INFLUENCE OF SILT CONTENT ON THE ENGINEERING PROPERTIES OF SATURATED AND UNSATURATED GRANULAR SOILS

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ABSTRACT
In geotechnical engineering practice, fines content can have a major impact on the hydraulic and mechanical performance of coarse-grained soils. This paper examines the effect of non-plastic silt content on the mechanical and hydraulic performance of a medium sized concrete sand. The results of standard Proctor compaction tests, direct shear tests and constant and falling head permeability tests, carried out on various concrete sand–silt mixtures, are described and their implications discussed.

RÉSUMÉ
Dans la pratique du génie géotechnique, le contenu en fines peut avoir un impact majeur sur la performance hydraulique et mécanique des sols à gros grains. Cet article examine l'effet du contenu en silt non plastique sur la performance mécanique et hydraulique d'un sable de taille moyenne pour bétons. On décrit les résultats et on discute des implications de test de compactage standard Proctor, de cisaillement direct et de perméabilité menés sur plusieurs mélanges de silt et sable à bétons.

1. INTRODUCTION

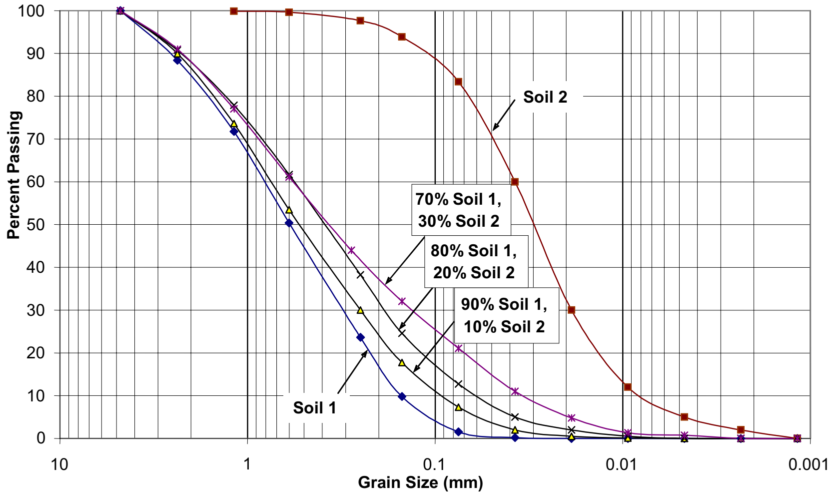
In geotechnical engineering practice, fines content (i.e. percentage of soil particles < 0.075 mm size) can have a major impact on the hydraulic and mechanical performance of coarse-grained soils. In some cases, fines are added to coarse soils to improve their performance, such as bentonite amendment of a sandy soil to form a bottom liner for a waste lagoon or landfill. In other cases, the presence of fines in a coarse grained soil can be detrimental to performance, such as the disruption of free drainage of a granular backfill soil behind a retaining wall. In many of these cases, depending on the specific project or application, geotechnical tests would be carried out to identify a threshold fines content that would give adequate performance, such as the minimum amount of bentonite needed to achieve a regulatory standard hydraulic conductivity or the maximum amount of fines allowed in a free draining backfill. Rarely, however, are the mechanical and hydraulic properties of coarse soil – fines mixtures examined in a systematic and comprehensive manner.

When examining the mechanical and hydraulic performance of coarse soil – fines mixtures, the pore size distribution and fabric of the mixture must be considered.
With the initial addition of fines to a coarse soil, the fines will start to fill the pore spaces between the coarse grained particles, with the coarse grained particles remaining in contact. At a certain point, enough fines will have been added to the mixture to completely fill the pore spaces between the coarse grained particles, but with the coarse-grained particle assemblage retaining its original fabric. Theoretically, this condition would give the maximum dry density of the mixture. This mixture would also be an optimum fines content for achieving low hydraulic conductivity. With the addition of more fines to the mixture, the volume of fines particles will exceed the volume of pore spaces of the coarse-grained soil fabric, with the particles still in contact, so the coarse particles will no longer be in contact. In this case the coarse particles would be "floating" in a fines matrix. The mechanical performance of the mixture at this stage would be dominated by the mechanical performance of the fines matrix.

This paper examines, in a systematic and comprehensive manner, the effect that the addition of fines, in this case a non-plastic silt, has on the mechanical and hydraulic performance of a medium sized concrete sand.

2. SOIL CHARACTERISTICS

The effect of silt size in a sandy soil was studied by mixing two granular soils, (a very clean medium sized concrete sand (soil #1) and a sandy silt (soil #2)) in various proportions. The grain-size distributions of soil 1 and soil 2 and of the various soil mixes are shown on Fig. 1. The compaction characteristics determined in standard Proctor tests for the two soils and for the soil mixes are shown in Fig. 2. With increasing silt fraction the maximum dry densities increased from 19 kN/m^3 for almost zero silt fraction (100% soil #1) to 20.8 kN/m^3 for 22% silt content but decreased subsequently for larger silt fractions as shown on Fig. 3. On Fig. 4 the optimum moisture contents are plotted versus silt fraction indicating that with increasing silt size the optimum moisture content decreased from 12.5% for zero silt-fraction to 8% for silt fraction between 15% and 28% but increased again for larger silt sizes up to 15% for soil #2 (84% silt sizes).



Sand			Silt and Clay
Coarse	Medium	Fine	

Fig. 1: Grain Size Distribution for Concrete Sand, Silt and Mixed Samples

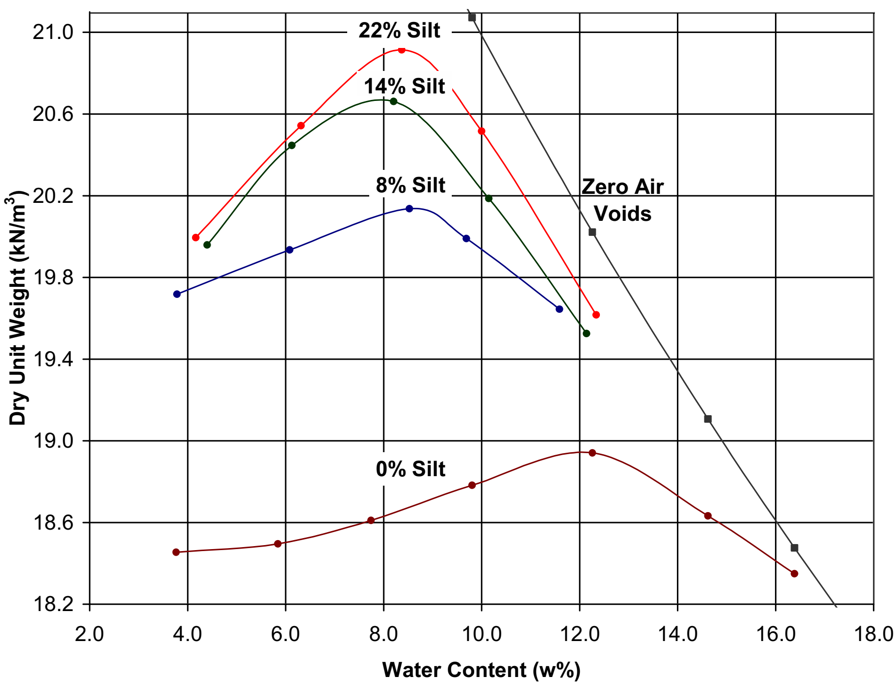


Fig. 2: Compaction Curves for Concrete Sand and Soil Mixes

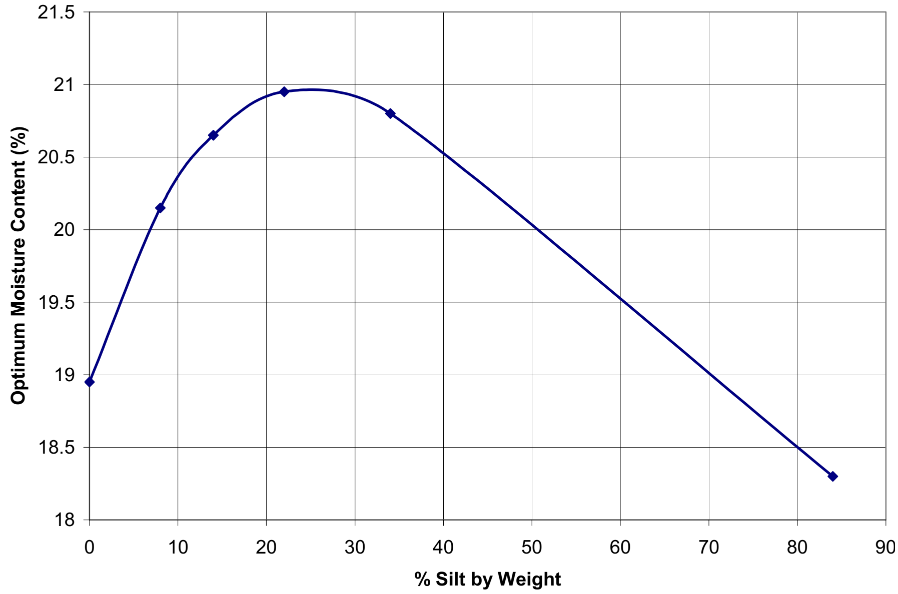


Fig. 3: Maximum Dry Unit Weight vs. % Silt Soil Content

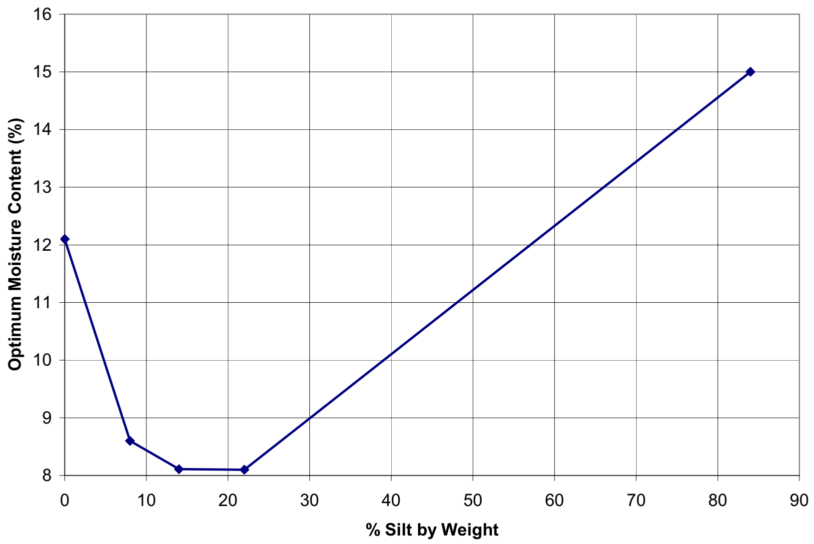


Fig. 4: Optimum Moisture Content vs. % Silt Soil Content

3. RESULTS

3.1 Shear Strength

The shear strength of the concrete sand (soil #1) and for various mixing proportions was determined in standard direct shear tests at constant normal load for three different compaction water contents: 2% wet of optimum; optimum; and 2% dry of optimum. The same compactive effort was applied to all specimens; thus the highest densities were obtained at the optimum moisture content. In addition, samples were submerged before shearing, trying to achieve saturated soil conditions during shear. Rate of shearing for all samples was 0.4 mm/min, resulting in maximum shearing resistance after 5 to 6 minutes.

Typical results are shown on Fig. 5 for a series of shear tests on samples with a mixing ratio of soil #1/soil #2 = 80/20 and placed and sheared at optimum moisture content. Distinct peaks were recorded at horizontal displacements of 1.2 to 2.0 mm reaching ultimate values after 5 to 6.5 mm horizontal displacements. During shear, vertical heave was measured in most cases identifying dilating soil conditions, reaching constant

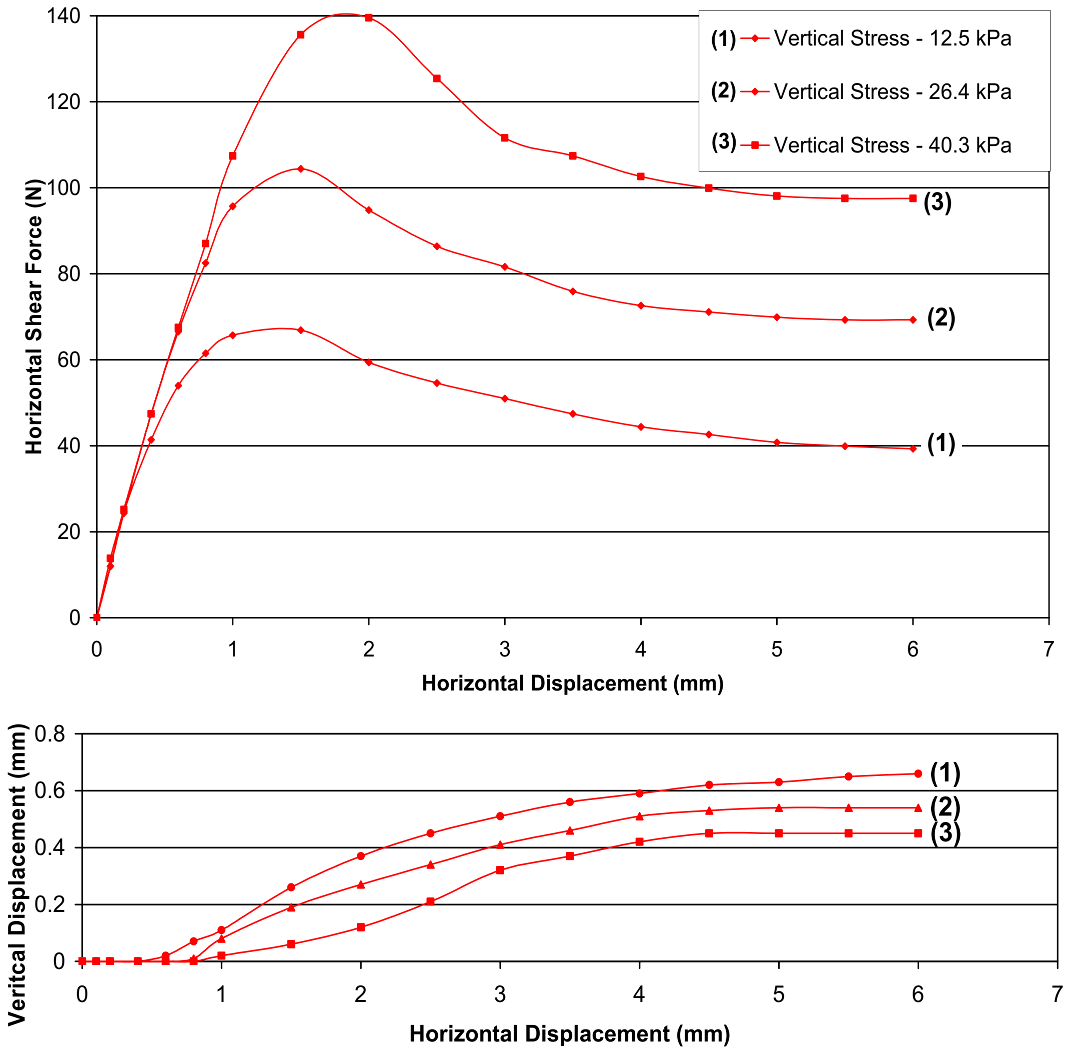


Fig. 5: Horizontal Shear Force vs. Horizontal Displacement For 14% Silt At Optimum Moisture Content

volumes after about 5 mm of horizontal displacements. This suggests that critical state conditions were valid when the ultimate shear strength values were recorded. The Mohr-Coulomb failure diagrams for peak and critical state strength conditions for samples with a mixing ratio soil #1/soil #2 = 80/20 are plotted for samples sheared "moist" at three different placement water contents on Fig. 6 and for the respective submerged samples on Fig. 7. For the "moist" soil on Fig. 6 cohesion intercepts are apparent for all three compaction water contents at peak and critical state. Values ranged for peak strength between 10 kPa for optimum moisture content to 3 kPa for wet of optimum moisture content. At critical state the cohesion intercepts were almost identical for all three placement conditions with values between 3.0 and 3.5 kPa.

On Fig. 7 the results of the respective submerged specimens are shown. For the samples that were placed at optimum and dry of optimum water contents small cohesion intercepts of 3 kPa are indicated for peak strength, but zero cohesion for the samples compacted wet of optimum and for all samples at critical state. This suggests that only the specimen compacted wet of optimum was fully saturated and that saturation was achieved along the slip surface for all specimens at critical state.

The friction angles measured at peak and at critical state for the "moist" samples are plotted versus silt fraction on Fig. 8. For all three placement conditions the angles of friction were the highest for samples placed at optimum moisture content and the smallest for samples placed wet of optimum, with values between ϕ = 38° to 40° for zero silt fraction to ϕ = 35° to 33° at silt sizes of 23% (the larger values are for optimum moisture conditions at maximum density and the lower values for wet of optimum conditions). The angles of friction at critical state were almost identical for all three placement conditions, decreasing from ϕ = 33°at zero silt fraction to ϕ = 31° at 23% silt fraction. For silt size contents larger than 23% no further change in ϕ values was indicated for peak and critical state conditions.

On Fig. 9 the cohesion intercepts for the moist specimens are plotted versus silt content for peak and critical state strength conditions. Again the largest values were recorded for the samples placed at optimum moisture content and the lowest for the samples placed wet of optimum. The wet of optimum values for peak strength are almost identical to the critical state values. In all cases the cohesion intercepts increased with increasing silt fraction.

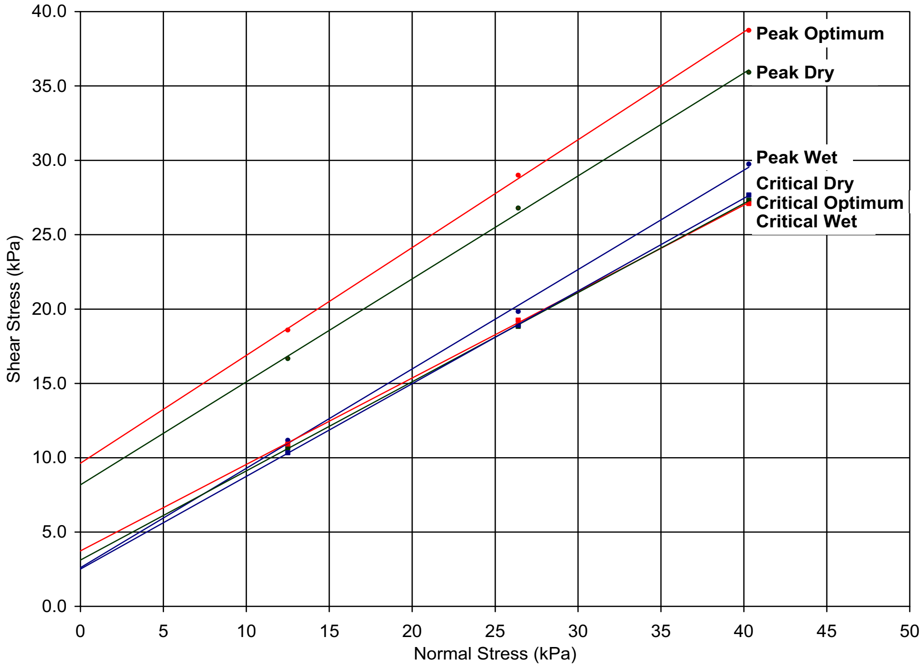


Fig. 6: Shear Stress vs. Normal Stress for 14% Silt – Peak and Critical State Shear Strength for Moist Specimens

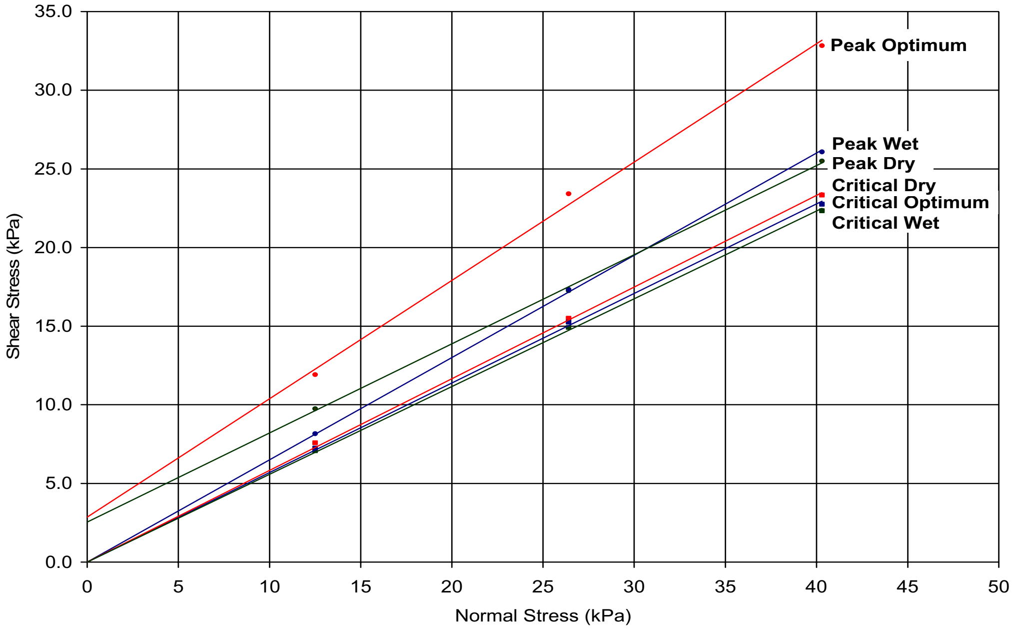


Fig. 7: Shear Stress vs. Normal Stress for 14% Silt – Peak and Critical State Shear Strength for Submerged Specimens

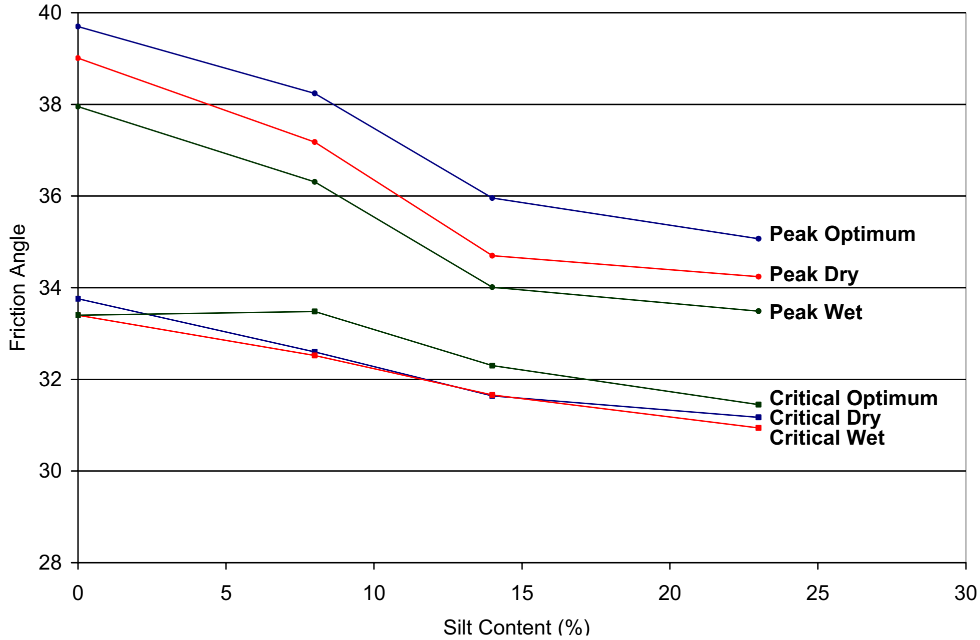


Fig. 8: Friction Angle vs. Silt Content for "Moist" Specimens

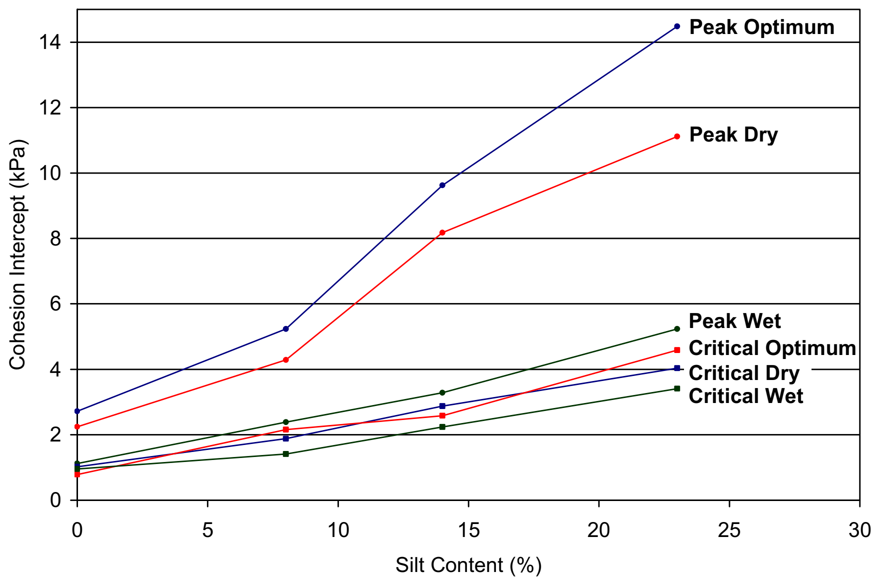


Fig. 9: Cohesion Intercept vs. Silt Content for "Moist" Specimens

3.2 Hydraulic Conductivity

Hydraulic conductivities of soil #2 and of various soil mixtures were determined with constant head and falling head tests. The soil samples were compacted in layers at the respective optimum water contents in the same cylinders in which subsequently the permeability tests were performed. The hydraulic conductivity of soil #1 was determined using Hazen's formula.

Differences between results form falling head and constant head tests were very small and were averaged for all soil mixtures. The average results are plotted on a log scale versus percent silt size (Fig. 10). It is apparent that the hydraulic conductivities decreased from 4 x 10^{-2} cm/s for soil #1 (zero silt fraction) to a value of 3.5 x 10^{-5} cm/s for 34% silt fraction but remained at this level for larger silt fractions.

4. DISCUSSION OF RESULTS

With increasing silt fraction the angle of friction decreased noticeably, reaching at 23% silt size the value of the silty soil #2 with a silt content of 84%. At this point the silty soil matrix was governing the frictional resistance suggesting that the larger soil particles were floating in the silty soil matrix. Compaction characteristics indicate that this occurs at approximately 20 to 30% silt content (see Fig. 3). The angle of friction at peak was the highest for samples compacted at optimum moisture content and the lowest for samples compacted wet of optimum. However, after continued shearing, when critical state conditions were reached, no significant difference between the compaction conditions is apparent in conformance with critical state theory.

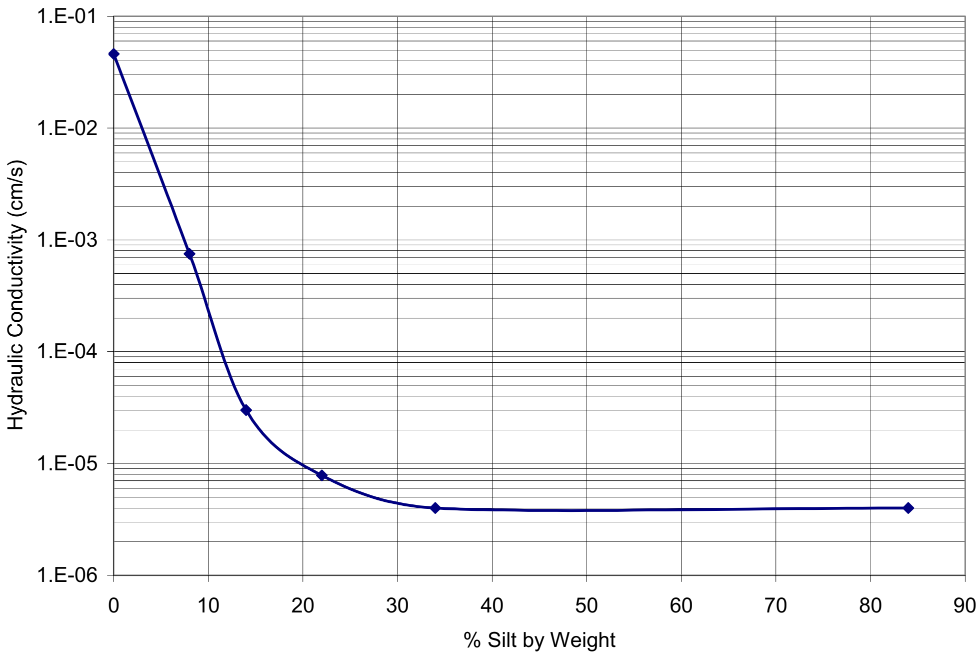


Fig. 10: Variation of Hydraulic Conductivity with % Silt by Weight for Saturated Specimens

For the samples sheared at unsaturated ("moist") conditions, cohesion intercepts were identified which increased with increasing silt content from almost zero for the clean sand (soil #1) with zero silt fraction to more than 14 kPa at 23% silt fraction. The cohesion intercepts represent apparent cohesion values caused by matric suction. The apparent cohesion values increased with increasing silt content, decreasing degree of saturation and increasing soil density. This cohesion intercept is $c = (u_a - u_w) \tan \phi^b$, where $(u_a - u_w)$ is the matric suction and ϕ^b is the angle indicating the shear strength contribution due to matric suction (Fredlund and Rahardjo 1993). The shear strength contribution due to matric suction, ϕ^b can be determined by plotting the relationship between the apparent cohesion and matric suction. However, in the present study, ϕ^b cannot be determined as the matric suction values of the specimens are not known.

It is interesting to note that at critical state conditions, after dilation along the shear zone had occurred, the cohesion intercepts had substantially decreased and were almost the same for all three compaction conditions. It can be visualized that during shear water was moving towards the dilating shear zone. The associated increase of degree of saturation resulted in a decrease in soil matric suction and thus resulted in a decrease in the apparent cohesion intercept. Thus, the unsaturated granular soils behaved similar to over-consolidated clays for which the cohesion disappears during shear as the soil dilates, reaching the "fully softened strength" when the critical state condition is attained.

In the case of the submerged specimens, incomplete saturation was indicated by the cohesion intercepts at peak for the specimens placed and sheared dry of optimum and at optimum water contents. These cohesion intercepts became zero once critical state conditions were reached and dilation had occurred due to the same mechanism.

Similar to the shear strength results, the hydraulic conductivities decreased with increasing silt fraction and were governed by the silt matrix for silt fractions larger than 34%. These results are comparable to observations reported by Kenney et al. (1991) for bentonite/sand mixtures and by Qian et al. (2002) for gravel/clay mixtures. It can be visualized that at this point the voids between the coarser particles have been filled with the fine grained soil which controls the hydraulic conductivity. In this context, it should be noted that maximum Proctor densities increased with increasing silt fractions up to a silt fraction of approximately 20 to 30% but subsequently decreased again. Similarly, the respective optimum moisture contents were at a minimum for a silt fraction between

14% and 22%. Comparable observations were reported by Kenny et al. (1991) for bentonite/sand mixes.

5. SUMMARY AND CONCLUSIONS

A laboratory program was undertaken on a medium sand in which the interaction of silt content, degree of saturation, shear strength and hydraulic conductivity was studied. The major findings are summarized as follows:

Frictional resistance and hydraulic conductivity decreased with increasing silt content up to a value of 25 to 30% silt fraction and remained constant for larger silt portions. On the other hand, the cohesion intercepts that were identified at peak strength for the unsaturated specimens, increased rapidly with increasing silt content.

During shear past the peak strength the cohesion intercepts decreased considerably when the respective critical state conditions were reached, and at this stage were only little affected by the silt content in the soil.

The cohesion intercepts were zero for fully saturated soil, independent of silt content.

The following conclusions can be drawn with respect to engineering applications:

For shallow engineering structures such as pavements, soils are typically unsaturated and thus their shear strength will be governed by the associated cohesion intercept. However, while the cohesion intercept increases with silt content the hydraulic conductivity of the soil decreases. Therefore, in order to maintain unsaturated conditions, the soil must be sufficiently free – draining; a silt content of less than 10% provides a reasonable balance between the two parameters.

When the water content increases, e.g. as a result of moisture migration due to temperature gradients, ground freezing, rise in water table or due to dilation during large shear deformations, the cohesion intercepts may decrease considerably. Thus, in the long term the apparent cohesion which is valid for unsaturated soils at small deformations, cannot be depended on. Accordingly, the silt content should be kept at a minimum, in order to ensure optimum drainage conditions and optimal frictional shearing resistance.

With respect to sand backfill behind walls or for soil liners, it can be concluded that for silt fractions larger than 25%, the silty soil matrix governs the hydraulic conductivity and frictional shearing resistance, even though the bulk of the material might be much coarser. This has positive implications for soil liners but negative implications for the performance of backfill material; even though the soil might be classified as a sand or gravel it is really performing like a silt, in terms of hydraulic conductivity and shear strength.

The apparent cohesion intercepts measured during shear of unsaturated granular soils are a direct reflection of the contribution of matric suction encountered along the shear zone. Thus, the development of cohesion during shear helps to explain the shearing behaviour of unsaturated soils.

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