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Cyclic behavior of various sands and structural materials interfaces

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Abstract. This paper presents the results of an intensive experimental investigation on cyclic behavior of various sands and structural materials interface. Comprehensive measurements of the horizontal displacement and shear stresses developed during testing were performed using an automated constant normal load (CNL) cyclic direct shear test apparatus. Two different particle sizes (0.5 mm-0.25 mm and, 2.0 mm-1.0 mm) of sands having distinct shapes (rounded and angular) were tested in a cyclic direct shear testing apparatus at two vertical stress levels (σ = 50 kPa, and 100 kPa) and two rates of displacement (R_D = 2.0 mm/min, and 0.025 mm/min) against various structural materials (i.e., steel, concrete, and wood). The cyclic direct shear tests performed during this investigation indicate that (i) the shear stresses developed during shearing highly depend on both the shape and size of sand grains; (ii) characteristics of the structural materials are closely related to interface response; and (iii) the rate of displacement is slightly effective on the results.

Keywords: interface; sand; structural materials; cyclic direct shear test

1. Introduction

Friction, a measure of the resistance employed by surfaces to sliding over each other, has been the subject of many studies. In geotechnical engineering applications, there are many cases where soils interact with different type of structural materials. The contact zone between the soil and a structural material is known as interface, through which applied stress is transferred from one medium to the other. The response of soil-structure interaction systems subjected to static and/or dynamic loading is affected by the mechanical behavior of such interfaces. Understanding the behavior at an interface is of great significance to solve some engineering problems related to soil-structure interaction. The fact is that the interface between the soils and structural materials plays a significant role in a variety of geotechnical systems including shallow foundations, piling, retaining walls, tunneling, and in the systems subjected to cyclic loadings, for example those resulting from earthquakes, machine foundation, sea waves, wind and traffic loads (Lehane *et al.* 1993, Fakharian and Evgin 1997). When the shear occurs along a soil-structural material interface, soil grains may slide along the structure surface as well as rotate. Hardness and roughness of the surface of structural material, dilatancy resistance of the bounding structure, mechanical properties of the soils (grain shape, grain size, gradation), density, and stress state significantly affect the resistance of the system. Many researchers have investigated interface friction (skin friction)

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developing between the soil grains and other structural materials surface (e.g., concrete, steel, geotextile) using various laboratory testing equipments, such as; direct shear, simple shear, and ring shear (torsion) devices (Potyondy 1961, Tsubakihara and Kishida 1993, Mortara *et al*. 2010). For example, early efforts were carried out using a slightly modified direct shear box, in which a specimen of structural material was placed in one halves of the testing box (Potyondy 1961, Clough and Duncan 1971, Kulhawy and Peterson 1979, Kishida and Uesugi 1987, Fakharian and Evgin 1995, 1996, Mortara *et al*. 2010). Potyondy (1961) concluded that the most important factors affecting the interface friction were vertical stress (σ), roughness, and the soil composition. In spite of the limitation in relative displacement that can be attended, the direct shear testing has easy availability, and sample preparation procedure in a relatively simple testing mechanism. Simple shear testing machines have been used for more than last two decades. Although the simple shear devices could result in several disadvantages (non-uniform stress distribution at the interface, complicated sample preparation, and limited displacement value), the testing equipment is able to measure separately the soil distortion and the total interface displacement (Uesugi and Kishida 1986, Uesugi *et al*. 1988, Desai and Rigby 1997, Shakir and Zhu 2009). Ring shear (torsion) devices have been developed to overcome some limitations (Brummund and Leonards 1973). It provides unlimited interface displacement, in spite of difficulties in sample preparation and non-uniform radial stress distribution (Stark *et al*. 1996). A comparison of various interface testing devices, and a detailed literature review on the behavior of interfaces between soil and structural materials were presented in Paikowsky *et al*. (1995).

It has been long understood that particle shape characteristics have a significant effect on the engineering properties of soil matrix (Terzaghi 1925, Gilboy 1928, Lees 1964, Olson and Mesri 1970, Clayton et *al*. 2009, Cabalar 2010, 2015, Cabalar et *al*. 2013, Cabalar and Mustafa 2015). Terzaghi was one of the first engineers to make an investigation to understand the shape characteristics using a flat-grained constituents (Terzaghi 1925). The observations made by Gilboy (1928) showed that any system of analysis or classification of soil, which neglects the presence and effect of the shape, will be incomplete and erroneous. Numerous studies have been carried out, because of the importance of particle shape and its role in the behavior of sands for practicing engineers and researchers in helping to estimate soil behavior. Wadell (1932), Krumbein (1941), Powers (1953), Youd (1973), and Cho *et al*. (2006) have introduced detailed explanations of particle shape. Two independent properties are typically employed to describe the shape of a soil particle: (i) Roundness is a measure of the extent to which the edges and corners of a particle has been rounded; (ii) Sphericity (form) described the overall shape of a particle, it is a measure of the extent to which a particle approaches a sphere in shape. Wadell (1932) proposed a simplified sphericity (S) parameter, ($D_{max\text{-}insc}/D_{min\text{-}circ}$), where $D_{max\text{-}insc}$ is the diameter of a maximum inscribed circle and $D_{min\text{-}circ}$ is the diameter of a minimum sphere circumscribing a gravel particle. Wadell (1932) defined roundness (R) as $D_{ave\text{-}insc}/D_{max\text{-}insc}$, where $D_{ave\text{-}insc}$ is the average diameter of the inscribed circle for each corner of the particle. Figs. 1-3 describe R, S and a chart for comparison between them to determine particle shape (Krumbein 1941, Powers 1953, Santamarina and Cho 2004).

Numerous experimental and modeling studies have been reported in the literature about the behavior of interfaces under monotonic and cyclic loadings (Desai *et al*. 1985, Uesugi *et al*. 1989, Paikowsky *et al*. 1995, Fakharian and Evgin 1996, 2002, Gomez *et al*. 2009, Mortara *et al*. 2010). However, they focused on the behavior of interfaces by employing one type of soil without addressing the significance of grain size and shape in their study. There exists a gap in basic understanding of the mechanisms that relate both size and shape of sand grains to interface

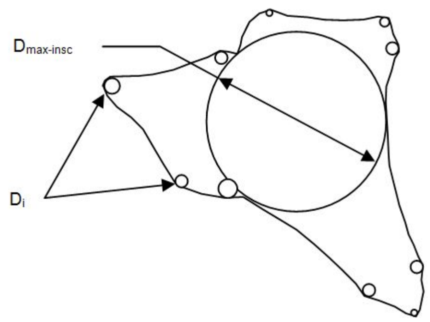


Fig. 1 Graphical representation of roundness, R (redrawn from Muszynski and Stanley 2012)

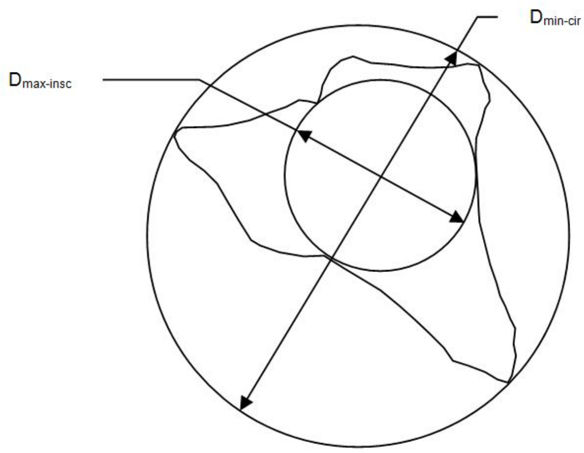


Fig. 2 Graphical representation of sphericity, S (redrawn from Muszynski and Stanley 2012)

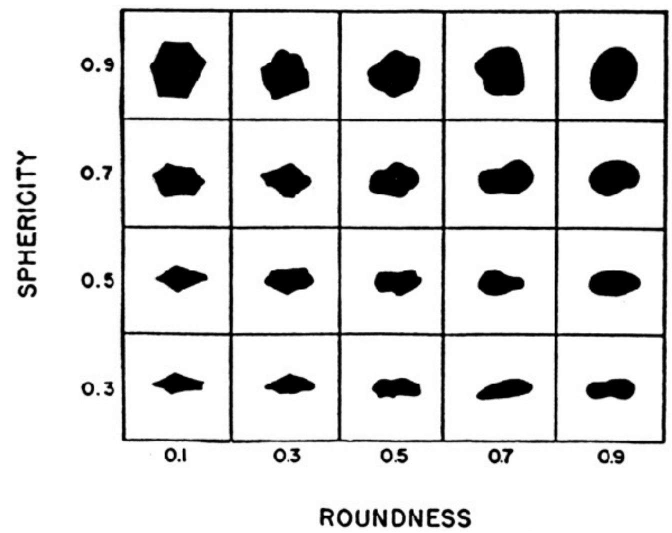


Fig. 3 Comparison chart (Santamarina and Cho 2004)

behavior. Therefore, this study aims to evaluate a new conceptual approach for quantifying size/shape of sand grain changes in interface behavior by exploiting constant normal load (CNL) cyclic direct shear tests on two different grain sizes (0.25 mm-0.5 mm and, 1.0 mm-2.0 mm) of sands having distinct shapes (rounded and angular). The sands were tested under two vertical stress levels (σ = 50 kPa, and 100 kPa) and two rates of shearing (2.0 mm/min and 0.025 mm/min). The CNL cyclic shear tests were carried out by changing the structural materials (i.e., steel, concrete, and wooden) placed in the lower part of the shear box.

2. Experimental study

2.1 Materials

Trakya Sand (TS), obtained from the Thrace Region in North-west of Turkey, was supplied by Set/Italcementi Group, Turkey, confirming to TS EN 196-1. A commercially available Crushed Stone Sand (CSS) was supplied from Southern-central of Turkey, which is widely consumed in earthworks, in Gaziantep City and its vicinity. The specific gravity of the grains were found to be 2.65 for Trakya Sand, and 2.68 for Crushed Stone Sand. Two different gradations of the sands falling between 0.5 mm and 0.25 mm, and 2.0 mm and 1.0 mm were artificially selected. D_{10}, D_{30}, D_{50}, and D_{60} sizes are around 0.28, 0.31, 0.36, and 0.45 for finer sands, 1.06, 1.18, 1.51, and 1.53 for coarser sands (Fig. 4). Thus, the coefficient of uniformity (c_u) and the coefficient of curvature (c_c) have been calculated as 1.44 and 0.86. Some properties of the sands including roundness (R) and sphericity (S) estimations based on the study by Muszynski and Stanley (2012) are listed in Table 1. Table 1 also presents the internal friction angle (φ) values of the clean sands using the

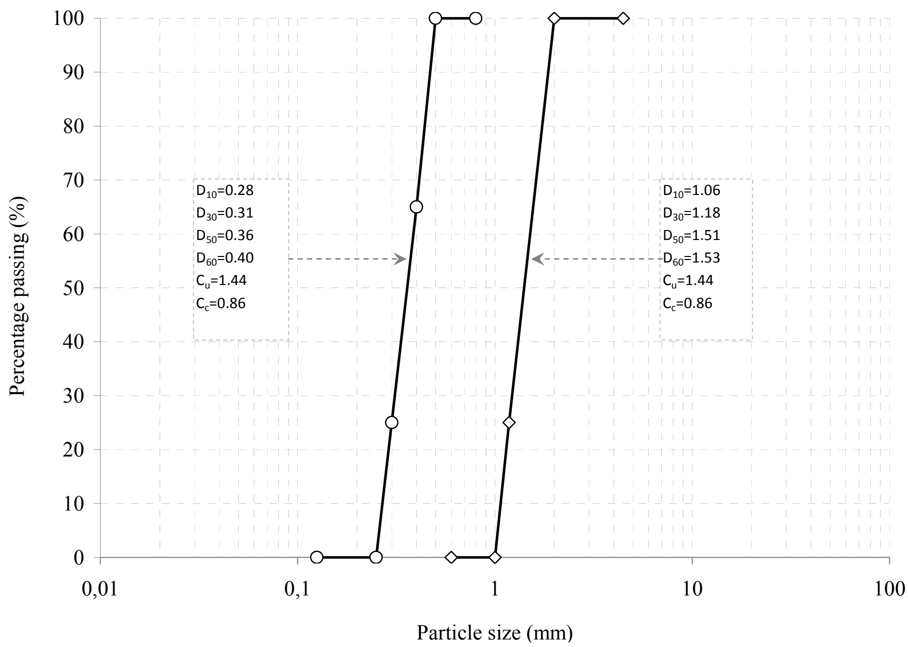
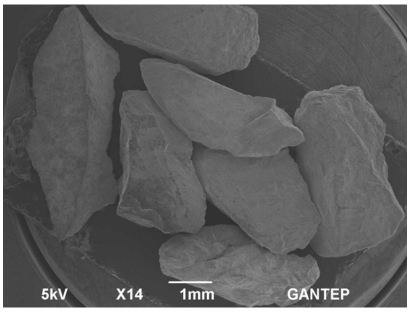


Fig. 4 Particle size distributions for the sands used during the experimental study

Table 1 Some properties of the sands used during the experimental study

Sand	Size (mm)	e_{max}	e_{min}	G_s	C_u	C_c	ϕ (°)	R	S
TS	0.25-0.5	0.97	0.69	2.65	1.44	0.86	34.1°	0.43	0.67
	2.0-1.0	0.99	0.59	2.65	1.44	0.86	39.6°	0.43	0.67
CSS	0.25-0.5	1.0	0.661	2.68	1.44	0.86	34.7°	0.16	0.55
	2.0-1.0	1.1	0.57	2.68	1.44	0.86	47.5°	0.16	0.55

TS: Trakya Sand, CSS: Crushed Stone Sand, R: Roundness, S: Sphericity



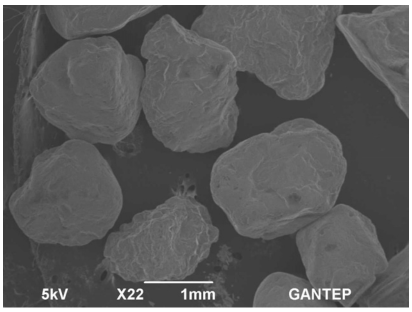


Fig. 5 SEM pictures of the CSS (left), and TS (right) used during the experimental study

same apparatus, which would be significant to clarify the results obtained on interface tests. Fig. 5 shows the Scanning Electron Micrograph (SEM) pictures of the sands used during the experimental investigations presented here.

Three different structural materials with different surface roughness and hardness were used during the tests. The steel, concrete, and wood samples were selected for the tests, as they are commonly used structural materials in construction industry. One material for each test was machined, and then placed in the lower part of the shear box. The maximum roughness r values of the concrete, wood, and steel, which were obtained using a Mitutoyo surface roughness measuring equipment, were found to be 110 μm, 10.6 μm, and 0.4 μm, respectively (ASTM D2487). Hardness of the structural materials, which were characterized according to Brinell scale (ASTM E10-14), were identified as 180HB, 150HB, and 3HB for concrete, steel, and wood, respectively.

2.2 Test set-up

Total number of 23 cyclic direct shear tests were carried out in a fully automated direct shear

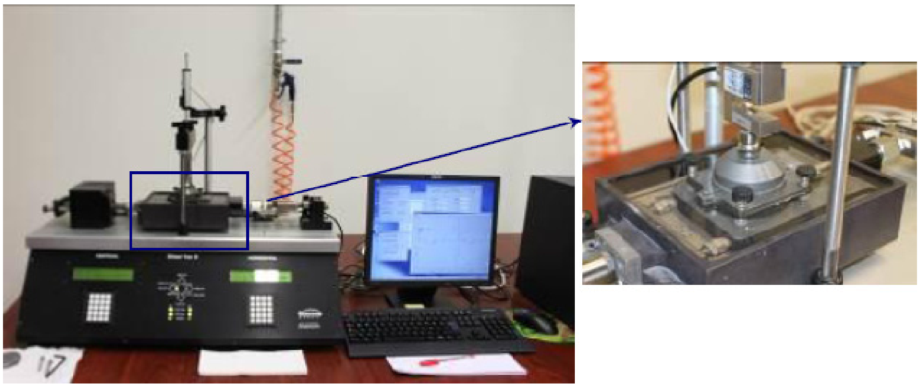


Fig. 6 Testing set-up employed during the experimental study

apparatus, which is a product of Geocomp, and confirming to ASTM D3080. The apparatus used is capable of performing the consolidation and shearing steps of a standard direct shear and residual shear test with fully automated (Fig. 6).

2.3 Specimen preparation

The structural materials are placed in lower part of the shear box. The required amount of sand was weighed, mixed with de-aired water and then spooned, without vibration, into the upper part of box. The relative density of all specimens fell between 33.5% and 37.3%, with most specimens having a relative density of about 35%. When the mould was completely filled, the top platen was placed on, and then desired amount of water was added to the shear box. Then, the specimens were loaded to vertical stress. After a soaking period of 24 h elapsed at a constant room temperature (20°C), the shearing process was started. The specimen tested in the apparatus had a diameter of 63.5 mm, and a height of 25.4 mm. The gap between the upper and lower parts of the box was adjusted to 0.20 mm.

2.4 Test procedure

The specimens in 'cyclic direct shear tests' were loaded to 50 kPa and 100 kPa vertical stresses (σ) before being sheared. Behavior of the interfaces between various sands and structural materials was investigated through constant normal load (CNL) tests. The cyclic tests were strain controlled tests with the displacement of ± 3 mm, and with the loading rates of 2 mm/min and 0.025 mm/min. The reason for selecting these two rates of loading and levels of effective stress was to understand the interface responses under different conditions.

3. Results and discussion

The series of experiments performed in this work presents shear tests between various sands and structural materials at different conditions (i.e., vertical stress, σ; rate of displacement, R_D). A conventional interface testing procedure has been specified. In this testing procedure, the normal stress employed on the interface zone is maintained constant. Actually, such experimental works would be beneficial for understanding some stability problems including retaining walls and the slopes stability.

Fig. 7 shows the clean Trakya Sand (TS) with two different size distributions (0.5 mm-0.25 mm, and 2.0 mm-1.0 mm), which were tested at the 0.025 mm/min rate of displacement (R_D). The

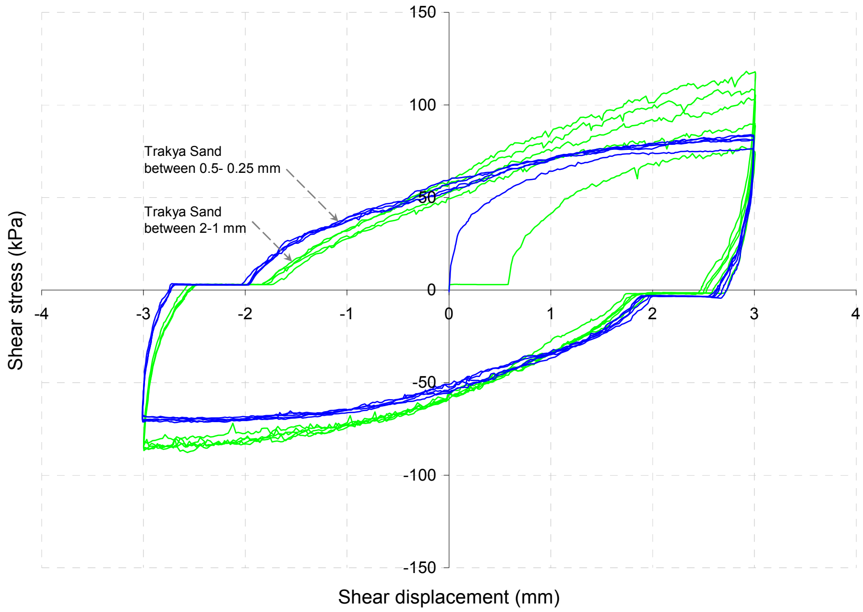


Fig. 7 Results of CNL tests on different graded clean TS (σ = 100 kPa, R_D = 0.025 mm/min)

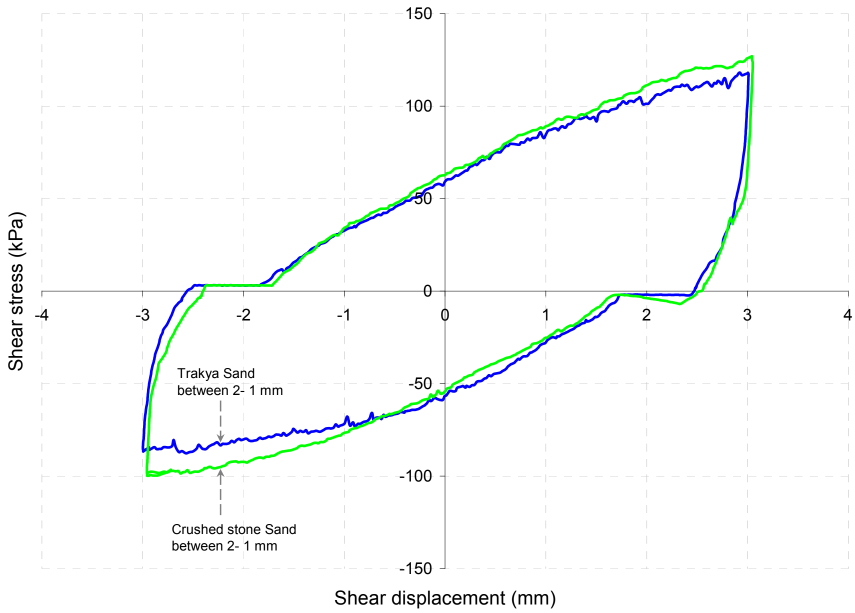


Fig. 8 5th loop of the response of clean TS, and CSS with same gradation (σ = 100 kPa, R_D = 0.025 mm/min) difference in behavior between positive and negative shear stress-deformation is because of the horizontal displacement in two opposite directions. Although grain shapes of the TS tested are same, different size of the sands results in different responses in stress-displacement curves. Maximum shear stress values in 0.5-0.25 mm TS specimen (80 kPa) is much lower than those in 2-1 mm TS specimen (120 kPa). There is trend of increasing shear resistance with increasing number of loading cycles for the 2-1 mm TS specimen. It is also observed that the 0.5-0.25 mm TS specimen exhibit a relatively smooth response in shear stress values, while the 2-1 mm TS specimen exhibit a series of fluctuations. Observing the response of same particle sizes (2.0 mm-1.0 mm) of TS and Crushed Stone Sand (CSS) having distinct shapes (rounded and angular) in the testing apparatus reveals that the CSS specimen has a higher shear stress than the TS specimen does (Fig. 8). As stated by Cernica (1995), it could be attributed mainly to the interlocking asperities in a sand packing that leads to a mechanism with higher internal friction between the soil grains (Table 1).

Variations of shear stress (kPa) with shear displacement (mm) for the interface between 2-1 mm CSS and various materials (steel, concrete, and wood) are presented in Fig. 9. A 50 kPa vertical stress was applied with a constant rate of 2 mm/min during the shear. As can be seen from the Fig. 9 that there is a difference of shear stress with the progress of cycles, and type of structural materials utilized during the tests. Almost no change in shear stress values at the CSS-steel interface is observed with the progress of cycles. The maximum shear stress value observed in the steel interface is around 15 kPa for each cycle. However, response at the sand-wood interface shows that the stress values are less in the earlier cycles, and undergoes a continuous increase with the progress of cycles. Similarly, stress values at the sand-concrete interface undergoes a continuous increase with cycling. Actually, the increase of stress with progress of cycles is a previously observed behavior of CNL tests (Desai *et al.* 1985, Uesugi *et al.* 1989, Mortara *et al.*

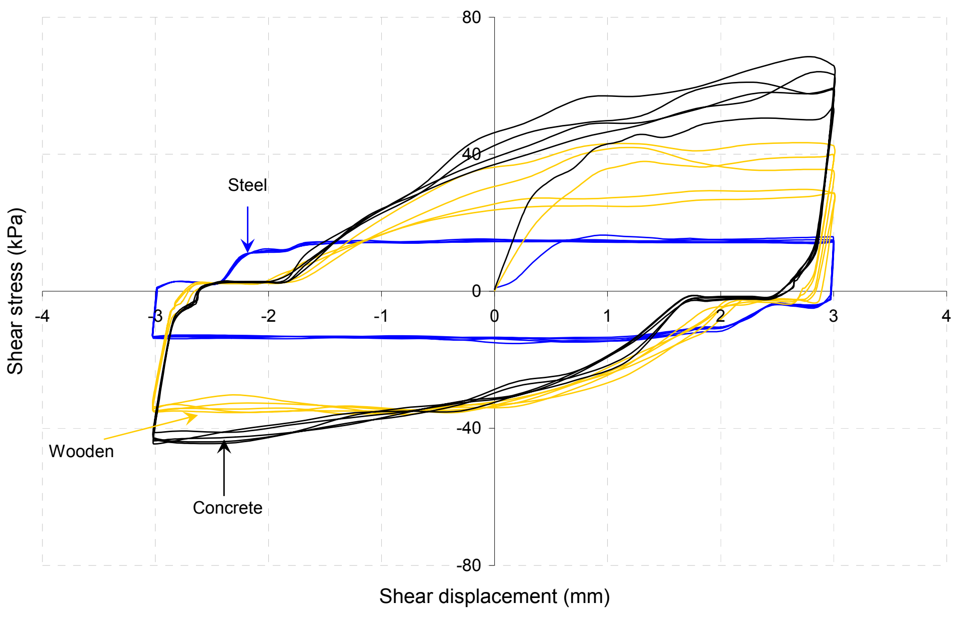


Fig. 9 Results of CNL tests on 2-1 mm CSS-various materials' interface (σ = 50 kPa, R_D = 0.025 mm/min)

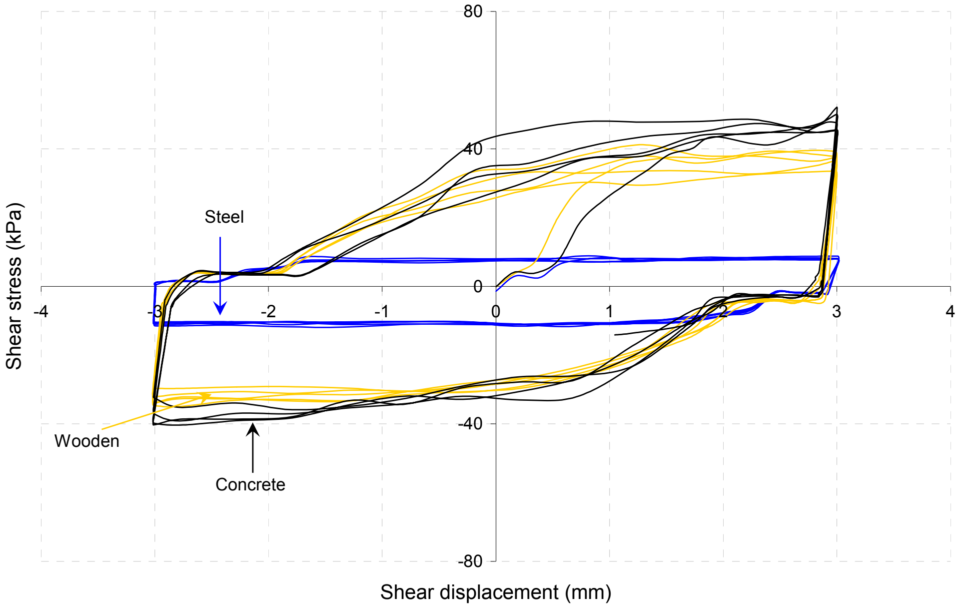


Fig. 10 Results of CNL tests on 2-1 mm TS-various materials' interface (σ = 50 kPa, R_D = 2.0 mm/min)

2010). For example, Desai *et al*. (1985) concluded that the interface response becomes stiffer with an increase in the number of cycles, and the rate of stiffening decreases as the number cycles increases.

Similar experiments were conducted using a relatively rounded Trakya Sand (TS) to further examination, and to establish a basis for evaluating the influence of particle shape on the experimental results under the condition of loading. Fig. 10 indicates the variations of shear stress (kPa) with shear displacement (mm) for the interface between 2-1 mm TS and various materials (steel, concrete, and wooden) tested under a 50 kPa vertical stress, and at a constant rate of 2 mm/min during the shearing process. It is observed that the maximum shear stress at the sand-steel interface stabilizes about 9 kPa. Stress values at the sand-wooden, and sand-concrete interface results in a continuous increase with the progress of cycles.

A comparison between the response of two different sands (Figs. 9 and 10) releases that the shear stress values observed at the CSS interfaces were increasing with number of loading cycles. However, shear stress increasing with number of loading cycles in the specimens with TS is relatively limited. These systematic increases in shear strength with number of loading cycles are probably related to the surface roughness of the structural materials. Because, such observations were not made on the tests with steel interface. The toughness of steel surface minimizes scratching, whereas the repeated loadings increased the roughness of wood and concrete surface. Although a very similar behavior pattern was realized for the tests conducted using two different type of sands (CSS, TS), an overall decrease in stress values was observed in the response of specimens with TS.

The Figs. 11-13 show further details on the tests conducted at various interfaces. Shear stresses developed at the 2-1 mm CSS/TS-steel interfaces are presented in Fig. 11. The tests were carried out under 50 kPa vertical stress (σ), and at a 2 mm/min rate of displacement (R_D). It is observed that the maximum shear stress reached to a peak of about 15 kPa at CSS-steel interface, and about 8 kPa at TS-steel interface during the first cycle (Fig. 11). Then, the shear stress values at the sand (CSS, TS)-steel interfaces stabilized at the values reached during the first cycle. The main reason of this behavior might lie in the fact that the steel has a relatively smooth surface, and the internal forces at the interface zone uniformly propagate through the specimen, but are not localized through interface zone of strained grains. Using these observations, it can be concluded that the maximum shear stress values at the sand-steel interfaces are neither influenced by the number of cycling nor the amount of mobilized sliding displacement. This behavior is different than the observations made by Uesugi *et al*. (1989), Fakharian and Evgin (1997), and Uesugi and Kishida (1991), who concluded that the dominant factor in the variation of the maximum shear stress at a sand-steel interface was the amount of sliding displacement at the interface. Actually, they employed a simple shear testing apparatus, that provides a stress controlled test. Conversely, the plots of shear stress versus shear displacement in Fig. 12 illustrates that the stress values for both interfaces (TS-wood, and CSS-wood) increase by cycling, within the measured number of cycles. The author observed similar response in the shear stress versus shear displacement values for the interfaces of CSS-concrete, and TS-concrete (Fig. 13). It is also observed that the stress values at the interface of CSS-structural materials are higher than the stress values at the interface of TS-structural materials, within the measured sliding displacement levels (± 3 mm). Fig. 14 indicates the effects of particle size on the experiments carried out using TS under 50 kPa vertical stress, with a 2 mm/min rate of displacement (R_D). The plot shows the response of the samples during the last (5th) cycle. Two different particle sizes of sand grains were used in the tests, which are the sand grains between 0.5 mm and 0.25 mm, and the sand grains between 2.0 mm-1.0 mm. As can be seen, there is a marked difference of maximum shear stress values observed in sand-steel

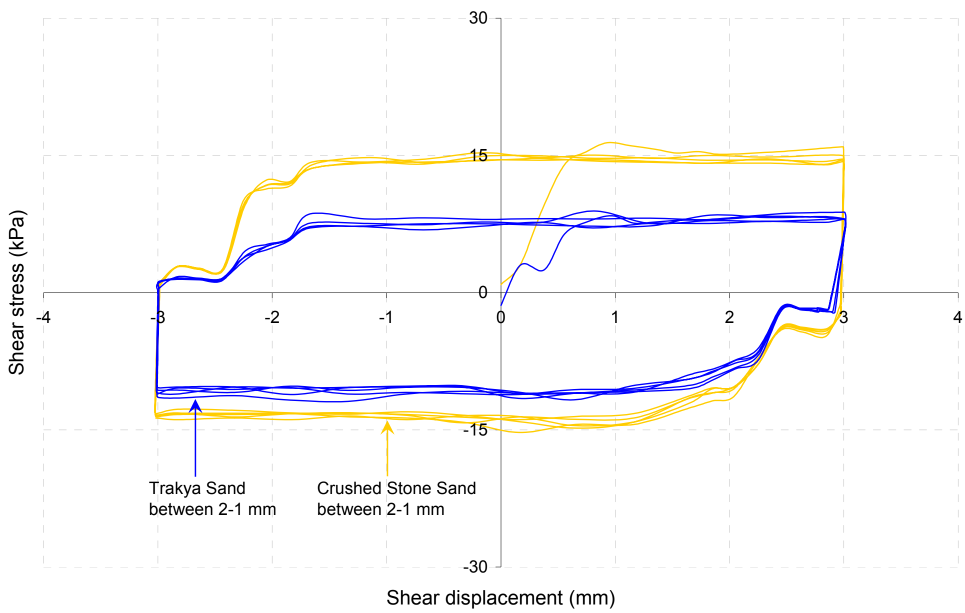


Fig. 11 Results of CNL tests on various sands-steel interface (σ = 50 kPa, R_D = 2.0 mm/min)

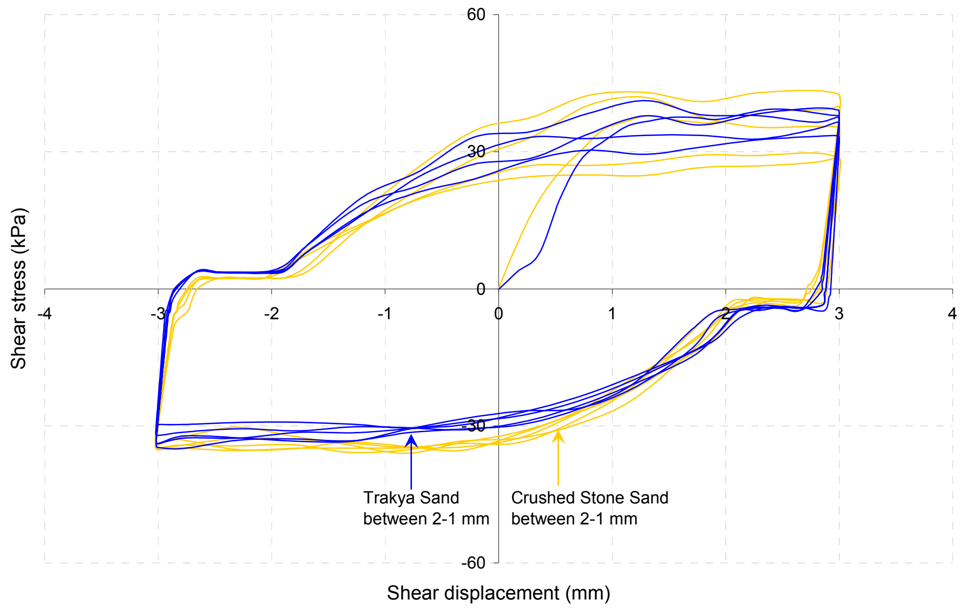


Fig. 12 Results of CNL tests on various sands-wood interface (σ = 50 kPa, R_D = 2.0 mm/min)

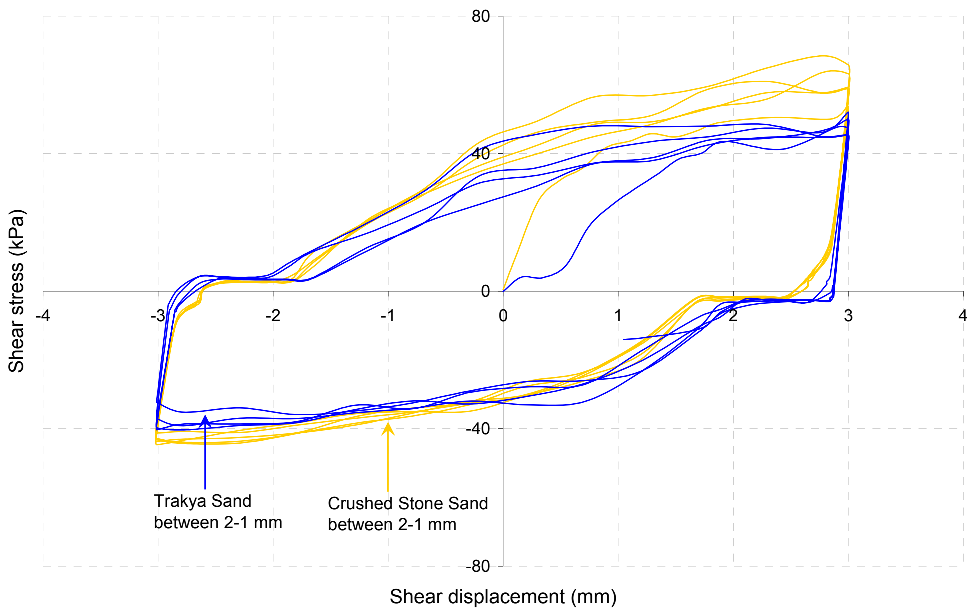


Fig. 13 Results of CNL tests on various sands-concrete interface (σ = 50 kPa, R_D = 2.0 mm/min)

interface with the different grain size employed during the tests. Considering the response of clean sands in the Fig. 7, size of the grains becomes a key element for understanding the behavior presented in Fig. 14. However, the shear stress values observed at the interfaces of sands with different sizes (0.5 mm-0.25 mm, and 2.0 mm-1.0 mm) and wood, or concrete were very close to

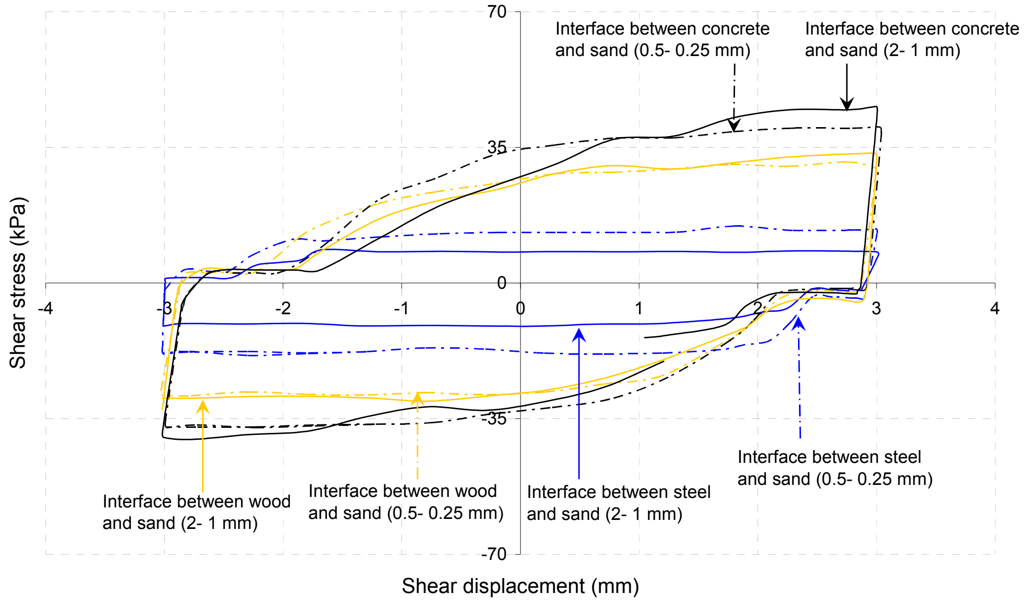


Fig. 14 Effects of particle size on the experiments carried out using TS (σ = 50 kPa, R_D = 2.0 mm/min)

Table 2 Friction angle values (δ) of the soil-structural material interfaces tested in cyclic direct shear box testing apparatus

Rate of loading (mm/min)	Structural material	Crushed Stone Sand (CSS)				Trakya Sand (TS)			
		2.0-1.0 mm		0.5-0.25 mm		2.0-1.0 mm		0.5-0.25 mm	
		50 kPa	100 kPa	50 kPa	100 kPa	50 kPa	100 kPa	50 kPa	100 kPa
2.0	Steel	16°	-	-	-	15°	-	9°	-
	Concrete	54°	-	-		42°	-	39°	-
	Wood	41°	-	-	-	32°	-	31°	-
0.025	Steel	22°	24°	20°	21°	-	-	18°	19°
	Concrete	51°	-	-	-	-	-	42°	-
	Wood	43°	45°	39°	41°	-	-	36°	38°

each other. In order to obtain a better understanding of this behavior, it is important to remember that the friction angle (δ) of the soil-structural interface depends on the material roughness (r) as well as the true friction angle (φ) between the soil grains and the structural material. Rowe (1963) reports that the δ is generally very close to the internal friction angle (φ) between soil grains. Alternatively, Subba Rao *et al.* (1998) carried out a series of tests using a modified shear box, and suggested that $\delta = \varphi'$ (effective angle of friction) might be in many circumstances be expected to be mobilized by enough displacement. In general, it is appropriate to estimate the stress analysis at an interface by the equation $(\tau/\sigma')_{max} = \tan\varphi'$. For example, from the Fig. 14, the estimated δ values via this approach were found to be about 42° for the 2-1 mm TS sand-concrete interface, 39° for the 0.25-0.5 mm TS sand-concrete interface, 32° for the 2-1 mm TS sand-wood interface, 31° for the 0.25-0.5 mm TS sand-wood interface, 15° for the 2-1 mm TS sand-steel interface, and 9° for

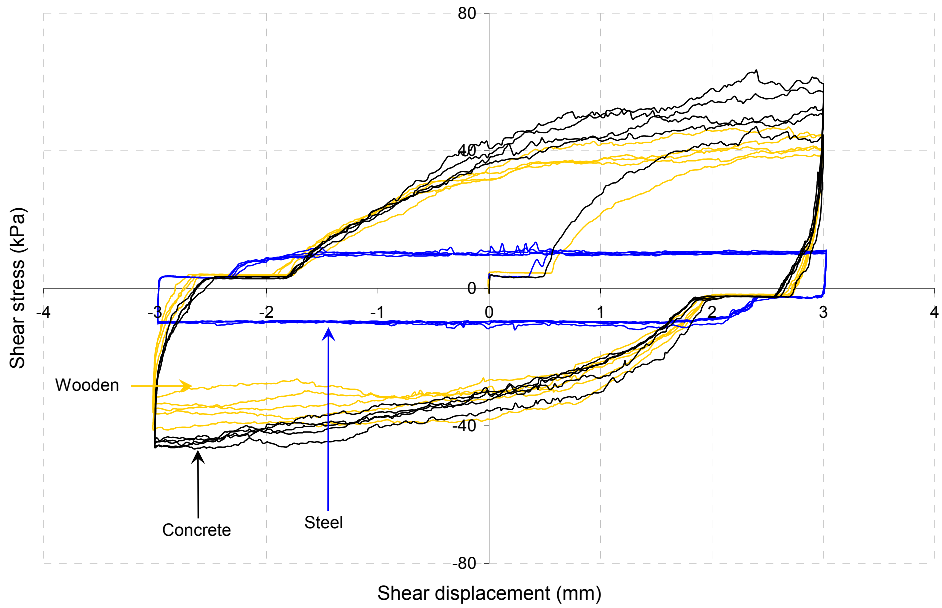


Fig. 15 Results of CNL tests on 2-1 mm CSS-various materials' interface (σ = 50 kPa, R_D = 0.025 mm/min)

the 0.25-0.5 mm TS sand-steel interface (Table 2). As can be seen from Table 2, the δ values of the soil-concrete interfaces were found to be higher than the others, while the δ values of the soil-steel interfaces were found to be the lowest. A finer size of materials provide a slightly higher δ value, because of a larger contact surface. It was also observed that the δ of the soil-structure interface slightly increase with the increase in vertical stress.

Fig. 15 presents the response of interface between Crushed Stone Sand (2-1 mm) and various materials under 50 kPa vertical stress, at a rate of displacement of 0.025 mm/min. Although a slightly different pattern, successive stress fluctuations, is realized for the tests conducted at the 0.025 mm/min rate of displacement, the shear stress values within the measured range of displacement are very close the tests conducted at a 2.0 mm/min rate of displacement. Accordingly, it is concluded that there is a slight effect of the rate of displacement on the response of the sand-structural materials tested in this investigation.

Fig. 16 presents the influence of vertical stress and type of interface material on the experiments carried out using 0.5-0.25 mm CSS at a 0.025 mm/min rate of displacement. As can be seen from the Fig. 16, the amount of vertical stress applied affects strongly the overall stress-displacement behaviors of the interfaces tested. A substantial increase is observed clearly in the shear stress values with an increase in vertical stress. The friction angles of the soil-structure interface slightly increase with the increase in vertical stress.

Fig. 17 illustrates the influences of CSS grains size, and type of structural materials on the tests conducted under a 100 kPa vertical stress, and at a 0.025 mm/min rate of displacement. It is seen that the shear stress values increased with the decrease of grains size of CSS tested with steel. However, a decrease at the wood-sand interface is observed. This might be attributed mainly to the wood's own material properties, and amount of vertical stress employed. The author considers that 2-1 mm CSS grains were embedded into the wooden surface, then the response of interface with 2-

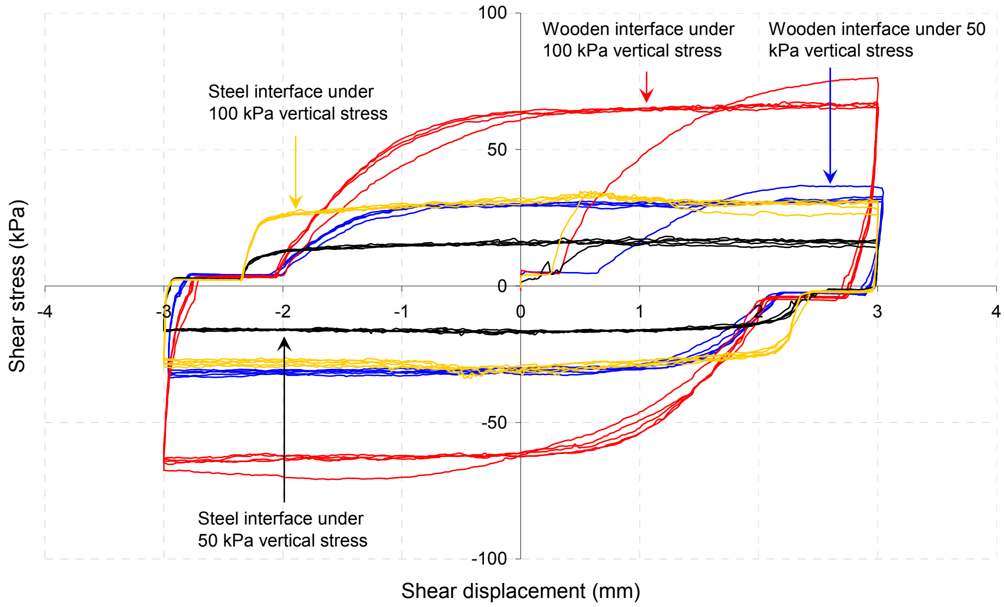


Fig. 16 Effects of vertical stress and type of interface material on the experiments carried out using 0.5-0.25 mm CSS (R_D = 0.025 mm/min)

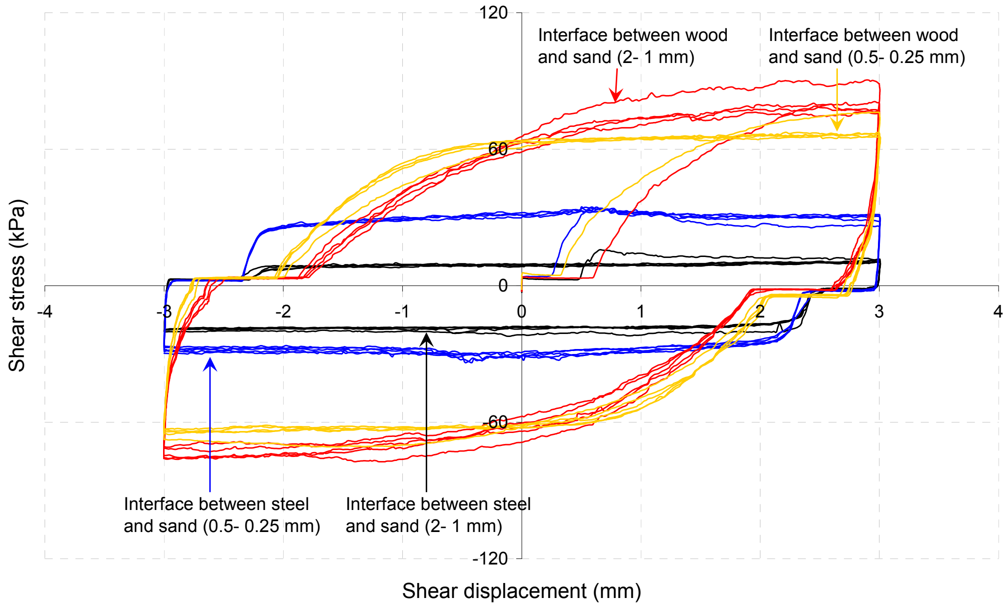


Fig. 17 Effects of particle size and type of interface material on the experiments carried out using CSS (σ = 100 kPa, R_D = 0.025 mm/min)

1 mm CSS grains is larger than the interface with 0.5-0.25 mm CSS grains. Whereas, the 2-1 mm CSS grains do not embed into the steel surface because of its hardness. Then, response of the interface between steel and 2-1 mm CSS gives lower stress values. This behavior is slightly

different than testing results observed in the interface with TS, due to the relatively rounded shape of the TS grains.

In order to draw a further comparison between the type of structural materials and the interface behavior, similar experimental investigation was performed using the 0.5 mm-0.25 mm TS under

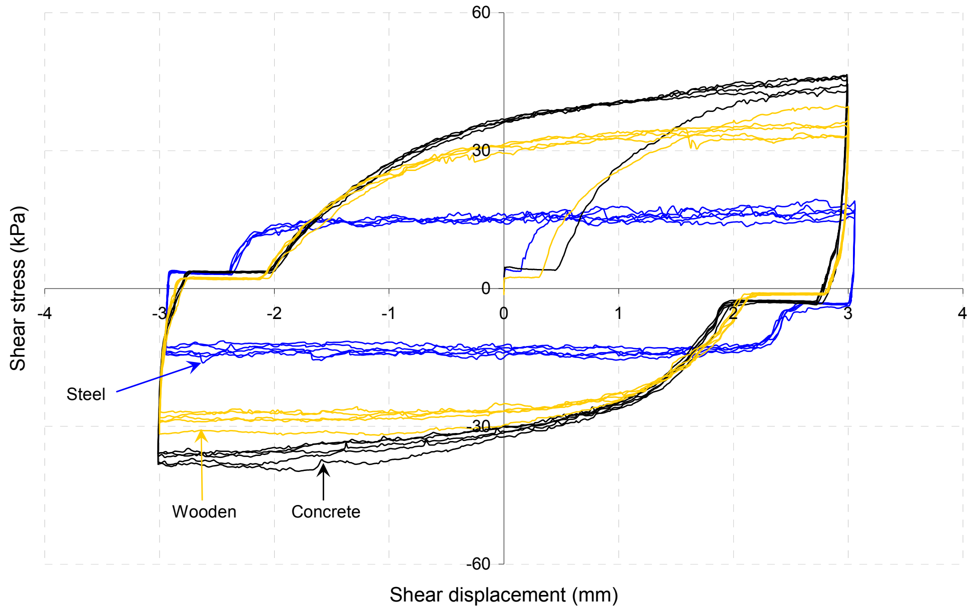


Fig. 18 Results of CNL tests on 0.5-0.25 mm TS-various materials' interface (σ = 50 kPa, R_D = 0.025 mm/min)

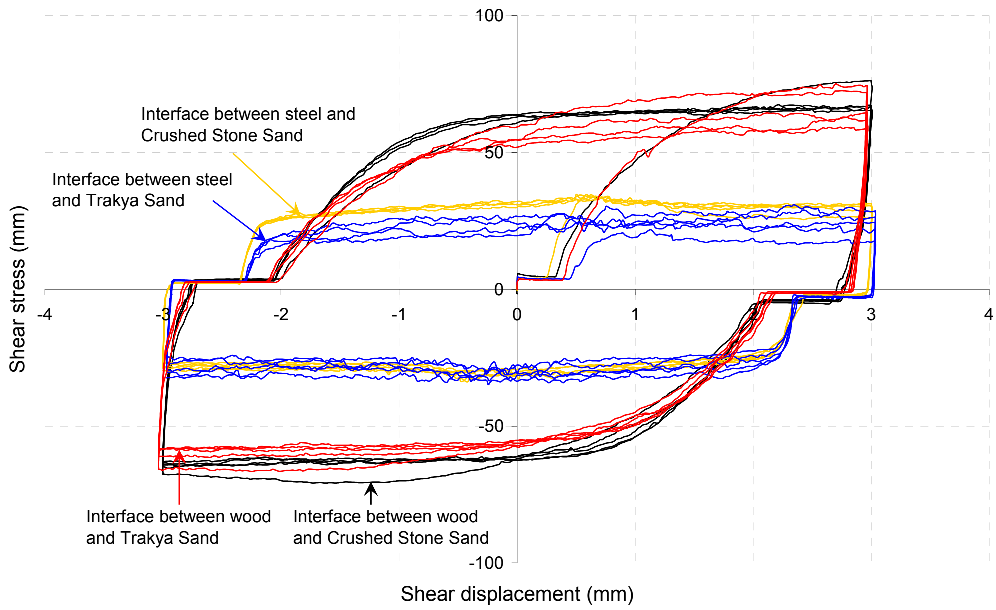


Fig. 19 Results of CNL tests on various interfaces (σ = 100 kPa, R_D = 0.025 mm/min)

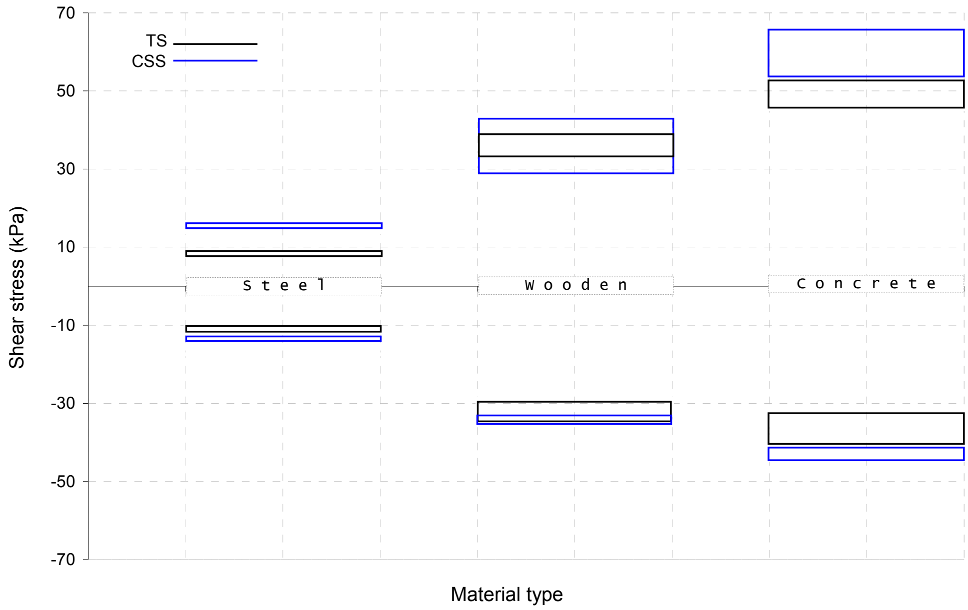


Fig. 20 Shear stress values of various structural materials and 1-2 mm diameter sands tested (σ = 50 kPa, R_D = 2 mm/min)

50 kPa vertical stress, at a 0.025 mm/min rate of displacement (Fig. 18). Shear stress values and the pattern of the loops depend on surface roughness and hardness of the structural materials. The stress values observed at the sand-steel interface reached their maximum values at a smaller shear displacement, and then stabilized. However, the stress values observed at the sand-wood, and sand-concrete interfaces increased gradually by the increasing displacement, and then stabilized. A higher maximum shear stress at the sand-concrete interface is observed comparing to that at the sand-wood interface. There is a slight difference between the interface behaviors using 0.5 mm-0.25 mm TS, and 0.5 mm-0.25 mm CSS with various structural materials tested at a 0.025 mm/min rate of displacement (Fig. 19). The most striking point in these plots is the stress fluctuations observed during the tests, which could be because of employing such a lower rate of displacement, and shape of the sand grains. Fig. 20 comprises the influences of various structural materials on the shear stress of different sands with the diameter of 1-2 mm, under a 50 kPa vertical stress, at a 2.0 mm/min rate of displacement. In the light of the studies by Jewell and Wroth (1987), Bosscher and Carlos (1987), Mortara *et al*. (2010), which indicated the maximum shear stress values ranged from 10 to 20 kPa for steel interfaces, from 30 to 40 kPa for wooden interfaces, and from 50 to 60 kPa for the concrete interfaces, the results obtained in the present study are considered acceptable.

4. Conclusions

This paper has presented an intensive series of experimental results on the cyclic behavior of various sand-structural material interfaces. Some typical testing results obtained under constant normal load (CNL) conditions have been presented to highlight the role of grains' size (i.e., 0.5 mm-0.25 mm, 2.0 mm-1.0 mm), and shape (i.e., rounded, angular) on the interface responses. The interface behavior between the sands and structural materials was tested at two vertical stress levels (σ = 50 kPa, and 100 kPa), and two rates of displacement (R_D = 2.0 mm/min, and 0.025 mm/min). The structural materials used in the experimental works were steel, concrete, and wood. The tests reported in this paper indicate four facets of behavior.

(1) Different size of sand grains contribute differently to the CNL testing behavior: Maximum shear stress values observed in the clean finer sands (τ_{TS} = 80 kPa, τ_{CSS} = 100 kPa) was found to be lower than the maximum shear stress values observed in the clean coarse sands (τ_{TS} = 115 kPa, τ_{CSS} = 130 kPa). Internal friction angle (φ) of a clean finer sand matrix (φ_{TS} = 34.1°; φ_{CSS} = 34.7°) was also found to be lower than that of a clean coarse sand matrix (φ_{TS} = 39.6°; φ_{CSS} = 47.5°). Maximum shear stress values observed at an interface between finer grain sands and any structural materials ranged from 15 kPa to 40 kPa, whilst those observed at an interface between coarser grain sands and structural materials ranged from 10 kPa to 50 kPa. Further, the interface friction angle (δ) values ranged from 9° to 42° for the finer sands, whilst those ranged from 11° to 54° for the coarse sands.

(2) The CNL testing behavior is influenced by the shape of sand grains: Maximum shear stress values of the clean sand grains with angular shape (R = 0.16, S = 0.55) were found to be between 100 kPa and 125 kPa, whilst those of the sand grains with rounded shape (R = 0.43, S = 0.67) were found to be between 80 kPa to 110 kPa. The clean sands with angular shape grains have φ values of 34.7° and 47.5° for finer and coarser grains, respectively, while the clean sand with rounded shape grains have φ values of 34.1° and 39.6° for finer and coarser grains, respectively. Similarly, maximum shear stress values obtained at an interface between sand with rounded shape grains and structural materials are less than those observed at an interface between sand with angular grains and structural materials. Accordingly, the interface friction angle (δ) values decreases with decrease in angularity of the sand grains.

(3) The sand-structural material interface behavior highly depends on the type of structural material: Maximum shear stress values and pattern of the loops depend on surface roughness, and hardness of the structural materials. The shear stress values observed at the sand-steel interface reaches their maximum values within a smaller range of shear displacement, and then stabilizes. Whereas, the shear stress values observed at the sand-wood, and the sand-concrete interfaces increase gradually throughout the range of measured displacement.

(4) There is a slight effect of the rate of displacement on the response of the sand-structural materials interface: Although, a slightly different pattern (i.e., a series of stress fluctuations) was realized for the tests conducted at a 0.025 mm/min rate of displacement, the shear stress values within the measured range of displacement are very close the tests conducted at a 2.0 mm/min rate of displacement.

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