ENGINEERING PROPERTIES OF HIGH SAND CONTENT SOILS USED IN GOLF PUTTING GREENS AND SPORTS FIELDS

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Introduction.

The primary objective of this work has been to apply the principles of geotechnical engineering to the question of ensuring stability of sand-textured rootzones used in golf putting greens and sports fields. This study was initiated with a complete investigation of the literature and followed with the characterization of sands falling within present-day USGA specifications for golf putting greens. Our next step was to measure strength and deformability parameters of the selected sands with the continued work of relating soil strength to soil physical properties. We have also developed a field-test for the measurement of soil strength and bearing capacity on many different putting greens (sand, push-up, topdressed, old, new, etc.) and sports fields having different turfgrass species at different times of the year.

Literature review

Effect of Grain Size

The shear strength of sands was first introduced by Coulomb. He simply assumed that frictional resistance increases with normal pressure. In fact, there are three components contributing to the strength of sand. According to Rowe (1962), these components are:

1. strength mobilized by frictional resistance;
2. strength developed by energy required to cause expansion or dilation of materials; and
3. strength developed by energy required to rearrange and reorient materials.

The first component is usually described as sliding friction, the second as interlocking friction, and the third as rolling friction.

Yong (1975) explained that sliding friction is included by microscopic interlocking arising from surface roughness; interlocking friction is caused by the physical resistance to relative particle translation affected by adjacent particles. The third component, rolling friction, might be ignored.

Koerner (1970a) investigated the influence of the effective size D_{10} for saturated sandy soils. The effective size was varied from fine gravel (2.6mm) through clay sizes. The results showed that friction angle increases with decreasing particle size. Zelasko et al. (1975) tested three sands and found that an increase in mean particle diameter causes a slight decrease in friction angle. Furthermore, it was indicated that the effect of particle diameter appeared insignificant. Bishop (1948) also made the same conclusion . Kirkpatrick (1965) studied the effects of particle size from tests on two cohesionless materials. Results showed that an increase in grain size reduces the friction angle. Hough (1957) explained that particle size affects the development of strength by influencing the amount of shearing displacement required to eliminate interlocking and to bring the solids to a free-sliding position.

In summary, the effect of particle size on friction angles of cohesionless materials is not clear through the literature. The main reason for the conflict may be the difficulty in separating all the contributing variables (such as texture and mineralogy) that influence the relationship between friction angle and particle size.

Effect of Grain Size Distribution

In general, the results of sieve analysis for cohesionless soils are presented as grain-size distribution curves. The diameter in the grain-size distribution curve corresponding to 10 % finer is defined as the effective size D_{10}; 60 % finer is D_{60}. Then, the uniformity coefficient C_u is given as $C_u = D_{60}/D_{10}$. A higher value of C_u indicates the soil sample is well-graded.

Bishop (1948) tested a full range of cohesionless soils (from sands to sandy gravels) in shear box tests. Two samples were of particular interest, a well graded sand of the Folkeston bed (C_u=2.5) and Ham River sand which is a uniform sieved fraction from the Thames Valley gravels (C_u=1.3). It was observed that in the plot of porosity versus friction angle, the curves of the two samples were almost parallel. Due to the lack of limiting porosities, the effect of C_u is not clear. Chen (1948) studied the strength characteristics of cohesionless soils by using triaxial compressions tests. He concluded the friction angle of these soils increases with increasing uniformity coefficient, varying from 25.5° for loose specimens to 51.5° for the well graded gravel.

Koerner (1970a) studied the effect of gradation on the strength of cohesionless soils using three single mineral particles (quartz, feldspar, and calcite). Gradation was evaluated by varying uniformity coefficient (C_u) from 1.25 to 5. The quartz soils were tested in the saturated and air-dry conditions with both drained and undrained triaxial tests. The conclusions were:

1. The drained friction angle for saturated feldspar and calcite soils increase with increasing value of C_u;

2. The effect of C_u on the drained friction angle for both saturated and dry quartz soils is negligible; and

3. C_u does not affect the undrained friction angle of quartz soils.

Zelasko et al. (1975) performed triaxial compressions tests using sand materials mainly consisting of quartz grains and the range of C_u values ranged between 1.2 and 2.0. Similar conclusions to Koerner's study were found that improved gradations have a minor influence on friction angle.

Effect of Grain Shape

In general, grain shapes of cohesionless soils were determined by examination of photomicrographs. There are two widely accepted definitions of grain shape which are roundness and sphericity. The concept of roundness was first proposed by Wadell (1935). The definition of roundness is defined as the ratio of the average of the radii of the corners of a sand grain image to the radius of the maximum circle that can be inscribed within the grain image. The range of roundness value is between zero and one. Furthermore, Youd (1973) added descriptions for roundness values which are given in the reference.

Zelaslo et al. (1975) concluded that friction angles decrease significantly with increasing particle roundness based on the experimental study of three sands. Increased roundness causes decreased frictional resistance between particles. However, there was an exception that strengths of three smaller sizes of one of the sands were lower that that of the larger particle size of that sand.

Koerner (1970a) studied the effect of particle shape as measured by its sphericity and angularity using three different saturated samples. The results showed the less spherical and more angular soils had significantly higher friction angles. From the literature it is relatively clear that friction angle increases with increasing angularity.

Gradations of sand

Sand is the primary component of the USGA root zone mix. Turfgrass growth and stability is greatly influenced by sand grain size, uniformity, and shape. The 1973 USGA Specifications (USGA Green Section Staff) was the first set of published standards that established an acceptable grain size distribution for the root zone mix. These specifications designated that the mix should contain no particles greater than 2mm, not more than 10% greater than 1mm, and not more than 25% less than .25mm, including a maximum 3% clay and 5 % silt. The current specifications, 1993 USGA Specifications (USGA Green Section Record, 1993), allows for coarser particles, an increase in medium range particles, and an decrease in very fine grain size particles. Table 1 lists the current specifications of the root zone mix.

Table 1. Current United States Golf Association particle-size distribution specifications.

PARTICLE SIZE DISTRIBUTION OF USGA ROOT ZONE MIX

Name	Particle Diameter	Specification	
Fine Gravel	2.0-3.4 mm	Not more than 10% of the total particles in this range,	
Very coarse sand	1.0-2.0 mm	including a maximum of 3% fine gravel (preferably none)	
Coarse sand	0.5-1.0 mm	At least 60% of the particles must fall	
Medium sand	0.25-0.50 mm	in this range	
Fine sand	0.15-0.25 mm	Not more than 20% of the particles may fall within this range	
Very fine sand	0.05-0.15 mm	Not more than 5%	Total particles in this
Silt	0.002-0.05 mm	Not more than 5%	range should not
Clay	> 0.002 mm	Not more than 3%	exceed 10%

Particle distribution influences many important parameters of the root zone mix. Kunze (1956), Howard (1959), and Baker (1983) all have concluded that the .25 to .5 mm range exhibits the best physical properties for putting green root zones. Particle uniformity and shape influences the interpacking of sands. Two important parameters define particle uniformity. Coefficient of uniformity (C_u) is defined as: $C_u=D_{60}/D_{10}$. The other parameter, coefficient of curvature is defined as: $C_c=(D_{30})^2/(D_{10})(D_{60})$. D_{10}, $D_{30,}$ and D_{60} are defined as the following:

D_{10} = grain diameter (in mm) corresponding to 10% passing by weight (or mass)
D_{30} = grain diameter (in mm) corresponding to 30% passing by weight (or mass)
D_{60} = grain diameter (in mm) corresponding to 60% passing by weight (or mass)

A sand with a C_c value between 1 and 3 along with a C_u value greater that 6 is considered to be well-graded. The coarsest and finest USGA gradations demonstrate uniformity by the following values: C_c=1.36, C_u=1.02 (coarsest gradation) and C_c=2.13, C_u=1.30 (finest gradation).

Strength of Sands

Friction Angle

The Mohr-Coulomb strength equation relates shear stress(τ) to normal stress(σ) at failure to obtain strength parameters ϕ (friction angle) and c (cohesion). The following is the Mohr-Coulomb strength equation:

$$\tau_{ff} = \sigma_{ff} \tan\phi + c$$

Since sand is cohesionless, c is considered to equal zero for the mohr-columb equation. The coefficient of friction can be determined by a direct shear test (ASTM D 5321). A Direct Shear machine was used to obtain normal and shear stresses at failure under various normal loads. A failure envelope is established by relating shear stress to normal stress at failure, which in turn establishes the friction angle (ϕ). The friction angle can be related to density or void ratio to establish a relationship between strength and particle interpacking. Direct shear test were run on 2NS, soil mix, crushed stone, and various processed forms of 2NS, soil mix, and crushed stone within USGA specifications. Test conditions included the following: dry compacted, dry uncompacted, wet compacted, wet uncompacted.

CBR(California Bearing Ratio) Test

The California Bearing Ratio test is an empirical test developed in the 1930's for determining a bearing capacity value of highway sub-bases and subgrades. CBR is defined as the ratio of the force required to penetrate a circular piston of 1935 mm^2 ($3in^2$) cross-section into soil in a special container at a rate of 1mm/min (0.05 in/min), to that required for similar penetration into a standard sample of crushed rock. (Head, 1994). The ratio is determined at penetrations of 2.5 and 5.0mm (0.1 and 0.2 in^2). The equipment used for both the field and lab CBR test can be slightly modified, along with the test procedures, to develop a measurement of turfgrass stability under applied vertical loads.

Lab CBR Equipment/Triaxial Equipment

The stability of experimental sands can be tested by using an Triaxial Loading Frame with a 2 in. dia. CBR penetration piston attached to vertical load cell. A CBR mold (6 in. inner dia, 7 in. high) is placed on a circular base plate which is load vertically upward at variable speeds (.00007 to .2 in/min). By attaching a vertical dial gauge to the CBR mold, the resultant normal load can be recorded against the vertical displacement until failure of the sand is observed. The sand can be tested dry-uncompacted, dry-compacted, moist-uncompacted, and moist-compacted to determine the optimum stability conditions of representative sands. The results obtain from this test includes bearing capacity vs. deformation.

Field CBR Equipment

The stability of the turfgrass structure can by determined by the use of the Field CBR device. The Field CBR device consists of a 2 in.diameter penetration piston attached to proving ring (force gauge), which is attached to a mechanical screw jack. This system is clamped to a truck bumper or any similar machine that will provide a suitable reaction. A vertical dial gauge is mounted to the penetration piston and positioned on a horizontal steel beam to record force vs. displacement as the piston is loaded vertically downward. The penetration piston is loaded vertically into 4, 6, and 8 diameter circular plates which represent an area similar to that of tires and athletic shoes. Again, force vs. displacement is recorded until failure of the turfgrass structure is observed. This test may be conducted with or without the layer of turfgrass to determine the strength of the underlying sand structure. The results obtain from this test includes bearing capacity vs. deformation.

Direct Shear Test/Coefficient of Friction

The direct shear test is a relatively simple way of determining the strength parameters of a soil (c and ϕ). ϕ refers to the coefficient of friction(or angle of internal friction) and c refers to the cohesion of the material. The Mohr-Coulomb strength equation ($\tau_{ff}=\sigma_{ff}\tan\phi + c$) for a soil specimen can be solved through the direct shear test. If sand, a cohesionless material, is the material to be tested, the c variable in the above equation drops out, becoming $\tau_{ff}=\sigma_{ff}\tan\phi$.

The direct shear apparatus consists of a 3 15/16in. X 3 15/16in. brass box which is divided into two equal halves. The test specimen is sheared with the top half of the shear box remaining stationary as the bottom half is sheared at a controlled rate of displacement. A force measuring device (a proving ring or load cell) is positioned in direct line with the stationary half of the shear box. The test is administered by applying a normal force upon the shear box and shearing the box to the right or left. Horizontal displacement is recorded vs. shear force and vertical displacement until failure of the specimen is achieved. The coefficient of friction can be determined by plotting shear stress vs. normal stress at failure of representative normal loads. The sand can be tested dry-uncompacted, dry-compacted, moist-uncompacted, and moist-compacted to determine the optimum stability conditions of representative sands.

Coefficient of Friction

The coefficient of friction can vary according to the condition of the sand being tested. The minimum value for ϕ is called the angle of repose. This angle is the steepest stable slope for loosely packed sand. Peak friction angles in a dense, well-graded, coarse sand usually range from 37° to 60°; for a dense, uniform, fine sand they are usually between 33° and 45°. (Lambe,1951).

Bearing Capacity/Friction Angle

Ultimate bearing capacity and friction angle values from the direct shear, lab CBR, and field CBR tests can all be tied together and a conclusion drawn relating strength and stability of the experimental sands to their gradation, particle size, and particle shape by applying the results to an empirical bearing capacity model. This is done by applying bearing capacity values of different size plates to the bearing capacity equation and then back-calculating the value of the friction angle. According to Meyerhof (1963) the ultimate bearing capacity equation is defined as the following:

$$q_u=cN_cF_{cs}F_{cd}F_{ci} + qN_qF_{qs}F_{qd}F_{qi} + 1/2\gamma BN_\gamma F_{\gamma s}F_{\gamma d}F_{\gamma i}$$

where

c=cohesion
q=effective stress at the level of the bottom of foundation
γ=unit weight of soil
B=width of foundation (=diameter for a circular foundation)
$F_{cs},F_{qs},F_{\gamma s}$=shape factors
$F_{cd},F_{qd},F_{\gamma d}$=depth factors
$F_{ci},F_{qi},F_{\gamma i}$=load inclination factors
N_c,N_q,N_γ=bearing capacity factors

Since our problem is treated as a surface footing problem and since sand is cohesionless the above equation reduces to the following:

$$q_u=1/2\gamma BN_\gamma F_{\gamma s}F_{\gamma d}F_{\gamma i}$$

where $N_\gamma=.2(N_q+1)\tan\phi)$

and $N_q=\tan^2(45+\phi/2)e^{\Pi\tan\phi}$

therefore once $F_{\gamma s}F_{\gamma d}F_{\gamma i}$ are determined, the friction angle can be calculated.

By knowing the friction angle at which the sands fail under different size plates and loading patterns, a turfgrass system can be developed and tested using an experimental sand matching the determined friction angle from the bearing capacity equation. This sand will follow closely within the USGA specifications for gradation. The effects of angularity, gradation and particle size on the drainage of the turfgrass system will also be taken into consideration once the strength issue is solved.

Materials and Methods

Instead of selecting sands available in the market, we chose to produce six sands to be used in our study of the strength characteristics of sands. From a widely available sand (2NS) with a very wide distribution of particle sizes, experimental sand mixes were produced. A coarse grade, a medium grade, and a fine grade mix with a low C_u and a coarse grade, a medium grade, and a fine grade mix with a high C_u were developed that fit the USGA Specification. Figures 1 and 2 show the gradations for the experimental sands and their position relative to the USGA Specification envelope. On these figures the upper limit of particle-size is indicated by the triangles and the lower limit by the diamonds. In Figure 1, the three sands slope as much as the specifications allow yielding as high as coefficient of uniformity (C_u) as possible. Figure 2 shows the three sands with a relatively low coefficient of uniformity. Our interpretation would be the sands with the greater C_u would display greater strength and bearing capacity through a higher friction angle.

Figure 1. Cumulative curve for the coarse grade, medium grade, and fine grade mix with as high a C_u as possible and still remain within the USGA specifications.

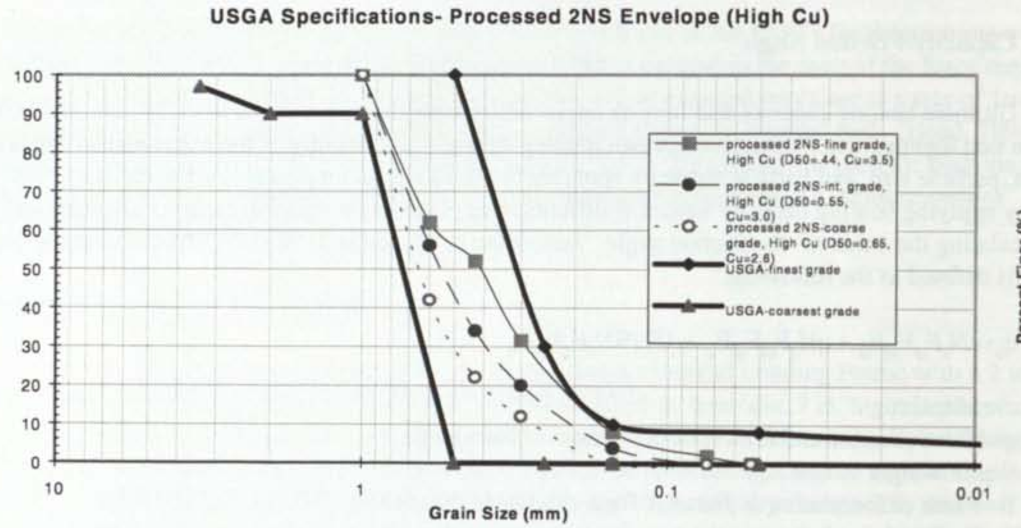
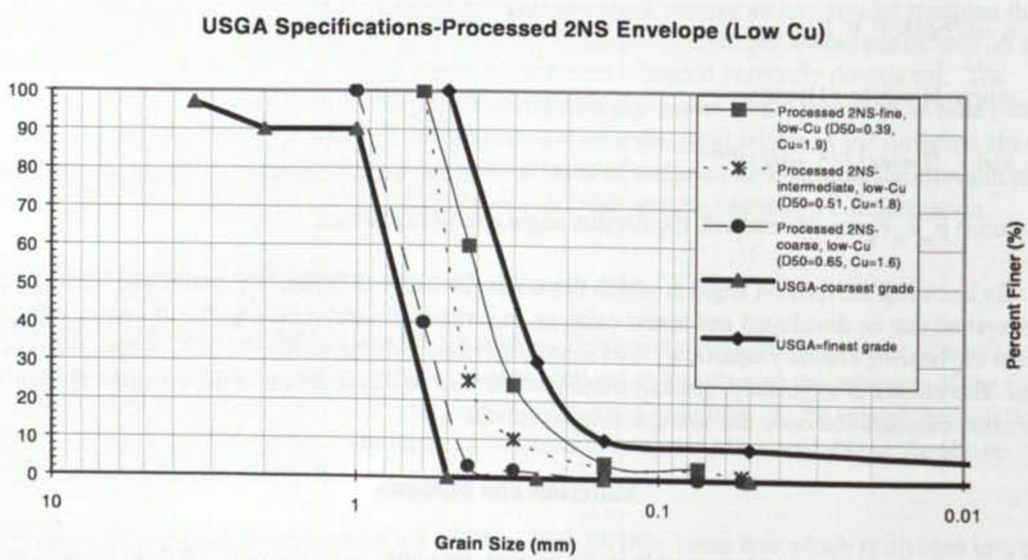


Figure 2. Cumulative curve for the coarse grade, medium grade, and fine grade mix with a low C_u.



Results and Discussion

To initiate our project we selected to study the strength of the selected sands before and after compaction under both dry and moist conditions. We know no putting green will be built with dry sands, but we need to understand how these sands behave with the controlling variables. From the literature review we know bulk density, porosity, moisture content, and particle-size distribution influence sand behavior.

Table 2 details soil bulk density before and after compaction under both dry and moist conditions. There are no surprises in these data as bulk density increases with compaction.

Table 2. Soil bulk density of the six processed sands dry or moist, and dense or loose.

EXPERIMENTAL DESIGN MATRIX -USGA TESTING							
Phase II - PROPERTIES OF EXPERIMENTAL SANDS							
Density (g/cm$_3$)							
COMPACTION		LOOSE		DENSE			
SATURATION		MOIST	DRY	MOIST		DRY	
SIZE-D_{50}	UNIFORMITY-C_U			initial density	density after compaction	initial density	density after compaction
COARSE	HI		1.610			1.609	1.865
	LOW		1.561			1.580	1.774
INTERMEDIATE	HI		1.642			1.614	1.897
	LOW		1.582			1.541	1.798
FINE	HI		1.579			1.621	1.871
	LOW		1.580			1.607	1.773

Table 3 shows the determined friction angles of the six sands when dry. We know the higher the friction angle the greater strength and bearing capacity the sand will exhibit. Our initial results indicate an increase in friction angle with compaction (expected) and that sands with a high coefficient of uniformity (C_u) have greater angles than those with lower angles (also expected).

These relationships are shown in Figures 3 and 4. In Figure 3 you can see how the friction angle is determined by plotting the relationship of normal stress (confining force) verses shear stress (pulling force) and the angle of the resultant regression line yields the friction angle. The higher this angle the more energy is required to shear the soil and the higher the bearing capacity.

Figure 4 displays the changes in this relationship with sample characteristics. The greatest friction angle is derived from the well-graded sand after compaction and the lowest angle is derived from the uncompacted uniform sample. From the review of the literature, this is the expected result. Then to increase the strength and stability of high sand putting green rootzones all that is needed is to increase particle-size distribution resulting in a higher uniformity coefficient (C_u).

There are some agronomic disadvantages of increasing the C_u of sands. Figure 5 indicates what happens to soil porosity after compaction of the six selected sands. It is a complex relationship, but basically we find a greater reduction in porosity after compaction with the well-graded sands as compared to the uniform sands. Although we have not yet measured the hydraulic conductivity of these sands, the implication is the well-graded sands would yield a lower conductivity than the uniform sands.

Table 3. Friction angle determined from shear testing of the six selected sands when dry.

EXPERIMENTAL DESIGN MATRIX -USGA TESTING					
Phase II - PROPERTIES OF EXPERIMENTAL SANDS					
Phi angle, forced through orgin					
COMPACTION		LOOSE		DENSE	
SATURATION		MOIST	DRY	MOIST	DRY
SIZE-D_{50}	UNIFORMITY-C_U				
COARSE	HI		32.8		36.6
	LOW		29.9		39.2
INTERMEDIATE	HI		32.4		36.1
	LOW		29.2		35.5
FINE	HI		30.5		32.0
	LOW		29.8		33.6

Figure 3. Plot of shear stress verses normal stress for the intermediate sized sand with a high coefficient of uniformity (Cu).

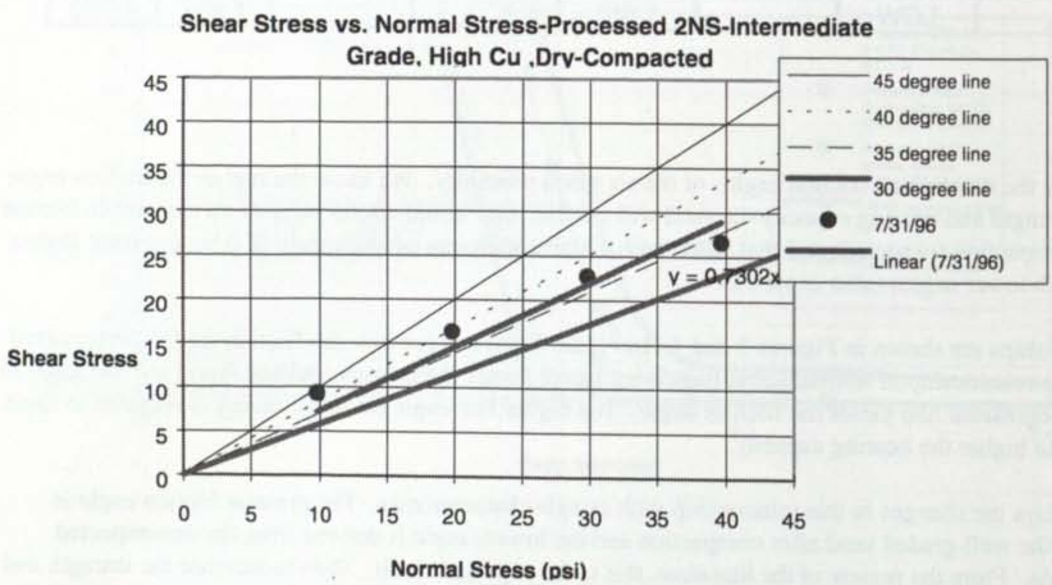


Figure 4. Plot of shear stress verses normal stress for the intermediate sized well-graded (high Cu)and uniform sands (low Cu) before and after compaction.

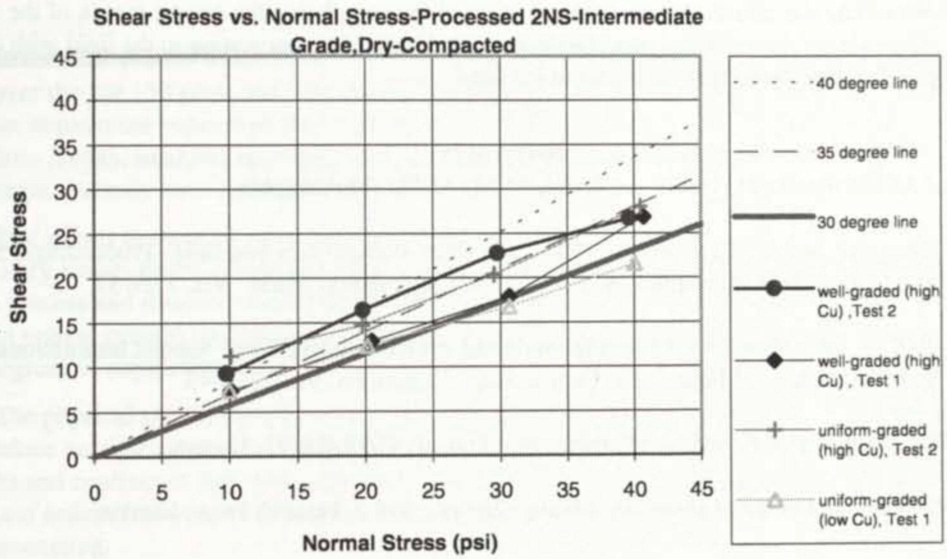
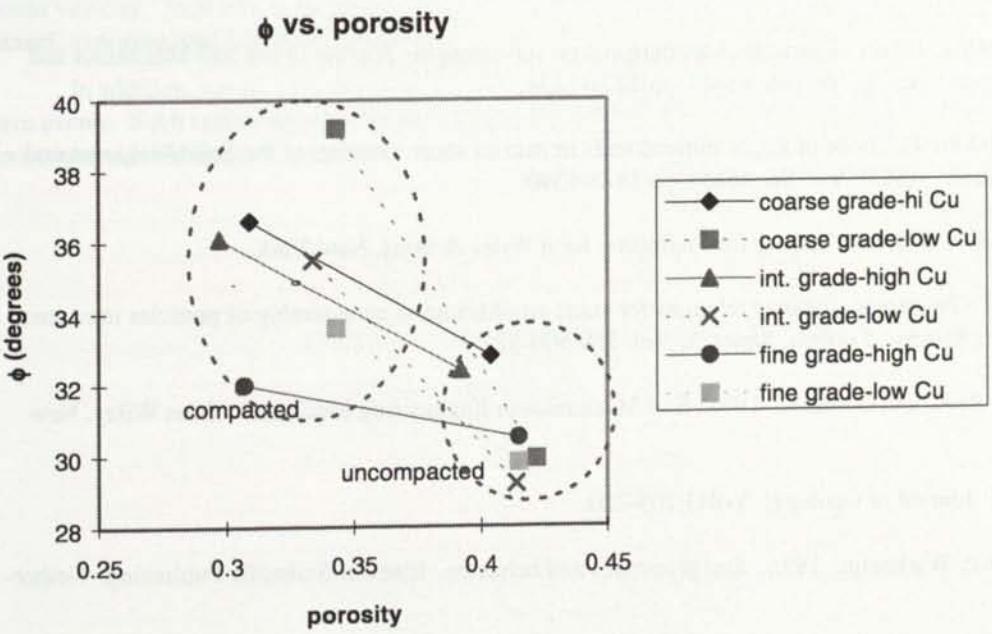


Figure 5. Plot of porosity verses friction angle before and after compaction of the six selected sands.



Summary

We feel we are making substantial progress in understanding the variables that control the engineering properties of high sand content rootzones. We know the wider the particle-size distribution of the sand, the greater will be its friction angle and the greater will be its strength and bearing capacity. Agronomically, as the distribution of the sand is widened soil porosity decreases. With a decreased porosity, saturated hydraulic conductivity will also decrease.

What we will concentrate our efforts on over the next year will be completing the testing matrix of the six selected sands, determining agronomicly important effects, and expanding our testing to the field with the CBR testing device to better understand the conditions in the field.

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