Enhancing the Interface Friction between Glass Fiber-Reinforced Polymer Sheets and Sandy Soils through Sand Coating

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Abstract

Soil-pile interface friction is an important geotechnical engineering factor to be considered in achieving a safe, cost-effective design. Conventional construction materials such as concrete, steel, and wood exhibit serious long-term soil substructure problems, particularly with regard to durability, deterioration, and corrosion. Fiber-reinforced polymer (FRP) composites are potential alternatives for addressing these long-term problems. FRP composites are corrosion resistant, with a higher strength to weight ratio and greater durability than conventional materials. More research and data, especially in terms of the interface with soil, are necessary to adapt these new materials to friction pile applications. This paper describes the results of an experimental study of the interface friction between sandy soil and glass FRP (GFRP) sheets coated with different ratios of sand per unit of surface area. A direct shear test was used to study 18 different groups of flat GFRP specimens. The test parameters were the amount of silica sand coating and normal stresses in the direct shear tests. The GFRP specimens were sheared against three types of soil: sand, silty sand, and sandy lean clay, of which the first two were used in both dense and loose states. The experimental results showed that coating the GFRP sheets with silica sand was effective in enhancing the interface friction with sandy soils under different normal stresses. A pile implication

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analysis was also performed to compare the effect of sand coated GFRPs on the load capacity of friction piles with different length to diameter ratios.

Keywords: Direct shear test, sandy soil, interface friction angle, soil strength parameters, fiber-reinforced polymer, GFRP, FRP piles.

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1. INTRODUCTION

The behaviour of interface friction between substructure materials and soils plays a significant role in many soil-structure systems, including friction pile foundations. The direct shear test is an effective means of obtaining strength parameters of the interface between soils and interfacing structures. Potyondy (1961) studied the friction behaviour of the interface between some conventional construction materials (i.e., concrete, steel, and wood) and soil. He found that the primary factors affecting the soil-structure interaction are surface roughness, moisture content, soil composition, and the magnitude of normal loading. To examine the pile-clay interface, Taha (2010) studied the shear behaviour of the interface between marine clay and concrete and steel piles. By using an automated direct shear machine, he found that the interface strength increased with increasing relative roughness of the material, resulting in an increased over consolidation ratio (OCR) and clay density. In contrast, he found that the interface shear strength decreased as the degree of soil saturation increased. Rouaiguia (2012) investigated the residual shear strength of a clay-structure interface by using a modified direct shear test. He found that surface roughness was the primary controlling parameter. Paikowsky et al. (1995) found that grain shape and surface roughness are key parameters which control the interface shear strength.

Chu and Yin (2006) investigated the soil-cement grout interface shear strength of soil nailing by using a large direct shear test apparatus. They found that the angle of interface friction increased with increased interface surface waviness and applied normal stresses. Goh and Donald (1984) studied a soil-concrete interface by using a simple shear apparatus. They found that the interface shear strength depends on the concrete surface texture and on the amount of clay in the soil. To investigate a pile-sand interface, Uesugi and Keshida (1986) studied the friction behaviour of the interface between steel and sand by using a simple shear apparatus. They found that the controlling parameters are normal stress and surface roughness. The following year, in a study of the interface of sand and high-density polyethene (HDPE), Uesugi (1987) found that the interface shear strength increased with increasing soil density. Lehan et al. (1993) also confirmed that the interface friction between the structural material and sand depends upon the density of the sand. This finding is consistent with the fact that the friction angle of dense sand is a greater than that of loose sand. Pando et al. (2002) found that particle angularity and surface roughness were the controlling parameters in the pile-sand interaction. They determined that lower surface hardness results in greater shear strength.

Conventional materials such as wood, steel, and concrete have been used extensively in pile applications, however, they have been observed to deteriorate over time, especially in coastal regions. Researchers are therefore looking for alternative materials such as fiber-reinforced polymers (FRP) to address this problem. Iskandar and Hasan (1998) investigated the performance of FRP piles. In comparison to steel and concrete piles for marine structures, the FRP piles exhibited greater durability, were lighter in weight, required less maintenance, and were more resistant to corrosion. Sakr et al. (2005) found that inexpensive interface shear tests can be used to capture the skin friction characteristics of FRP piles installed in granular soils. Pando (2003) performed laboratory and field studies of FRP piles for bridge substructures. In an evaluation of the soil-pile interface behaviour of five composite piles and two conventional piles, he found that the interface friction angle for the FRP piles increased with increasing relative asperity height and decreasing relative asperity spacing. He also found that soil particle size and angularity were controlling parameters for the soil-pile interface behaviour. Sakr et al. (2004) determined that the lifetime of a deep foundation can be increased by using FRP piles made of self-consolidated concrete (FRP-SCC), by increasing the durability and corrosion resistance so as to reduce the life cycle cost. Frost and Han (1999) studied the friction behaviour of the interface between FRP and sand by using a direct shear test. They found relative roughness (surface roughness/particle mean size) to be a controlling parameter for interface friction, with little influence being exerted by specimen thickness, rate of shearing, or method of preparation.

Recently, Toufigh et al. (2015) performed a laboratory study of the behaviour of the interface between carbon FRP (CFRP) and sand. It was found that the interface behaviour was determined primarily by surface roughness and normal stress, and to a lesser extent by the curing age and rate of shearing. The experimental results of the direct shear tests showed that as the normal stress on CFRP interfacing with sand increased, the interface friction angle increased. Vineetha and Ganesan (2014) studied the interface friction between glass FRP (GFRP) and gravel soil. By using a direct shear test, they found that the interface friction angle was greater when the fiber direction was perpendicular to the shearing load. Lavanya et al. (2014) found that the interface friction angle of CFRP was greater when sheared with well graded gravel than when sheared with poorly graded gravel. Giraldo and Rayhani (2013) studied interfaces of both CFRP and GFRP with clay. Their results showed that in terms of the interface friction angle, FRP equalled or surpassed the performance of traditional steel piling under both drained and undrained conditions.

In designing pile foundations, many engineers consider that δ, the interface friction angle, should be equal to 1/2 to 2/3 of φ, the internal friction angle of the soil, depending upon the materials used. For example, in the case of concrete, it is commonly considered that δ should be 2/3 of φ. However, designers continue to use an approximate value for the friction angle of the interface between different pile materials and soil, because no precise value or ratio is available. Aksoy et al. (2016) indicate that a higher value of δ results in a more economical design and decreased project costs, due to its role in determining the number of piles needed for construction, and their length and diameter.

For this reason, this study was designed to investigate the effect of enhancing the surface roughness of GFRP specimens by using a newly proposed sand coating, with different sand ratios per unit area. The new GFRP surface can be used as a roughened skin for frictional piles to improve their frictional load bearing capacity. The study also provides an in-depth understanding of the frictional behaviour of the enhanced GFRP interface with different types of sandy soils. In addition, a parametric study was conducted to investigate the implications of the proposed interface on the load-bearing capacity of GFRP frictional piles, and to compare the results with the currently available alternatives of conventional GFRP, steel and concrete piles.

2. MATERIALS AND METHODS

Several flat GFRP specimens were coated with sand and tested in contact with different types of soil in a direct shear test, to characterize the friction behaviour of the GFRP-soil interface. The following sections present the details of the experimental program.

2.1. Test Matrix

A total of 27 groups of specimens (99.7 mm x 99.7 mm) were prepared, of which 18 groups were GFRP specimens. Each GFRP specimen was fabricated from epoxy resin and two layers of unidirectional fiberglass fabric. Silica sand was added to the surface of 15 of the GFRP specimens. The test parameters were the amount of sand coating per unit area and the applied normal stress in the direct shear test. The ratios of sand added to the surface of the specimens were 0, 500, 1000, 1500, 2000, and 2500 g/m^2. To provide a basis of comparison for the performance of the sand coated sheets, nine groups of smooth GFRP, steel, and concrete specimens were sheared with dense sand. In the direct shear tests, the normal stresses applied to the specimens were 50, 100, and 200 kPa. In each group, three identical specimens were tested as shown in Table 1. The tested specimens used for comparison purposes were identified by the specimen identification (ID): Smooth GFRP-NY, Steel-NY, and Concrete-NY, where N stands for normal stress, and Y is a numerical indication of the normal stress applied to each specimen in the direct shear test. The GFRP specimens were identified by the ID: GSX-NY, where G stands for GFRP specimen, S stands for sand, and X is a numerical indication of the amount of sand added per unit area (g/m^2). For example, the identification GS1000-N50 indicates a GFRP specimen which has a sand coating of 1000 g/m^2 and is tested under a normal stress of 50 kPa in the direct shear test.

2.2. Material Properties

2.2.1 Glass Fiber Reinforced Polymer

All specimens were prepared with the same unidirectional fiberglass fabric, with two layers on top of one another as a single laminate (468.3 g/m^2 per fabric layer). The laminate was bonded with an epoxy resin (West System 105) and a hardener (West System 206). The tensile strength of the fiberglass fabric (dry fiber) was greater than 1500 MPa, with an areal fabric weight of 450 g/m^2, elongation of 2.8%, and E-modulus greater than 72 GPa, as reported by the manufacturer (Haining Anjie Composite Material Co., Zhejiang, China). The tensile strength and elastic modulus of the GFRP composite were determined to be 502 MPa and 32 GPa, respectively, based on tensile tests.

2.2.2 Coating Sand

In order to determine the properties of the silica sand sprinkled on the GFRP composite, sieve analysis testing was carried out in accordance with the American Society for Testing and Materials (ASTM) C136-14 (2014). The silica sand gradation curve is shown in Figure 1(a). From the curve obtained, the values of D_{10}, D_{30}, D_{50}, and D_{60} were 1.2, 1.5, 1.8, and 1.9 mm, respectively. The uniformity coefficient, C_u, was found to be 1.6, and the coefficient of gradation, C_c, was 1. In the sieve analysis, the percentage of the soil retained in sieve no. 16 from the total silica sand sample was 96.3%. The used silica sand had an angular to sub-angular particles. Based on the unified soil classification system (USCS), the silica sand used was classified as poorly graded sand (SP). The silica sand used for sprinkling the surface of the GFRP sheets was that retained in sieves #16 and #8 only as 96.3 % of silica sand retained on sieve # 16, and sieve analysis shown in Figure 1(a) was performed only on this retaining sand used for coating.

2.2.3 Soils

Three types of sandy soil were used in this experimental study, namely sand, silty sand and sandy lean clay. The engineering properties of soils used were classified by sieve analysis testing in accordance with ASTM C136-14 (2014) to determine the gradation curve shown in Figure 1(a) with sieve openings #4, 8, 16, 30, 40, 50, 60, 100, and 200. From the curve obtained, the values of D_{10}, D_{30}, D_{50}, and D_{60} for the sand were 0.2, 0.4, 0.7, and 0.9 mm, respectively. The uniformity coefficient, C_u, was 3.9, and the coefficient of gradation, C_c, was close to 1. Based on the USCS, the sand was classified as poorly graded sand (SP) with rounded to sub-rounded grain shape. The maximum dry density of the sand and the optimum water content shown in Figure 1(b) were determined by the laboratory compaction characteristics of the soil, by using standard effort according to ASTM D698-12 (2012). The maximum dry density of the sand was 1717 kg/m^3 with optimum water content 14%.

The second type of soil used was silty sand (SM), which contains 40% silt and 60% sand. The maximum dry density of the silty sand was 1883 kg/m^3 and the optimum water content was 11%. The values of D_{50}, and D_{60} for the silty sand were 0.13, and 0.24 mm, respectively, according to sieve analysis shown in Figure 1(a). Two different densities of both sand and silty sand were examined, as follows: dense sand (DS) with relative density of 95% (degree of compaction 99%), loose sand (LS) with relative density of 30% (degree of compaction 88%). The sand samples with both densities were prepared using the optimum water content. The dense silty sand (DSS) had a relative density of 94% (degree of compaction 99%), and the loose silty sand (LSS) had a relative density of 35 % (degree of compaction 86%). The silty sand with both densities was also prepared using the optimum water content for silty sand. In the direct shear box used for the shear test, dense soil was achieved by compacting it to the desired level in three layers, while loose soil was obtained by filling the shear box with soil with no compaction by using a cone to sparkle the soil from a height of 300 mm.

The third type of soil used in this investigation was sandy lean clay (CL), with a liquid limit (LL) of 25.2%, a plastic limit (PL) of 15.9%, and a plasticity index (PI) of 9.3. The sandy lean clay had a maximum dry density of 1840 kg/m3 (degree of compaction 99%). The sandy lean clay sample was prepared using the optimum water content (14%). The soil specimens were sheared under a drained condition using porous plates which allows water drainage during testing.

All soils were sheared alone and with GFRP specimens. The sand and the silty sand were sheared in both dense and loose states. In order to characterize the shear strength parameters of the soil, the internal friction angle, φ, and the interface cohesion value, C, were determined from shear stress versus normal stress graphs for each type and state of soil. The objective was to determine the interface friction parameters: internal friction angle of the soil, cohesion of the soil, friction angle of the interface between the material and the soil, and adhesion between the material and the soil. The shear strength parameters for each type of soil used in this study is presented in the following paragraph.

As shown in Figure 2, the internal friction angle, φ, was 44.1° for sand in the dense state, and 34.7° for sand in the loose state. For silty sand in the dense state, the internal friction angle, φ, was 42.7° and the cohesion, C, was 19.0 kPa; while for silty sand in the loose state φ was 37.0° and the cohesion was 3.7 kPa, as shown in Figure 3. The silt added to the sand provided cohesion to the soil. As shown in Figure 4, for sandy lean clay, the internal friction angle was 22.5°, and the cohesion was 15.1 kPa.

2.3. Specimen Fabrication

A total of 6 types of GFRP sheets (406 mm x 406 mm) were fabricated initially. Three sheets were manufactured of each type for testing and for repeatability purposes. Each sheet consisted of two layers of glass fabric (936.7 g/m2 dry fabric). 68.8 g of epoxy resin plus hardener was applied to the top and bottom surface of each glass fabric layer. Wax paper was used beneath each sheet, to prevent the resin from sticking to the workspace. Five of the six types of sheets were sprinkled with silica sand, as shown in Figure 4. For each of the five sheet types, a different ratio of sand per surface area was used: 500, 1000, 1500, 2000, and 2500 g/m^2. After application of the sand coating, the weight of the composite sheets: GS0, GS500, GS1000, GS1500, GS2000, and GS2500 was

1902, 2557, 3179, 3617, 4035, and 4247 g/m^2, respectively. The uniformity of sand coating over the GFRP sheets area was controlled manually by ensure a uniform distribution of the sparkled sand over the surface area and uniform distance between the sand coating particles. The sheet GS0, which was used as a control specimen, had no sand coating on its surface.

All the sheets were cured at room temperature for a total of seven days from the date of fabrication. After curing was completed, each sheet was cut with a diamond blade saw into nine squares (99.7 mm x 99.7 mm) to be used as specimens for testing with the direct shear test. For each set of parameters, three identical specimens were tested under different normal load as discussed later. For comparison with the sand coated GFRP specimens, a smooth GFRP composite sheet was also prepared. The surface of this composite sheet was smoothed by using a roller over wax paper. Moreover, steel and concrete specimens were prepared as conventional materials to be tested in comparison with the GFRP specimens. The Steel used was a typical smooth surface sheet taken from Dalhousie University laboratory without any additional treatment. The concrete specimen used were prepared in the lab using wooden formwork to produce a typical concrete surface anticipated in construction sites.

2.4. Test Setup

A direct shear test (DST) was used to evaluate the internal friction angle of soil samples and the friction angle of the interface between the soil and GFRP as shown in Figure 6. A direct shear box with dimensions 99.7 mm x 99.7 mm and a depth of 29.6 mm was used in this study. In the lower half of the box was a steel plate. An epoxy resin was used to attach the GFRP specimen to the steel formwork. The top half of the box was filled with soil, and the GFRP specimen was sheared with the soil. The shear box was connected to dial gauges to measure the horizontal and vertical displacement of the specimen in the box, as shown in Figures 7. The direct shear test was carried out in accordance with ASTM D3080-11 (2011). Normal stress was applied through a steel bearing arm connected to the top section of the shear box. Three different normal pressures: 50, 100, and 200 kPa were applied to simulate typical lateral earth pressures along a pile shaft (interface friction) at a moderate driving depth. The soils were consolidated before shearing and were tested under drained condition where drainage was allowed during shearing.

A horizontal shear force was applied to the sample, with a shearing rate of 0.24 mm/min. The shearing rate was chosen based on the equations provided in ASTM D3080-11 (2011), and the average rate was taken for three types of soils used. Frost and Han (1999) presented that the rate of shearing has less influence on the interface friction coefficient between GFRP and soil. The peak shear stress versus the corresponding normal stress curves was plotted for each test to find the interface friction parameters (interface friction angle, and adhesion between GFRP specimen and soil). For the loose samples, no residual strength was observed as expected, only for dense sand the peak shear strength was used to determine the interface friction angle. When the shear stress-strain curve does not present a peak, the peak shear stress was taken equals to the shear stress corresponding to the 10% shear strain.

3. RESULTS AND DISCUSSION

As reported by Uesugi and Keshida (1986), the interface friction angle depends upon the material surface roughness. In addition, Pando et al. (2002) indicated that particle angularity affects the behaviour of pile-soil interfaces. For this reason, silica sand with angular to sub-angular particles was used to coat the surface of 15 GFRP specimens, with different sand ratios per unit of surface area. The GFRP/sand interface shear strength was investigated. The objective was to determine whether greater surface waviness of sand coating of the GFRP specimens contributes to higher shear strength values when the specimens are sheared with sandy soils, and to identify which GFRP surface provides the most optimal results.

3.1. Interface with Sand

The GFRP specimen GS0 without sand coating was sheared with both dense sand (DS) and loose sand (LS). The difference between the peak interface friction angle, δ, for GS0 with dense and loose sand was measured. As shown in Figures 8(a) and 8(b), the interface friction angle for GS0/DS is 38.7°, while the interface friction angle for GS0/LS is 36.3°.

The effect of sand coating is shown in Figures 8(c) and 8(d), where the interface friction angle, δ, increases to 40.3° for GS500/DS, and 38.2° for GS500/LS, the peak values of shear stresses for GS500/DS were taken close to the residual as neglecting a sudden jump occurred in Figure 8(c) following the same trend instead. The effect of sand coating can also be seen in Figures 9(a) and 9(b), where δ is 41.4° for GS1000 with dense sand, which is higher than the value for GS500/DS. In the GS1000 specimen, the sand particles are able to penetrate the voids in the silica sand coating, resulting in greater strength of the interface between the soil and the material. The interface friction angle, δ, for GS1000/LS is 38.2°.

Increasing the sand coating ratio above 1000 g/m^2 increased the interface friction angle with sand. As shown in Figures 9(c) and 9(d), for GS1500 with dense sand the interface friction angle is 42.0°. This specimen was found to have an optimum sand coating. Here the increase in the sand coating ratio gives rise to more interlocking between the particles, resulting in greater interface friction. For GS1500/LS, the interface friction angle is 38.2°.

Increasing the sand coating ratio to more than 1500 g/m^2 began to cause a decrease in the interface friction angle with sand. As shown in Figures 10(a) and 10(b), GS2000/DS has an interface friction angle of 39.9°, which is less than the value for GS1500/DS. In Figures 10(a) and 10(b) it can be seen that GS2000/LS has an interface friction angle of 36.8°.

A decrease in the interface friction angle is shown in Figures 10(c) and 10(d), where GS2500/DS has an interface friction angle of 39.5°, which is smaller than that of GS1500/DS and GS2000/DS. The reduced number of voids in the silica sand coating in GS2500 results in less interlocking with the soil, which decreases the friction angle with sand. For GS2500/LS, the interface friction angle is only 33.2°. To ensure repeatability, the average results of the interface shear tests were taken out of three interface shear tests against sand only in both dense and loose states. However, it would be very busy to present all the repeated results and figures, so the average results were presented for illustration with error bars in Figure 11.

3.2. Interface with Silty Sand

As shown in Figures 12(a) and 12(b), for GS0 sheared with dense silty sand (GS0/DSS) and loose silty sand (GS0/LSS), the interface friction angles are 37.1° and 30.9°, respectively; and the adhesion values are 13.0 kPa and 4.0 kPa, respectively.

The effect of sand coating is shown in Figures 12(c) and 12(d), where the interface friction angle increases to 38.8° for GS500/DSS and the adhesion is 2 kPa. For GS500/LSS, δ is 34.6°, with an adhesion of 6.5 kPa. As shown in Figures 13(a) and 13(b), GS1000/DSS has an interface friction angle of 38.5° and an adhesion of 19.9 kPa; whereas GS1000/LSS has an interface friction angle of 34.1° and an adhesion of 3.0 kPa.

It can be seen in Figures 13(c) and 13(d) that the interface friction angle increases to 40.4° for GS1500/DSS, with an adhesion of 5.7 kPa. For GS1500/LSS, the interface friction angle is 34.6°, with an adhesion value close to zero. As shown in Figures 14(a) and 14(b), the interface friction angle for GS2000/DSS is higher than that for GS1500/DSS. The small particles of soil are able to penetrate the voids in the silica sand coating of GS2000, forming a strong adhesion with the coating, with an optimum interface friction angle of 43.3° and an adhesion of 7.0 kPa. This was the highest interface friction found among all the GFRP specimens tested with sand. For GS2000/LSS the interface friction angle is 36.9°, with an adhesion of 4.0 kPa.

For GS2500/DSS, as shown in Figures 14(c) and 14(d), the interface friction angle, δ, decreases to 40.2°, with an adhesion value of 11.6 kPa. GS2500/LSS also has a decreased interface friction angle of 34.5°, with an adhesion value of 1.9 kPa. Increasing the sand coating ratio of the GFRP specimen to more than 2000 g/m^2 resulted in a decreased interface friction angle with silty sand, due to less interlocking with the material surface. Figure 15 shows a comparison of the interface parameters for different GFRP sheets, with dense and loose silty sand.

3.3. Interface with Sandy Lean Clay

As shown in Figures 16(a) and (b), GS0 with sandy lean clay (GS0/SLC) has an interface friction angle of 15.7°, with an adhesion value of 22.2 kPa. The effect of sand coating can be seen in Figures 16(c) and 16(d), where GS500/SLC has an interface friction angle of 21.5°, which is greater than that of GS0/SLC. The rougher surface of the GS500 specimen provides more friction with the clay particles, resulting in greater interface strength and adhesion between the soil and the material, with an adhesion value of 23.1 kPa.

The effect of sand coating can also be seen in Figures 17(a) and 17(b), where the interface friction angle increases to 25.2° for GS1000/SLC, which is higher than the value for GS500/SLC. The rougher surface of the GS1000 specimen provides greater friction with the sand particles, resulting in the highest optimum adhesion, with a value of 64.0 kPa. As shown in Figures 17(c) and 17(d), for GS1500/SLC the adhesion is 46.2 kPa and the interface friction angle is 27.3°, which is greater than the value for GS1000/SLC. As can be seen in Figures 18(a) and 18(b), with a sand coating ratio of 2000 g/m^2, an optimum interface friction angle of 36.4° was found for GS2000/SLC, with an adhesion of 29.6 kPa. Increasing the sand coating ratio to 2500 g/m^2 resulted in a decreased interface friction angle of 30.6° for GS2500/SLC, with an adhesion value of 24.2 kPa, as shown in Figures 18(c) and 18(d). Increasing the sand coating ratio of the GFRP specimen to more than 2000 g/m^2 caused the interface friction angle with sandy lean clay to decrease, due to fewer voids in the particles of the material and less interlocking. Figure 19 presents a comparison of the interface parameters for different GFRP sheets with sandy lean clay.

For silty sand and sandy lean clay, the maximum interface friction is observed under a sand coating ratio of 2000 g/m^2, and for interface adhesion, the optimum sand coating ratios were 500 and 1000 g/m^2, respectively. In this study, the optimum sand coating ratio was chosen by the optimum interface friction angle as it's the factor affecting the pile design under drained condition which affects the friction resistance of the pile.

3.4. Comparison with Conventional Pile Materials

For purposes of comparison with the experimental results for sand coated GFRP specimens, three different materials: smooth GFRP composite sheet (1852 g/m^2), steel, and concrete were sheared against dense sand under three different normal pressures: 50, 100, and 200 kPa. As shown in Figures 20(a) and 20(b), the smooth GFRP specimen sheared with dense sand has an interface friction angle, δ, of 32.7°. The ratio of the interface friction angle to the internal friction angle of the soil (δ/φ) is 0.7, with a ($\tan\delta/\tan\varphi$) ratio of 0.7. The δ/φ ratio for the optimum sand coated specimen GS1500 (the sand coated specimen which exhibited the greatest interface friction angle with sand) is close to 1, with a ($\tan\delta/\tan\varphi$) ratio of 0.95. The percentage gain of the sand coated GFRP specimen GS1500 in comparison to the smooth GFRP specimen is 28.5%.

The second material used for comparison was steel. The Steel used was a typical smooth surface sheet taken from Dalhousie University laboratory without any additional treatment. As can be seen in Figures 20(c) and 20(d), the steel specimen sheared with dense sand has an interface friction angle of 28.6°. The ratio of the interface friction angle to the internal friction angle of the sand (δ/φ) is 0.7, with a (tanδ/tanφ) ratio of 0.6. The percentage gain of the sand coated GFRP specimen GS1500 in comparison to the steel specimen is 47.0%.

The third material used for comparison was concrete. The concrete specimen used were prepared in the lab using wooden formwork to produce a typical concrete surface anticipated in construction sites. As shown in Figures 20(e) and 20(f), the mould side surface of the concrete specimen sheered with dense sand has an interface friction angle of 38.8°. The ratio of the interface friction angle to the internal friction angle of the sand (δ/φ) is 0.9, with a (tanδ/tanφ) ratio of 0.8. The percentage gain of the sand coated GFRP specimen GS1500 in comparison to the concrete specimen is 8.1%. Figure 21 presents a comparison of the interface friction angles of smooth GFRP, steel, concrete, and the GS1500 specimen, with dense sand.

3.5. Pile Friction Capacity Implication

To investigate the effect of the interface friction angle of sand coated GS1500, smooth GFRP, steel, and concrete specimens with dense sand, an empirical study was implemented by using the pile friction capacity ($P_{friction}$) formula for driven piles:

$$P_{friction} = Q_s A_s \tag{1}$$

where Q_s is the average unit pile-soil shear resistance, and A_s is the pile surface area. These can be expressed as:

$$A_s = \pi D L \tag{2}$$

$$Q_s = \sigma_{0avg} K_s \tan\delta \tag{3}$$

where D is the pile diameter, L is the pile length, σ_{0avg} is the average effective stress over the pile length taken as $\gamma h/2$, γ is the maximum dry density of the soil used (17.17 KN/m^3), h is the soil depth, K_s is the lateral earth pressure coefficient for driven piles ($1.4\ K_o = 1.4\ (1 - \sin\varphi)$), δ is the interface friction angle of the pile material with dense sand, and φ is the internal friction angle of dense sand (44.1°). As shown in Figure 22, for L/D = 20 with different pile diameters (D = 0.3, 0.4, 0.5, and 0.6 m), this empirical study found that the pile friction capacity ($P_{friction}$) for a GFRP sand coated pile with a sand coating ratio of 1500 g/m^2 driven in dense sand is greater than the friction capacities of the other pile materials tested (concrete, smooth GFRP, and steel).

In accordance with this empirical study, as shown in Figure 22, for pile diameters of 0.3, 0.4, 0.5, and 0.6 m, the friction capacities of concrete piles are 100.0, 237.1, 463.0, and 800.1 KN, respectively. For steel piles, the friction capacities are 67.6, 160.3, 313.1, and 541.1 KN; and for smooth GFRP piles the friction capacities are 79.6, 188.7, 368.6, and 637.0 KN, respectively. For sand coated GFRP piles with a sand coating ratio of 1500 g/m^2, the friction capacities are 111.9, 265.1, 517.8, and 894.8 KN, respectively.

For the newly proposed sand coated GFRP pile with a sand coating ratio of 1500 g/m^2 and L/D = 20, the percentage gains in comparison with concrete, smooth GFRP, and steel piles in dense sand are 11.8%, 40.5%, and 65.4%, respectively. For marine construction, use of the newly proposed GFRP surface coated with 1500 g/m^2 of silica sand is calculated to increase the GFRP pile friction capacity by 40.5% in comparison with a smooth GFRP pile. The use of concrete and steel piles for marine construction can result in serious interface durability problems due to deterioration. The newly proposed GFRP surface has the potential not only to solve these interface problems but also to increase the pile friction capacity in comparison to concrete and steel piles in dense sand, with percentage gains of 11.8%, and 65.4%, respectively.

4. CONCLUSIONS

This experimental study was conducted to investigate the properties of the interface between sand coated GFRP sheets and sandy soils. Six different ratios of silica sand to GFRP sheet surface area were studied: 0, 500, 1000, 1500, 2000, and 2500 g/m^2. Different types of soil (sand, silty sand, and sandy lean clay) were placed on top of different sand coated GFRP specimens in a direct shear box, under three different normal pressures: 50, 100, and 200 kPa. The following conclusions can be drawn from the results of this study:

- In comparison to uncoated sheets, the silica sand coating increased the interface friction of GFRP sheets with sandy soils, by enabling soil particles to interlock with the interface by filling voids in the sand coating of the GFRP specimens, thus enhancing the interface behaviour with sandy soils.
- GFRP specimens with a sand coating ratio of 2000 g/m^2 had the greatest interface friction angle (43.3°) with dense silty sand. This value is 16.8% higher than that for GFRP specimens without sand coating, and also exceeds the soil/soil friction angle of 42.7°. For dense sand, GFRP specimens with a sand coating ratio of 1500 g/m^2 had the greatest interface friction angle (42.0°) in this group.
- For sandy lean clay, the optimum sand coating ratio was exhibited by GFRP specimens with a sand coating ratio of 2000 g/m^2. This increased the interface friction angle to 36.8°, with a percentage gain of 131.3% in comparison to GFRP specimens without sand coating. The highest adhesion value (64.0 kPa) was exhibited by GFRP specimens with a sand coating ratio of 1000 g/m^2.
- For dense sand, interface friction angles were compared for steel, concrete, smooth GFRP, and GFRP with a sand coating ratio of 1500 g/m^2. It was found that the sand coated GFRP had the

greatest interface friction angle (42.0°) with dense sand, with percentage gains of 8.1%, 28.5%, and 47.0% in comparison to concrete, smooth GFRP, and steel, respectively.

- The maximum interface friction angle is observed at GS1500 for poorly graded sand, while for silty sand and sandy lean clay the maximum interface friction angle is observed at GS2000. The larger particle sizes of poorly graded sand were able to fill the larger voids between the silica sand coating of GS1500 creating a strong interlocking between the GFRP specimen and soil. For GS2000, the smaller particle sizes of silty sand and sandy lean clay were able to fill the voids of GS2000 which is less than those of the GS1500 creating and strong interlocking between the GFRP specimen and soil.

- A design example of driven pile friction capacity showed that with dense sand a GFRP pile with a sand coating ratio of 1500 g/m^2 had a friction capacity exceeding that of other sand coated GFRP specimens, smooth GFRP, steel, and concrete piles. For a pile length to diameter ratio of 20, the pile friction capacity gains in dense sand for the GFRP pile with a sand coating ratio of 1500 g/m^2 were 11.8%, 40.5%, and 65.4% in comparison to concrete, smooth GFRP, and steel piles, respectively.

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Table 1. Test Matrix

Group #	Specimen ID	Ratio of Sand Coating (g/m^2)	Normal Stress (kPa)
1	GS0-N50	0	50
2	GS0-N100	0	100
3	GS0-N200	0	200
4	GS500-N50	500	50
5	GS500-N100	500	100
6	GS500-N200	500	200
7	GS1000-N50	1000	50
8	GS1000-N100	1000	100
9	GS1000-N200	1000	200
10	GS1500-N50	1500	50
11	GS1500-N100	1500	100
12	GS1500-N200	1500	200
13	GS2000-N50	2000	50
14	GS2000-N100	2000	100
15	GS2000-N200	2000	200
16	GS2500-N50	2500	50
17	GS2500-N100	2500	100
18	GS2500-N200	2500	200
19	Smooth GFRP-N50	0	50
20	Smooth GFRP-N100	0	100
21	Smooth GFRP-N200	0	200
22	Steel-N50	0	50
23	Steel-N100	0	100
24	Steel-N200	0	200
25	Concrete-N50	0	50
26	Concrete-N100	0	100
27	Concrete-N200	0	200

Note: For each group, three identical specimens were prepared and tested.

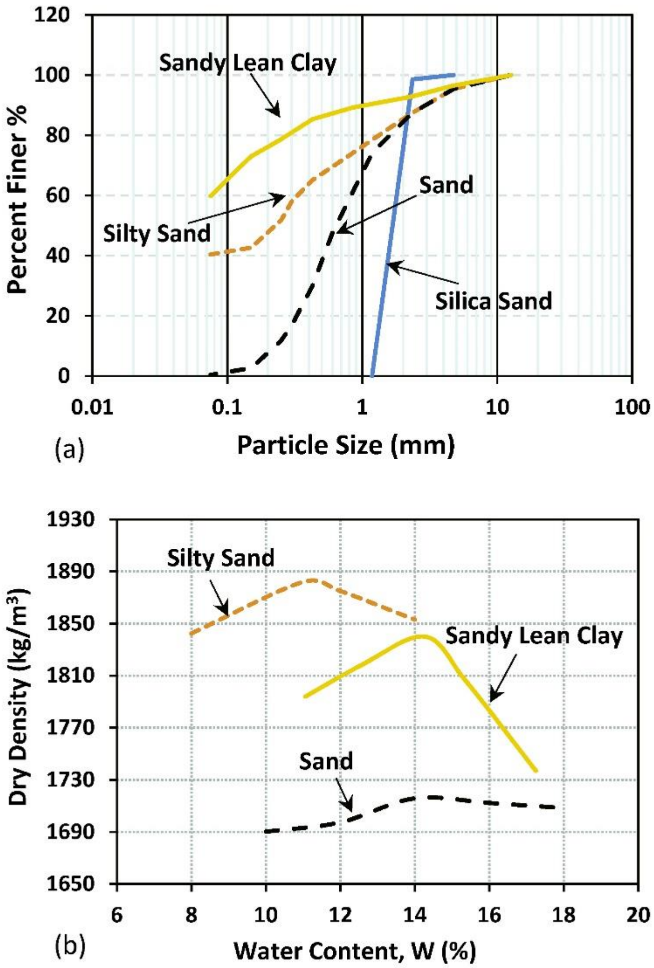

Figure 1. Soil properties: (a) gradation curves, and (b) maximum dry density vs. optimum water content

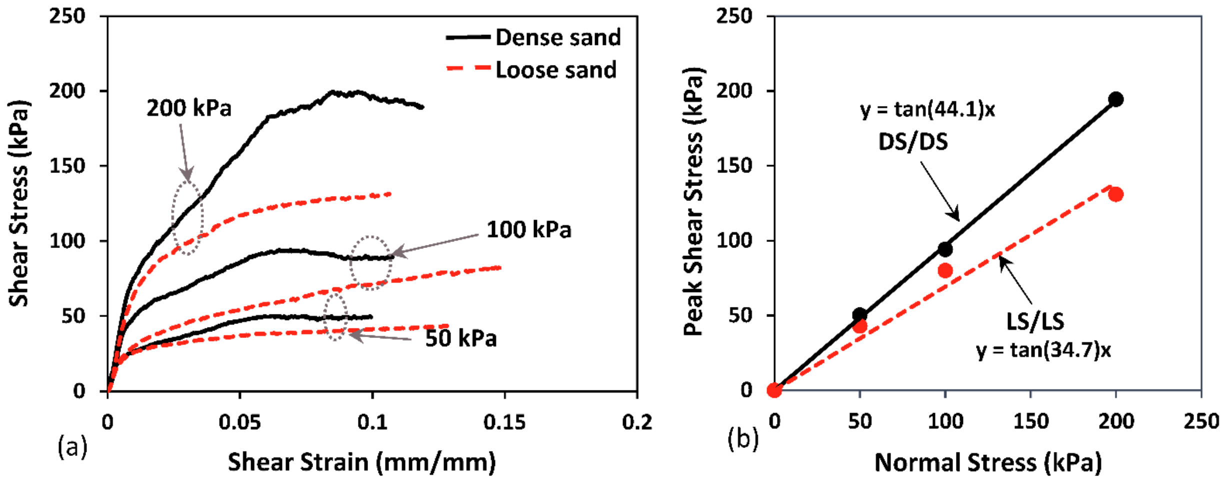

Figure 2. Direct shear tests of loose sand (LS) and dense sand (DS): (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress

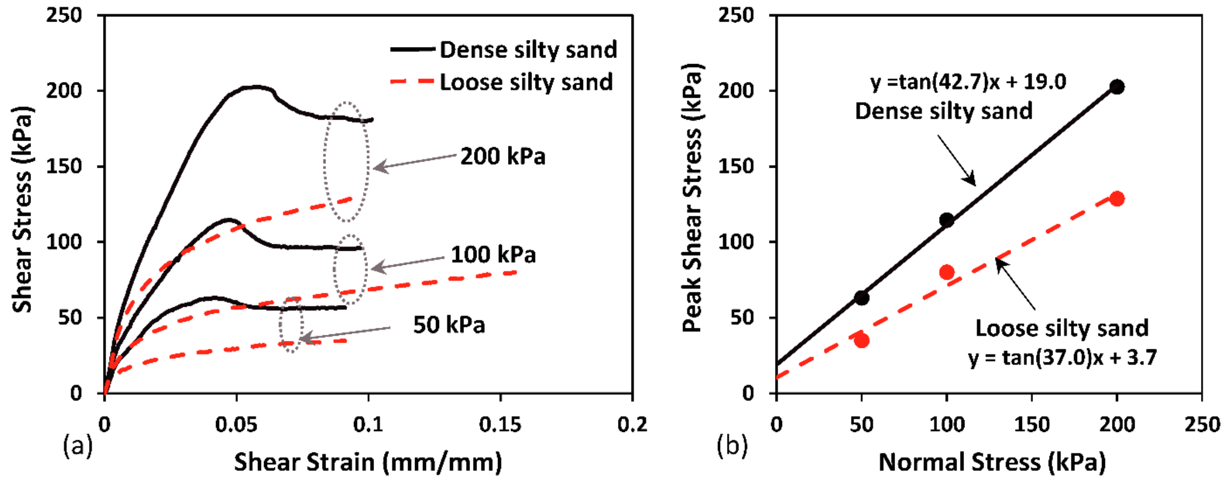

Figure 3. Direct shear tests of loose silty sand (LSS) and dense silty sand (DSS): (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress

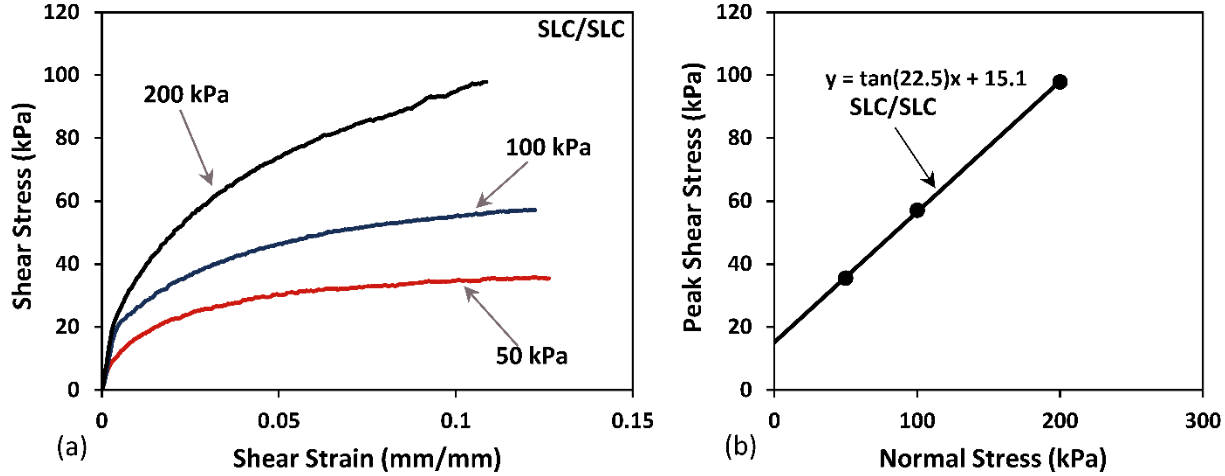

Figure 4. Direct shear tests of sandy lean clay (SLC): (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress

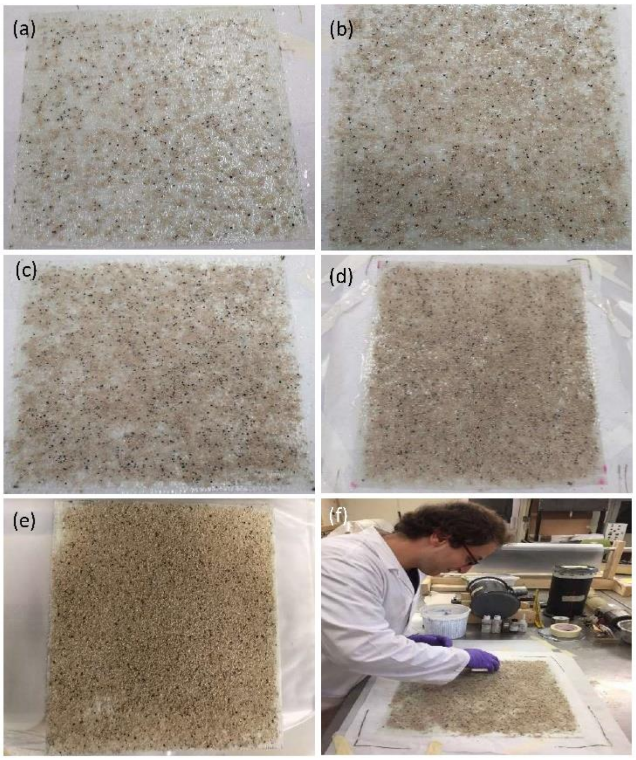

Figure 5. Sand coated GFRP sheets: (a) GS500 specimen, (b) GS1000 specimen, (c) GS1500 specimen, (d) GS2000 specimen, (e) GS2500 specimen, and (f) manufacture of GFRP sheet coated with silica sand

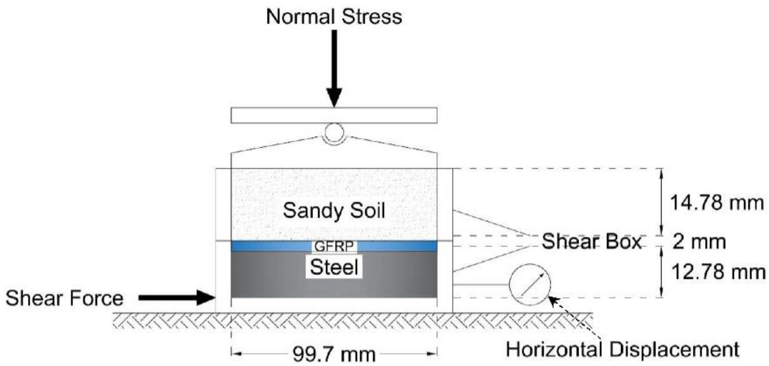

Figure 6. Test set-up for interface friction measurement

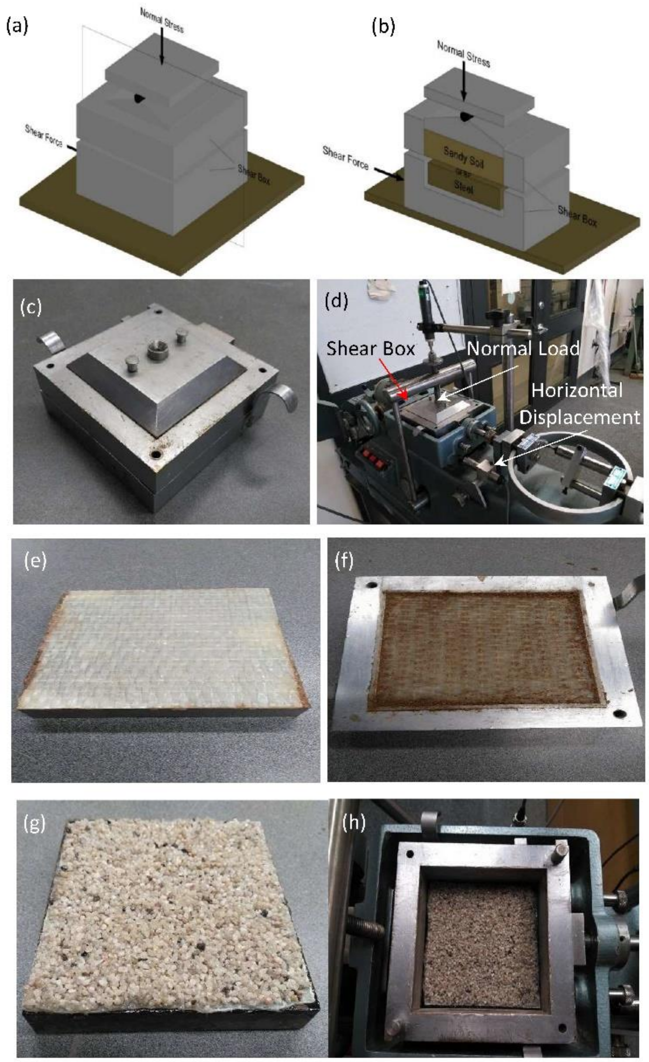

Figure 7. Test set-up: (a) schematic diagram of direct shear box, (b) cross-section of direct shear box, (c) photograph of the direct shear box used, (d) illustration of the test set-up, (e) GFRP specimen on the steel formwork prior to the test, (f) GFRP specimen inside the shear box after the test, (g) GS2500 specimen before testing, and (h) GS2500 specimen inside the shear box

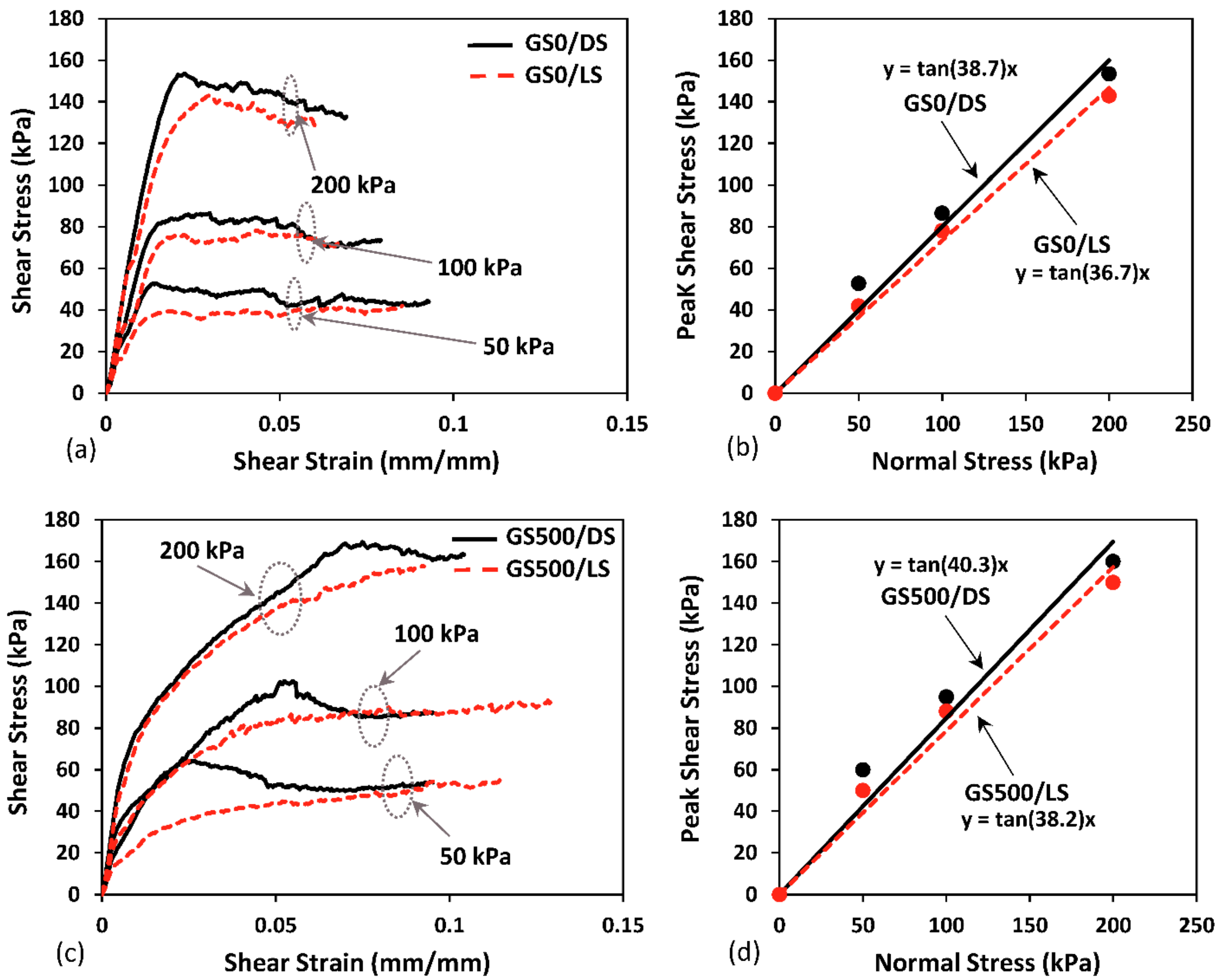

Figure 8. Direct shear tests of loose sand (LS) and dense sand (DS), with GFRP without sand coating (GS0): (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress; and with sand coated GFRP GS500: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress

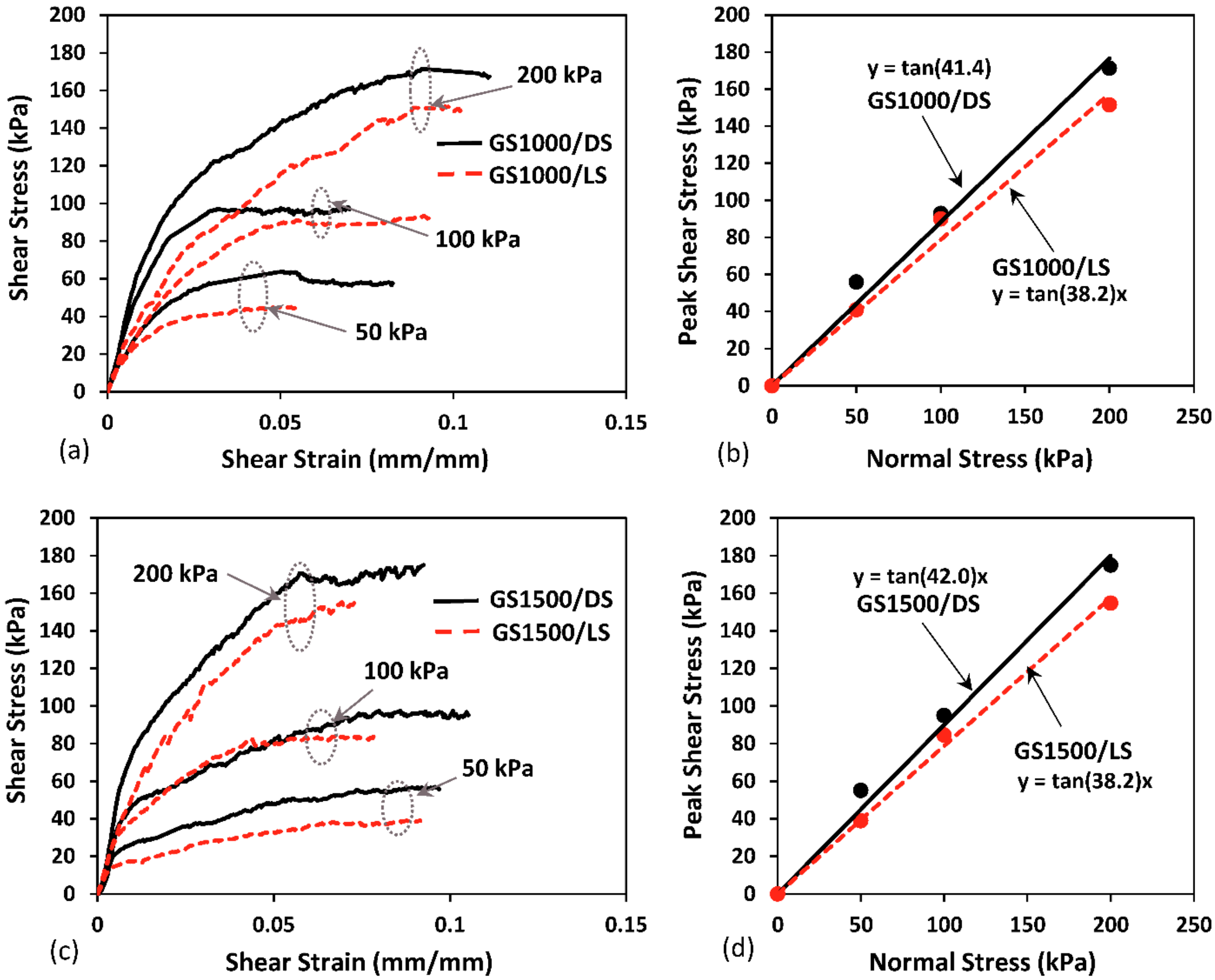

Figure 9. Direct shear tests of loose sand (LS) and dense sand (DS), with sand coated GFRP GS1000: (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress; and with sand coated GFRP GS1500: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress

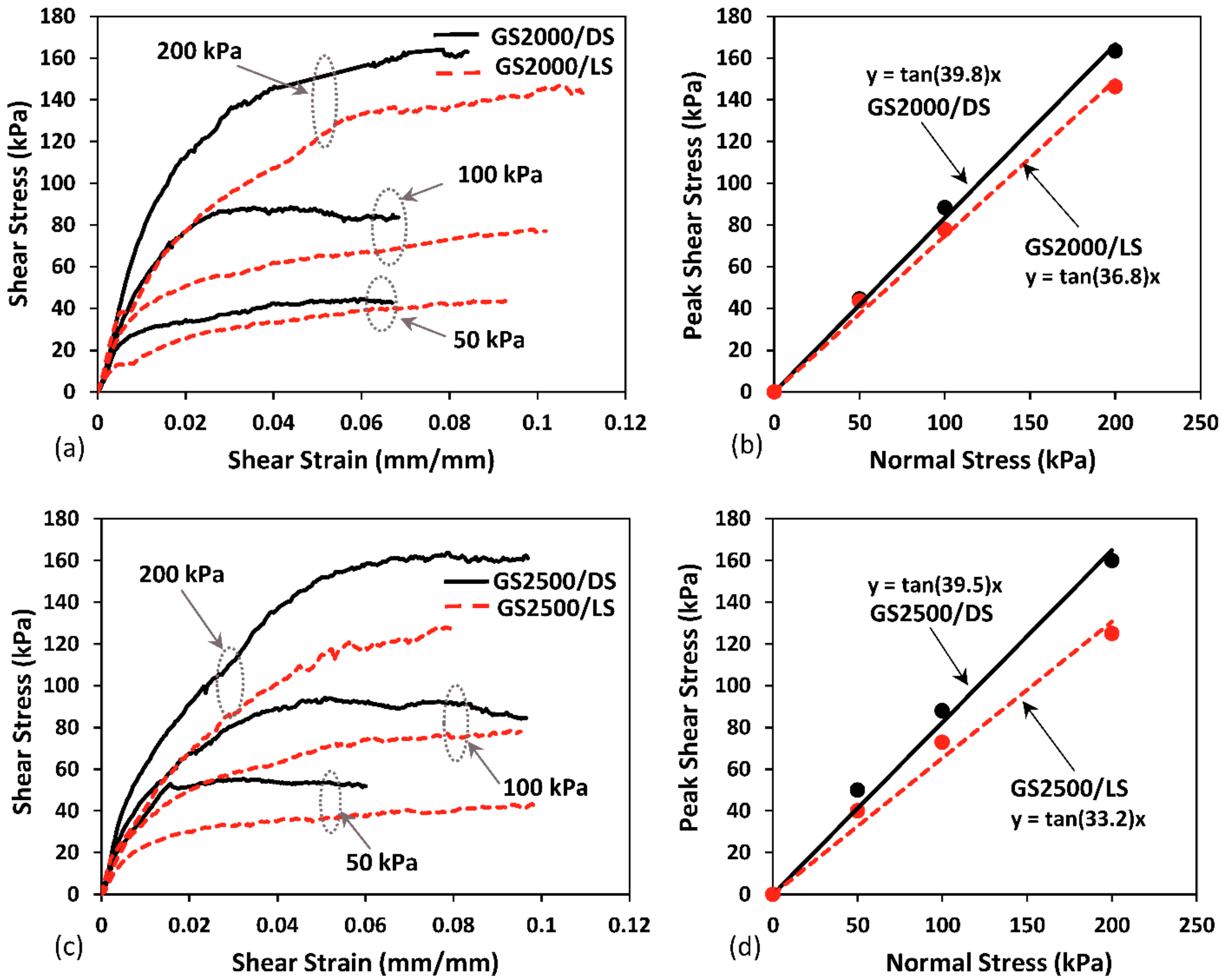

Figure 10. Direct shear tests of loose sand (LS) and dense sand (DS), with sand coated GFRP GS2000: (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress; and with sand coated GFRP GS2500: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress

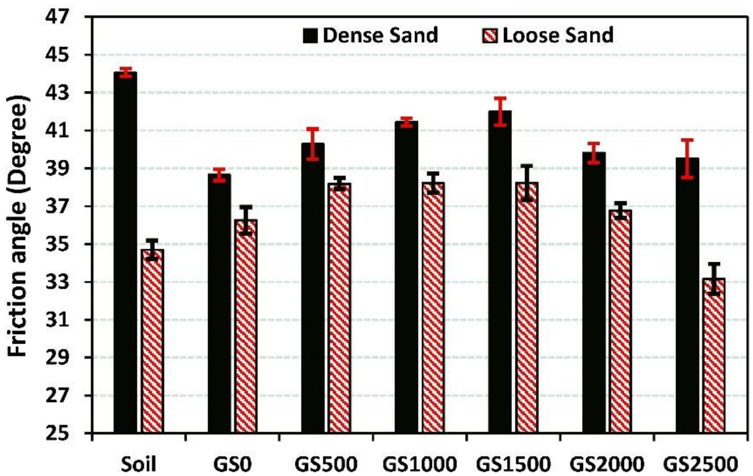

Figure 11. Comparison of test results: friction angles with dense and loose sand

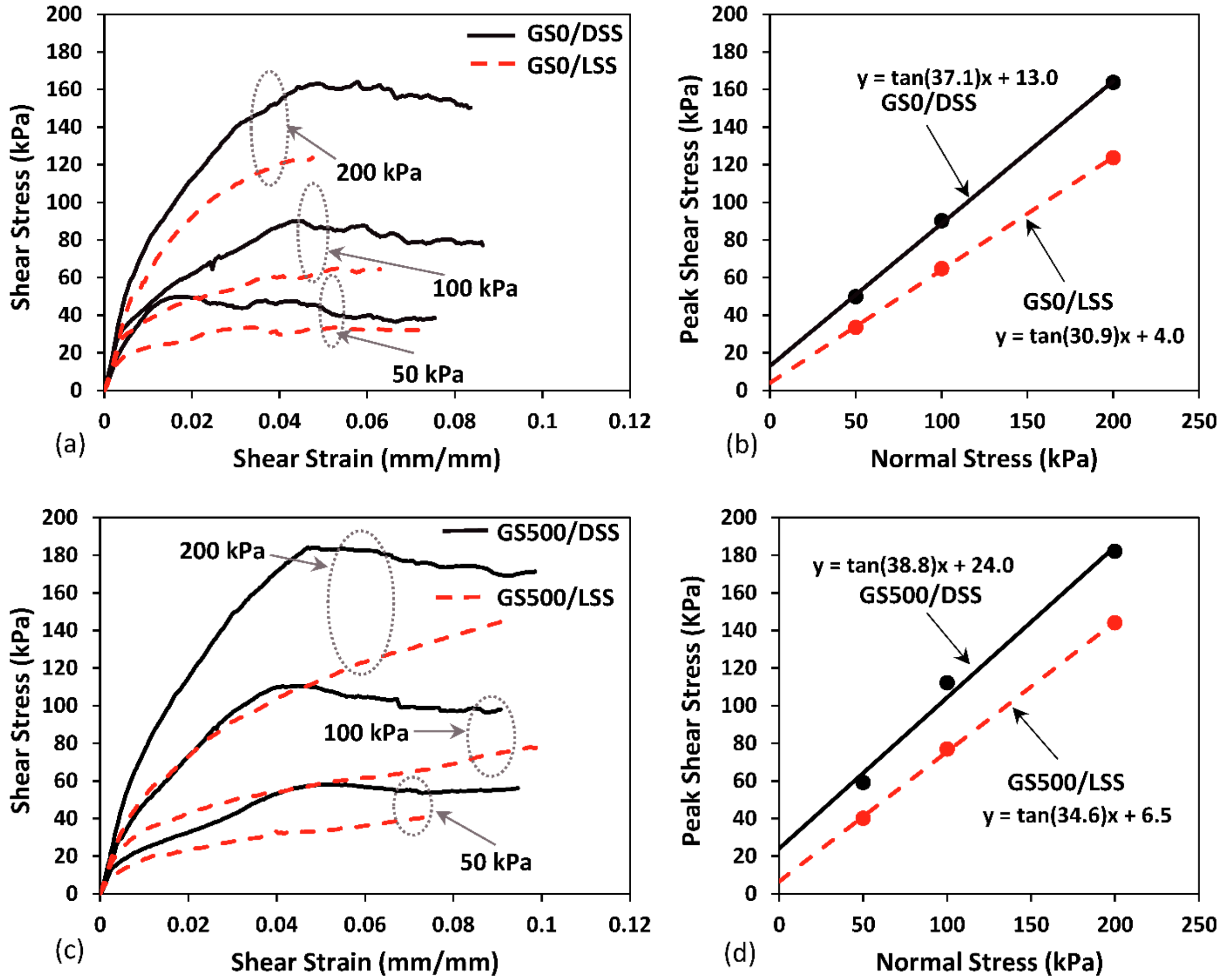

Figure 12. Direct shear tests of loose silty sand (LSS) and dense silty sand (DSS), with GFRP without sand coating (GS0): (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress; and with sand coated GFRP GS500: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress

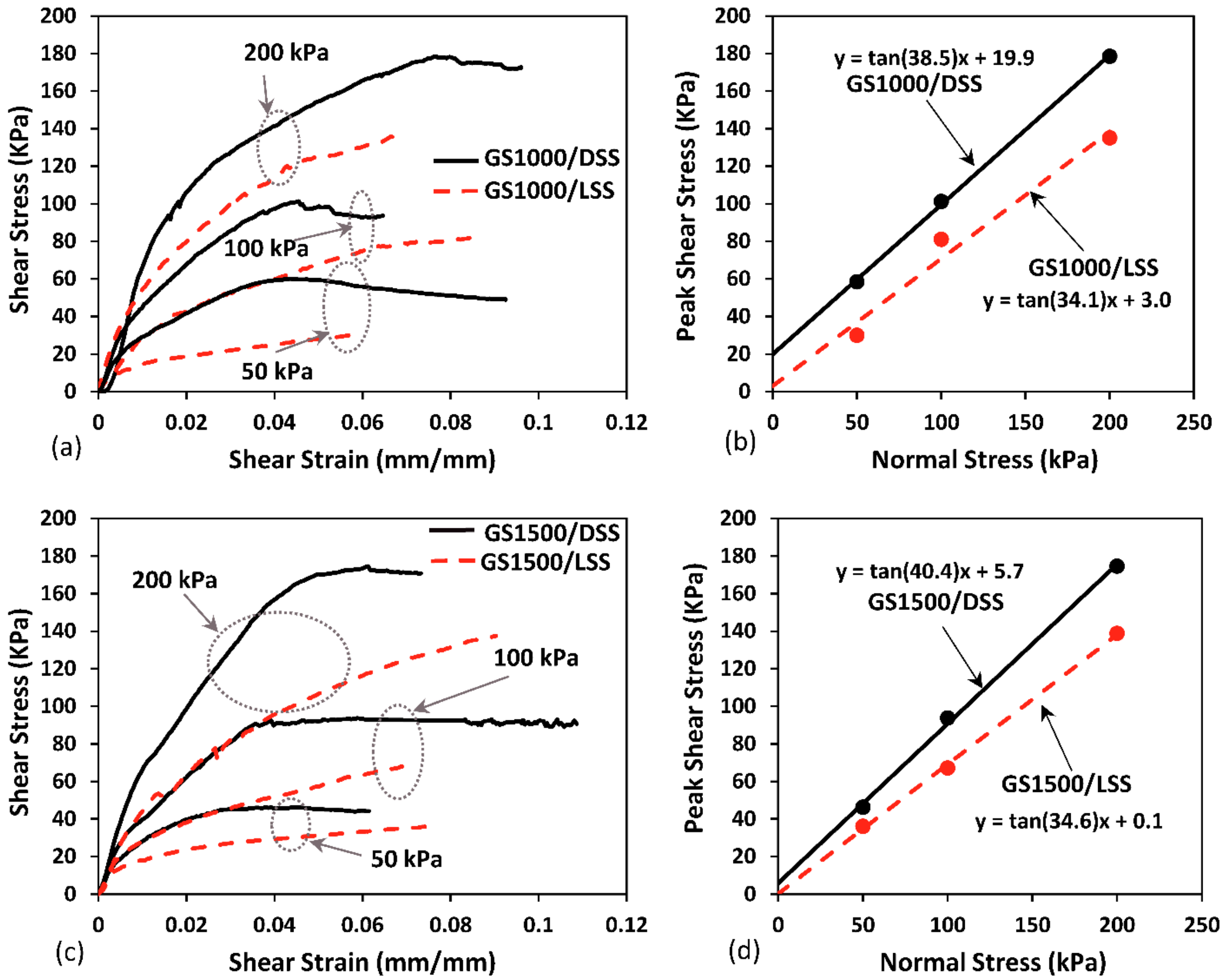

Figure 13. Direct shear tests of loose silty sand (LSS) and dense silty sand (DSS), with sand coated GFRP GS1000: (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress; and with sand coated GFRP GS1500: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress

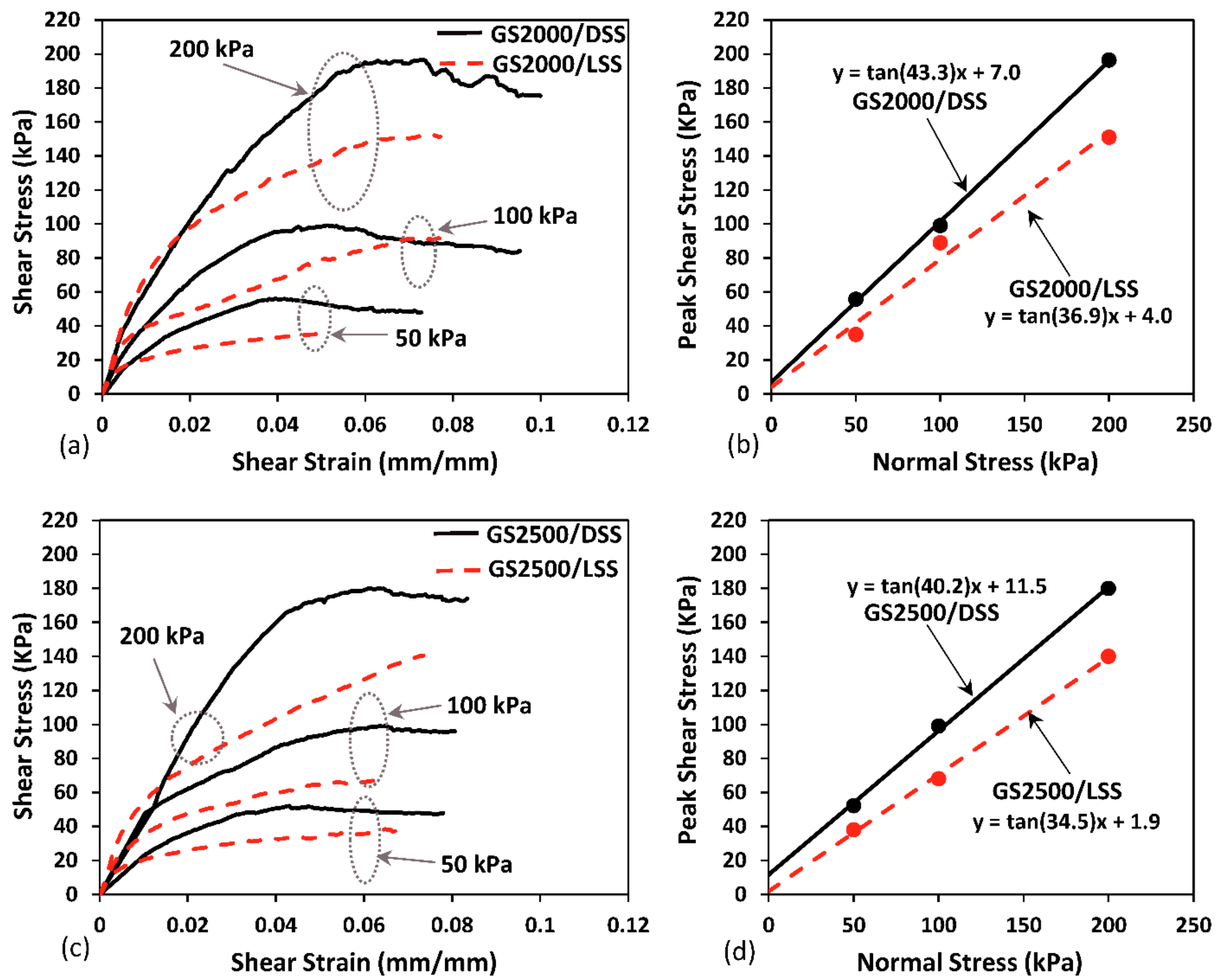

Figure 14. Direct shear tests of loose silty sand (LSS) and dense silty sand (DSS), with sand coated GFRP GS2000: (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress; and with sand coated GFRP GS2500: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress

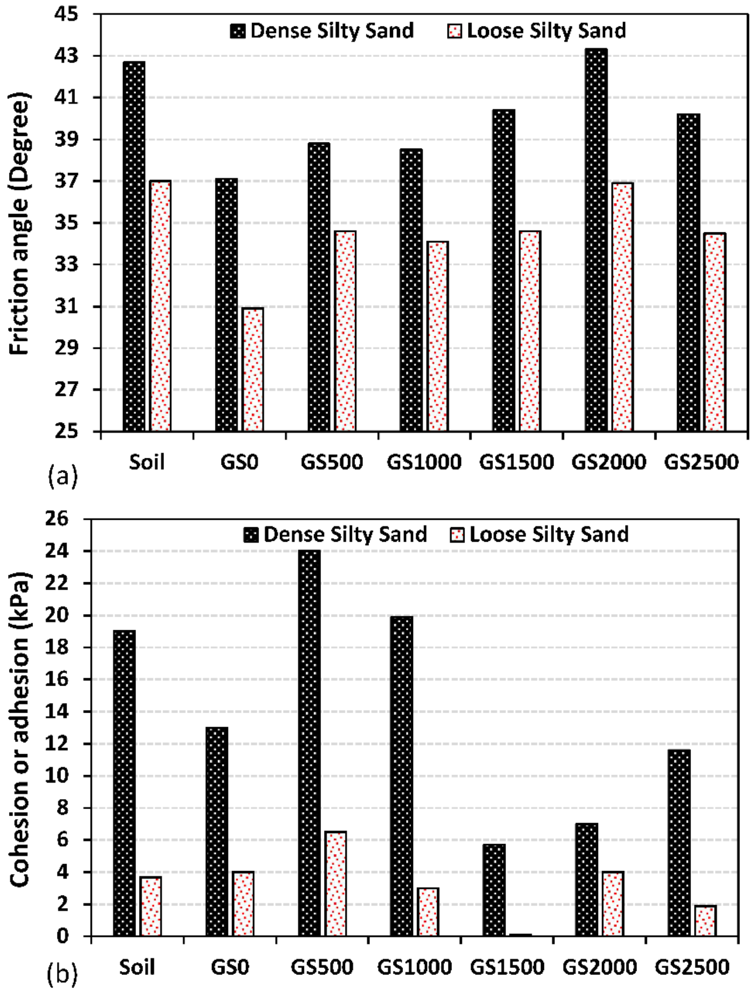

Figure 15. Comparison of test results: (a) friction angles with dense and loose silty sand, and (b) cohesion or adhesion with dense and loose silty sand

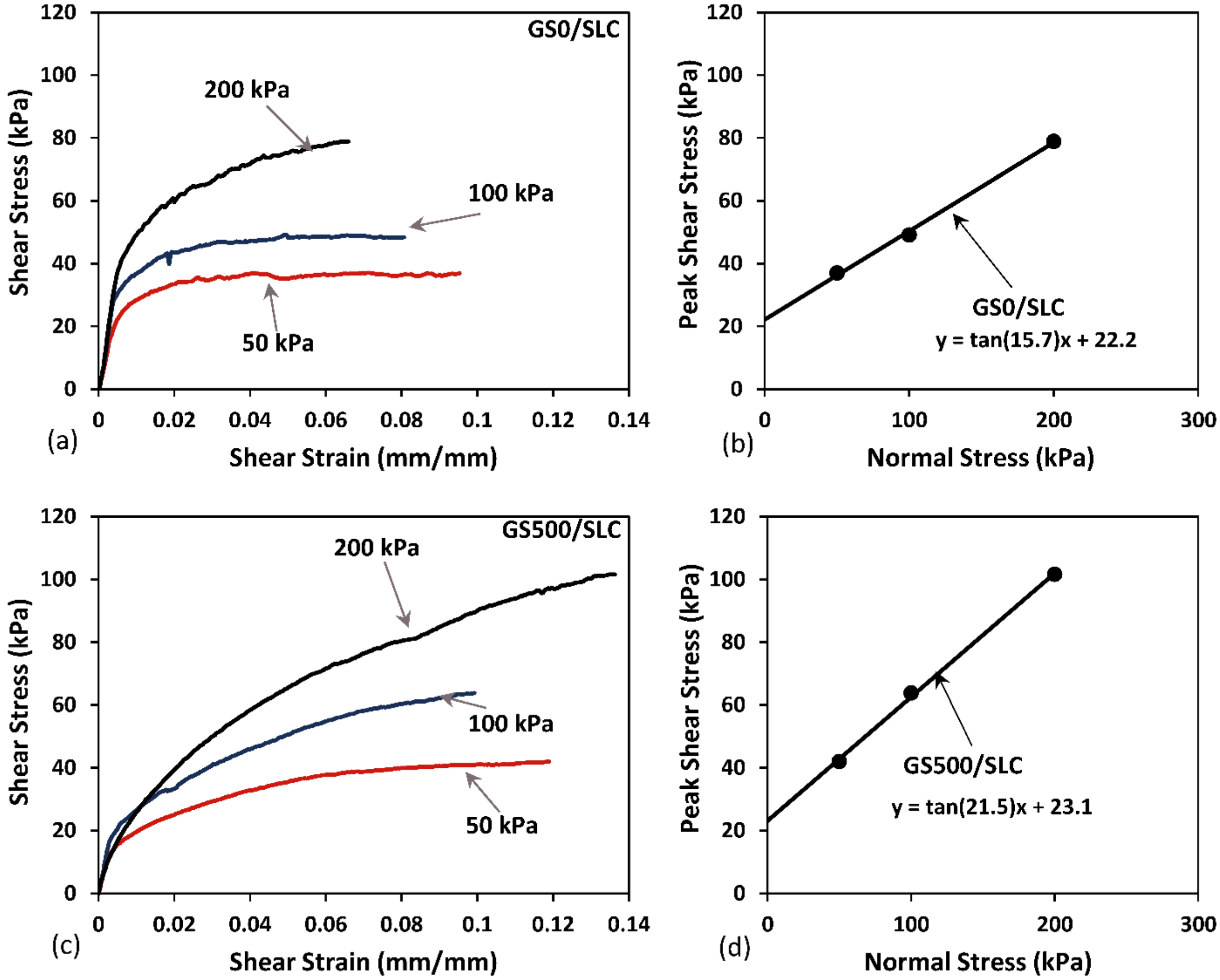

Figure 16. Direct shear tests of sandy lean clay (SLC), with GFRP without sand coating (GS0): (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress; and with sand coated GFRP GS500: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress

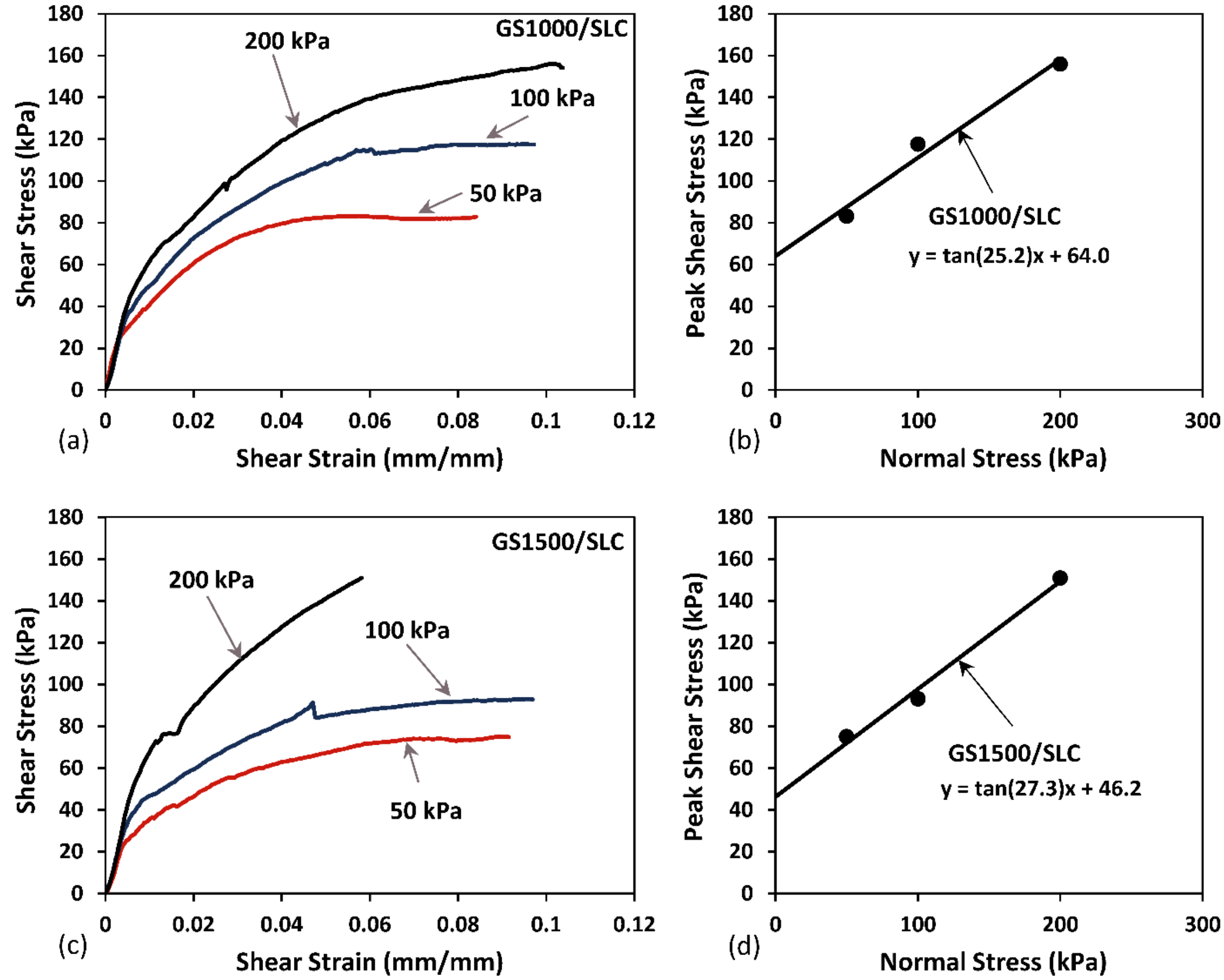

Figure 17. Direct shear tests of sandy lean clay (SLC), with sand coated GFRP GS1000: (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress; and with sand coated GFRP GS1500: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress

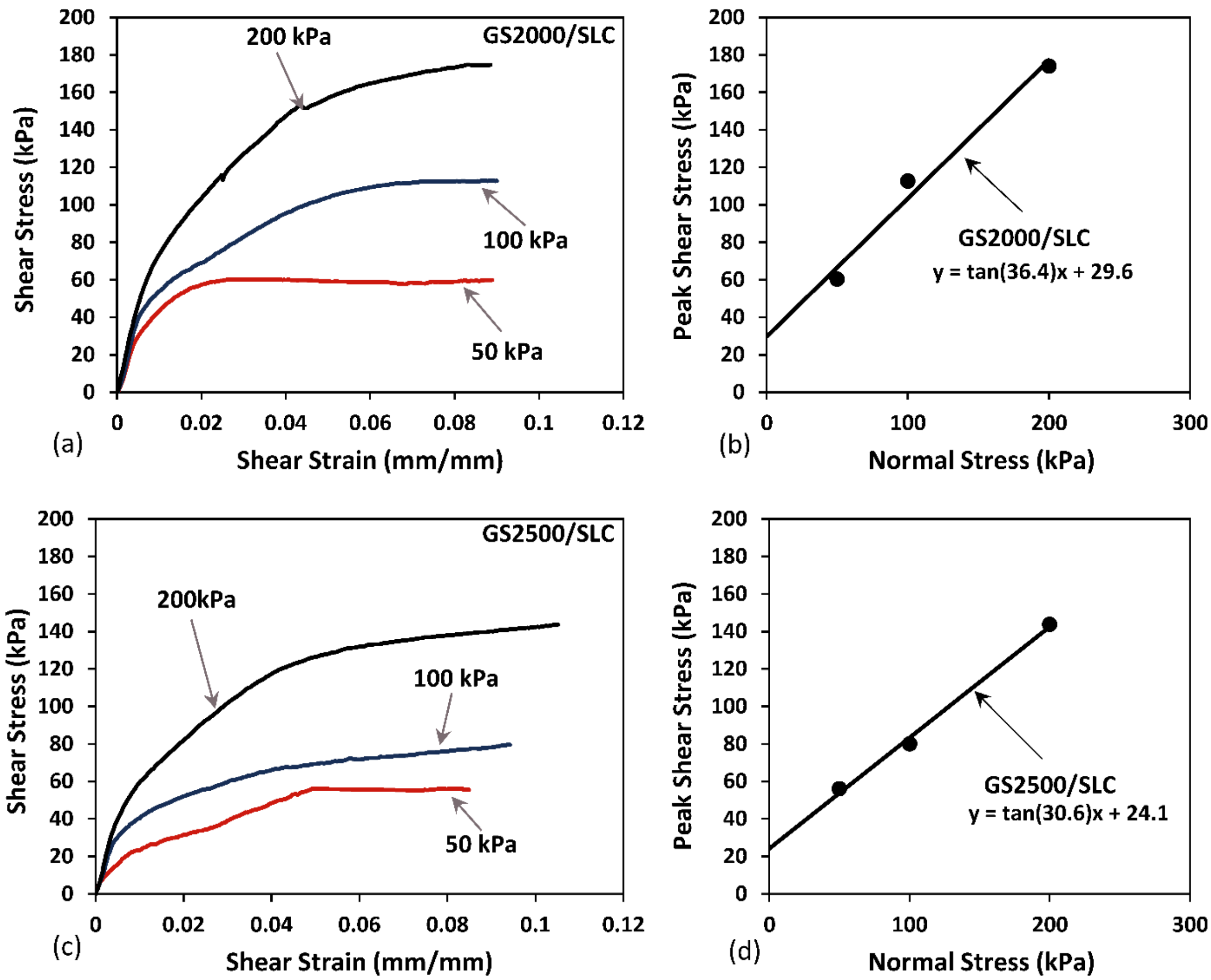

Figure 18. Direct shear tests of sandy lean clay (SLC), with sand coated GFRP GS2000: (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress; and with sand coated GFRP GS2500: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress

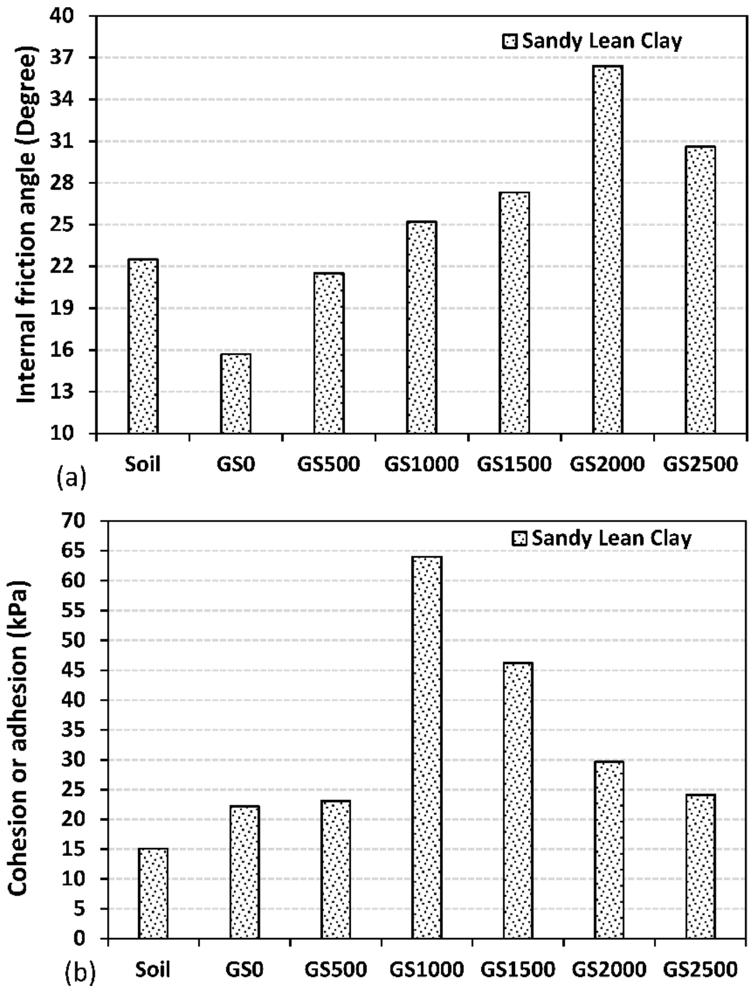

Figure 19. Comparison of test results: (a) friction angles with sandy lean clay, and (b) cohesion or adhesion with sandy lean clay

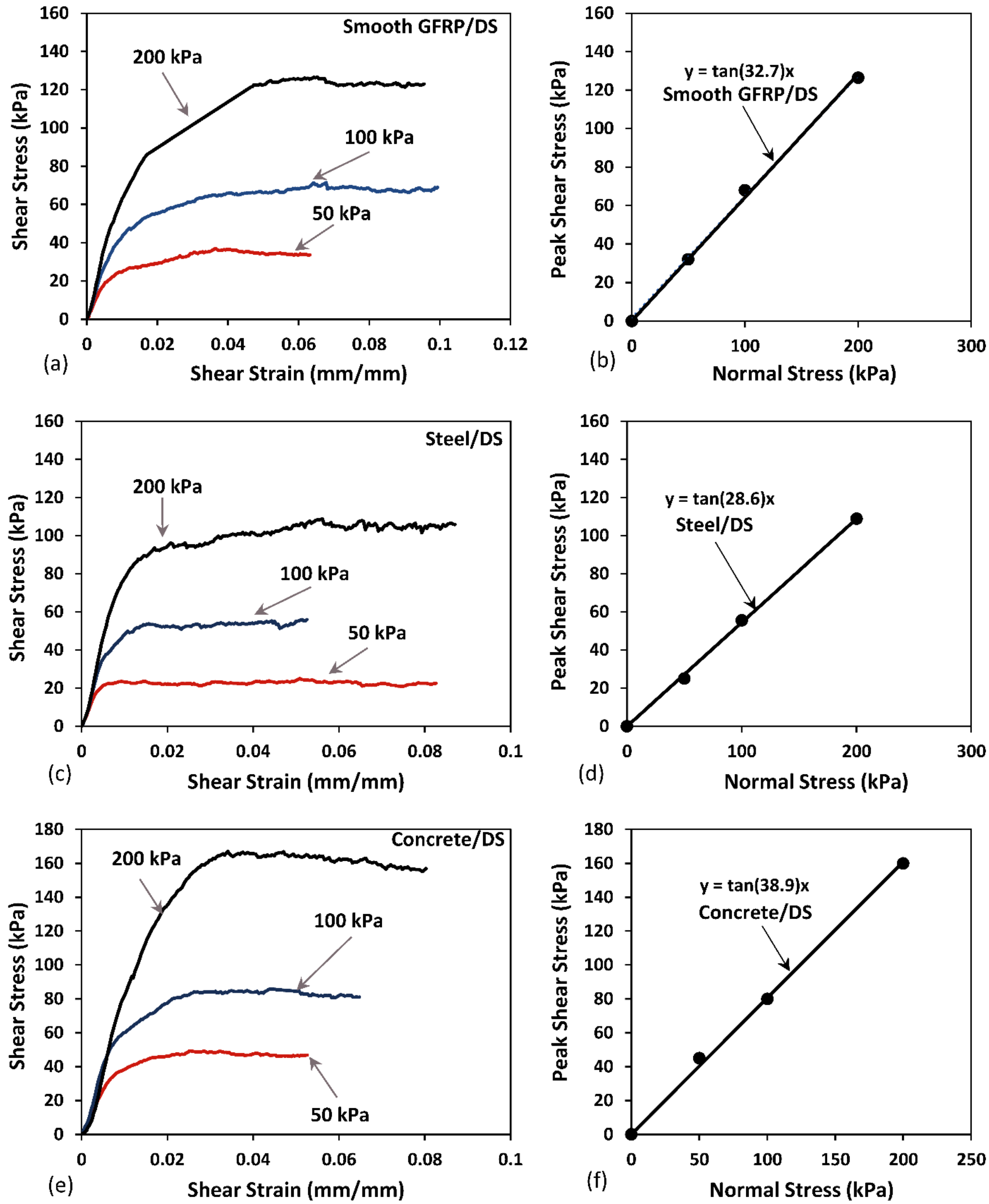

Figure 20. Direct shear tests of dense sand (DS), with smooth GFRP: (a) shear stress vs. shear strain, and (b) peak shear stress vs. normal stress, with steel: (c) shear stress vs. shear strain, and (d) peak shear stress vs. normal stress; and with concrete: (e) shear stress vs. shear strain, and (f) peak shear stress vs. normal stress

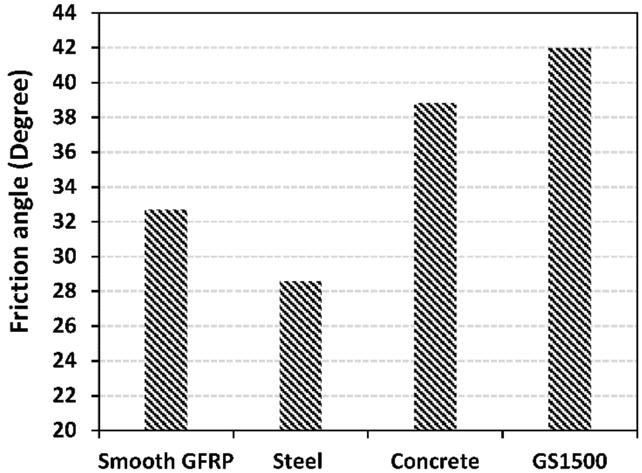

Figure 21. A comparison of interface friction angles for dense sand with smooth GFRP, steel, concrete, and sand coated GFRP GS1500

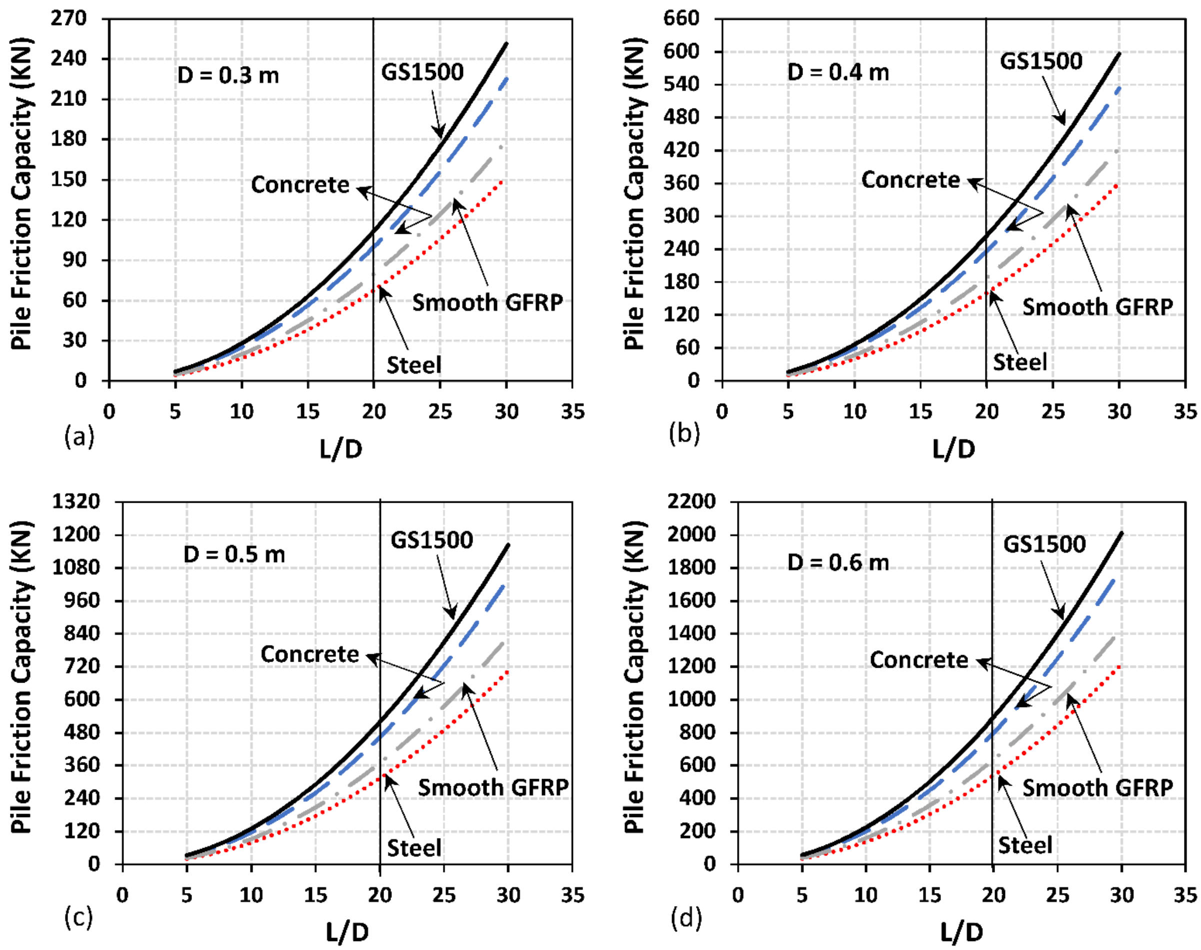

Figure 22. Friction capacities for sand coated GFRP GS1500, smooth GFRP, steel, and concrete driven piles in dense sand vs. pile length/pile diameter ratio for: (a) pile diameter 0.3 m, (b) pile diameter 0.4 m, (c) pile diameter 0.5 m, and (d) pile diameter 0.6 m