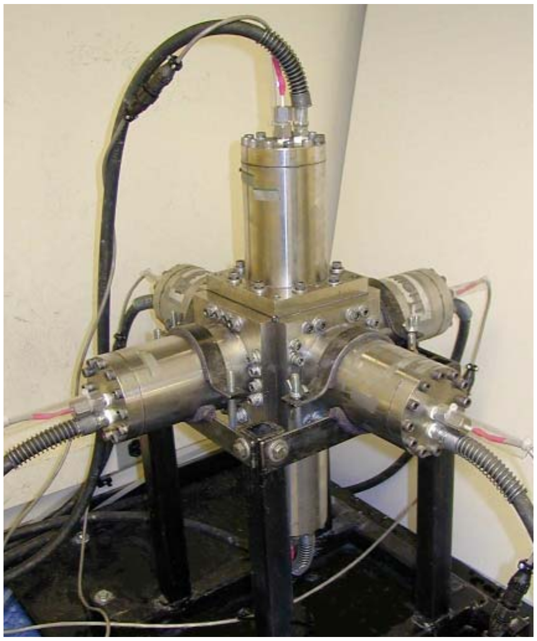
Turfgrass and Environmental Research Online

...Using Science to Benefit Golf



Researchers at The Pennsylvania State University are using a engineering device called the cubical triaxial tester to compare the strength and stability characteristics of sands composed of angular versus round particles.

Volume 1, Number 18
November 15, 2002

PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 215 projects at a cost of $21 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

Editor

Jeff Nus, Ph.D.
904 Highland Drive
Lawrence, KS 66044
jnus@usga.org
(785) 832-2300
(785) 832-9265 (fax)

Research Director

Michael P. Kenna, Ph.D.
P.O. Box 2227
Stillwater, OK 74076
mkenna@usga.org
(405) 743-3900
(405) 743-3910 (fax)

Importance of Particle Shape and Size on Rootzone Sands' Bulk Mechanical Behavior

V. M. Puri and C. F. Mancino

SUMMARY

The mechanical behavior of sands is important in golf course construction whether you are considering the stability of sand-based putting green rootzones or the playbility of sand bunkers. Researchers at the Pennsylvania State University investigated different sized round versus angular sands for their mechanical behavior under pressure. Their findings include:

- Rootzone sand mixtures comprised of round particles have higher initial bulk density and lower porosity compared with angular sands.
- In general, angular sands are more compressible than round sands.
- Bulk modulus, a measure of resistance to compressibility, increases with pressure for all sand shapes, with angular sands having lower bulk modulus values.
- Strength of angular sand mixtures are 14% to 64% higher than those of round sands.
- Shear modulus, a measure of resistance to distortion, increases with pressure for all shapes, with angular sands having higher shear modulus values.
- Sand mixtures' compression proceeds through three distinct stages of filling of voids: collapse, rapid but continuously declining rate, and slow evolving rate.

It is well known that the shape and size of particles comprising the rootzone mixtures have a decisive influence on the bulk mechanical behavior of mixtures such as strength, compressibility, and stability. These attributes, in turn, determine the longevity and quality of the turfgrass playing surface (Figure 1).

Golf course superintendents and turfgrass managers select particular rootzone sand mixtures often based on their availability. While these decisions are made based on many years of invaluable practical experience and financial and manpower constraints, making available quantita tive data on rootzone mixtures' mechanical performance would add an important dimension to the decision making process.

A study was initiated at Penn State University to systematically study the effect of sand shape, particle size distribution, moisture content and organic content (such as peat) on the bulk mechanical properties of the rootzone sand mixtures. The effect of these parameters on the bulk mechanical properties of rootzone sands was quantified using the cubical triaxial tester (cover photo and Figure 2). Given the comprehensive nature of this study, in this article only the performance characteristics of two monosize (0.375 mm and 0.675 mm) and one binary size (50:50 of 0.375 and 0.675 mm size) mixtures of the two extreme shapes (round and angular sands) are presented.

Insights and results on other attributes of rootzone sand mixtures such as addition of moisture, presence of peat, and the use of USGA-recommended sand size distributions will be presented in the future.

Figure 1. The grain size and angularity of sand particles contribute to the overall stability of putting green rootzones.

V. M. PURI, Ph.D., Professor, Department of Agricultural and Biological Engineering, The Pennsylvania State University, University Park, PA; C. F. MANCINO, Ph.D., Senior Scientist, The Scotts Company, Marysville, OH.

USGA Turfgrass and Environmental Research Online 1(18):1-9.
TGIF Record Number: 83192

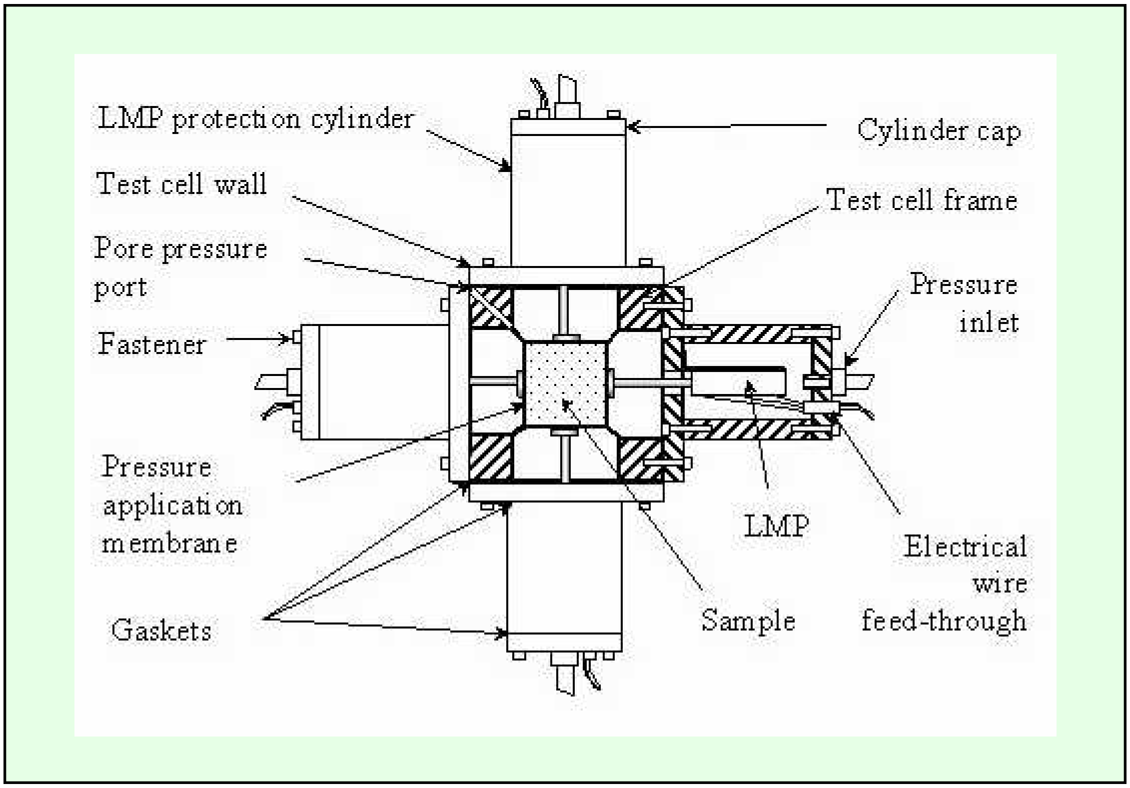


Figure 2. Cross-sectional view of test cell of the cubical triaxial tester

Basics

Powder mechanics provides the basic framework to analyze and describe the mechanical behavior of rootzone sands. Generally, the transmission of compression and failure forces follows a complex pathway through a sand bed. The volume reduction during compression occurs in four stages: 1) rearrangement of particles, 2) elastic deformation of particles, 3) plastic deformation and/or brittle fracture of particles, and 4) compression of the solid crystal lattice. The various mechanisms are not necessarily sequenced as listed, but may act simultaneously.

In the case of sand compaction, due to the low pressures (~ 200 kPa), the dominant stages are those of slippage, rearrangement and onset of elastic deformation. Limited localized initial elastic deformation is expected in the particle-to-particle contact zone. However, in certain cases (such as angular sands), plastic deformation or brittle fracture of particles may take place.

To characterize the compressibility of rootzone sand mixtures, bulk modulus and volumetric strain values are presented. These two parameters provide a wealth of information about sand mixtures' compressibility. The bulk modulus (an elastic property of the rootzone sand mixtures) quantifies the resistance to volume change. Accordingly, a higher value indicates that the rootzone sand can withstand higher forces to bring about the same volume change. Volumetric strain is simply the volume change that is referenced to the original volume. In this article the usual sign convention is used (i.e., positive values indicate compression and negative values indicate expansion or extension).

Failure of sand bed occurs when the rootzone mixture cannot withstand the shear forces responsible for distorting the stable sand structures. The continuing deformation leads to less and less stable structure which culminates in total collapse. In most instances, the failure of the sand bed structure is accompanied by volume expansion, a telltale sign that significant changes have occurred, or are about to occur.

To characterize the failure of rootzone sands, shear modulus and failure value are used. Rootzone sands that have higher shear modulus

Sand shape	Composition details	Nomenclature
Round	Monosized fraction of 0.375 mm particles	Round_375
	50:50 mixture (by mass) of 0.375 and 0.675 mm particles	Round_500
	Monosized fraction of 0.675 mm particles	Round_675
Angular	Monosized fraction of 0.375 mm particles	Angular_375
	50:50 mixture (by mass) of 0.375 and 0.675 mm particles	Angular_500
	Monosized fraction of 0.675 mm particles	Angular_675

Table 1. Specifications of monosize and binary sand mixtures for compressibility and failure testing

offer greater resistance to distortion (i.e., tend to be more stable). Similarly, higher failure values for a given rootzone sand mixtures imply greater stability. Together, these two parameters provide quantitative information about rootzone sands' stability response.

Measurement Devices

Specifications of the monosize and binary mixture of rootzone sand results reported in the article are given in Table 1. Initial porosity and bulk density of the four sands were measured during sample preparation. True density (density of sand grain) was also measured by using Quanta Chrome™ MultiPycnometer. Tests were conducted using a cubical triaxial tester (cover photo and Figure 2)) developed by Li and Puri (1, 2).

In this tester, 0 to 700 kPa air pressure (low pressure setting) or 0 to 35 MPa gas pressure (medium pressure setting) can be applied to the six surfaces of a 50.8 X 50.8 X 50.8 mm cube-shaped powder specimen via flexible rubber membranes. The pressure in vertical direction (top-bottom faces of the powder specimen) and the pressure in horizontal direction (left-right faces and front-back faces) can be controlled independently. Data measured and collected in the tester are pressures and displacements (deformation) in three orthogonal directions (i.e., vertical direction and two perpendicular horizontal directions).

A large number of tests at varying loading and loading rates, and loading boundary conditions have demonstrated the precision and robustness of this test device. The cubical triaxial tester can be used to measure compression behavior, flow properties, strength, 3-D stress-strain load-response, and time-dependent mechanical behavior of rootzone mixtures and particulate materials. Using the CTT, the rootzone sands were tested for their compressibility and failure responses.

Initial porosity, bulk density and sand particle density

The particle density of all sands is nearly 2.64 g/cc as shown in Table 2, which is almost

Sand shape	Nominal particle size (mm)	Initial porosity* (%)	Initial bulk density** (g/cc)	Sand particle density (g/cc)
Round	0.375	38.8	1.61	2.65
	0.500	40.4	1.57	2.64
	0.675	42.0	1.53	2.64
Angular	0.375	47.5	1.39	2.63
	0.500	46.9	1.40	2.64
	0.675	48.9	1.35	2.64

Table 2. Initial porosity, bulk density and particle density values. * Initial porosity values were calculated based on measured initial bulk density and true density values. ** Standard deviation values of initial bulk density were 0.00 except for Angular_675 sand, which had a standard deviation value of 0.01.

identical to the theoretical density of quartz (2.65 g/cc). From Table 2, round sand mixtures had lower porosity values (~ 39-42%) compared with angular sand (~ 47-49%) mixtures. Clearly, the porosity of a microstructure tends to increase with angularity. In the case of Angular_500 sand, the particles do not properly orient, thereby leading to the large voids in the packing and increased porosity values (~ 47%). The porosity value of the Angular_500 mixture was slightly less than Angular_375 porosity values by 1.26%.

Therefore, in the 50:50 mixtures, the smaller size particles fill the available void spaces; however, the pore sizes are not sufficiently large enough to fill all the void interstices to produce a denser structure. Similar observations can be made for initial bulk density values.

Compressibility of sand mixtures

A typical compressibility response of Round_375 sand samples is shown in Figure 3. The response profile includes one unloading-reloading curve at 50 kPa. From Figure 3, the following observations were noted:

The compression response of the sand samples is path-dependent and nonlinear, i.e., the response depends on previous loading history.

During unloading and reloading there is certain recovery, which, as a result, exposes some irrecoverable (or permanent) compression.

The mean compressibility responses of six sand compositions are shown in Figure 4. From Figures 4a and 4b, the angular sand was more compressible than round sand regardless of particle size. Among the three groups of sands, the 50:50 sand mixtures were clearly less compressible than 0.375 mm and 0.675 mm sands. However, the 0.375 mm sands had slightly less compressibility compared with 0.675 mm sands.

As expected, the volumetric strain (volume change of sand mixture per unit original volume) values tend to increase with pressure. The differences in volumetric strain values can be attributed to the differences in initial bulk density or initial porosity values. The microstructure of the angular sands was much more porous com-

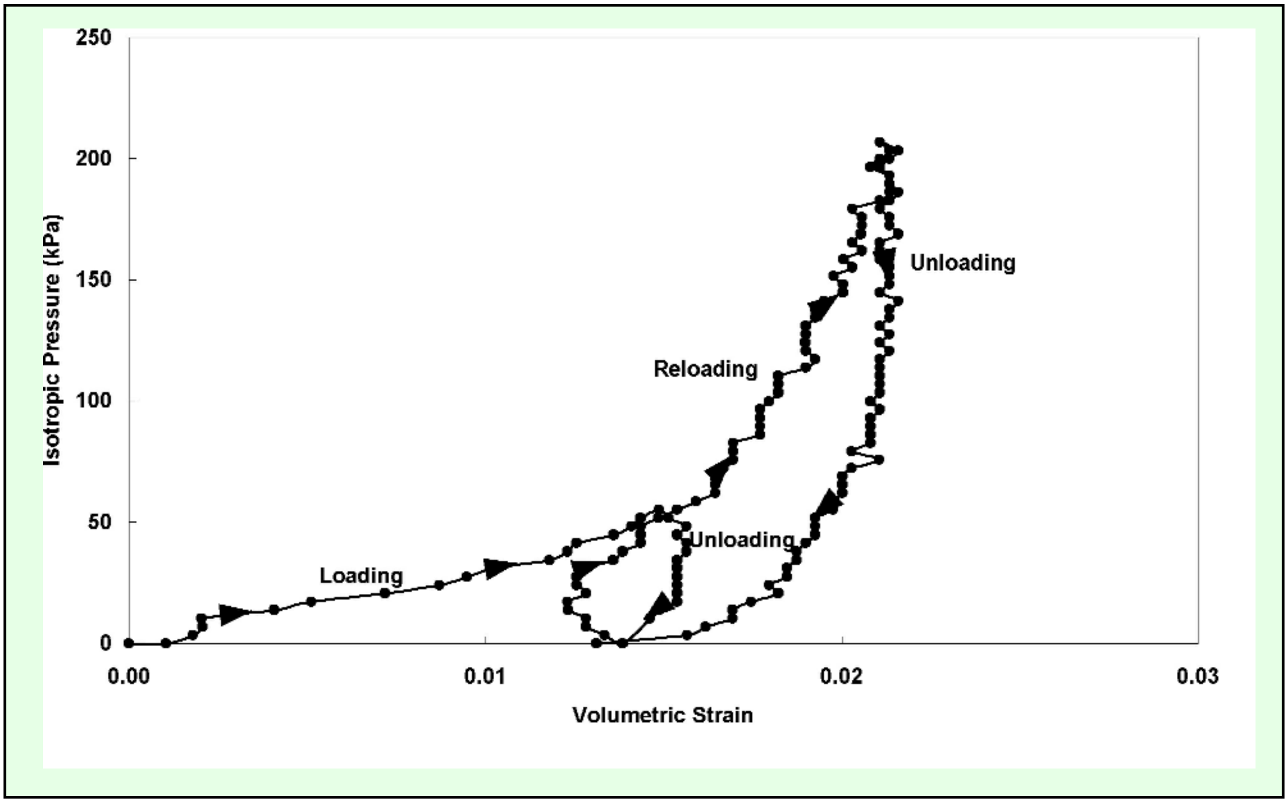


Figure 3. Typical compression response of Round_375 sand sample showing loading, unloading, and reloading response segments

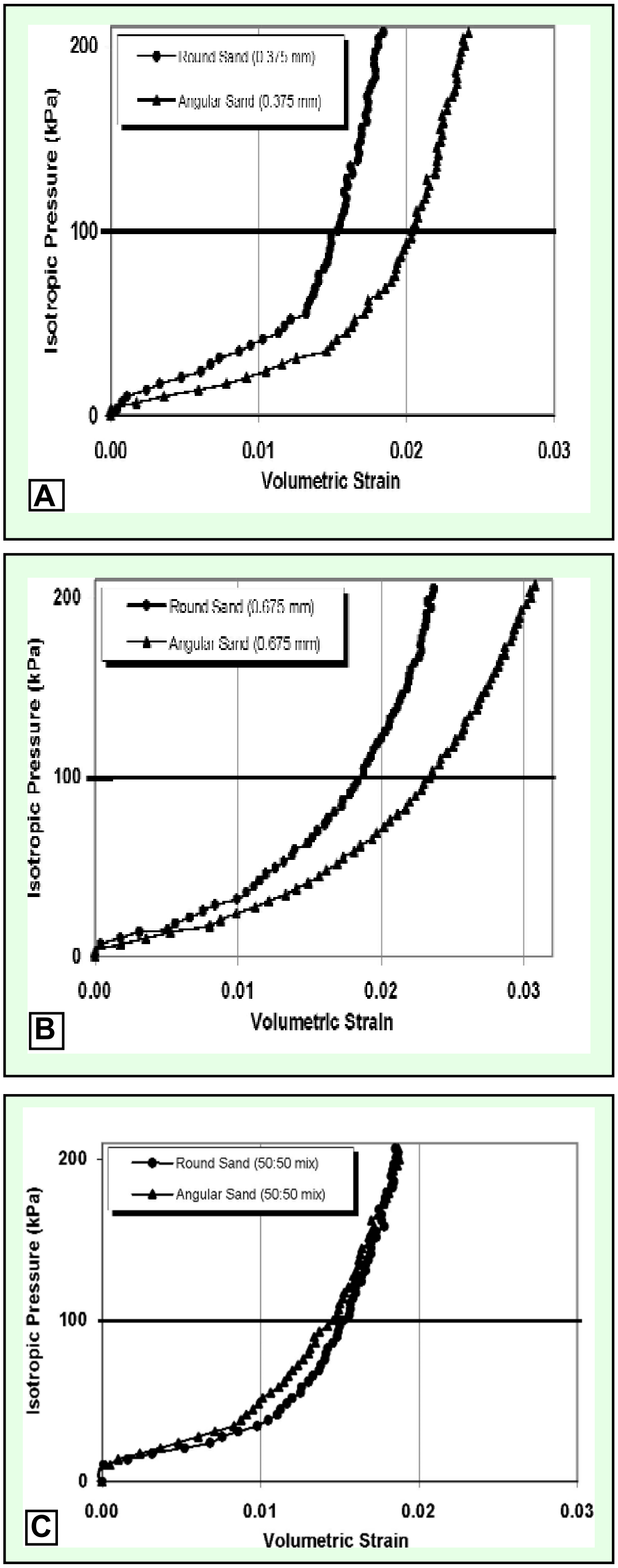


Figure 4. Comparison of the compressibility of sands with different particle sizes and shapes. **A** compares 0.375-mm round versus angular sand; **B** compares 0.675-mm round versus angular sand; and **C** compares 50:50 mixes of 0.375 mm and 0.675-mm round verus angular sand.

pared to that of the round sands. Hence, the stage of particle rearrangement was much more pronounced in case of the angular sands and, therefore, the higher volumetric strain values were observed for angular sands. In case of the monosized sands, due to the high sphericity of the round sand particles, the microstructure was much more stable leading to lower volumetric strain values compared to the monosized angular sands.

One observation that deserves mention is the 50:50 mixes have better compaction resistance, (i.e. retaining porosity) than both the 0.375 mm and 0.675 mm sands. For the binary mixtures, the smaller Round_500 particles packed much more tightly in the void spaces between larger Round_500 particles size. Therefore, particle size grading is much more effective in the case of Round_500 sand leading to lower volumetric strain values than Angular_500 values. However, the difference between the volumetric strain values of the 50:50 mixtures of the two sands is not large, indicating that binary mixtures are more stable than monosized fractions for any sand shape.

Stages of compression

An in-depth analysis of the compressibility profiles revealed three distinct predominantly rearrangement stages during compression. However, the mechanisms for filling of the voids are different (3). These three compressibility stages, shown in Figure 5, are summarized as follows.

During Stage I of compression, the volume reduction is proportional to applied pressure. This volume reduction is independent of particle size. In Stage I, the large voids present during sand deposition are filled by collapse of the local structure in the voids vicinity, which is shown as segment AB in Figure 5.

During Stage II, the voids continue to fill rapidly. However, the rapid filling of available voids slows down as their availability declines. This stage of compression is noticeable by an ever-present knee-shaped portion of the response curve shown as segment BC in Figure 5.

At the conclusion of Stage II, rearrangement of particles (i.e. filling of voids) is nearly

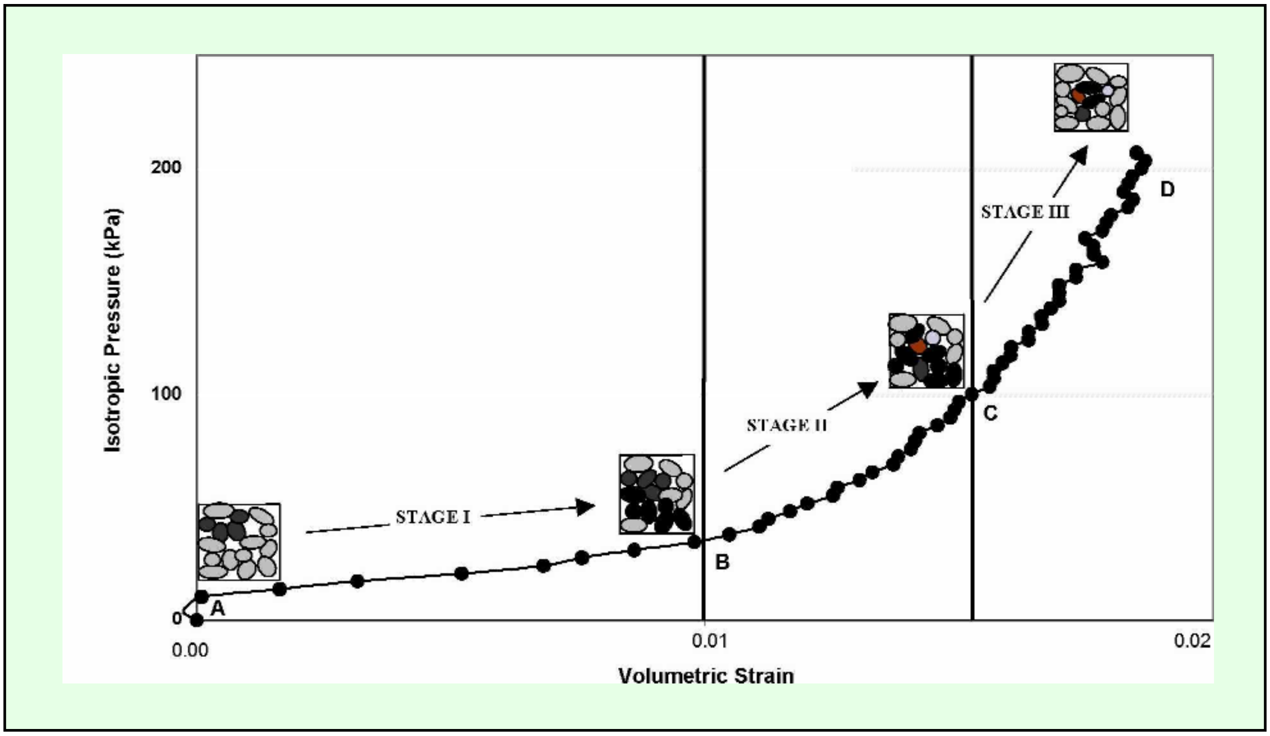


Figure 5. Compression stages for monosize and binary rootzone sand mixtures.

complete. Then the localized, i.e., at contact point, initial particle deformation stage commences at point C to the end of loading at point D (Figure 5).

Bulk modulus

Bulk modulus of sands indicates the resistance to elastic deformation during compression. Average bulk modulus values are listed in Table 3. Generally, the bulk modulus (K) values increase as the pressure increases. Doubling of pressure from 34.5 kPa to 69 kPa, the bulk modulus of Round_675 increased 143%, quadrupling of pressure to 138 kPa resulted in increase of 154%. Similar trends were also observed for Angular_675 sand.

Particle shape	Nominal particle size (mm)	Pressure (kPa)	Average bulk modulus (kPa)
Round	0.375**	55	7740
	0.500	34*	2940
		69	6900
	0.675	34*	6770
		69*	9690
		138	10400
Angular	0.375**	69*	8760
	0.500	34*	1430
		69	6250
	0.675	34*	2340
		69	5020
		138	8120

Table 3. Average bulk modulus values of sands at different pressures. * Averaged with only two test runs. **Data at 69 kPa was not available.

Sands comprising of larger particle sizes had larger K values compared with smaller particles and binary mixtures. This trend in bulk modulus values is consistent with previous observations of compression profiles since larger monosized sand particles had higher initial porosity values. Consequently, initial voids accentuate plasticity of sand mixtures and result in smaller recovery.

However, round particle sands have greater bulk plasticity in spite of their lower compressibility and initial bulk density, which results in larger bulk modulus than angular sands. This is attributed to the angular shape of particles that form unstable structures or are in meta-stable equilibrium state. Therefore, angular sands are more prone to moves and shifts in orientation and structure during release of applied pressure.

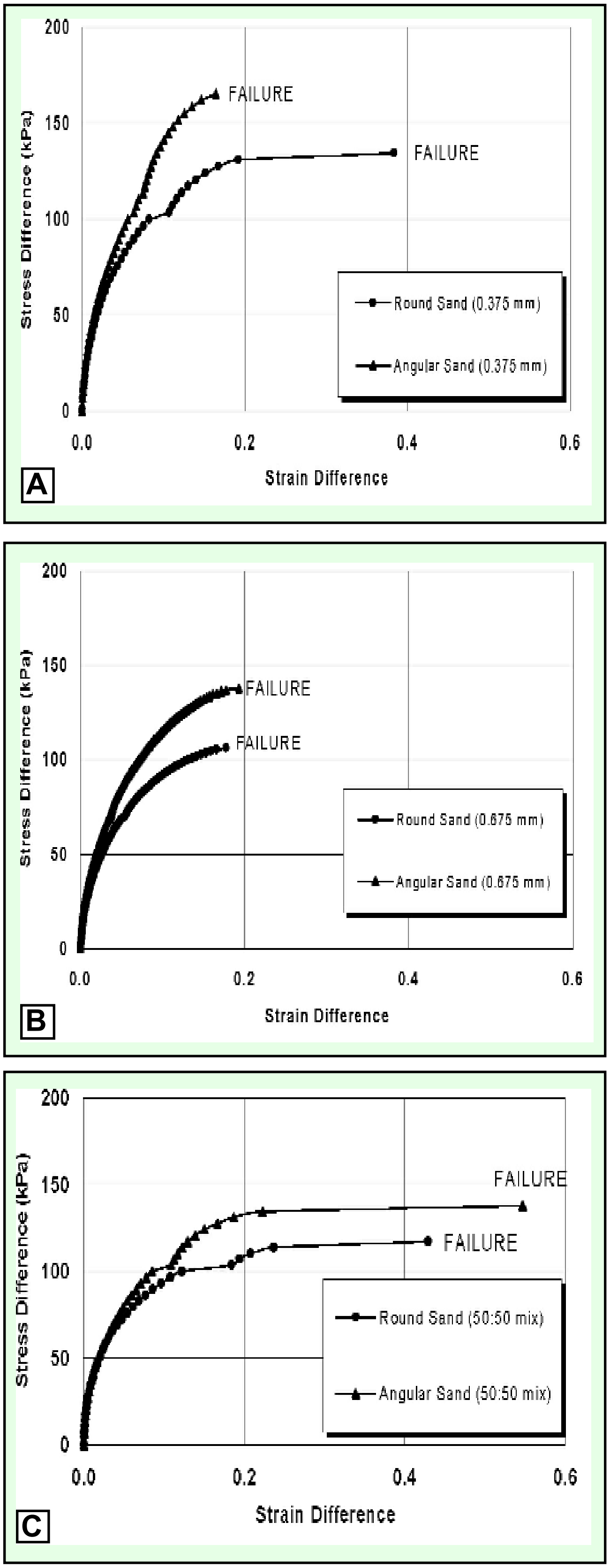


Figure 6. Comparison of shear responses to failure for different size fractions and shapes. A compares 0.375-mm round versus angular sand; B compares 0.675-mm round versus angular sand; and C compares 50:50 mixes of 0.375 mm and 0.675-mm round verus angular sand.

Failure strength

Typical failure strength-related curves for the two sand shapes and 0.375 mm and 0.675 mm particle sizes and binary mixtures are given in Figure 6. These shear responses to failure are at 34.5 kPa confining (i.e., holding) pressure. Generally, failure strength of angular sands was higher than round sands due to the greater interlocking between angular particles. The mean failure strengths of the six sands are shown in Table 4.

For the 0.375 mm sands, at both 17.2 kPa and 34.5 kPa confining pressures, the strength of angular sand is higher than the round sand by 14% and 64% (Table 4). In the case of 0.675 mm sands, at 17.2 kPa confining pressure, the round sand is most prone to failure. Therefore, golf courses constructed of round sands are likely to fail more often compared with Angular_675 sands. At 34.5 kPa confining pressure, the similar trend is observed (Table 4).

Particle shape	Nominal particle size (mm)	Confining pressure (kPa)	Average failure stress (kPa)
Round	0.375	17.2 34.5	84 178
	0.500	17.2 34.5	86 154
	0.675	17.2 34.5	52 108
Angular	0.375	17.2 34.5	119 202
	0.500	17.2 34.5	100 174
	0.675	17.2 34.5	65 139

Table 4. Failure strength values for monosize and binary sand mixtures

For the 50:50 mixtures, at both 17.2 and 34.5 kPa confining pressures, the strength of the bulk angular sand is 14-16% higher than the bulk round sands. From physical standpoint, the angularity of sand particles promotes the particle interlocking effect, which resulted in increase in strength for sands.

Based on particle size, at both 17.2 and 34.5 kPa confining pressures, the failure strengths of 0.375 mm > 50:50 mix (0.5 mm of nominal size) > 0.675 mm. Clearly, smaller particle sizes

Particle Shape	Particle size (mm)	Confining Pressure (kPa)	Average Shear Modulus (kPa)
Round	0.375	17.2	996
		34.5	1046
	0.500	17.2	544
		34.5	732
	0.675	17.2	914
		34.5	1512
Angular	0.375	17.2	803
		34.5	1180
	0.500	17.2	749
		34.5	1145
	0.675	17.2	1626
		34.5	2406

Table 5. Shear modulus values of rootzone sands

tend to make a stronger bulk, and consequently, raise the failure strength. The measured increases were from 40% to 65%.

Shear modulus

The shear modulus (G) values increased with increase in mean pressure for all samples (Table 5). When the confining pressure was doubled, sands comprising of round shape particles had an increase of 35% in shear modulus. For angular sands, the observed increase was nearly 50%. From particle shape perspective, angular sands have higher shear modulus values (i.e., one to five times larger than round sands). From the particle size perspective, larger particle size sands have larger shear modulus values.

Conclusions

Two types of rootzone sands (round and angular) that are commonly used to prepare putting greens of golf courses were studied using the cubical triaxial tester. Two monosize sands (0.375 mm and 0.675 mm) and their binary mixtures were tested. From the experimental results and analysis, the following conclusions were drawn.

Round sand had initial bulk density values ranging from 1.53-1.61 g/cc. The angular sand had initial bulk density values ranging from 1.35-1.40 g/cc. The round sand had lower porosity values (~39-42%) compared with angular sand which had high porosity values (~47-49%). Therefore, it was concluded that the porosity of a microstructure tends to increase with angularity.

In general, angular sand was more compressible than round sand. Angular sand had an average volumetric strain value from 1.2 to 3.1%; whereas, round sand had an average volumetric strain value from 1.5 to 2.4%.

The bulk modulus values demonstrated an increasing trend with increasing pressure. This was observed for all sand shapes and all mixtures. Among the two sand shapes, angular sand had smaller bulk modulus values.

Generally, failure strength of the angular sands was higher than that of round sands. From a physical standpoint, the angularity of sand particles promotes the particle interlocking effect, which results in increase in sand's failure strength. Among all the different types of sand mixtures, Angular_375 sand has higher failure stress values.

It was observed that the shear modulus values increased with increase in mean pressure for all samples. When the confining pressure was doubled, sands comprising of round shaped particles had an increase of 35% in shear modulus. For angular sands, the observed increase was nearly 50%. From particle shape perspective, angular sands have much higher shear modulus values, for example, one to five times than round sands. From the particle size perspective, larger particle size sand mixtures have larger shear modulus values.

Acknowledgements

This study was made possible by a grant from the USGA. This article has been adapted from a more comprehensive publication by Yi et al. (2001).

Literature Cited

1. Li, F. and V.M. Puri. 1996. Measurement of anisotropic behavior of dry cohesive and cohesionless powders using a cubical triaxial tester. *Powder Technology* 89: 197-207.

2. Li, F and V.M. Puri. 1997. Development of a medium pressure flexible boundary cubical triaxi-

al tester for measuring mechanical behavior of particulate materials. Pages 313-321. *In:* R. Hogg, C. C. Huang and R. Cornwall (eds.). Proceedings of Fine Powder Processing Technology International Conference, 1997. Penn State, University Park, PA.

3. Yi, H., F. Li, B. Mittal, V. M. Puri, and C. F. Mancino. 2001. Measurement of bulk mechanical properties and modeling the load-response of rootzone sands: Part 1, Round and angular mono-size and binary mixtures. *Particulate Science and Technology* 19(2):145-173. (TGIF Record 83105)