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SOIL MECHANICS

SHEAR RATE EFFECT ON STRENGTH CHARACTERISTICS OF SANDY SOILS

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In this study, the effects of different shear rates during direct shear tests on variations in the strength characteristics were investigated for the sand samples of various particle size distribution. Direct shear tests were carried out at nine different shear rates ranging from 0.05 to 5 mm/min under normal stresses of 54.5, 109, and 218 kPa. Both sample groups were tested under a condition of defined water content and in a water-filled condition. Results show that with increasing shear rate, the internal friction angle and peak shear strength values increased. The increase in the internal friction angles and peak shear strengths were particularly evident for shear rates higher than 1 mm/min. Even though the effect of grain size on the variation in strength parameters due to shear rate is limited for the soils examined in this study, the effect should be considered.

Introduction

Shear strength characteristics (cohesion c, internal friction angle φ, peak strength T) are important soil parameters in geological and geotechnical engineering practice. Triaxial compression and shear box tests are commonly used testing methods to determine the shear strength characteristics of soils. The shear box test is commonly utilized because it is simple and practical to apply it to disturbed and undisturbed soils. This relatively simple test directly measures shear forces, as the sample is deformed at a controlled rate until failure occurs. The testing device is forced to yield the sample through a shear plane at varying shearing rates.

For loess samples (i.e., sandy, clayey, silt), Horn [1] determined a loading rate of 0.15 mm/min as the maximum shear rate under drained direct shear conditions. He attributed the increase of shear stress (τ_f) with increasing displacement rate to pseudo-plasticity (i.e., viscosity decreases with increasing shear stress). Thermann et al. [2] used a direct shear apparatus and applied different shear rates (SR) on silty sand soils to examine the effects of SR on φ, c, and T. Saito et al. [3] carried out direct shear tests on silica sands with illite and bentonite at four different shear rates (e.g., 0.01, 0.1, 1 and 10 mm/min). These researchers observed that the effective residual internal friction angle of the silica sands was almost constant at 34° for all shear rates. Nakao et al. [4] carried out shear box tests on coarse grained granular backfill soils and determined that peak and residual internal friction angles varied in response to different shear rates. McCartney et al. [5] carried out direct shear tests on a geo-synthetic clay liner at low shear rates ranging between 0.0015 mm/min and 1 mm/min. It was found out that under relatively high normal stresses (e.g., 250 kPa), there was a decrease in shear rates and an increase in the peak shear strength. However, the authors determined that under low normal stresses (e.g., 50 kPa), there was a decrease in shear rates and decrease in the peak shear strength. For soils with varying clay and silt con-

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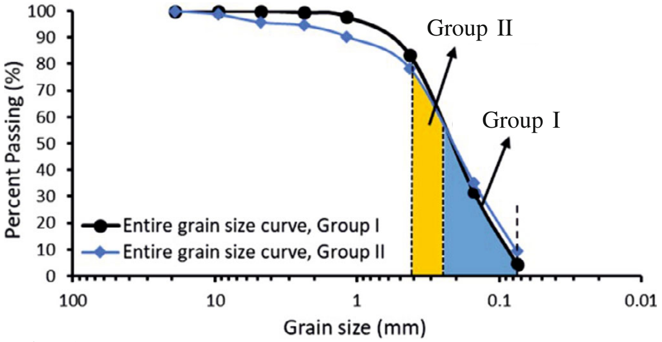

Fig. 1. Grain size distribution curves of groups I and II.

tents, Teuten [6] utilized shear tests with different shear rates and observed almost the same peak and ultimate strength values for different shear rates. For mixed samples of kaolinite and bentonite, Bro et al. [7] claimed that the ratio of shear stress to normal stress decreases with increasing shear rates. Li et al. and Raj Bhat et al. [8, 9] tested soils ranging in composition from clay to fine sand under varying shear rates and announced contradictory results for the change in shear strength and internal friction angles due to shear rates. Kimura et al. [10] investigated the effect of the *SR* (0.01 and 0.5 mm/min) on the residual strength parameters of various soil types (e.g., high and low plasticity clay rich, silt and sand-rich soils) and found that the shear rate has a slight effect on the residual internal friction angle.

The studies mentioned above describe conflicting results for how shear strength characteristics are influenced by shear rates for various soil types. Many other researches [2, 3, 7] emphasize the importance of the shear rate due to its effect on pore water pressures developed during shearing. For these reasons, this research utilized shear box tests to analyze the effect of shear rate on the shear strength characteristics of two samples of fine sand from Neogene-age lacustrine sediments in Denizli (Turkey) with varying grain sizes with respect to a wide range of shear rates between 0.05 and 5 mm/min, which cover most of the shear rate intervals of previous studies.

Sample Preparation and Testing Procedure

Both sand samples obtained from the field were filtered with #200 sieve under wet conditions. The sample group I was selected from sands retained by #200 and #60 sieves, group II – by #60 and #40 sieves. Figure 1 represents the grain size distribution of the sand samples.

During the shear box tests, a device digitally controlled by a computer system was used to record lateral and vertical deformations and shear stresses simultaneously. The shear strength characteristics (c, φ, and T) were analyzed using DS7 software. To examine the effects of the shear rate on the shear strength characteristics, nine shear rates (0.05, 0.1, 0.3, 0.5, 0.7, 1, 2, 4, and 5 mm/min) were employed for the two groups of disturbed sand samples.

After sieving, the samples were homogeneously mixed with the same water content to obtain a conforming material. Next, the mixture of sand and water was placed in a standard shear box with dimensions 6 × 6 × 2 cm and compacted with a mallet. The tests were performed under two different conditions. The first group of tests was completed without adding any additional water to the shear box (testing condition A). The second group of tests was conducted by adding water to the shear box until the shear box was water-filled (testing condition B).

Three normal stress levels (54.5, 109, and 218 kPa) were assigned to determine the strength envelope. In total, 105 tests were performed following the suggestions of the ASTM D 3080 [11] standard. The testing device permits adjustment of the rate of displacement from 0.0025 to 1.0 mm/min, which meets the requirements of the suggested standard. The samples were sheared with a constant shear rate up to a minimum of 9 mm (displacement) or until failure is observed. The tests were repeat-

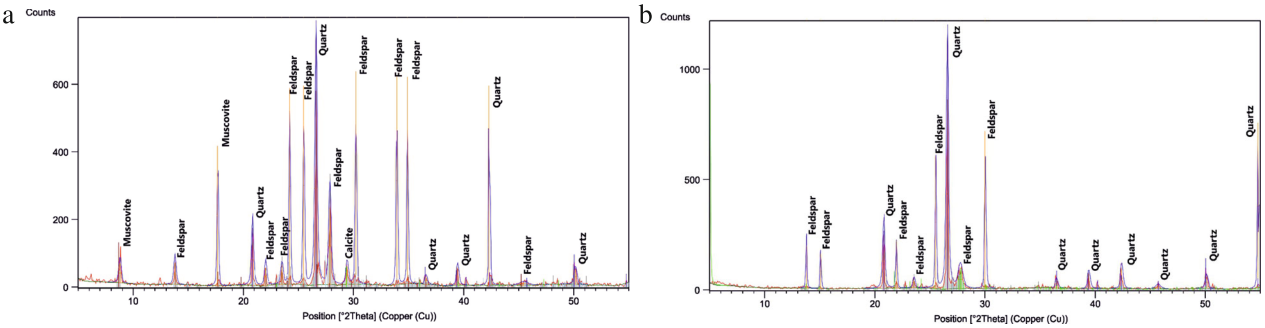

Fig. 2. XRD data for: a) Group I and b) Group II samples.

TABLE 1

Shear rate, mm/min	Group I						Group II					
	Testing condition A			Testing condition B			Testing condition A			Testing condition B		
	φ	c, kPa	T, kPa*	φ	c	T, kPa*	φ	c	T, kPa*	φ	c	T, kPa*
0.05	31.25	4.40	139.7	30.67	3.91	133.5	31.68	5.58	143.0	31.78	1.21	140.3
0.1	31.18	4.10	138.1	30.69	4.04	133.4	31.09	5.40	143.6	31.87	1.18	139.8
0.3	31.68	3.00	139.9	31.10	4.49	135.6	32.04	4.30	142.6	31.68	1.23	141.7
0.5	31.38	4.20	139.2	31.65	3.96	136.4	32.29	5.03	143.0	32.05	1.03	139.1
0.7	32.06	3.04	141.2	31.88	4.01	137.5	32.59	2.45	143.5	32.15	0.72	140.9
1	32.10	2.61	139.3	32.96	1.25	141.8	32.46	3.67	144.3	32.90	0.70	143.1
2	32.54	2.05	141.1	–	–	–	33.50	1.91	146.2	33.05	1.06	144.0
4	32.77	2.01	142.1	33.10	1.26	142.7	33.42	2.51	145.7	32.77	0.80	142.4
5	33.33	1.36	143.7	33.14	2.45	142.4	34.14	2.31	148.5	33.08	0.75	143.8

Note: *) under 218 kPa normal stress

ed under three different normal stresses, and the peak shear strength values and shear strength characteristics were obtained. After completion of the tests, Mohr failure envelopes were drawn, and cohesion, internal friction angles, and shear strengths were determined for each tested sample.

Physical Properties and Mineralogical Studies

The specific gravity of both sample groups was measured using powdered specimens and utilizing the pycnometer method [12]. The permeability of the same sample groups was obtained using the constant-head method [13]. The porosity of the sands was measured and calculated following [14].

The mineralogy of the samples was determined using X-ray diffraction analysis (XRD) of randomly oriented powdered specimens. The powder specimens used during XRD analysis were made by crushing and homogenizing the sand samples. The measurements were step-scanned at temperature 5°C-55°C.

Results

The average specific gravity value for groups I and II samples are 2.64 and 2.63, respectively, the porosities are 0.42 and 0.39, respectively. The modified water content was 26.8% and the hydraulic conductivity was 1.2×10^{-6} m/sec for group I samples, and 23.7% and 1.6×10^{-6} m/sec for group II samples, respectively.

Analysis under a binocular microscope revealed that the mineral grains of both sample groups were angular in shape, but it was evident that the grain edges of group I were sharper than the grain edges for group II. Group I samples contained primarily quartz with lesser amounts of feldspar. Mafic mineral (biotite and amphibole) grains were rarely observed in both groups. Quartz and feldspar mineral grains constituted the majority of the group II samples (the feldspars were more altered).

The mineralogical assemblages obtained from the XRD studies support the analyses under the binocular microscope. The XRD data given in Fig. 2 show that groups I and II samples mostly consist of quartz and feldspar minerals. The only difference is that the group I samples contain less feldspar.

The internal friction angle φ, cohesion c, and peak shear strength T data obtained after analyzing the test results are given in Table 1. For group I samples in testing condition A, it was observed that

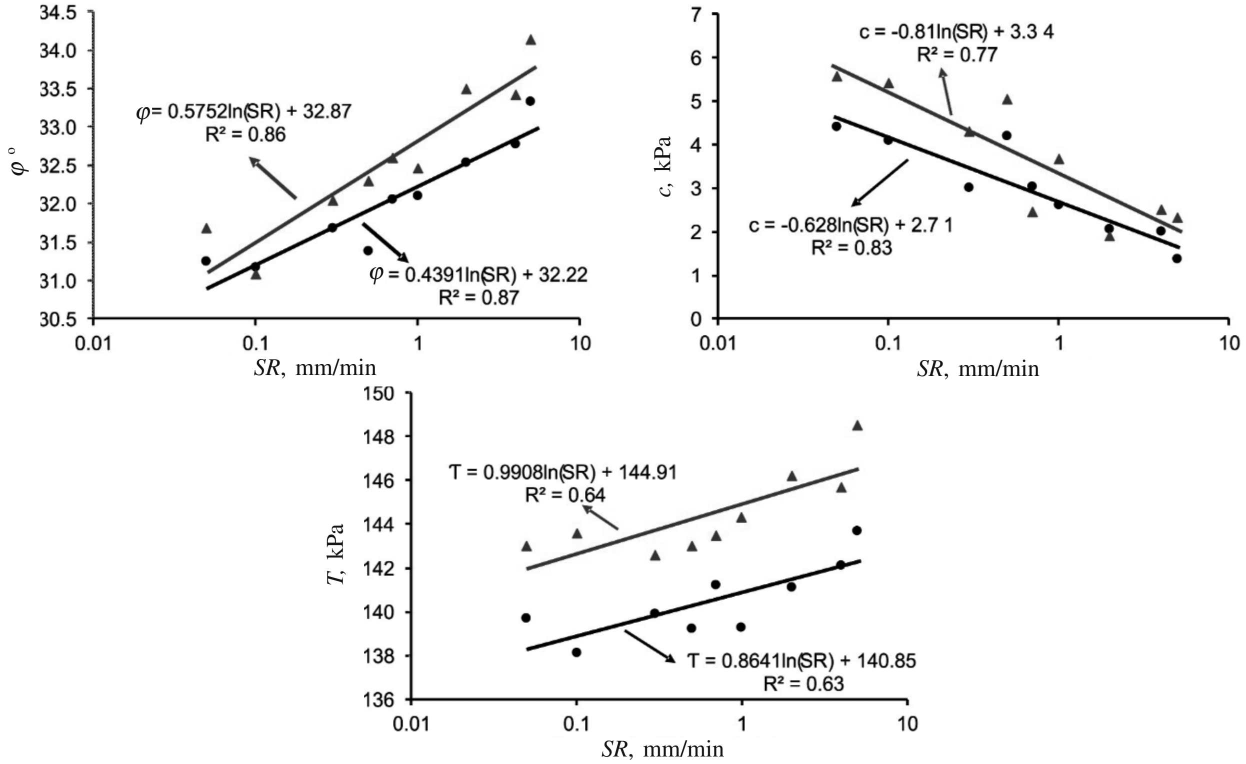

Fig. 3. Variations of shear characteristics with increasing shear rates for sample group I (●) and group II (▲) in testing condition A.

as *SR* increased, *φ* increased by 2.080, and *T* increased from 139.7 to 143.7 kPa, whereas *c* decreased from 4.40 to 1.36 kPa. For testing condition B, *φ* increased by 2.470, and *T* increased from 133.5 to 142.4 kPa, whereas *c* decreased from 3.91 to 2.45 kPa. Similar changes were observed for the group II samples for both testing conditions.

The influence of shear rate on *T*, *φ*, and *c* under both testing conditions for the two different sample groups are plotted in Figs. 3 and 4, where logarithmic functions represent the best fitting curves. Simple regression analyses reveal that the relationship between *SR* and *φ* for both specimen groups and both testing conditions exhibit high coefficients of correlations. Since the relationship between *SR*, *c*, and *T* varied for both specimen groups under different testing conditions, the increase in *T* and the decrease in *c* with increasing *SR* is apparent. For group II specimens in testing condition B, the lowest coefficients of correlation obtained were between *SR*, *c*, and *T*.

Generally, in shear tests, applied shear forces are measured by load rings, since the rings are relatively flexible and store strain energy as the shear force is applied. As the shear strength limit of the specimen is approached, this strain energy is released. The amount of strain energy stored is a function of the shear rate, which could affect the "measured" shear strength. This fact should be considered in evaluating the test results.

Discussion

The shear rate has an important effect on *φ*, *c*, and *T* under both testing conditions for the two groups of samples. A greater increase was observed for *φ* and *T*, especially for *SR* higher than 1 mm/min (Figs. 3 and 4, Table 1). The low *c* values observed during the tests are probably related to the apparent cohesion of fine sands with a particular water content. Thus, the effect of *SR* on *c* is more likely a function of the predefined water content (e.g., 7.5%) for the fine sands studied in testing condition A. A sim-

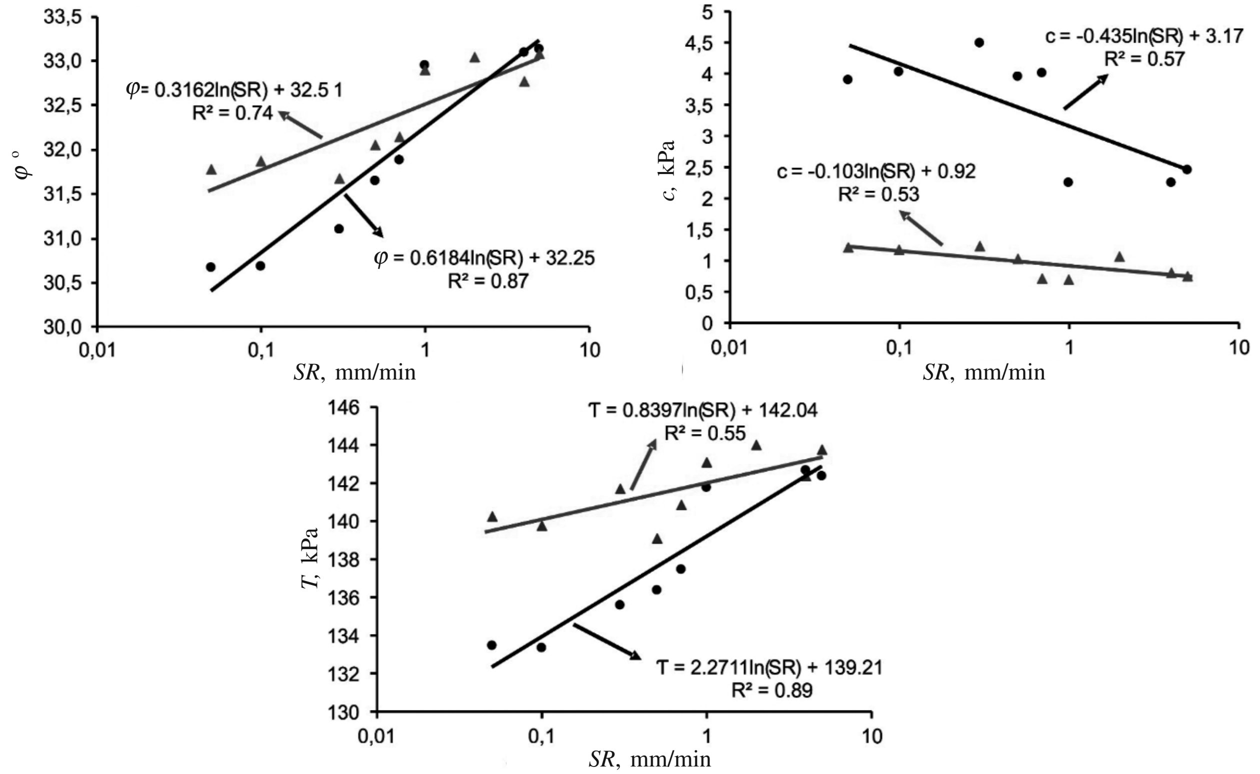

Fig. 4. Variations of shear characteristics with increasing shear rates for sample group I (●) and group II (▲) in testing condition B.

ilar trend in behavior was not apparent in testing condition B, probably due to the higher water content (Fig. 4).

Previous researchers [2, 3, 9, 15] have indicated a change in excess pore pressures resulting from changing shear rates. For this study, it is assumed that at low shearing rates, effective excess pore pressures do not exist or only exist at a minor level. Conversely, at higher shearing rates, effective excess pore pressure along the shear plane increases, as water in the voids cannot mobilize given the shearing rate. The correlation coefficients for the relationship between *SR*, *c*, and *T* for the group II sand samples are relatively low. The results suggest that the coarser grain size of this sample group (#60-#40 sieves) hinders the increase in excess pore pressure, leading to a slower increase in shear characteristics. Additionally, the grains of group I samples are observed to be more angular in shape than those of group II. Angular shaped grains generate rough surfaces along the shear planes, and the roughness due to the angular shapes of grains increases the amount of energy that is needed to generate a shear surface along the boundaries of neighboring angular grains. At low shearing rates, the soil has time to deform, and the effect on strength is more limited. However, as *SR* increases, more angular grains along the grain boundaries will be in contact for a longer period of time, and there will be no time for each grain to mobilize (deformation of soil will be delayed). To form a shear surface, all of these angular contacts must yield, which results in an increase in shear strength and the internal friction angle. However, for less angular or more spherical grains, the grains will slide past each other, and the effect of shear rate is not observed to be significant. For this reason, higher strengths for increasing shear rates are obtained for angular grains. Thus, the combined effect of the increase of excess pore pressure and grain angularity leads to higher peak shear strength for both sample groups, but due to the more angular grains of group I samples, the trend is more evident.

Even though previous researchers have announced the change of shear parameters with changing shear rates, the level of these changes is different. Thermann et al. [2] applied shear rates of 0.005, 0.05

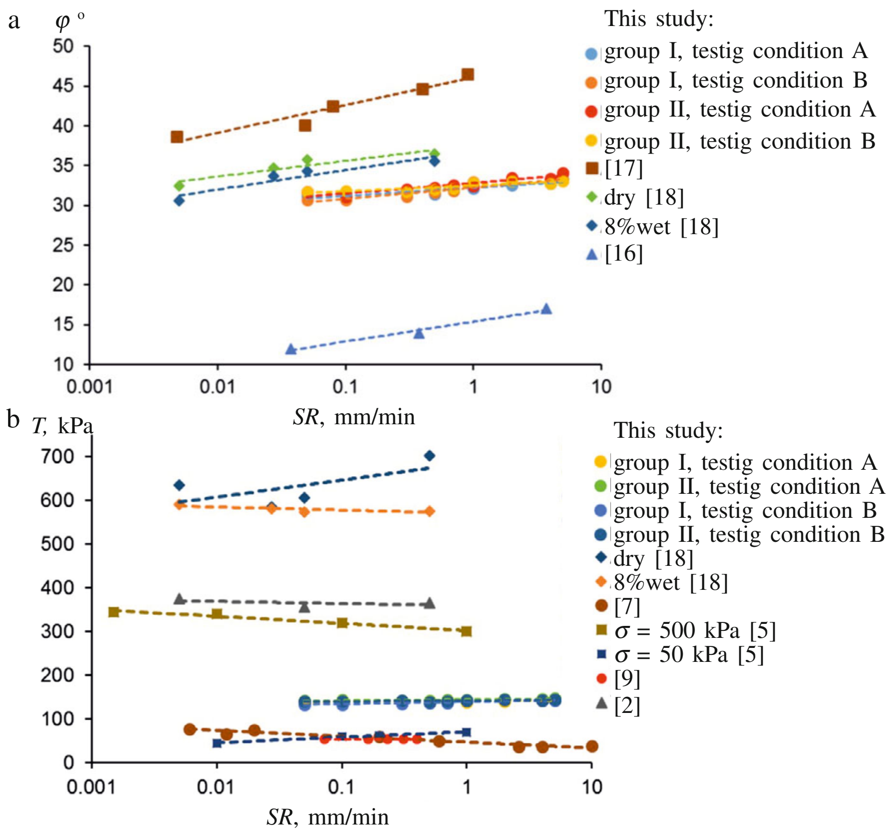

Fig. 5. Correlation of previous studies and this study regarding the effect of shear rate on: a) internal friction angle and b) peak shear strength.

and 0.5 mm/min to silty sand materials to compare the effects of the shear rate on shear strength parameters. Their results suggest that φ decrease with increasing *SR*. This result, which contradicts the findings of this research, probably occurred due to the lower shear rates. Moreover, the three shear rate levels used may mask the wider range of behavior of soils. Li et al. [8] also measured decreasing shear strength with increasing shear rates for high and low plasticity clay samples using shear rates of 0.1, 1, and 10 mm/min. Even though the shear rates are in the range used in this study, the grain size of the samples tested is considerably finer. These contradictory results can be attributed to the difference in sample grain size. Furthermore, the grain shape becomes irrelevant for silt and clay, as shown by the results of Thermann et al. [2] and Li et al. [8]. As the grain size increases, however, the grain shape has a greater effect on the shear characteristics.

Owolabi et al. [16] analyzed soils ranging in grain size from silt to fine sand under three shear rates (0.0375, 0.375, and 3.75 mm/min). It was concluded that the shear strength and shear parameters increase with increasing shear rate. The results for silt and sandy soils are in agreement with the findings of this study. A comparison of the relationships regarding the effect of *SR* on φ and shear strength obtained by previous researchers and determined from this study is shown in Fig. 5.

Al-Mhaidib and Anim proposed equations to estimate the relationship between *SR* and φ for sand samples:

$\varphi = 1.50\ln(SR)+46.08$, $R^2 = 0.93$ (sand poorly graded) [17];

$\varphi = 0.8513\ln(SR)+37.5$, $R^2 = 0.87$ (fine-coarse sand (dry)) [18]

$\varphi = 0.9755\ln(SR)+36.7$, $R^2 = 0.89$ and $\varphi = = 0.9755\ln(SR)+36.7$, $R^2 = 0.89$ (fine-coarse sand (wet 8%)) [18].

These equations describe trends in which φ significantly increases with increasing *SR*. The equations determined in this study and those proposed in [17, 18] are in good agreement.

The results presented above regarding the effect of shear rate on various shear strength characteristics obtained from previous studies suggest that the grain size has an impact on shear characteristics with varying shear rates due to the effects on pore water pressure and the impact on the shearing surface.

Conclusions

1. Increasing shear rate (from 0.05 to 5 mm/min) causes an increase in the internal friction angle and peak shear strength for the studied sand samples,
2. The cohesion values tend to decrease with increasing shear rates under both testing conditions for the studied sands,
3. The effect of grain roughness defined by grain angularity has a high impact on the increase of shear strength and internal friction angle by increasing shear rate. Moreover, the effect of pore water pressure on the shear characteristics changes with grain size. The combined effect of grain shape, grain size, and pore water pressure is responsible for the changes in shear characteristics for the studied sands,
4. At higher shear rates (e.g., above 1 mm/min) the influence of grain shape, grain size, and pore water pressure on shear characteristics is more apparent as the grains cannot find time to compensate shear stresses by generating a deformation, and thus an increase in strength occur.

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