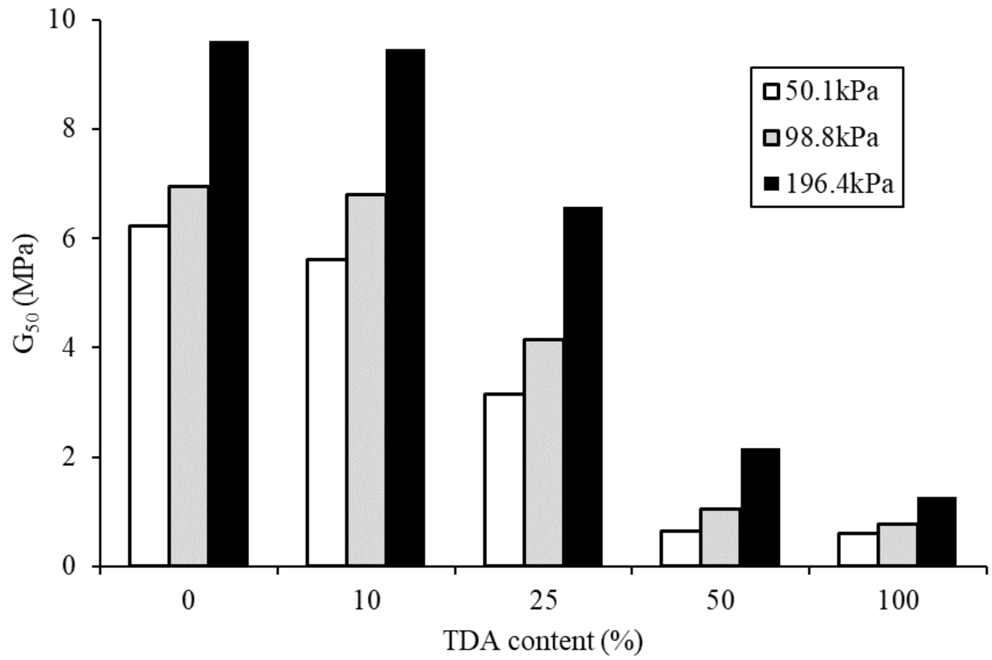


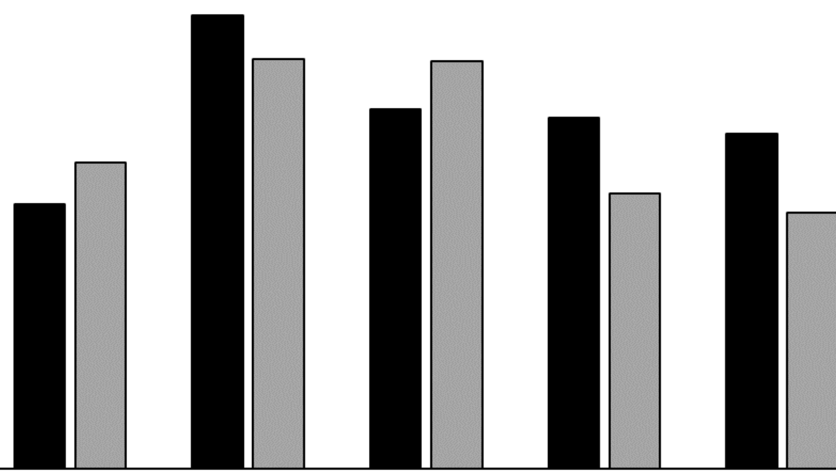
Figure 4.28 Variation of secant shear modulus with TDA content for the sand-TDA mixtures

4.7 Shear Strenght Parameters of the Clay-TDA Mixtures

4.7.1 Angle of Internal Friction and Cohesion

Figure 4.29 shows the variation of angle of internal friction and cohesion with TDA content for the clay-TDA mixtures. As shown in the figure, the addition of up to 10% TDA content by weight to the clay increased the angle of internal friction considerably from 18.8 to 32.3° (by about 72%). It may be argued that the adhesion between clay particles resulted in a bond between TDA particles, and contributed to the reinforcement of the soil upon shearing at all the considered confining pressures. Consequently, the angle of internal friction was increased up to 10% TDA content. However, increasing TDA content from 10 to 25% then reduced the angle of internal friction significantly from 32.3 to 25.6°. It may be argued that for mixtures containing more than 10% TDA content, the clay particles were not able to create a bond between the TDA particles, and therefore the angle of internal friction was deceased.

It should be noted that the cohesion obtained for the clay was not just due to the confining pressures. There is also adhesion between clay particles in a natural condition that contributed to the cohesion. It was observed that the addition of up to 25% TDA content increased the cohesion from 21.8 to 29 kPa. It may be argued that the addition of up to 25% TDA content to the clay decreased the mobilization of shear stress upon shearing at the considered confining pressures, and therefore the cohesion intercept was increased. Then, for the mixtures containing more than 25% TDA content, the cohesion intercept was decreased. It may be argued that, due to the considerable reduction of the clay in the mixtures, the adhesion was negligible between particles. Hence, the confining pressure only contributed to the cohesion, and the cohesion intercept was decreased.



	CT0	CT10	CT25	CT50	CT100
■ ϕ (deg)	18.8	32.3	25.6	25.0	23.9
□ c (kPa)	21.8	29.2	29.0	19.6	18.2

Figure 4.29 Summary of the shear strength parameters of the clay-TDA mixtures

4.7.2 Shear Modulus

Figure 4.30 illustrates the variation of secant shear modulus with TDA content for the clay-TDA mixtures at 50.1, 98.8, and 196.4 kPa confining pressures. As shown in the figure, the addition of up to 10% TDA content by weight to the clay increased the secant shear modulus at all the confining pressures significantly. However, adding more than 10% TDA content by weight then reduced the secant shear modulus at all the confining pressures sharply. Also, it is evident from the picture that, for mixtures containing the same amount of TDA content, increasing the confining pressure from 50.1 to 196.4 kPa enhanced the secant shear modulus considerably.

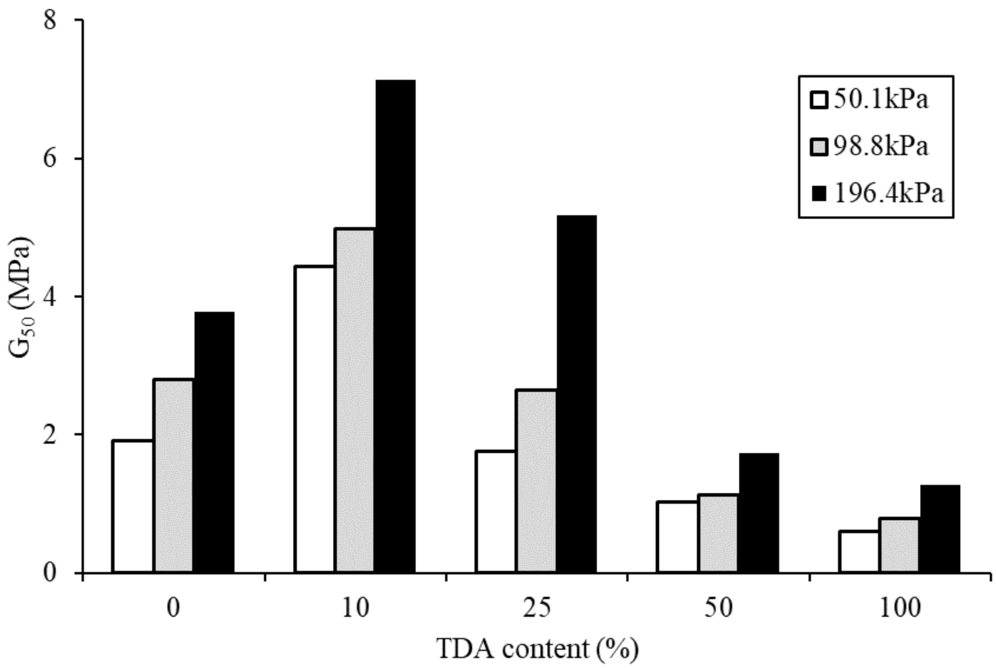


Figure 4.30 Variation of secant shear modulus with TDA content for the clay-TDA mixtures

4.8 Comparison of the Shear Strength Parameters of the Mixtures

4.8.1 Angle of Internal Friction

Variation of the angle of internal friction (φ) with TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures is shown in Figure 4.31.

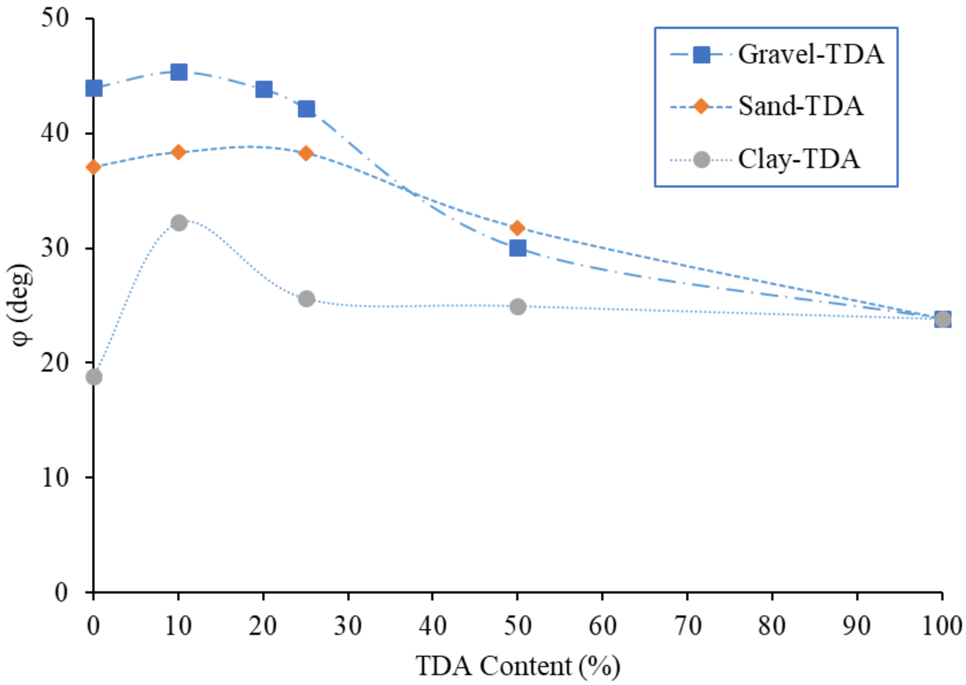


Figure 4.31 Angle of internal friction vs. TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures

In the figure, for comparison purpose, the TDA content ranges from 0%, corresponding to soil alone, to 100%, which means TDA alone. Therefore, the effect of TDA content on the angle of internal friction of the various soil types is presented. It is seen that the addition of up to 10% TDA content by weight to the clay significantly enhanced the angle of internal friction, from 18.8 to 32.3°. However, adding up to 10% TDA content by weight to the gravel or sand slightly increased the angle of internal friction. Then, adding TDA content from 10 to 25% to the clay sharply reduced the angle of internal friction. However, increasing the TDA content up to 25% to the gravel and sand did not change the angle of internal friction considerably. It should be noted that the addition of more than 25% TDA content to the gravel and sand reduced the angle of internal friction significantly. However, adding more than 25% TDA content to the clay did not change the angle of internal friction considerably.

4.8.2 Cohesion

Figure 4.32 illustrates the variation of cohesion intercept with TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures

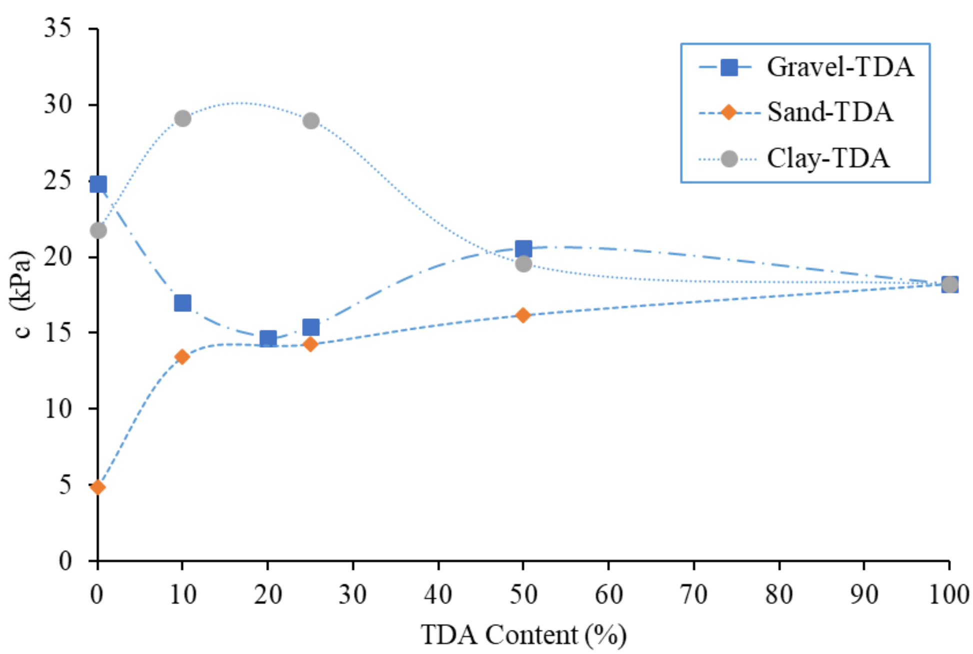


Figure 4.32 Cohesion intercept vs. TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures

It is seen that adding up to 20% TDA content by weight to the gravel decreased the cohesion intercept sharply. However, the addition of up to 20% TDA content by weight to the sand and clay increased the cohesion. It should be noted that increase in the cohesion intercept was continued for the sand at a higher TDA content. However, increasing TDA content from 20 to 40 % enhanced the cohesion for the gravel-TDA mixtures and reduced for the clay-TDA mixtures. Then, the addition of more than 40% TDA content to the clay and gravel did not change the cohesion intercept significantly.

4.9 Strain Compatibility for the TDA

Based on the direct shear test results, the addition of TDA content to the soils increased the deformability behavior of the soil-TDA mixtures without being failed upon shearing at all the considered confining pressures. In other words, adding TDA content to the soils contributed to the strain-hardening behavior for the soil-TDA mixtures. In this study, to find the shear strength parameters of the soil-TDA mixtures, the shear strength was taken at a peak shear stress, or 10% relative lateral displacement when there was no peak shear stress. As noticed before, failure occurred before 10% relative lateral displacement in the conventional soils. When the TDA content was added to the soils, the peak shear resistance was observed at a higher horizontal displacement and finally no peak shear resistance was obtained at a higher TDA content up to 14% relative lateral displacement. Hence, strain compatibility needs to be taken into account when determining the shear strength parameters of the soil-TDA mixtures. Figure 4.33 and 4.34 show the variation of the angle of internal friction and cohesion with shear strain for the pure TDA used in this study. As shown in the figures, the angle of internal friction and cohesion intercept were decreased for the TDA at a lower shear strain.

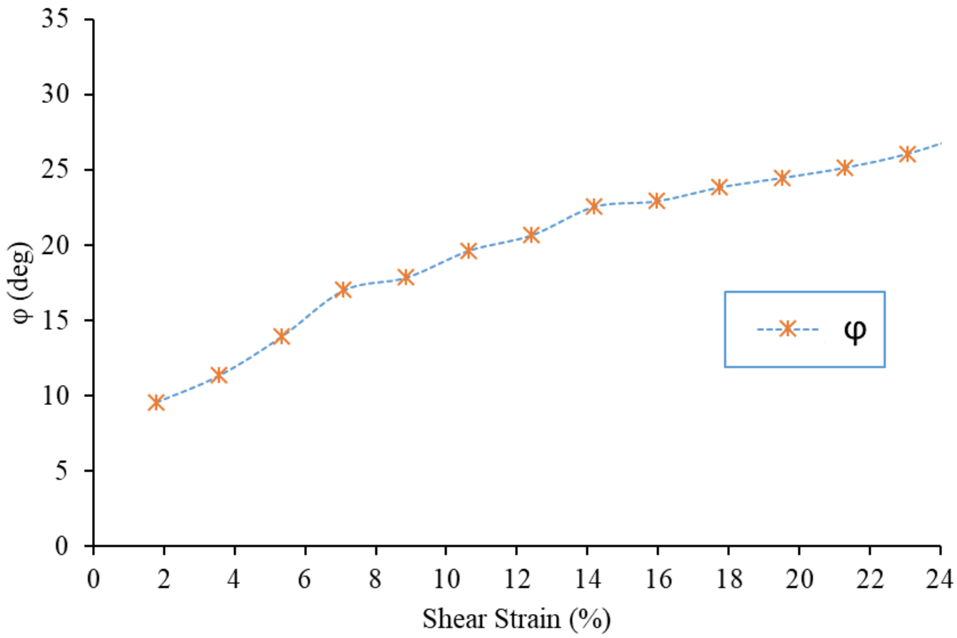


Figure 4.33 Angle of internal friction vs. Shear Strain for the TDA

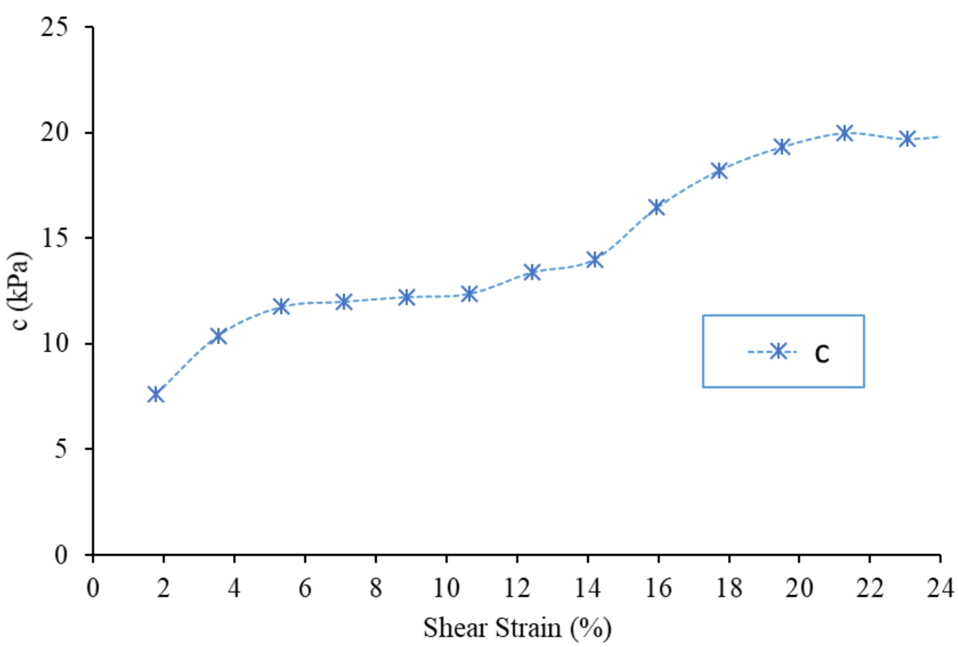


Figure 4.34 Cohesion Intercept vs. Shear Strain for the TDA

4.10 Normalized Lateral Earth Pressure at-Rest

Normalized lateral earth pressure at-rest is an important factor used in designing a geotechnical application such as a retaining wall. The angle of internal friction and dry unit weight are two variables that affect the normalized lateral earth pressure at-rest. Equations 4.3 is used to find the normalized lateral earth pressure at-rest condition (DAS 2014).

$$\frac{p_0}{z} = (1 - sin\,\varphi)\gamma_d \tag{4.3}$$

where $\frac{p_0}{z}$ is normalized lateral earth pressure at-rest condition, z is depth, φ is angle of internal friction, and γ_d is dry unit weight. Figure 4.35 illustrates the variation of normalized lateral earth pressure at-rest with TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures.

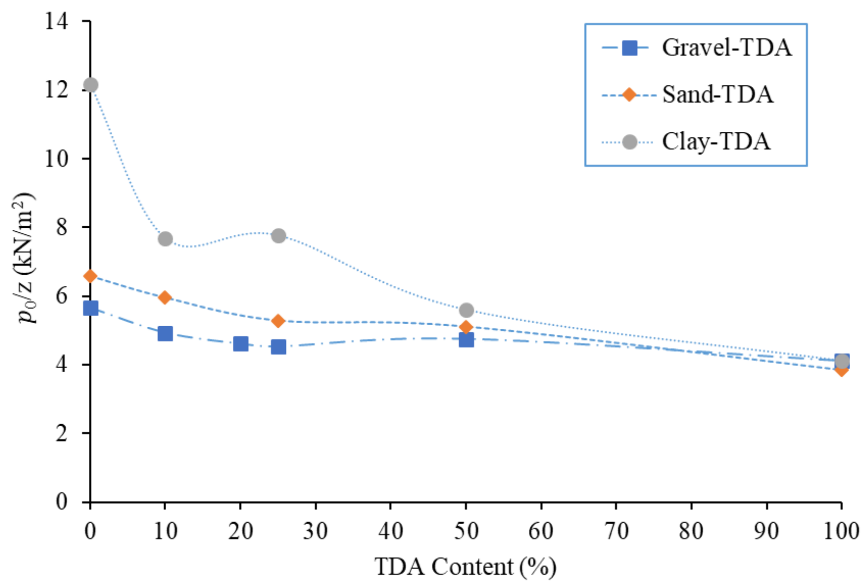


Figure 4.35 Variation of normalized lateral earth pressure at-rest with TDA content for the considered mixtures

It is seen that the addition of up to 10% TDA content by weight to the soils decreased the normalized lateral earth pressure at-rest. It should be noted that the reduction of the normalized lateral earth pressure at-rest was significant for the clay-TDA mixture up to 10% TDA content. Increasing TDA content from 10 to 25% to the clay then stabilized the normalized lateral earth pressure at-rest. However, the normalized lateral earth pressure at-rest continued to decrease for the gravel-TDA and sand-TDA mixtures in this range. Finally, the addition of more than 25% TDA content to the gravel and sand did not change the normalized lateral earth pressure at-rest significantly. However, it continuously decreased for the clay-TDA mixtures.

CHAPTER 5: CONCLUSIONS

In this chapter, the findings of this research are presented, and some recommendations for future studies are proposed.

5.1 Findings of this Research

The main objective of this study was to investigate the shear strength behavior of various soil types ranging from coarse to soft grains mixed with TDA content (smaller than 75 mm in length) from 0 to 100% by weight. Also, the compressibility behavior of the TDA and soil-TDA mixtures upon shearing at various TDA content and confining pressures were evaluated. According to the Mohr-Coulomb failure criterion, the failure envelopes were drawn. Then, the shear strength parameters of the mixtures at various TDA content were determined and compared. Also, the shear strength parameters of the TDA at various horizontal displacement were discussed. Then, the effect of TDA content on the normalizes lateral earth-pressure were investigated. The following conclusions can be drawn from this study:

1- The addition of TDA content to the gravel, sand, and clay decreased the dry unit weight of the mixtures almost linearly.

2- The addition of TDA content to the gravel decreased the shear resistance of the mixtures upon shearing at all the considered confining pressures. However, adding TDA content to the sand and clay initially increased the shear resistance, and then decreased upon shearing at all the confining pressures. Also, increasing the confining pressures enhanced the shear resistance of the mixtures.

3- The gravel-TDA and sand-TDA mixtures containing up to 25% TDA content were initially compressed, and then dilatated upon shearing at all the considered confining pressures. The addition of TDA content to the gravel and sand increased the compressibility behavior of the mixtures upon shearing at all the confining pressures. A similar observation was made for the clay-TDA mixtures at 50.1 kPa confining pressure. However, at 98.8 and 196.4 kPa confinement, adding up to 10% TDA content to the clay initially decreased the compressibility behavior of the clay-TDA mixture, and then increased at a higher TDA content.

4- Adding up to 10% TDA content by weight to the gravel and sand increased the angle of internal friction slightly (by about 3%). In general, the addition of up to 25% TDA content by weight to the gravel and sand did not change the angle of internal friction significantly. Then, adding more than 25% TDA content to the soils decreased the angle of internal friction sharply. However, adding up to 10% TDA content to the clay sharply increased the angle of internal friction, and then reduced at a higher TDA content.

5- The addition of TDA content up to 20% by weight to the gravel decreased the apparent cohesion. However, the addition of TDA content up to 20% by weight to the sand and clay increased the cohesion intercept. The increase in the cohesion intercept was continued for the sand at a higher TDA content. However, increasing TDA content from 20 to 40 % enhanced the cohesion for the gravel-TDA mixtures and reduced for the clay-TDA mixtures.

6- The angle of internal friction and cohesion intercept of the pure TDA were determined to be 23.9^{o} and 18.2 kPa, respectively.

7- The addition of TDA content to the gravel and sand decreased the secant shear modulus at all the confining pressures. However, adding TDA content up to 10% by weight to the clay increased the secant shear modulus at all the confining pressures, and then reduced at a higher TDA content. Also, increasing confinement from 50.1 to 196.4 kPa enhanced the secant shear modulus significantly for mixtures with the same TDA content.

8- The addition of TDA content to the soils contributed to the strain-hardening behavior. Therefore, strain compatibility needs to be considered in a design when mixing TDA content with soil.

9- Adding TDA content up to 10% by weight to the gravel, sand, and clay decreased the normalized lateral earth pressure at-rest. This reduction was shaper for the clay-TDA mixture up to 10% TDA content. Increasing the TDA content from 10 to 25% in the gravel and sand decreased the normalized lateral earth pressure at-rest, and then did not change significantly at a higher TDA content. However, adding TDA content from 10 to 25% to the clay stabilized the normalized lateral earth pressure at-rest, and then sharply decreased at a higher TDA content.

5.2 Recommendations for Future Research

Based on the current study, the following ideas and recommendations are suggested for future research:

1. Long-term performance of soil-TDA mixture in geotechnical applications needs to be investigated. This includes long-term compression or dilation, settlement, and changes in the shear strength behavior of the mixture over the time.

2. Direct shear test on TDA type B alone and mixed with various soil types is recommended to determine their shear strength behavior. This can improve our understanding about the shear strength behavior of the TDA content with larger sizes.
3. The shear strength parameters of TDA content obtained from direct shear tests should be used in slope stability analysis to evaluate the effectiveness of the direct shear test results.
4. Field test is recommended to determine the shear strength behavior of TDA content type B, since there is only limited research on mixtures of TDA content type B with soil in field conditions.

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