Evaluation of the Shear Strength Behavior of TDA Mixed with Fine and Coarse Aggregates for Backfilling around Buried Structures

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Abstract: Although some discarded tires are reused in various applications, a considerable number end up in landfills, where they pose diverse environmental problems. Waste tires that are shredded to produce tire-derived aggregates (TDA) can be reused in geotechnical engineering applications. Many studies have already been conducted to examine the behavior of pure TDA and soil-TDA mixtures. However, few studies have investigated the behavior of larger TDA particles, 20 to 75 mm in size, mixed with various types of soil at percentages ranging from 0% to 100%. In this study, TDA was mixed with gravelly, sandy, and clayey soils to determine the optimum soil-TDA mixtures for each soil type. A large-scale direct shear box (305 mm × 305 mm × 220 mm) was used, and the mixtures were examined with a series of direct shear tests at confining pressures of 50.1, 98.8, and 196.4 kPa. The test results indicated that the addition of TDA to the considered soils significantly reduces the dry unit weight, making the mixtures attractive for applications requiring lightweight fill materials. It was found that adding TDA to gravel decreases the shear resistance for all considered TDA contents. On the contrary, adding up to 10% TDA by weight to the sandy or clayey soils was found to increase the shear resistance of the mixtures. Adding up to 10% TDA by weight to the clayey soil also sharply increased the angle of internal friction from 18.8° to 32.3°. Moreover, it was also found that the addition of 25% TDA by weight to the gravelly or sandy soils can reduce the lateral earth pressure on buried structures by up to 20%. In comparison, adding 10% TDA to clay resulted in a 36% reduction in the lateral earth pressure.

Keywords: tire-derived aggregates (TDA); fine aggregates; coarse aggregates; soil-TDA mixtures; large-scale direct shear box

1. Introduction

Growing populations are generating significant numbers of discarded scrap tires every year. Disposing of waste tires in landfills contributes to serious environmental problems, and it is crucial to find an environmentally friendly solution. Since scrap tires are bulky, they occupy considerable space in landfills. In addition, during rainy seasons, stockpiled tires collect rainwater, which provides a breeding ground for 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 [1]. Over 500 million scrap tires are discarded in the USA annually [2]. Only around 22% of them are recycled and reused in various applications, while the rest end up in landfills and illegal dumps [1]. According to the Rubber Association of Canada, approximately 30 million scrap tires are generated in Canada each year, which is almost one tire per person [3]. Fortunately, some countries such as Canada and the USA are currently implementing an active tire recycling program. To fund the program, an environmental fee is applied to the purchase of new tires, and the money collected is used to divert scrap tires from landfills.
Scrap tires are comprised of synthetic rubber, fibers, and steel cords. Steel and fiber wires reinforce the rubber, and a steel belt is positioned below the tread. Table 1 lists the typical materials used in passenger car and truck tires.

Table 1. Typical composition of tires [4].

| 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    |            |

Tire shreds can be categorized based on their size and the shredding techniques used. According to Strenk et al. [5], tire particles ranging from 50 to 305 mm are referred to as tire shreds, while those ranging from 12 to 50 mm are called tire chips. These two particle types are commonly known as tire-derived aggregate (TDA). Tire particles less than 12 mm in size are referred to as granular or crumb rubber. Because smaller tire particles require greater processing and shredding time, their production cost is higher than that of larger alternatives. Table 2 presents the cost of processing and shredding scrap tires based on the particle size. As shown in the table, reducing the particle size leads to higher processing costs.

Table 2. Tire shredding costs [4].

| Particle Size | Cost per Ton | Process Rate (tons/hour) |
|---------------|--------------|--------------------------|
| 50 mm         | $12          | 10–12                    |
| <50 mm        | $31          | 7                        |
| <12.5 mm      | $31–$68      | 2–3                      |

Based on ASTM D6270 [6], tire shreds are classified into two types, A and B. Type A tire shreds have a maximum dimension of 200 mm in any direction. Type B tire shreds have a maximum dimension of 450 mm in any direction, or a maximum dimension of 300 mm for at least 90% of the sample by weight.

TDA and soil-TDA mixtures have been used for many years in geotechnical engineering applications. Such mixtures can be used as lightweight embankment fill, retaining wall backfill, backfill above and around buried pipes, culverts and cut-and-cover tunnels, underneath shallow foundations or as landfill drainage layers, and in vibration control applications, among several other civil engineering applications [7–20]. Pure TDA fill up to 3 m in thickness can be used without leading to internal heating problems [6]. Fill layers thicker than 3 m may suffer from self-ignition due to internal heating. Soil-TDA mixtures have great potential as a lightweight fill material that can reduce the problem of TDA self-ignition and decrease compressibility behavior [21]. Several researchers investigated various soil-TDA mixtures. For instance, Kim and Santamarina [22] mixed TDA with small particle sizes (granulated with D_{50} = 3.5 mm) with Ottawa sand at different mixture compositions. The obtained results revealed that the mixture response was controlled by the behavior of the sand for low TDA content mixtures; however, at higher TDA contents, the response was governed by the behavior of the TDA. Likewise, Mashiri et al. [23] mixed sand with various contents of small TDA particles (8 mm × 20 mm). It was found that adding up to 35% TDA to the mixture improved the shear strength and resulted in a significant reduction in the dilatancy. Soltani et al. [24] examined the potential of mixing TDA with clay with high expansivity. The TDA used in the examined mixtures had a mean particle diameter, D_{50}, ranging between 0.46 mm to 3.34 mm. The study concluded that adding 10% TDA, with gradation equivalent to medium or coarse sands, enhances the
strength of the mixture and reduces the soil’s swelling potential from high to moderate expansivity. Furthermore, Araujo et al. [25] mixed TDA having a mean particle diameter, $D_{50}$ of 20 mm, with fine lateritic soil from the Central-West region of Brazil. The study showed that the mixture with 5% TDA content was the optimum mixture composition.

As shown above and further in the next section, most previous research has been focused on small TDA particles that do not contain steel wires. Hence, the primary objective of this study is to investigate the shear stress-strain behavior of various types of soil mixed with TDA with large particle sizes. Moreover, testing several soil-TDA mixtures and comparing their results side by side will enable a comprehensive insight into the behavior of the different mixtures and facilitate direct comparisons between the performance of each of them. The study also determines the effect of the TDA content on the stiffness behavior of the mixtures. Another objective is to examine how the TDA content affects the shear strength parameters of the mixtures, including the cohesion and the angle of internal friction.

2. State-of-the-Art Review of the TDA Shear Strength Behavior

This section first presents results of previous studies of the shear strength behavior of TDA and soil-TDA mixtures obtained from direct shear tests. Then, research results concerning the shear strength behavior of TDA and soil-TDA mixtures obtained from the triaxial compression method are described. Finally, a comparison is made between direct shear tests and the triaxial compression method to determine the advantages and disadvantages of each testing method.

2.1. Direct Shear Tests

Humphrey and Sandford [26] conducted a series of large-scale direct shear box tests on pure tire shred samples from three different suppliers, with particle sizes ranging from 13 to 76 mm. The tests were conducted under low confining pressures of 17, 34, and 68 kPa. Failure was defined at a peak, and in some cases, in the absence of a peak, at 10% relative lateral displacement. Internal friction angles ranging from 19° to 25° and cohesion intercepts from 7.7 to 11.5 kPa were reported for the tire shreds. Similarly, Zahran and El Naggar [27] and El Naggar et al. [28] studied the effect of sample size and particle size of pure TDA samples on the shear strength behavior by using a large-scale direct shear apparatus. TDA particles ranging in size from 12 mm to 100 mm were considered. In addition, tests to determine the effect of the sample size were conducted by using five different square shear boxes ranging in size from 60 mm to 305 mm. Zahran and El Naggar [22] found that the angle of internal friction increased slightly as the shear box dimensions decreased. However, they reported that the maximum variation in the angle of internal friction and cohesion results for the different shear boxes was only $1.9^\circ$ and 2.4 kPa, respectively. The study recommended that a shear box with a ratio between the width of the box and the maximum particle size ($W/D_{\text{max}}$) greater than or equal to 4 should be used when evaluating the shear strength parameters of TDA to completely eliminate the effect of the size of the shear box. Their studies reported internal friction angles ranging from 22° to 25° and cohesion intercepts from 14.2 to 16.6 kPa for different particle and specimen sizes. Foose et al. [29] carried out a series of large-scale direct shear tests on sand-tire shred mixtures to determine the effects of the applied normal stress, sand matrix unit weight, shred content, and shred length and orientation on the shear strength behavior of sand-TDA mixtures. Foose et al. [29] used three TDA samples, with particle sizes of <50 mm, 50 to 100 mm, and 100 to 150 mm. They mixed each sample with sand in the amount of 10%, 20%, and 30% TDA. These researchers applied normal stresses ranging from 3 to 120 kPa to each sample upon shearing. Failure was defined at a peak or, in the absence of a peak, at 9% relative horizontal displacement. The tire shred content, sand matrix unit weight, and normal stress were found to be the main factors affecting the shear strength behavior of the mixtures. Adding 30% tire shreds with a particle length of 150 mm to sand was observed to enhance the shear strength, achieving an internal friction angle as large as
67°. For pure tire shreds, regardless of length, the results showed an internal friction angle of 30° and cohesion of 3 kPa, a slightly higher friction angle and lower cohesion than what was reported by [26–28]. Similarly, El Naggar et al. [3] conducted a series of large-scale direct shear box tests to study the effect of TDA gradation on the shear strength properties of sand-TDA mixtures. TDA samples with particle sizes of 0.3, 23.5, and 48.5 mm were selected and mixed with sand in the amounts of 15%, 25%, 50%, and 100% TDA by volume. They found that a composition of 15% TDA by volume (with 25% of the particles 0.3 mm in length, 25% 23.5 mm in length, and 50% of the particles 48.5 mm in length) resulted in a greater shear strength than other sand-TDA mixtures. El Naggar et al. [3] also recorded an increase of 3° to 6.5° in the angle of internal friction of the mixtures compared to pure sand. They noted that the addition of TDA to the sand resulted in a strain-hardening behavior of the mixture. Likewise, Tatlisoz et al. [30] conducted a series of large-scale direct shear tests on clean sand and sandy silt mixed with tire chips to determine the shear strength properties of the mixtures. Tire shreds with a length of 30 to 110 mm were mixed with the soils in the amount of 10% to 100% by volume. These researchers applied three low normal stresses of less than 50 kPa upon shearing. The addition of 30% tire shreds by volume to the clean sand was found to increase the mixture shear strength significantly, but the further addition of tire shreds beyond 30% then reduced the shear strength. It was observed that the addition of more than 30% tire shreds to the sand contributed to the segregation of the soil and the tire shred particles, resulting in a soil-TDA mixture with weak shear strength properties. It should be noted that according to Tatlisoz et al. [30], no significant increase in shear strength was observed when tire shreds were added to the sandy silt. Furthermore, a study was performed by Akbulut et al. [31] to investigate the shear strength behavior of clayey soil mixed with randomly oriented scrap rubber tire or synthetic fibers ranging from 2 to 15 mm in length (i.e., small particles). These researchers used a small-scale direct shear ring with a ring diameter of only 60 mm and a height of 35 mm. Akbulut et al. [31] found that adding waste tire rubber to clayey soil enhanced the shear strength properties of the soil. The length and percentage content of the rubber tire fibers were found to be the main factors influencing the shear strength of the mixture. Akbulut et al. [31] observed that the shear strength increased when up to 2% rubber tire fibers with a length of 10 mm were added to the soil, but then decreased with the further addition of rubber tire fibres.

2.2. Triaxial Compression Tests

Wu et al. [32] carried out a series of small-scale triaxial compression tests with a constant stress path method to examine five tire chip products having different sizes and shapes. The tire chips ranged from 2 to 38 mm in length, and the shapes were flat, granular, elongated, and powdered. These researchers conducted tests at low confining pressures ranging from 34.5 to 55 kPa and observed that the shear strength was fully mobilized at an axial strain of more than 5%. Wu et al. [32] recorded tire chip internal friction angles ranging from 44° to 56° at various axial strains. The largest interparticle friction angle was recorded for flat tire chips with a length of 38 mm. These researchers also noted that the effect on the cohesion intercept was negligible due the low confining pressures, ranging from 34.5 to 55 kPa. El Naggar and Zahran [33] carried out a series of large-scale triaxial compression tests of large size TDA particles at confining pressures ranging from 50 to 200 kPa to investigate the effect of the particle size on the TDA shear strength parameters. Whereas El Naggar et al. [34] conducted consolidated drained triaxial tests on TDA with large particles using the same large-scale triaxial apparatus of [33] to develop an empirical hyperbolic material for TDA. El Naggar and Zahran [33] and El Naggar et al. [34] reported internal friction angles ranging from 21.3° to 25.6° and cohesion intercepts from 28 to 32 kPa for different particle sizes when the failure was assumed to occur at 15% as per the ASTM standards as no peak was observed. Ashari et al. [35] carried out a series of large-scale triaxial compression tests of sand-TDA mixtures at confining pressures ranging from 50 to 200 kPa. These researchers noted that the friction angle remained relatively constant, but the cohesion increased as the TDA content increased in
Ahmed [36] carried out a series of large-scale triaxial compression tests to examine the shear strength behavior of tire chips and sand-tire chip mixtures. He compacted the tire chips by using various compaction energy methods (modified, standard, and 50% standard) and applied confining pressures ranging from 31.02 to 206.8 kPa to the specimens. Ahmed [36] determined the shear strength of the mixtures at 5%, 10%, 15%, and 20% axial strains and found that adding up to 38% tire chips by weight to the sand reduced the dry unit weight while increasing the shear strength of the mixture. He reported internal friction angles ranging from 25.46° to 38.1° and cohesion intercepts from 36.4 to 49.99 kPa for TDA mixing ratio of 38% tire chips at axial strains of 5% to 20%. Masad et al. [37] conducted a series of triaxial compression tests utilizing smaller samples (with a specimen diameter of 71.1 mm) for small-size tire shreds, sand, and sand-tire shred mixtures. The maximum particle size of the tire shreds used was 4.75 mm. These researchers found that the addition of tire shreds to sand increased the compressibility and reduced the density of the mixture. They also noted that the modulus of elasticity of the sand-tire shred mixture was significantly lower than that of sand alone. However, at a higher confining pressure, the resilient modulus of the mixture was higher than that of sand alone. They concluded that sand-tire shred mixtures can be used as a lightweight material beneath conventional soils, and can exhibit a high resilient modulus due to confinement. Masad et al. [37] also observed a strain-hardening behavior in pure tire chips similar to the observations of [33,34]. Lee et al. [9] performed a series of large-scale triaxial compression tests to study the shear strength behavior of tire chips mixed with sand. They removed exposed steel from the tire chips and limited the size of the tire chips to 30 mm. The vibration method was used to compact the mixtures. Tests were performed on specimens in a consolidated drained condition, and confining pressures ranging from 28 to 193 kPa were applied to the specimens. The test results showed that the relationship between deviatoric stress and the axial strain was almost linear up to a strain of 25%. A similar observation was made for volumetric change versus strain. Lee et al. [9] also noted that the addition of tire chips to the sand resulted in increased dilatancy behavior. Shear strength properties of tire shreds mixed with sand were also studied by Youwai and Bergado [38], who used a series of triaxial compression tests. They selected mixing ratios of 0:100, 50:50, 60:40, 70:30, 20:80, and 100:0 by weight, and limited the maximum tire shred size to 16 mm. They found that the addition of tire chips to sand contributed to a mixture with both dilation and compression characteristics. The amount of deformation was significant for mixtures containing more than 70% tire shreds. These researchers also developed a constitutive model within a critical state framework to predict the stress versus strain behavior of sand-tire shred mixtures. They noted that due to the high deformability of the mixtures upon axial loading, such a model should be considered as both elastic and plastic. The study also found that adding up to 70% tire shreds by weight to the sand reduced the internal friction angle from 34° to 30°. Likewise, Zornberg et al. [39] performed a series of large-scale triaxial compression tests to examine the shear strength behavior of pure tire shreds and sand-tire shred mixtures. The tire shreds had a maximum length of 102 mm and were mixed with the sand in amounts of 0% to 100% by weight. The tests were performed under confining pressures ranging from 48.3 to 207 kPa upon axial loading. Zornberg et al. [39] found that the percentage of tire shreds and the aspect ratio were the main factors affecting the shear stress versus strain behavior of the mixtures. They noted that an increase in aspect ratio enhanced the shear strength of the mixtures. They also found that adding up to 35% tire shreds to the sand increased the shear strength of the mixtures, but further addition of tire shreds beyond 35% then reduced the shear strength. Zornberg et al. [39] also found that adding tire shreds to the sand resulted in a mixture that did not fail up to 15% axial strain. Their results showed that compaction energy had a negligible effect on the shear strength properties of the mixtures. Finally, Rao and Dutta [40] conducted a series of small-scale triaxial compression tests on sand-tire chip mixtures having a maximum particle size of only 20 mm. The tire chips were mixed with sand in the amounts of 0%, 5%, 10%, 15%, and 20% by weight and were distributed randomly in the sand. Rao and Dutta [40] noted that...

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increasing the tire chip content from 0% to 20% by weight increased the angle of internal friction slightly from 38° to 40.1° and increased the cohesion intercept from 0 to 18.4 kPa. They reported that adding 20% tire chips to the sand resulted in a mixture with behavior similar to that of a sand-gravel mixture. They also noted that adding tire chips to the sand resulted in increased compressibility.

Most studies confirm that, within limits, the addition of TDA to soil results in enhanced shear strength properties while reducing the dry unit weight. Thus, soil-TDA mixtures can be used as a lightweight alternative in geotechnical engineering applications such as highway embankment fill and retaining wall backfill. The reuse of scrap tires in geotechnical engineering applications is a practice that promises to benefit the environment by diverting stockpiled tires from landfills.

Direct shear testing and the triaxial compression method have been widely used for many years to determine the shear strength behavior of soil. The two approaches provide comparable results regarding soil shear strength parameters, such as the cohesion intercept and the angle of internal friction. According to Foose et al. [29], the shear strength parameters of TDA and soil-TDA mixtures obtained from a direct shear test are more accurate than those obtained from a triaxial compression test. These researchers noted that the main factor affecting the triaxial compression test results is the ratio between the maximum particle size and the specimen size. According to ASTM D7181 [41], the largest particle size must be six times smaller than the specimen diameter in a triaxial compression test. Thus, the most commonly available triaxial apparatuses are not large enough to accommodate TDA particle sizes, and hence direct shear tests are the preferred option.

3. Methodology

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

Previous research has utilized different experimental approaches, including direct shear tests and the 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 of the confining pressure and saturation, and the failure progresses in a natural plane. However, there is no control over the pore water pressure at the shear surface in direct shear tests, and the failure plane lies in a predetermined horizontal direction, which may not be the weakest plane. On the other hand, the greater simplicity of direct shear tests compared to the triaxial compression method has made direct shear testing a versatile, frequently used tool for geotechnical designers.

4. Laboratory Experiments

4.1. Materials

4.1.1. Tire-Derived Aggregate (TDA)

The TDA sample used in this study was type A TDA, which was shredded and processed by Halifax C&D Recycling Ltd., located in Enfield, Nova Scotia, Canada. A photograph illustrating the TDA sample used in this study is shown in Figure 1. Because most of the TDA particles were flat and elongated, a histogram analysis was performed to find the particle size distribution of the TDA sample, as recommended by Foose et al. [29] and El Naggar et al. [3]. To conduct the histogram analysis, a TDA sample weighing about 5 kg was randomly selected and a ruler was used to measure the particles in every direction.
According to ASTM D3080 [42], the maximum particle size of aggregates should be at least 10 times smaller than the length of the shear box, to eliminate boundary effects. However, Humphrey and Sandford [26] have suggested that for aggregates with 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. The test results of these researchers showed that the boundary effect is minimized in this case, and the particles are sheared in the box with minimal external effects. This finding was confirmed by Zahran and El Naggar [27], who likewise recommended the aspect ratio of particles four times smaller than the length of the shear box to eliminate the effect of the size of the shear box in the evaluation of TDA shear strength parameters.

In addition, according to Foose et al. [29], the use of tire shreds with a maximum length that is 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 exceeding 75 mm in length were removed from the sample (amounting to only 3.9% of the sample). Thus, the maximum particle size was limited to one-fourth of the shear box length, to eliminate boundary and size effects [26,27]. Figure 2a presents the histogram of the initial TDA sample, and Figure 2b shows the histogram of the sample used in this study, following the removal of the particles exceeding 75 mm in length. As shown in Figure 2, TDA particle lengths were mainly in the ranges of 30–40 mm, 40–50 mm, 50–60 mm, 60–70 mm, and 70–75 mm.

![Figure 1. Photograph of the TDA sample used in this study.](image)

![Figure 2. Histograms of (a) the initial TDA sample and (b) the TDA sample used in the shear box tests.](image)
accordance with the standard test method described in ASTM D698 [43]. It should be noted that due to the flexibility of the TDA particles, the compaction energy had a negligible effect on the dry unit weight. Therefore, in accordance with Humphrey and Sandford [26], 60% of the standard Proctor energy was applied to the specimen. Similarly, because the addition of water to the TDA sample had no effect on the dry unit weight, the compaction test was performed on an air-dried sample [1 and 6]. Table 3 shows the physical properties of the TDA sample used in the shear box tests.

Table 3. Characteristics of the TDA and soils used in this study.

| Characteristics       | TDA | Gravelly | Sandy | Clayey |
|-----------------------|-----|----------|-------|--------|
| D_{10} (mm) \(^1\)   | 19  | 0.30     | 0.24  | 0.007  |
| D_{30} (mm) \(^1\)   | 28  | 2.40     | 0.42  | 0.021  |
| D_{50} (mm) \(^1\)   | 45  | 5.90     | 0.65  | 0.048  |
| D_{60} (mm) \(^1\)   | 49  | 7.00     | 0.80  | 0.075  |
| Coefficient of uniformity, C_u \(^2\) | 2.58 | 23.33 | 3.33  | 10.71  |
| Coefficient of curvature, C_c \(^2\) | 0.84 | 2.74  | 0.92  | 0.84  |
| Optimum water content, ω (%) | -   | 7.50   | 13.0  | 14.0   |
| Maximum dry density, γ_m (kN/m\(^3\)) | 6.82 | 19.2   | 16.8  | 18.4   |
| Plasticity index, PI | -   | -      | -     | 9.3    |

\(^1\) D_{10}, D_{30}, D_{50}, \text{ and } D_{60} \text{ represent the particle diameters where the percentage of particles with diameters below these values are 10\%, 30\%, 50\% and 60\%, respectively.} \(^2\) C_u = \frac{D_{60}}{D_{10}}, \ C_c = \frac{D_{30}^2}{D_{10}^2}.

According to ASTM D6270 [6], to ensure the effective use of TDA particles, rubber-to-rubber contact should be maximized by reducing the amount of exposed steel. In this study, wire cutters were therefore used to remove exposed wires from the edges of the TDA particles.

4.1.2. Soil Samples

Relatively uniform gravelly and sandy soils obtained from a local supplier were used in this study. In addition, a clayey soil was obtained from land in Enfield, Nova Scotia. In a natural condition, the clayey soil sample had a clayey till characteristic. Therefore, it was first dried at 110 °C for 24 h, and then broken down into fine grains before being used in the study.

The particle size distribution of the soil samples was determined by using a sieve analysis in accordance with ASTM D422 [43]. It should be noted that for the clayey soil, first a sieve analysis was performed to find the distribution of particles larger than 75 µm (retained on the no. 200 sieve). Then, a hydrometer analysis was conducted to find the distribution of particles smaller than 75 µm (which passed through the no. 200 sieve). Figure 3 shows the particle size distribution of the TDA and soil samples used in this study.

To find the dry unit weight and optimum water content (ω) of the soil samples, standard Proctor compaction tests were performed in the laboratory in accordance with ASTM D698 [44]. An Atterberg limit test was also performed on the clayey soil, in accordance with the standard test method described by ASTM D4318 [45], to determine the plasticity index. Table 3 presents the physical characteristics of the soil samples used in this study. In accordance with the unified soil classification system procedure (USCS, ASTM D2487 [46]), the gravelly soil was classified as well-graded gravel with sand, the sandy soil was classified as poorly graded sand, and the clayey soil was classified as sandy lean clay. Similarly, the TDA was classified as poorly graded, in accordance with the USCS.
4.2. Sample Preparation

As described above, in this study three types of soil were selected to be mixed with TDA particles. Before being mixed with the TDA, the soil samples were dried in an oven for 24 h at 110 °C and were then broken down into fine grains if required. The TDA sample was air dried at room temperature for 72 h. Following drying of the materials, the required percentages of the soil and TDA samples were measured carefully by weight, according to the planned mixing ratios. In addition, the optimum water content of each soil sample was determined, and a corresponding amount of water was added to each soil sample. The materials were transferred to a tray, where they were mixed carefully until a consistent mixture was obtained. As mentioned above, the optimum water content for compaction of the TDA particles was found to be zero; hence, no water was added to the TDA particles. The mixed materials were then poured gently into the shear box in five layers and compacted by using standard compaction efforts. At each step, the mixture on the tray was mixed thoroughly before being poured into the shear box. Special care was taken, and continuous observations were made, to prevent any inconsistency in the mixtures. This ensured that segregation of the soil and TDA particles did not occur as the sample was prepared and transferred into the shear box. It should be noted that segregation is likely to occur in mixtures with high percentages of TDA. When segregation occurs, the soil settles beneath the TDA particles, and the mixture loses its consistency. Edil and Bosscher [47] conducted a series of triaxial tests on mixtures of sand and tire chips. They found that with a tire chip content greater than 30% by volume, segregation increased between the sand and the tire chip particles. Bosscher et al. [48] likewise conducted a field study, where they observed that segregation occurs in mixtures containing more than 50% TDA by volume.

Table 4 shows the percentage of TDA by weight for each mixture. TDA percentages of 0%, 10%, 25%, 50%, and 100% were used. The name of each mixture indicates the mixture contents, where G stands for gravel, S for sand, C for clay, and T for TDA. The digits at the end of each mixture name indicate the percentage of TDA by weight. For example, mixture GT25 contains gravel and TDA, with 25% TDA by weight. It should be noted that the percentage of TDA by weight is defined as the ratio of the weight of the TDA to the total weight of the soil-TDA mixture.
Table 4. Properties of the soil-TDA mixtures.

| Mixtures   | TDA % (by Weight) | Soil % (by Weight) | $\gamma_{\text{bulk}}$ (kN/m$^3$) | Friction Angle (°) | Cohesion (kPa) |
|------------|-------------------|--------------------|-----------------------------------|-------------------|--------------|
| Gravel-TDA |                   |                    |                                   |                   |              |
| GT0        | 0                 | 100                | 19.84                             | 44.0              | 24.8         |
| GT10       | 10                | 90                 | 18.38                             | 45.4              | 17.0         |
| GT25       | 25                | 75                 | 14.77                             | 43.9              | 14.7         |
| GT50       | 50                | 50                 | 10.21                             | 42.2              | 15.4         |
| GT100      | 100               | 0                  | 6.81                              | 23.9              | 18.2         |
| Sand-TDA   |                   |                    |                                   |                   |              |
| ST0        | 0                 | 100                | 18.73                             | 37.1              | 4.8          |
| ST10       | 10                | 90                 | 17.72                             | 38.4              | 13.4         |
| ST25       | 25                | 75                 | 15.73                             | 38.3              | 14.3         |
| ST50       | 50                | 50                 | 12.06                             | 31.8              | 16.2         |
| ST100      | 100               | 0                  | 6.81                              | 23.9              | 18.2         |
| Clay-TDA   |                   |                    |                                   |                   |              |
| CT0        | 0                 | 100                | 20.40                             | 18.8              | 21.8         |
| CT10       | 10                | 90                 | 18.93                             | 32.3              | 29.2         |
| CT25       | 25                | 75                 | 15.33                             | 25.6              | 29.0         |
| CT50       | 50                | 50                 | 11.00                             | 25.0              | 19.6         |
| CT100      | 100               | 0                  | 6.81                              | 23.9              | 18.2         |

The particle size distributions of the gravel-TDA, sand-TDA, and clay-TDA mixtures are presented in Figure 4. Figure 4a shows that for a TDA content of up to 25% TDA by weight, the gravel mixtures had fairly similar gradation characteristics, with $D_{50}$ values ranging from 9 mm to 13 mm. The gradation characteristics of the gravel-TDA mixture with 50% TDA varied to a greater extent, as the $D_{50}$ of this mixture was 21 mm, approximately double that of the mixtures GT0, GT10, and GT25. As can be seen in Figure 4b, the sand-TDA mixtures exhibited a similar trend, which was further accentuated in the clay-TDA mixtures, shown in Figure 4c.

Figure 4. Particle size distributions of the (a) gravel-TDA, (b) sand-TDA, and (c) clay-TDA mixtures.
5. Laboratory Experiments

Following the preparation of the mixtures, large-scale direct shear tests were performed for each mixture. The direct shear tests were carried out according to the standard testing procedure described by ASTM D3080 [42].

Figure 5 shows the large-scale direct shear box apparatus used in this study. The square box, with nominal dimensions 305 mm × 305 mm × 220 mm, was 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 had a height of 80 mm. To accommodate the high compressibility of the TDA sample and soil-TDA mixtures during shearing, the apparatus was customized, and an extension with a height of 50 mm was constructed and mounted on top of the upper half of the shear box. Thus, the total height of the shear box amounted to 220 mm. To shear the mixtures in the box, the upper half of the box was fixed in place, while the lower half of the box was moved at a controlled rate, powered by an electric motor. The specimen could therefore be sheared near a single shear plane in the middle of the shear box. As shown in Figure 5, the confining pressures, which were applied to each specimen by dead weights, were transferred to the top of the specimen via 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 the confining pressure was then applied to the specimen. As shown in Figure 6, a load cell with a linear variable displacement transducer (LVDT) was installed to measure the shear force. In addition, two other LVDTs were installed to monitor the horizontal displacement and vertical displacement of the mixture during shearing. One LVDT, which was installed above the box, contacted a steel plate over the sample to measure the vertical displacement. The other LVDT, which was installed horizontally, contacted the lower half of the box to measure the horizontal displacement. All the LVDTs were connected to a data acquisition system (CAMPBELL SCIENTIFIC CR200 Series), and the data were recorded and monitored with the aid of a computer. The positioning of the LVDTs can be seen in Figure 6.

Figure 5. The large-scale direct shear apparatus with a square box.
In this study, the TDA content and the confining pressures were the primary variables considered. The direct shear tests were conducted on mixtures with 0%, 10%, 25%, 50%, and 100% TDA by weight, at confining pressures of 50.1, 98.8, and 196.4 kPa.

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

The mixtures were tested at relatively high confining pressures, ranging from 50.1 to 196.4 kPa. It should be noted that at lower confining pressures, the shear stress cannot mobilize completely through the shear plane, which may result in some slip and pull-out effects during shearing. In other words, lower confining pressures can influence the shear strength behavior of the mixtures and contribute to an apparent friction angle [49].

All tests were performed in strain-controlled conditions with a constant shear rate. While each test was running, the shear force, horizontal displacement, and vertical displacement were recorded, up to a total relative lateral displacement of 14%. Then, at 14% relative lateral displacement, the test was terminated, and all the data were collected. It should be noted that the shear rate of clayey soil needs to be slow enough to prevent the buildup of excess pore water pressure in the specimen, allowing the dissipation of pore water pressure during shearing. Hence, it may take several days to perform a direct shear test on clayey soil. However, according to Bowles [50], a shear rate of 1.2 to 1.3 mm/min gives a close approximation to the drained shear strength of a clayey soil obtained from a direct shear test. Therefore, a slow shear rate of 0.5 mm/min was used in this study.

As mentioned above, the shear force was applied by an electric motor and was recorded during shearing by using LVDTs. After each shear test was terminated, the shear stress was calculated by dividing the shear force by the horizontal cross-sectional area of the box (930.25 cm²). Then the shear strength of the mixture was defined at a peak shear stress. If no peak shear stress occurred prior to 14% relative lateral displacement, the shear stress at 10% relative lateral displacement was taken as the shear strength of the mixture (ASTM D3080 [42]).

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

6.1. Dry Unit Weight of the Mixtures

In Figure 7, bulk unit weight is plotted against TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures used in the large-scale direct shear tests. For comparison purposes, the TDA content ranges from 0% (corresponding to pure soil) to 100% (corresponding to pure TDA). It can be seen that the dry unit weight of the mixtures decreased considerably as the percentage of TDA increased. It should be noted that this decrease in dry unit weight is due to the low dry unit weight of the TDA (6.82 kN/m$^3$), which is less than half that of the conventional soils used in this study. A reduction in dry unit weight is beneficial for the design of a retaining wall or a box culvert, since in such applications, the lateral earth pressure needs to be minimized for an economic design. In addition, if the soil beneath a fill layer is weak, the use of a light soil mixture helps to overcome this problem. Hence, soil-TDA mixtures can be a useful lightweight alternative in geotechnical applications, especially for backfilling over or around buried pipes and culverts.

![Figure 7. Bulk unit weight versus TDA content for the soil-TDA mixtures.](image)

6.2. Shear Stress versus Shear Strain Behavior

For all of the considered soil-TDA mixtures (i.e., gravel-TDA, sand-TDA, and clay-TDA), direct shear tests were conducted at three confining pressures of 50.1, 98.8, and 196.4 kPa. Figure 8 shows the shear stress plotted against shear strain for all mixtures at the considered confining pressures. As shown in Figure 8, for 100% gravel (GT0), a peak shear stress was observed at all confining pressures, indicating the shear strength of the samples. Likewise, for the 100% sand (ST0) sample, a clear peak shear stress was also observed at all the confining pressures, indicating the shear strength of the samples in a similar fashion. On the other hand, for the clay-TDA mixtures CT0 and CT10, a peak shear stress was observed at a confining pressure of 50.1 kPa, indicating the shear strength of the samples. However, up to a shear strain of 24%, no peak shear stress was exhibited by any of the samples at confining pressures of 98.8 and 196.4 kPa; in other words, the clay-TDA mixtures exhibited strain-hardening behavior.

It can be seen in Figure 8 that the addition of TDA to the gravel decreased the shear resistance of the mixtures upon shearing at all of the considered confining pressures. It should be noted that the addition of up to 10% TDA by weight to the gravel did not result in a significant reduction in shear resistance at the confining pressures of 98.8 and 196.4 kPa. It is evident from the figure that the addition of up to 25% TDA by weight to the gravel at confining pressures of 50.1 and 98.8 kPa and the addition of up to 10% TDA by weight at a confining pressure of 196.4 kPa decreased the peak shear resistance gradually at a higher shear strain. For mixtures containing more than 25% TDA by weight at confining pressures of 50.1 and 98.8 kPa, and more than 10% TDA by weight at 196.4 kPa, no peak shear stress was exhibited up to a shear strain of 24%. In other words, the addition of TDA to the gravel
resulted in a strain-hardening behavior of the gravel-TDA mixtures, and they did not fail upon applied shearing.

Figure 8. Shear stress versus shear strain for the gravel-TDA, sand-TDA, and clay TDA mixtures at confining pressures of 50.1, 98.8, and 196.4 kPa.
It can also be seen from Figure 8 that the addition of up to 10% TDA by weight to the sand then increased the peak shear stress at a similar shear strain. At a confining pressure of 50.1 kPa, increasing the TDA content from 10% to 25% further increased the peak shear stress at a greater shear strain. However, at confining pressures of 98.8 and 196.4 kPa, increasing the TDA content from 10% to 25% by weight did not significantly change the peak shear resistance of the sand-TDA mixtures. However, the peak shear resistance of the ST25 mixture occurred at a higher shear strain than was the case for the ST10 mixture. Increasing the TDA content to more than 25% then reduced the shear resistance of the mixtures at all the confining pressures considered. It should be noted that mixtures containing more than 50% TDA at a confining pressure of 50.1 kPa and more than 25% TDA at confining pressures of 98.8 and 196.4 kPa did not reach a peak shear stress upon shearing. In other words, the addition of TDA contributed to a strain-hardening behavior of the mixtures in a similar fashion to that observed in the gravel-TDA mixtures.

On the other hand, it is evident from Figure 8 that adding up to 10% TDA by weight to the clay increased the peak shear stress significantly at all the confining pressures considered. However, the further addition of TDA beyond 10% by weight then decreased the shear resistance of the mixtures, with no failure occurring up to a shear strain of 24%. It should be noted that although increasing the TDA content from 10% to 25% decreased the shear resistance of the mixtures, the shear resistance was still higher than the shear resistance of clay alone (CT0). It should likewise be noted that, if failure is considered to occur at 10% relative lateral displacement for mixtures that do not exhibit a peak shear stress, among all the mixtures, the highest shear resistance was observed for mixture CT10 and the lowest shear resistance was observed for clay alone (CT0) at all the confining pressures considered.

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

6.3. Vertical Displacement versus Shear Strain Behavior

Figure 9 shows the vertical displacement plotted against shear strain for the gravel-TDA, sand-TDA, and clay TDA mixtures at the three considered confining pressures. It was observed that gravel-TDA mixtures containing up to 25% TDA by weight were initially compressed and then dilated upon shearing. For 100% gravel (GT0), compression was negligible at a confining pressure of 50.1 kPa, and the specimen was mainly dilated upon shearing. However, gravel mixtures containing more than 25% TDA by weight were mainly compressed upon shearing at all the confining pressures considered.

It should be noted that in gravel-TDA mixtures containing up to 25% TDA by weight, the dilation upon shearing was greater at a lower TDA content, with 100% gravel (GT0) exhibiting the greatest dilation. In mixtures containing more than 25% TDA by weight, compression increased at a higher TDA content, with pure TDA (GT100) exhibiting the greatest compression.

In general, adding TDA to gravel increased the compressibility behavior of the mixtures upon shearing. Figure 9 also indicates that the dilation behavior of the mixtures decreased at greater confining pressures. In mixtures containing more than 25% TDA by weight, increasing the confining pressure from 98.8 to 196.4 kPa caused only a slight change in the compressibility behavior of the mixtures upon shearing.

For the sand-TDA mixtures, it was observed that mixtures containing up to 25% TDA by weight were initially compressed and then dilated upon shearing, at all the confining pressures considered similar to the same trend observed for gravel mixtures. For 100% sand (ST0), the dilation upon shearing was not significant at any of the confining pressures, and the sample returned to almost its initial height after compression. In contrast, mixtures containing more than 25% TDA by weight were mainly compressed upon shearing. It should be noted that sand-TDA mixtures containing 10% and 25% TDA by weight exhibited a similar dilation upon shearing at confining pressures of 98.8 and 196.4. However, mixtures
containing 50% and 100% TDA by weight exhibited similar compression behavior upon shearing at all the confining pressures considered.

Figure 9. Vertical displacement versus shear strain for the gravel-TDA, sand-TDA, and clay TDA mixtures at confining pressures of 50.1, 98.8, and 196.4 kPa.
In general, adding TDA to sand increased the compressibility behavior of the mixtures upon shearing. Figure 9 also indicates that the dilation behavior of the sand mixtures decreased at greater confining pressures opposite to the behavior observed in the gravel mixtures.

As shown in Figure 9, at a confining pressure of 50.1 kPa, pure TDA (CT100) was only compressed upon shearing, but all the other mixtures were initially compressed and then dilated upon shearing. For 100% clay (CT0), the amount of dilation upon shearing was insignificant at a confining pressure of 50.1 kPa, and the specimen returned to its initial height after compression. Thus, at a confining pressure of 50.1 kPa, the addition of TDA increased the compressibility behavior of the mixtures upon shearing, with pure TDA (CT100) exhibiting the greatest compression. It should be noted that clay mixtures containing up to 10% TDA by weight exhibited similar compression upon shearing at a confining pressure of 50.1 kPa. However, the dilation of the mixture containing 10% TDA (CT10) was greater than that of clay alone (CT0). At confining pressures of 98.8 and 196.4 kPa, all the clay mixtures were only compressed upon shearing. It should also be noted that adding up to 10% TDA to the clay decreased the compression behavior of the mixture upon shearing significantly at confining pressures of 98.8 and 196.4 kPa. The further addition of TDA, beyond 10% by weight, then increased the compressibility behavior of the mixtures, however the compression observed was still less than that of clay alone. At confining pressures of 98.8 and 196.4 kPa, the greatest compression upon shearing was exhibited by 100% clay (CT0). Figure 9 also indicates that the compression behavior of the mixtures increased at greater confining pressures.

6.4. Mohr–Coulomb Failure Criterion for the Mixtures

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

The Mohr–Coulomb failure envelope is defined as a linear relationship between the 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 (1) expresses the Mohr–Coulomb failure criterion [51]:

$$\tau = c' + \sigma \tan \varphi'$$  

where $\tau$ is the shear stress at failure, $c'$ is the cohesion intercept, and $\varphi'$ is the angle of internal friction. The Mohr–Coulomb failure envelopes (Figure 10) for the mixtures were determined by referring to the shear stress versus relative lateral displacement behavior of the mixtures, as obtained from the direct shear tests. The shear strength parameters of the mixtures (the cohesion and the angle of internal friction) were then determined from the failure envelopes. The properties of the mixtures considered in this study are summarized in Table 4. A discussion of the shear strength parameters ($\varphi'$ and $c'$) of the gravel-TDA, sand-TDA, and clay-TDA mixtures is presented in the following section.

6.5. Shear Strength Parameters of the Soil-TDA Mixtures

6.5.1. Angle of Internal Friction

Figure 11 shows the angle of internal friction plotted against the TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures. As shown in Figure 11, adding up to 10% TDA by weight to the gravel increased the angle of internal friction slightly, from 44° to 45.4°. The further addition of TDA up to 25% by weight then reduced the angle of internal friction from 45.4° to 42.2°. In general, the addition of up to 25% TDA by weight to the gravel did not change the angle of internal friction significantly. It may be argued that for these mixtures, gravel was the dominant particle in the shear plane and thus controlled the shear strength behavior of the mixtures. Adding more than 25% TDA by weight to the gravel then sharply reduced the angle of internal friction.
6.4. Mohr–Coulomb Failure Criterion for the Mixtures

The properties of the mixtures considered in this study are summarized in Table 1. The cohesion and the angle of internal friction were then determined from the shear strength parameters of the mixtures, as obtained from the direct shear tests. The shear strength parameters of the gravel did not change the angle of internal friction significantly. It may be argued that the application of high confining pressures ranging from 50.1 to 196.4 kPa to the specimens upon shearing resulted in apparent cohesion in these mixtures. At lower confining pressures, the angle of internal friction for the soil-TDA mixtures used in this study, particularly gravelly and sandy soils mixed with TDA, was tested at the three normal stresses: 50.1, 98.8, and 196.4 kPa. Failure was defined at a peak or, in the absence of a peak, at 10% relative lateral displacement. Figure 10 presents the Mohr–Coulomb failure envelopes (Figure 10) for the mixtures. The shear strength behavior of the mixtures. Adding more than 25% TDA by weight to the gravel then sharply reduced the angle of internal friction from 44° to 45.4°. The further addition of TDA up to 25% by weight then reduced the angle of internal friction considerably, from 18.8° to 32.3° (an increase of approximately 72%). It may be argued that the adhesion between clay particles resulted in a bond with the TDA particles, and therefore the angle of internal friction decreased. However, adding up to 10% TDA by weight to the clay increased the angle of internal friction slightly, from 37.1° to 38.4° (an increase of approximately 4%). In general, adding up to 10% TDA by weight to the sand did not change the angle of internal friction significantly. It may be argued that for mixtures containing up to 25% TDA by weight, sand was the dominant particle in the shear plane and thus controlled the shear strength behavior of the mixtures.

Figure 10 also shows that adding up to 10% TDA by weight to the sand increased the angle of internal friction slightly, from 37.1° to 38.4° (an increase of approximately 4%). In general, the addition of up to 25% TDA by weight to the sand did not change the angle of internal friction significantly. It may be argued that for mixtures containing up to 25% TDA by weight, sand was the dominant particle in the shear plane and thus controlled the shear strength behavior of the mixtures. Increasing the TDA content from 25% to 50% then sharply reduced the angle of internal friction from 38.3° to 31.8° (a reduction of about 20%). The angle of internal friction then continued to decrease as the TDA content increased, up to 100% TDA.

The addition of up to 10% TDA by weight to the clay increased the angle of internal friction considerably, from 18.8° to 32.3° (an increase of approximately 72%). It may be argued that the adhesion between clay particles resulted in a bond with the TDA particles and contributed to the reinforcement of the soil upon shearing at all the confining pressures.
considered. Thus, the angle of internal friction increased up to a TDA content of 10%. However, further increasing the TDA content to more than 10% then significantly reduced the angle of internal friction. It may be argued that for clay-TDA mixtures containing more than 10% TDA by weight, the clay particles were not able to create a bond with the TDA particles, and therefore the angle of internal friction decreased.

In general, adding up to 10% TDA by weight to the clay significantly enhanced the angle of internal friction. However, adding up to 10% TDA by weight to the gravel or sand only slightly increased the angle of internal friction. Furthermore, adding more than 10% TDA to the clay then sharply reduced the angle of internal friction; however, adding up to 25% TDA to the gravel or sand changed the angle of internal friction only slightly. It should be noted that the further addition of TDA to the gravel or sand, beyond 25% TDA by weight, then reduced the angle of internal friction significantly. However, adding more than 25% TDA to the clay did not significantly change the angle of internal friction.

6.5.2. Cohesion

Figure 12 shows the cohesion intercept plotted against the TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures. The cohesion intercept obtained for the gravelly and sandy soils mixed with TDA is referred to as apparent cohesion. It may be argued that the application of high confining pressures ranging from 50.1 to 196.4 kPa to the specimens upon shearing resulted in apparent cohesion in these mixtures. At lower confining pressures, the shear stress cannot mobilize completely through the shear plane, which can result in some slip and pull-out effects during shearing. In other words, confining pressures lower than 50 kPa can influence the shear strength properties of the mixtures and contribute to an apparent friction angle (Gray and Ohashi [49]). Therefore, to avoid an apparent friction angle, the confining pressures of 50.1, 98.8, and 196.4 kPa were considered in this study.

![Figure 12. Cohesion intercept versus TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures.](image_url)

As seen in Figure 12, the addition of up to 25% TDA by weight to the gravel decreased the cohesion intercept from 24.8 to 15.4 kPa. An explanation may be that due to the high flexibility of the TDA particles, adding up to 25% TDA by weight to the gravel increased the mobilization of shear stress in the shear plane, and thus decreased the apparent cohesion. Increasing the TDA content from 25% to 50% then increased the apparent cohesion from 15.4 to 20.6 kPa. It may be argued that the gravel-TDA mixtures containing more than 25% TDA by weight had a strain-hardening behavior, and their shear strength parameters were thus obtained at 10% relative horizontal displacement. Therefore, a larger displacement at failure increased the apparent cohesion.

As shown in Figure 12, the addition of TDA to the sand increased the apparent cohesion. An explanation may be that because the TDA particles were coarser than the sand grains, the TDA decreased the mobilization of shear stress in the shear plane upon shearing at all the confining pressures considered, thus increasing the apparent cohesion.
Furthermore, the sand-TDA mixtures containing more than 25% TDA by weight had a strain-hardening behavior, and their shear strength parameters were thus obtained at 10% relative horizontal displacement. Therefore, a larger displacement at failure increased the apparent cohesion.

It should be noted that the cohesion results obtained for the clay were not solely attributable to the confining pressures. There is also adhesion between clay particles in a natural condition, which contributed to the cohesion. It was observed that the addition of up to 25% TDA by weight increased the cohesion from 21.8 to 29 kPa. It may be argued that the addition of up to 25% TDA by weight to the clay decreased the mobilization of shear stress upon shearing at the confining pressures considered, thus increasing the cohesion intercept. For clay-TDA mixtures containing more than 25% TDA by weight, the cohesion intercept then decreased. This may be attributable to the lower percentage of clay in the mixtures, causing the adhesion between clay particles to become less significant. Hence, the observed cohesion for these mixtures would be due mainly to the confining pressure, causing the cohesion intercept to decrease.

In general, adding up to 25% TDA by weight to the gravel caused a sharp decrease in the cohesion intercept. However, the addition of up to 25% TDA by weight to the sand or clay resulted in increased cohesion. It should be noted that for the sand, the cohesion intercept continued to increase as the TDA content increased. When the TDA content increased from 25% to 50%, the cohesion of the gravel-TDA mixtures increased, and the cohesion of the clay-TDA mixtures decreased. The further addition of TDA, beyond 50% by weight, did not significantly change the cohesion intercept of the clay or gravel mixtures.

6.6. Shear Modulus

The shear modulus is a mechanical parameter used to analyze the behavior of material during shearing. Equation (2) was used to calculate the shear modulus (Das [51]):

\[ G = \frac{\tau}{\varepsilon} \]  

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

Figure 13 shows the secant shear modulus plotted against the TDA content for the soil-TDA mixtures at confining pressures of 50.1, 98.8, and 196.4 kPa. It can be seen that the addition of TDA to the gravel decreased the secant shear modulus at all the confining pressures considered. However, it should be noted that at a confining pressure of 196.4 kPa, the decrease in the shear modulus was not significant for a TDA content of up to 10% by weight. It can also be noticed from Figure 13 that adding up to 10% TDA by weight to the sand did not affect the secant shear modulus significantly. However, the further addition of TDA to the sand, beyond 10% by weight, then sharply decreased the secant shear modulus at all the confining pressures considered.

It can be concluded that for both gravel-TDA and sand-TDA mixtures, the stiffness behavior of the mixtures is governed by the parent solid particles at low TDA contents. As the TDA content increases, the behavior of the TDA particles starts controlling the stiffness behavior of the mixture and results in the sharp stiffness decline. On the other hand, for the clay mixtures, as shown in Figure 13, adding up to 10% TDA by weight to the clay significantly increased the secant shear modulus at all the confining pressures considered. However, the further addition of TDA, beyond 10% by weight, then sharply reduced the secant shear modulus at all the confining pressures. This behavior is different than that observed in the other two mixture groups. The initial increase in the stiffness of the clay-TDA mixture with low TDA content is different than the behavior observed in the gravel-TDA and sand-TDA mixtures. A possible cause of this behavior change may be related to the fact that the pure solid gravel and sand particles in the mixture matrix

...
had a higher stiffness than that of the rubber TDA particles. Moreover, there were fewer available voids in the gravel and sand in their pure state, and therefore introducing the TDA to them increased the voids and reduced the collective stiffness of the mixture. On the other hand, the used clay sample was softer and had more voids than the used gravel and sand samples. Accordingly, the stiffness of the pure clay was almost 50% of that of the gravel and the sand. However, the mixing effort introduced during mixing the clay with the TDA particles (at low TDA contents) compacted the voids and enhanced the stiffness of the mixture. When the TDA content increased to 50% and more, however, segregation started to occur in the mixture and consequently, the stiffness decreased.

Finally, it is evident from Figure 13 that for mixtures containing the same amount of TDA, increasing the confining pressure from 50.1 to 196.4 kPa considerably enhanced the secant shear modulus.

6.7. Normalized Lateral Earth Pressure at Rest

The normalized lateral earth pressure at rest is an important factor used in the design of a geotechnical application such as a retaining wall. The angle of internal friction and the dry unit weight of the soil are two variables that affect the normalized lateral earth pressure. Equation (3) was used to determine the normalized lateral earth pressure at rest [51]:

\[
\frac{p_0}{z} = (1 - \sin \phi') \gamma_d
\]

where \(\frac{p_0}{z}\) is the normalized lateral earth pressure at rest, \(z\) is the depth, \(\phi'\) is the angle of internal friction, and \(\gamma_d\) is the dry unit weight of the soil. Figure 14 shows the normalized lateral earth pressure at rest plotted against the TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures.

Figure 13. Secant shear modulus versus TDA content for the (a) gravel-TDA, (b) sand-TDA, and (c) clay-TDA mixtures.

\[
p_0 = z (1 - \sin \phi') \gamma_d
\]
6. The effect of the TDA content on the normalized lateral earth pressure was then investigated. The following conclusions can be drawn from this study:

4. The gravel-TDA and sand-TDA mixtures containing up to 25% TDA by weight were initially compressed, and then dilated upon shearing at all the confining pressures considered. The addition of TDA to the gravel or 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 a confining pressure of 50.1 kPa. However, at confining pressures of 98.8 and 196.4 kPa, the compressibility behavior of the clay-TDA mixture initially decreased with the addition of up to 10% TDA by weight, and then increased with further addition of TDA;

7. Conclusions

The main objective of this study was to investigate the shear strength behavior of coarse-grained to fine-grained soils containing 0% to 100% TDA by weight, with TDA particles less than 75 mm in length. In addition, the compressibility behavior upon the shearing of TDA and soil-TDA mixtures with various TDA contents was evaluated at different confining pressures. The shear strength parameters of mixtures with various TDA contents were determined and compared according to the Mohr–Coulomb failure criterion. The effect of the TDA content on the normalized lateral earth pressure was then investigated. The following conclusions can be drawn from this study:

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

2. The addition of TDA to the gravel decreased the shear resistance upon shearing at all the confining pressures considered. However, the addition of TDA to the sand or clay initially increased and then decreased the shear resistance upon shearing at all the confining pressures. It was also found that increasing the confining pressure enhanced the shear resistance of the mixtures;

3. The gravel-TDA and sand-TDA mixtures containing up to 25% TDA by weight were initially compressed, and then dilated upon shearing at all the confining pressures considered. The addition of TDA to the gravel or 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 a confining pressure of 50.1 kPa. However, at confining pressures of 98.8 and 196.4 kPa, the compressibility behavior of the clay-TDA mixture initially decreased with the addition of up to 10% TDA by weight, and then increased with further addition of TDA;

It can be seen that adding up to 10% TDA by weight to the soils decreased the normalized lateral earth pressure at rest. For the clay-TDA mixture, adding up to 10% TDA by weight significantly reduced the normalized lateral earth pressure at rest; however, increasing the TDA content from 10% to 25% then stabilized the normalized lateral earth pressure at rest. In contrast, for the gravel-TDA and sand-TDA mixtures, the normalized lateral earth pressure at rest continued to decrease as the TDA content increased from 10% to 25%. With the further addition of TDA, beyond 25% by weight, the normalized lateral earth pressure at rest continued to decrease for the clay-TDA mixtures but did not change significantly for the gravel-TDA and sand-TDA mixtures.

Hence, it can be concluded that the addition of 25% TDA by weight to gravel results in a 20% reduction in the lateral earth pressure. Likewise, the addition of 25% TDA by weight to sand results in a 19.5% reduction in the lateral earth pressure. However, adding only 10% TDA by weight to clay can reduce the lateral earth pressure by 36%, which can result in huge savings.

Figure 14. Normalized lateral earth pressure at rest versus TDA content for the gravel-TDA, sand-TDA, and clay-TDA mixtures.
4. Adding up to 10% TDA by weight to the gravel or sand increased the angle of internal friction slightly by about 3%. In general, adding up to 25% TDA by weight to the gravel or sand did not significantly change the angle of internal friction. However, the addition of further TDA, beyond 25%, to the gravel-TDA and sand-TDA mixtures then sharply decreased the angle of internal friction. In contrast, the addition of up to 10% TDA by weight to the clay sharply increased the angle of internal friction, which then decreased with further addition of TDA;

5. The addition of up to 25% TDA by weight to the gravel decreased the apparent cohesion. In contrast, the addition of up to 25% TDA by weight to the sand or clay caused the cohesion intercept to increase. The cohesion intercept for the sand-TDA mixtures then continued to increase as the TDA content increased. However, increasing the TDA content from 25% to 50% by weight enhanced the cohesion of the gravel-TDA mixtures and reduced the cohesion of the clay-TDA mixtures;

6. The addition of TDA to the gravel or sand decreased the secant shear modulus at all the confining pressures considered. However, for the clay, the secant shear modulus increased at all the confining pressures with the addition of up to 10% TDA by weight, and then declined as the TDA content increased further. For mixtures with the same TDA content, increasing the confining pressure from 50.1 to 196.4 kPa significantly enhanced the secant shear modulus;

7. Adding up to 10% TDA by weight to the gravel, sand, or clay reduced the normalized lateral earth pressure at rest. The reduction was the sharpest for the clay-TDA mixture. For the gravel and sand, the normalized lateral earth pressure at rest decreased as the TDA content increased from 10% to 25% by weight, and then did not change significantly as the TDA content increased further. However, for the clay, the normalized lateral earth pressure at rest stabilized as the TDA content increased from 10% to 25% and then decreased sharply with further addition of TDA.

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