Effect of Low-Plastic Fines Content on the Properties of Clean Sand

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Abstract. Physical properties of clean sand and pure clay are well established with different theories in the geotechnical literature; however, the properties of sand with fines soils are still not well determined and not fully understood. To address such matter, a series of laboratory tests were performed to investigate the effects of low-plastic silty/clayey fines on the engineering and mechanical properties of clean sand. Poorly graded clean sand was mixed with fines content percentages of 0%, 10%, 20%, and 40%. The results indicate that the shear strength parameters of tested sand measured using consolidated drained triaxial tests decrease with the increase of fines content. The internal friction angle dropped from 35° at 0% fines content to 26.86° at 40% fines content. As for the sand deformability, the modulus of elasticity (E_{50}) measured at a confining pressure of 100 kPa dropped from a value of 12823 kPa at 0% fines content to 5720 kPa at 40% fines content. The void ratio decreased as fines content increased up to 15%, then increased dramatically with further increase in fines content. Finally, to investigate the potential of using sand with fines as backfill for mechanically stabilized earth walls, the effect of fines content on interface properties between sandy soils and geogrid is also investigated by collecting data from literature and conducting regression analyses to determine the interface strength reduction factor (R_{inter}) to be used in the numerical modeling of such walls.

1 Introduction

Natural siliceous sand consists of fines and sand particles with different portions. The percentage of fines directly affects sand properties. Shear strength (effective friction angle and cohesion) and compaction characteristics of a specific soil are considered as major parameters for conducting stability analysis for almost every earthwork. Typically in construction projects, local backfill may be preferable rather than clean sand due to the high cost of replacement with clean sand and possible environmental effects. Many studies have adequately assessed the soil behavior of clean sand and pure clay; however, limited studies have thoroughly studied the behavior of sandy soil with different fines content as it is not easy to predict the response of the hybrid soil depending on the established data of clean sand (Phan et al. 2016).

L. Hoyos and H. Shehata (Eds.): GeoMEast 2019, SUCI, pp. 29–40, 2020.
https://doi.org/10.1007/978-3-030-34206-7_3

Najjar et al. (2015) investigated the effect of natural clay on the shear strength of clean sand. A decrease of 44% in internal friction angle of clean sand was observed in the case of mixing clean sands with 40% clay. However, Phan et al. (2016) reported that the internal friction angle of clean sand would decrease by 20% in the case of mixing with 30% clay at constant relative density.

The soil shear strength basically depends on the resistance due to interlocking, friction, and cohesion among the soil particles. Accordingly, Islam et al. (2017) defined a fineness modulus (FM) as the percentage of the cumulative retained soil on sieves up to No. 100 and limited the decrease in friction angle with the increase of fines content only for FM up to 1.5; but for FM greater than 1.5, the internal friction angle is almost constant.

Not only shear strength properties would be affected but also compaction characteristics would be changed by increasing the fines content. Despite the decrease in shear strength due to the increase in the fines content, minimum void ratio requirements would be enhanced with increasing fines content up to about 18% (Phan et al. 2016).

In the current study, a series of laboratory tests were employed to investigate the effects of fines content on shear strength properties, soil stiffness, and void ratio of sandy soil. This study is a part of an ongoing research investigating the potential use of sands with different fines contents as backfill for mechanically stabilized earth (MSE) walls. Therefore, the effect of fines content on the interface properties between the backfill soil and geogrid used in MSE walls is also investigated by collecting data from literature and conducting regression analyses to determine the interface strength reduction factor (R_{inter}) to be used in the numerical modeling of such walls.

2 Test Material

The sand used in the current study is classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS) (ASTM D2487). Fines mixed with the sand samples has a liquid limit of 24.5% and plasticity index of 5.6%. The fines are classified as low plastic silt/clay (CL/ML) according to USCS.

Tests were performed on four sand-fines mixtures defined by dry weight: 100% sand (sample 1), 90% sand plus 10% fines (sample 2), 80% sand plus 20% fines (sample 3), and 60% sand plus 40% fines (sample 4). The measured specific gravity of clean sand is 2.69 and of fines is 2.75; hence, the specific gravity of the three mixtures ranges from 2.69 to 2.75 depending on the amount of fines in the mixture. Specific gravity values of 2.7, 2.7, and 2.71 were determined for sample 2, sample 3, and sample 4, respectively. Grain size distribution curves for different sand-fines mixtures are presented in Fig. 1.

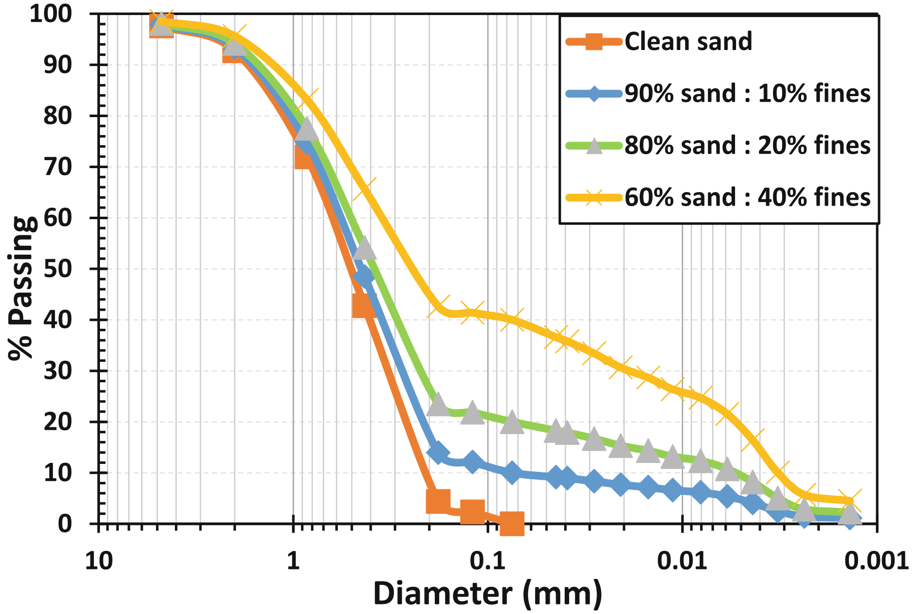


Fig. 1. Grain size distribution of different soil mixtures under study

3 Experimental Program

It is worth mentioning that there are no applicable ASTM standard procedures for determining the maximum and minimum void ratios for all investigated ranges of fines content (Phan et al. 2016). The ASTM D4254 and D4253 methods are limited to the determination of maximum and minimum void ratios with a maximum fines content of 15% in the mixture. Despite these limitations, the maximum and minimum soil density are still tested according to this specification. The ASTM D4253 and D4254 were used to test the maximum density to obtain the minimum void ratio index and the minimum density to obtain the maximum void ratio index, respectively.

A series of consolidated drained (CD) triaxial tests were performed according to ASTM D7181 to evaluate the shear strength and stiffness parameters of different sand/fines mixtures. Samples were tested at a constant relative density of 75% under confining stresses of 50 kPa, 100 kPa, and 200 kPa. The dry screening method as defined in ASTM D7181 was used during samples preparation then backpressure; with a value of 300 kPa; was added gradually to saturate the specimen, which was considered achieved when the pore-pressure coefficient “B” (Skempton 1954) was 0.95 or greater. Vertical stress, confining pressures, volume change, and vertical displacement were measured during shearing.

Primary compression elastic modulus for different mixtures calculated from one-dimensional consolidation test was evaluated according to ASTM D2435. The samples were loaded with stresses (5, 50, and 100 kPa) to record the primary compression for each stage. The initial void ratio of samples was calculated to achieve the target relative density of 75%.

4 Test Results and Discussions

4.1 Maximum and Minimum Soil Densities Test

The values of maximum density recorded were 1.74, 1.79, 1.75, and 1.69 g/cm^3 for sample (1), sample (2), sample (3), and sample (4), respectively. And minimum density values were 1.53, 1.57, 1.52, and 1.30 g/cm^3 for the same samples. The test results indicate that the increase in fines content lead to a decrease in the measured void ratio values up to an optimum value, which occurs at a critical fines content of about 15%; then a drastic increase in void ratio was observed as shown in Fig. 2.

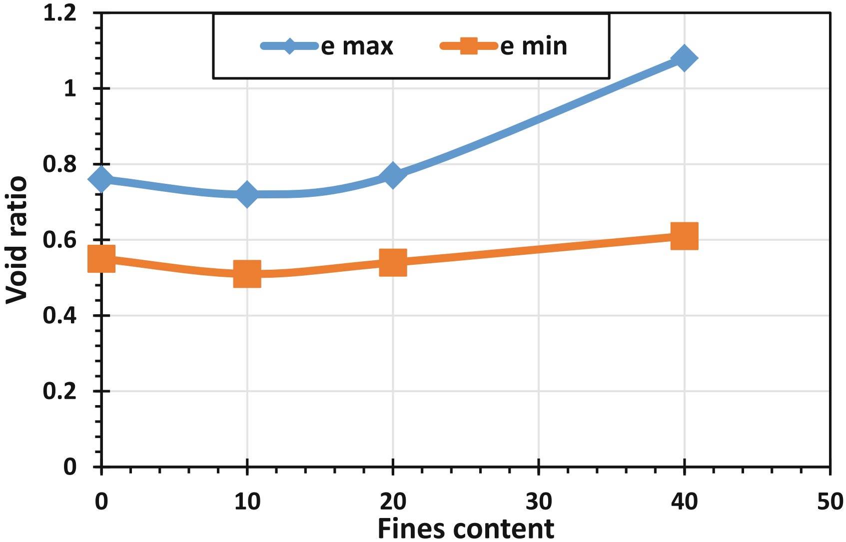
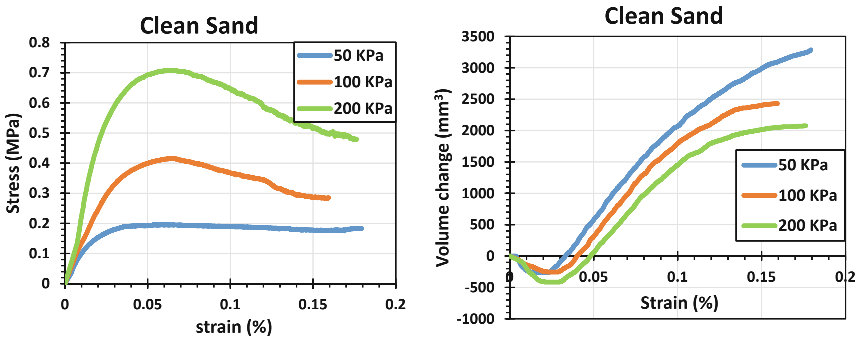


Fig. 2. Effect of fines content on void ratio index

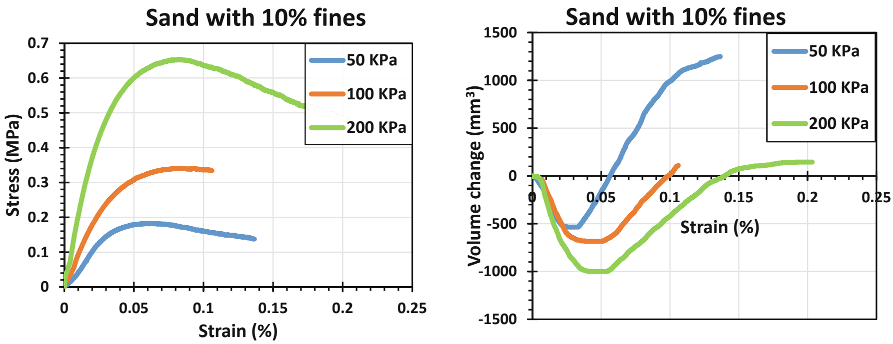
Generally, the critical fines content corresponding to minimum void ratio changes from one soil mixture to another. It greatly depends on the summation of particles surface area which controls the natural void ratio of any soil where each particle is surrounded by air voids. In the presented study, the sand particles and corresponding fines have an initial independent void ratio before mixing. During mixing, air voids in sand samples are gradually replaced by fines until reaching a state where all sand particles are enclosed by fines (i.e., critical fines content). After which, any increase in the fines content has no effect on the voids within the sand samples but increases the void ratio of the mixture.

4.2 Triaxial Test

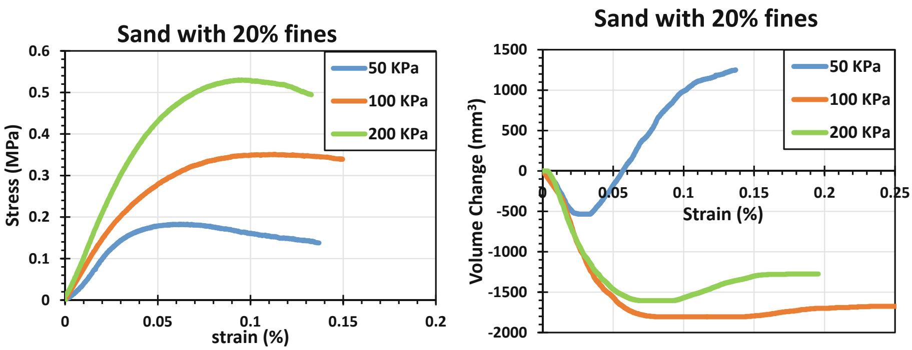
Shear stress and volume change versus vertical displacement were measured as presented in Fig. 3. It was observed that all soil samples exhibit the same stress-strain-strength behavior of peak and residual strength, the drop from peak to residual can be



(a) Clean sand without fines (Sample 1)

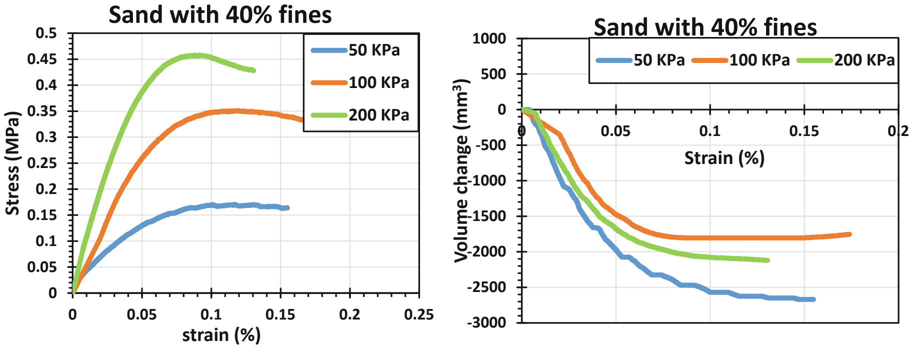


(b) Sand with 10% fines (Sample 2)



(c) Sand with 20% fines (Sample 3)

Fig. 3. Shear stress and volume change versus vertical displacement for four different mixtures under study



(d) Sand with 40% fines (Sample 4)

Fig. 3. (*continued*)

Table 1. Soil shear strength and stiffness parameters of different investigated soil samples

	Sample 1	Sample 2	Sample 3	Sample 4
Friction angle (ϕ')	35.02°	32.46°	29.16°	26.86°
E_{50} (at confining pressure of 100 kPa)	12823 kPa	8996 kPa	7111 kPa	5720 kPa

attributed to the orientation of soil particles along the slip surface that can lead to a volume decrease and also attributed to the increase in water content because of the dilatancy of soil particles over the shear zone. These two effects increase with the increase of the sand content (Cetin and Söylemez 2004). The difference between the peak and residual was observed to increase with the increase of the sand content at different stress levels.

It can be observed that the soil behavior changed gradually from dense to loose sand with the increase in the fines content. Upon shearing, the clean sand sample showed strain hardening behavior and dilate while the volume change showed hardening behavior for clean sand then moved toward softening behavior with the increase of the fines content. Volume change curves indicated that clean sand compresses at small displacements, then dilates until failure was reached. This compression was noticed to increase gradually with the increase in the fines content; from approximately 5% strain (in case of clean sand) to no dilation behavior (in the case of 40% fines).

The gradual change of sand to looser sand behavior can be also observed from shear strength parameters. The internal friction angle ($\phi°$) decreased with the increase of fines content; however, no cohesion (c) value was measured at the different fines content because of the non-plastic fines behavior. The stress curves show that clean sand failed at low strains, which increased gradually with the increase of fines content. In addition, the soil strength for any given confining pressure decreased with the increase of fines content and this means that the Mohr-Column envelope failure plane moved downwards causing a decrease in shear strength parameters (internal friction angle ϕ, cohesion c) and soil stiffness (E_{50}) as shown in Table 1. The internal friction angle dropped from 35.0° (in case of clean sand) to 26.86° (in case of 40% fines). Figure 4 shows the decrease of internal friction angle with fines content increase. An empirical relationship shown below can be estimated for internal friction angle prediction with fines content as follows:

$$\phi^\circ = -0.2046\,(\%F.C) + 34.456^\circ \tag{1}$$

where (ϕ) is the internal friction angle in degree and %F.C is the percentage of fines content. This relationship is only valid for clean sand with ϕ = 34°–36° mixed with low plastic fines.

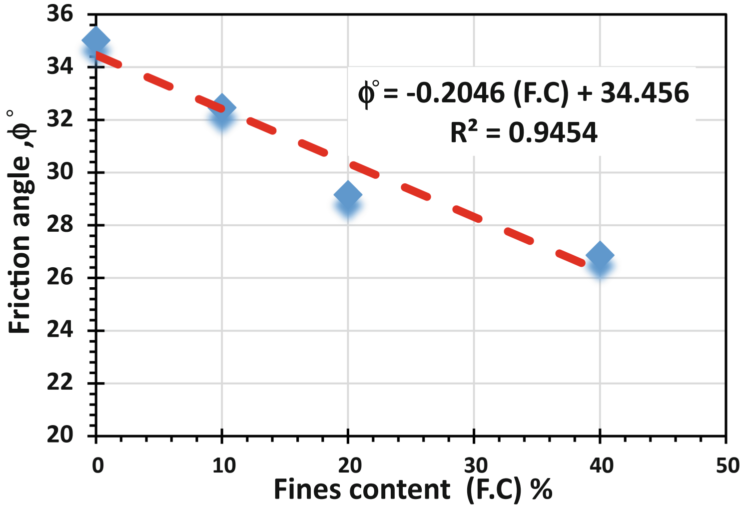


Fig. 4. Change of effective friction angle with fines content

It is worth mentioning that the B value, which represents the degree of saturation of tested soil, plays a vital role. All tests are performed for B value over 95% the wide range of B value effect can be observed in volume change for sand with 20% fines and sand with 40% fines. For sand with 20% fines, the volume change of the test at 100 kPa is lower than that at 200 kPa which can be attributed to a higher degree of saturation (high B value) for 100 kPa sample. The same explanation could be for sand with 40% fines at 50 kPa confining pressure sample.

4.3 One Dimensional Consolidation Test

The coefficient of volume compressibility (m_v) was determined for the stress range 50 to 100 kPa. The values of E_{oed} obtained were approximately the same of E_{50} from the triaxial test (Abdelmawla et al. 2014) as shown in Table 2.

Table 2. Modulus of elasticity of different samples under study due to primary compression.

	Sample 1	Sample 2	Sample 3	Sample 4
E_{oed} (kPa)	13248	8898	6920	5522

5 Interface Strength Reduction Factor (R_{inter}) with Geo-Grid

This study is part of an ongoing research investigating the potential use of sands with different fines contents as backfill for mechanically stabilized earth (MSE) walls. Therefore, the effect of fines content on the interface properties between the backfill soil and geogrid used in MSE walls is also investigated. Evaluating soil-geogrid reinforcement interaction is essential for accurate analysis and design of reinforced soil systems. Soil shear strength properties are reduced by a reduction factor on the geogrid interface (R_{inter}), which is defined as the ratio between soil-geogrid shear strength and soil-soil shear strength. Over the past years, numerous experimental studies with direct shear and pullout tests have been conducted to improve the understanding of geogrid-soil interaction. The geogrid embedded in granular soil can resist pullout force by friction and bearing resistances (Sukmak et al. 2016). Moreover, few numerical studies have been undertaken to validate experimental results (Abdelmawla et al. 2014; Hegde and Roy 2018; Touahmia et al. 2018), and other studies have tried to predict the pullout behavior of geogrid embedded in granular soil theoretically (Moraci et al. 2007).

For numerical pullout simulation for sandy soil, some studies assumed a value of 0.67 for R_{inter} as per FHWA-NHI-00-043, 2001 which is only valid for clean sand with fines content up to 15%, uniformity coefficient (Cu) should be greater than or equal 4, and plasticity index (PI) should not exceed 6 (Abdelmawla et al. 2014). Other studies assumed that the soil-geogrid surface is rigid and thus a value of 1.0 for R_{inter} was assumed (Touahmia et al. 2018). Hegde and Roy (2018) changed the value of R_{inter} until the results matched performed pullout test. Generally, R_{inter} ranges between 0.67 and 1 for clean sands depending on soil condition, geogrid type, and test condition.

Although many studies have mentioned factors that affect soil-geogrid interface, till now there are a lot of uncertainties regarding the selection of appropriate design parameter of R_{inter} for geogrid-reinforced soil systems. These uncertainties may be due to duplicate or not take all influencing factors into account.

In this study, R_{inter} back-calculated from pullout tests and numerical simulation results reported in the literature were investigated along with its corresponding test and soil condition to study which factors have a significant effect on R_{inter}. Studied factors were soil relative density (D_r), soil internal friction angle (ϕ), soil mean particle size (d_{50}), normal stress applied during the test (σ_n), geogrid length (L), number of transverse geogrid members, and geogrid opening size (#).

It was observed that R_{inter} is a characteristic value that only depends on soil and geogrid properties. However, test conditions like normal stress affects peak and residual strength but the fraction from this strength transmitted to the geogrid interface (R_{inter}) remains constant. Internal friction angle (ϕ) and soil mean particle size (d_{50}) were observed to have much more effect on R_{inter} values. Moreover, relative density affected R_{inter} values indirectly by changing the internal friction angle (ϕ). Also, geogrid opening size (#) was observed to be the most influential factor on R_{inter} for geogrid. Thus, such factors can be summarized in three major factors: geogrid geometry (#), mean grain size of soil (d_{50}) and soil internal friction angle (ϕ).

Table 3 shows data carefully collected from previous studies in the literature (covering several sand sites from China and Poland). R_{inter} values greater than one were excluded as they seemed unrealistic to develop a relationship estimating R_{inter} value from the geogrid opening size (#), the mean grain size of soil (d_{50}), and soil internal friction angle (ϕ).

Table 3. Pullout tests data collected from different researches

Reference	R_{inter}	tan ϕ	d_{50} (mm)	Opening (mm)
Lentz and Pyatt (1988)	0.95	0.676	0.35	47
Duszyńska and Bolt (2004)	0.93	0.721	1.19	46.69
Hsieh et al. (2011)	0.93	0.748	0.64	27.24
	0.88	0.793	6.9	27.24
Shi and Wang (2013)	0.87	0.637	0.26	55.15
Wang et al. (2018)	0.73	0.675	0.25	300.66

Figure 5 shows the results of simple regression analysis for the collected data from which the following equation can be developed

$$R_{inter} = -0.0016\left(\frac{\#^{0.2}(\text{mm})}{d_{50}(\text{mm}).\tan\phi}\right)^2 + 0.0222\left(\frac{\#^{0.2}(\text{mm})}{d_{50}(\text{mm}).\tan\phi}\right) + 0.874 \quad (2)$$

where R_{inter} is reduction factor on the geogrid interface, # is the geogrid opening size in mm, d_{50} is mean grain size of soil in mm and ϕ is the internal friction angle of the soil in degrees.

Figure 5 shows that R_{inter} would slightly increase by increasing the fraction of $\frac{\#^{0.2}(\mathbf{mm})}{\mathbf{d_{50}(mm).tan\phi}}$ From zero up to 7, that's because this part of the curve sandy soil-geogrid interaction approached gravel-geogrid interaction behavior, high $d_{50,}$ and tan ϕ, then transmitted gradually to sand behavior. The remaining part of the curve for fraction value above 7 shows the effect of fines content on R_{inter}. This relationship verifies the fact that R_{inter} value depends on soil properties more than that of the geogrids which is well established by (Hossain et al. 2011).

The above-concluded relationship is applied on different soil mixture samples to evaluate R_{inter} values with a geogrid of opening size 16 × 219 mm. R_{inter} values are 0.95, 0.93, 0.89 and 0.53 for sample 1, sample 2, sample 3 and sample 4 respectively.

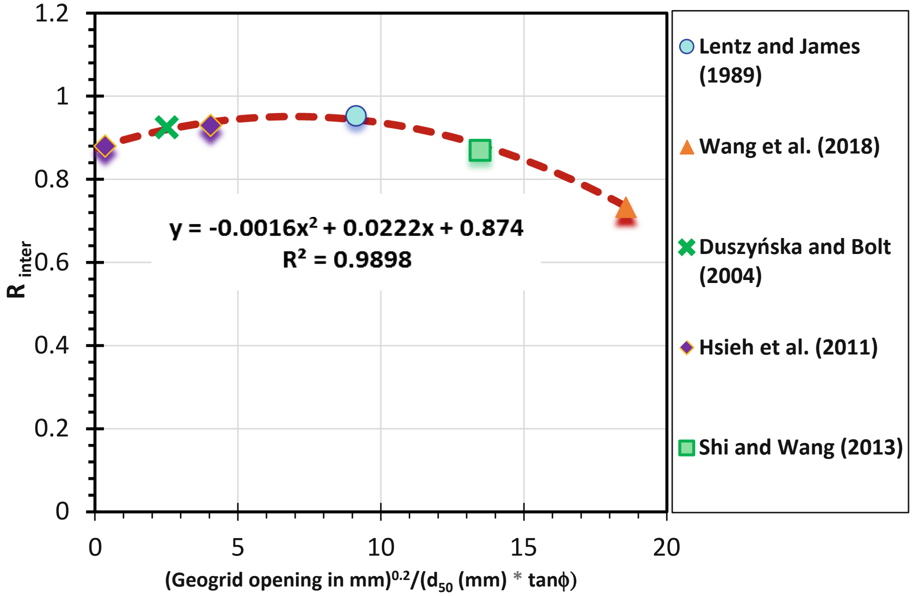


Fig. 5. Prediction of sandy soil R_{inter} value at different geogrid and mean particle size conditions

6 Conclusions

In the presented study, the effects of low plastic fines content on properties of sand were investigated by a series of laboratory tests (sieve analysis, hydrometer test, Atterberg limits, specific gravity, CD Tri-axial test, one dimensional consolidation test and maximum and minimum densities) conducted on poorly graded sand mixed with fines in different portions (0%, 10%, 20% and 40% by weight) and pullout test results data collection from the geotechnical literature. Based on the collected and measured data, the following conclusions can be derived:

- The smallest values of maximum and minimum void ratio were measured at fines contents of 15%.
- Low plastic fines have no effect on the cohesion of the sand under study.
- The soil behavior changed gradually from stiff to weak soil behavior with the increase of fines content from 0% to 40%, the internal friction angle (ϕ°) dropped to a value equal to 75% of the initial measured value, whereas, the modulus of elasticity (E_{50}) measured at a confining pressure 100 kPa dropped to a value equal to 45% of the initial one.
- Modulus of elasticity values due to primary compression (E_{oed}) are approximately equal to the modulus of elasticity obtained from the triaxial test (E_{50}) at the same confining pressure (100 kPa).
- Interface strength reduction factor (R_{inter}) is affected by fines content which in turn affects different soil properties.

– An empirical relationship was introduced to determine the interface strength reduction factor (R_{inter}) for usage in various numerical modeling applications based on the internal friction angle of the soil, mean soil particles diameter and geogrid opening size.

Acknowledgments. Sincere thanks and appreciation are expressed to Dr. Mohamed El Kholy, Dr. Mohamed Kamal, and Eng. Islam Mamdouh for their support, valuable contribution, and guidance during conducting the experimental work.

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