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This laboratory study at Purdue University evaluated the physical properties and visual characteristics of more than 20 bunker sand materials. No single sand physical property or combination of properties which included particle size distribution, coefficient of uniformity (Cu), gradation index (GI), geometric mean particle diameter (GMD), or angle of repose was able to accurately predict sand firmness or resistance to golf ball penetration.

Volume 7, Number 3
February 1, 2008

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 350 projects at a cost of $29 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***.

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The demand for manicured perfection throughout the entire golf course have resulted in unrealistic player expectations for perfect lies, even in areas defined as "hazards". For the golf course manager this results in the pursuit of consistently firm, smooth bunker surfaces.

maintains firmness, drains quickly, does not easily erode from slopes after moderate rainfall or irrigation, and is sized similar to those used for sand-based rootzones (9) so when it is splashed onto the putting surface it does minimal damage to the mowing equipment when picked up during mowing and does not negatively impact the composition of the sand-based rootzone over time.

Currently, there are no clear specifications for golf course bunkers sands, and the information that does exist serves primarily as a guideline which is based mostly on sand particle size distribution (PSD) and a measurement of surface firmness. In general, it is suggested that bunker sands should have a large majority of the particles in the 0.25-1.0 mm range (8). In terms of sand mineralogy, silica sand is often preferred since silica resists weathering and retains its original shape longer. Other materials may also be suitable, however, limestone sands are more prone to weathering and may result in significant fine particles over time which can affect drainage and playability.

In terms of sand particle size distribution, previous research has documented that particle size distribution greatly influences sand strength and, specifically, that the quantity and ratio of fine textured particles can have a strong influence on strength (3, 4). These authors suggest that when evaluating a particle size distribution based on its coefficient of uniformity (Cu), higher Cu values for sands are preferred and that the Cu could be adjusted by adding a small percentage of finer textured particles such as native sandy-loam soil. In their studies increasing the Cu value from 1.8 to 3.0 resulted in a doubling of the sand's bearing capacity or, in essence, a much firmer sand rootzone surface (3, 4). For bunker sands that need to infiltrate and drain rapidly, the addition of significant fines would be risky, as it may result in excess water retention and make the sand more prone to erosion when installed on slopes.

In addition to particle size distribution, sand particle shape has a strong influence on playing quality and maintenance. Particle shape is classified by examining both the relative sharpness of particle edges and the overall particle shape, referred to as angularity and sphericity, or roundness. These characteristics can have a strong influence on surface firmness and resistance to erosion. For example, a low-sphericity, very angular sand generally has a high surface strength and would likely stay in place on bunker faces. By contrast, a high-sphericity, rounded sand is more likely to be soft and more prone to erosion during regular maintenance or following irrigation and rainfall events.

Complicating the bunker sand selection process is that subjective qualitative characteristics such as color or immediate cost often strongly influence the final decision with little thought being placed on the possible implications regarding long-term maintenance needs or costs.

The objectives of this laboratory study were to: (1) characterize the physical properties of a wide variety of commercially available sand-sized materials that are being used in golf course sand bunkers and (2) determine if certain physical properties can be used as reliable predictors for sand surface hardness or resistance to golf ball penetration as measured using a modified pocket penetrometer.

Materials and Methods

Twenty-six sand materials were collected from a variety of sand suppliers from across the United States (Table 1). Approximately one gallon of each sample was obtained, air-dried, and well mixed prior to analysis. Sub-samples (60

Sand	Particle size distribution								Calculated property		
	>2.0	1.0	0.5	0.25	0.15	0.1	0.05	<0.05	GMD [†]	Cu [‡]	GI [§]
	g kg^{-1}								--mm---	unitless	
Autumn Gold	7	45	64	532	305	24	9	15	0.60	2.00	3.24
Bunker Sand	1	79	261	375	217	27	29	11	0.66	3.63	2.00
Caylor White Sand	3	46	193	599	127	9	5	18	0.66	1.82	3.32
Crushed Limestone	3	363	548	67	11	3	4	1	0.95	1.86	3.53
Extra Firm Bunker Sand	1	59	198	337	263	76	48	17	0.59	2.85	6.23
Fine Topdressing Sand	0	2	2	127	462	190	165	53	0.35	3.60	2.40
Glass beads	0	0	296	704	0	0	0	0	0.71	1.61	2.57
Gray Walreth Double Wash	0	17	204	584	137	16	12	30	0.63	2.22	3.83
Green Plus	6	130	270	448	110	6	5	26	0.71	2.38	5.24
Holliday (Banner Springs)	2	24	173	545	191	38	23	4	0.63	3.94	2.24
Holliday (Miss. River)	1	55	270	533	137	3	0	0	0.70	3.70	1.91
Klassic White Sand	8	77	173	515	206	6	3	12	0.67	2.11	4.74
Kosse White B.S.	2	6	37	372	518	37	13	14	0.54	1.47	2.41
Orlando White	4	31	108	430	314	41	20	52	0.55	2.20	3.87
Pro Angle	10	163	328	281	149	30	19	21	0.72	3.33	7.78
Pro White Bunker Sand	0	8	86	649	204	21	10	21	0.60	2.50	4.69
Putting Green Sand	0	48	324	503	84	14	14	13	0.70	5.28	2.56
Shelby Bunker Sand	9	69	306	473	121	6	4	12	0.71	2.00	3.79
Sidley # 1600	10	12	70	415	379	77	35	2	0.56	2.25	4.17
Stone White Sand	0	0	0	350	555	40	14	41	0.50	1.53	2.53
Tan Bunker Sand	3	58	410	401	81	13	10	23	0.71	2.43	3.96
Tour Grade 50/50	43	184	190	307	192	24	13	47	0.68	2.72	8.89
Tour Grade 535	0	14	59	493	370	28	23	12	0.57	1.82	2.76
Tour Grade Signature	58	193	190	315	181	23	17	22	0.71	3.06	8.89
USGA Bunker Sand	0	35	220	495	194	19	10	27	0.63	2.35	8.41
White Bunker Sand	0	35	227	462	197	39	25	14	0.63	4.76	2.65

[†] Geometric mean particle diameter (GMD) = calculated from the sand particle size distribution.

[‡] Cu (Coefficient of uniformity) = where D60/D10; "acceptable value" = 2 to 4, higher value = less uniformity, optimum value = 2 to 3, a value < 2 less likely to pack tightly.

[§] GI (Gradation index) = where D90/D10; lower values indicate a higher potential for surface instability, acceptable range 3 to 6, preferred range 4 to 5.

Table 1. Particle size distribution and calculated physical properties of commercially available sand materials from various regions in the United States.

grams) from the center of each sand were removed and oven dried to determine particle size distribution (PSD) using both the pipet method and dry sieving on three replicate samples. The remaining sand was used to determine sand firmness as measured by resistance to penetration with a modified pocket penetrometer (2).

Briefly, each sample was placed into the standard measurement vessel (a rigid wooden box with interior dimensions of 11.4 x 12.7 cm) and compacted to a 7.6 cm depth. The modified penetrometer was inserted using even and steady pressure until half the depth of a USGA-approved golf ball was buried. The value was recorded and the device reset. This procedure was replicated five times, and between measurements the sand surface was re-smoothed and re-packed.

To determine angle of repose, 20-gram samples of oven-dried sand were placed in a 26-mm diameter plastic centrifuge tube with a 5-mm diameter opening at the bottom which was mounted perpendicular to a standard microscope stage. On the microscope stage, a circular pad marked with a measurement scale (marked in mm) radiated out from a central point. The tube was placed flush in the center of the measurement scale and the sand was installed. The tube was raised slowly and steadily until all sand exited. The distance from the center of the scale to the edge of the resultant sand cone was recorded at eight locations and the height of the sand cone measured using calipers to the nearest mm. This process was repeated three times and the average radius and cone height were used to calculate angle of

Sand	Sphericity	Angularity	GMD[†]	Cu[‡]	GI[§]	Angle of repose
			-- mm --			--- degrees ---
Autumn Gold	Medium	Sub-angular	0.60	2.00	3.24	30.3
Bunker Sand #1	Medium	Sub-angular	0.66	3.63	2.00	31.1
Bunker Sand #2	Medium	Sub-rounded	0.63	2.35	8.41	30.9
Caylor White Sand	Low	Angular	0.66	1.82	3.32	32.5
Crushed Limestone	Medium	Angular	0.95	1.86	3.53	34.9
Extra Firm Bunker Sand	Medium	Sub-angular	0.59	2.85	6.23	31.6
Fine Topdressing Sand	Medium	Sub-rounded	0.35	3.60	2.40	30.4
Glass beads	High	Rounded	0.71	1.61	2.57	21.8
Gray Double Wash	Medium	Sub-angular	0.63	2.22	3.83	34.4
Green Plus	Medium	Sub-angular	0.71	2.38	5.24	33.1
Holliday (Banner Springs)	Medium	Sub-angular	0.63	3.94	2.24	32.0
Holliday (Miss. River)	Medium	Sub-angular	0.70	3.70	1.91	31.4
Klassic White Sand	Low	Angular	0.67	2.11	4.74	34.8
Kosse White B.S.	Medium	Rounded	0.54	1.47	2.41	30.8
Orlando White	Medium	Sub-angular	0.55	2.20	3.87	31.6
Pro Angle	Medium	Very angular	0.72	3.33	7.78	33.1
ProWhite Bunker Sand	Low	Very angular	0.60	2.50	4.69	33.4
Putting Green Sand	Medium	Sub-angular	0.70	5.28	2.56	32.2
Shelby Bunker Sand	Medium	Sub-rounded	0.71	2.00	3.79	31.6
Sidley # 1600	Medium	Sub-angular	0.56	2.25	4.17	32.4
Stone White Sand	Medium	Sub-angular	0.50	1.53	2.53	32.9
Tan Bunker Sand	Medium	Sub-angular	0.71	2.43	3.96	34.2
Tour Grade 50/50	Medium	Sub-angular	0.68	2.72	8.89	35.4
Tour Grade 535	Medium	Sub-angular	0.57	1.82	2.76	30.7
Tour Grade Signature	Low	Angular	0.71	3.06	8.89	33.9
White Bunker Sand	Medium	Sub-angular	0.63	4.76	2.65	34.6

[†] Geometric mean particle diameter (GMD) = calculated from the sand particle size distribution.

[‡] Cu (Coefficient of uniformity) = where D60/D10; "acceptable value" = 2 to 4, higher value = less uniformity, optimum value = 2 to 3, a value < 2 less likely to pack tightly.

[§] GI (Gradation index) = where D90/D10; lower values indicate a higher potential for surface instability, acceptable range 3 to 6, preferred range 4 to 5.

Table 2. Sand particle shape characteristics, calculated physical properties, and angle of repose of commercially available sand materials from various regions in the United States.

The data most helpful for determining surface hardness is the modified pocket penetrometer test. This test, however, has met with some criticism due to perceived reliability and variability in measurements among users.

repose. Additionally, each sand was visually evaluated for overall particle shape and color using angularity/sphericity and Munsell color charts (data not presented), respectively.

The particle size distribution of each sand was used to calculate geometric mean diameter (GMD), coefficient of uniformity (Cu), and gradation index (GI) (5, 6, 7). In addition to the bunker sand materials, three materials were included for general comparison and these "standards" included a medium-coarse putting green rootzone sand, a medium-fine topdressing sand, and rounded laboratory glass beads.

What We Discovered

In this laboratory study we evaluated a variety of commercially available sand products from several regions of the United States. The sands included naturally mined sands, screened and washed sands, as well as some manufactured sands generated by a rock-crushing process. In addition to the bunker sand products, three sand-sized materials were included for general comparison. These "standards" included a putting green rootzone sand, a fine sand topdressing and laboratory glass beads. All sands were evaluated for visual characteristics such as particle shape and color but also for their general physical properties (Table 1).

As expected, sand color varied widely ranging from white to cream, tan and brown (data not presented). Of all selection characteristics, color appears to be the most subjective criteria and should be one of the last factors considered when selecting a sand for bunker use. Probably one of the more routine measurements conducted on sands is that of determining the sand's particle

One additional measurement that may help laboratories predict sand firmness is the angle of repose (Table 2). This measurement which is a calculation expressed as degrees is derived from measuring the mean diameter of the base and apex height of a dry sand cone. As one would expect, coarser textured, more angular sands with wider PSDs are more likely to stack higher result in a narrower base and taller cone apex and ultimately a greater angle of repose.

size distribution. Once the particle size distribution is determined, this data can sometimes be used to infer physical performance characteristics. Three properties, geometric mean diameter (GMD), the coefficient of uniformity (Cu), and gradation index (GI) were calculated from the particle size distribution. As expected, there was a wide range in particle size distribution which resulted in quite a bit of variation in the associated calculated values.

For geometric mean diameter (GMD), which is one method for distilling a particle size distribution (PSD) down into a single value and provides an overall sense for the relative coarseness or fineness of the sand, values ranged from 0.35 - 0.95 mm (Table 1). Although this is a convenient method for reducing a PSD down into a single manageable value, it can also be somewhat misleading. For example, the laboratory glass beads had a very narrow PSD with 100 % of the particles in the 0.5 and 0.25 mm size classes, and a GMD of 0.71. This value was similar to five other sand materials including the standard putting green sand (GMD = 0.70), which contained a much wider range of particle size classes.

Based on the very narrow particle size distribution of the glass beads, it would be predicted that this material would be rather unstable or soft, simply due to the lack of bigger or smaller size classes necessary to fill in voids around the existing two size classes and increase surface stability. In general, however, for a bunker sand, a mini-

Penetrometer Value (kg cm^{-2})	Potential for Golf Ball Burying	Number of Sands in Each Category
> 2.4	Very low tendency to bury	2
2.2-2.4	Slight tendency to bury	2
1.8-2.2	Moderate tendency to bury	6
< 1.8	High tendency to bury	15

Table 3. Interpretation of modified penetrometer test values and their influence on performance characteristics for bunker sands (Thomas Turf Services) as well as the number of sands falling into the various firmness categories.

mum value > 0.5 mm would be desirable because below this value the sand may drain too slowly when installed in low lying bunker bottoms. This would result in wet or soft playing conditions.

For the coefficient of uniformity (Cu), which is a numerical expression of how uniform the particle sizes are and another value that could be utilized to predict how likely sand particles are to pack, the values ranged from 1.47 - 5.28. Some references suggest that "acceptable" Cu values are between 2 and 4 (6). In general, a higher value suggests less uniformity and a greater range of particle sizes. Cu values below 2 suggest a tendency for the particles to pack less tightly. Of the sands evaluated, 19 of the 26 sands fell within the "acceptable" range.

A similar calculated property is the gradation index (GI), for which values ranged from 1.91 - 8.89. For GI values, lower values indicate a higher potential for surface instability with a suggested "acceptable range" of 3 to 6, and a preferred range of 4 to 5. For these sands, eleven of the twenty-six fell in the "acceptable" range while only three were in the "preferred" range and included Green Plus, Pro White Bunker sand, and Sidley # 1600.

In addition to analysis of data associated with the PSD, visual inspection of the sand particles resulted in a substantial variation. For sphericity or roundness, the sands ranged from low to high, with most sands possessing a medium sphericity. The laboratory glass beads were, of course, highly spherical. For angularity, the sands ranged from sub-angular to very-angular, with the majority of sands possessing a sub-angular shape. In general, a more angular and less rounded sand has a higher tendency to pack tightly and result in a desirable firm sand characteristic.

One additional measurement that may help laboratories predict sand firmness is the angle of repose (Table 2). This measurement which is a calculation expressed as degrees is derived from measuring the mean diameter of the base and apex height of a dry sand cone. As one would expect, coarser textured, more angular sands with wider PSDs are more likely to stack higher result in a narrower base and taller cone apex and ultimately a greater angle of repose. For the sands evaluated in this study, the angle of repose values ranged from 21.8 - 35.4 degrees. The lowest values occurred for the rounded laboratory glass beads and the highest value was associated with Tour Grade 50/50. Most sands had an angle of repose between 31 and 32 degrees.

Relating Physical Properties to Sand Firmness

Besides the highly subjective characteristic, color, one of the most important bunker sand properties is firmness manifested as resistance to golf ball penetration or the sand's ability to avoid producing a buried golf ball lie. The values for the modified pocket penetrometer ranged from 1.22 - 3.31 kg cm^{-2}, with values of 1.66 and 1.59 kg cm-2 for the mean and median penetrometer values respectively (data not presented).

When interpreting this data, the scale most often used is presented in Table 3. This scale indicates that a lower threshold of 1.8 kg cm^{-2} be considered the value below which a sand would be most prone to producing a buried or plugged golf ball lie. Of the sands evaluated, 10 sands had a penetrometer value > 1.8 kg cm^{-2}, while the majority of the sands were between 1.2 and 2.2 kg cm^{-2}. As expected, the rounded laboratory glass beads with a narrow particle size distribution and spherical shape had the lowest penetrometer value of 0.1 kg cm^{-2} and would be considered "softest". Generally values > 2.2 kg cm^{-2} would be desirable because above this value the sand would most likely only have a slight or no tendency to produce a buried golf ball lie (Table 3).

Conclusion

When evaluating all the physical data for these bunker sands, no single measured or calculated property (e.g. Cu or angle of repose) was a strong indicator or predictor for penetrometer values. Although 10 sands had penetrometer values > 1.8 kg cm^{-2}, which is the suggested threshold for an "acceptable" dry sand firmness value, only five sands were > 2.2 kg cm^{-2}. In an attempt to relate these physical property data to penetrometer values, linear regression was conducted with the GI, Cu, and angle of repose data. The results of these analyses resulted in R^2 values of 0.0715, 0.0051, and 0.2566, for the GI, Cu, and angle of repose data, respectively. In other words, due to the high degree of variability, there was little to no relationship between these properties and sand surface firmness.

As an example of the variability present in these sand properties, one of the crushed sand products had the highest penetrometer value, 3.31, but also possessed a Cu and GI value of 1.86 and 3.53, respectively. If one were to characterize this sand based solely on the Cu or GI data, they would predict that this sand would be less likely to pack since the Cu was < 2.0 and that it was barely "acceptable" regarding surface instability due to the GI value falling barely inside the 3-6 "suggested" range. Based on this information it is apparent that many properties likely influence sand surface hardness. These include particle size distribution, particle shape and other less quantifiable characteristics such as particle surface roughness.

Mechanically crushing minerals into sand-sized products certainly affects surface roughness. This rough particle surface architecture may allow particles to bridge or link with adjacent particles better than smoother naturally occurring materials. By contrast, however, the use of rough or highly angular particles may also have negative effects on turf health as there may be a higher chance for mechanical damage from turf abrasion when these sands are splashed onto putting greens and collars in locations where mowers turn sharply and often.

In summary, when evaluating sands for golf course bunker use, enlisting the assistance of an accredited testing laboratory is highly recommended. These laboratories can run a variety of physical analysis tests and be extremely helpful during the selection process. Besides the tests conducted in this study, these laboratories can also assess other properties like crusting potential, water retention, and infiltration rate. Additionally, these laboratories are probably familiar with many of the existing regionally available sands which may already have been characterized.

To date, the procedure most used for evaluating surface hardness is the modified pocket penetrometer test. This test, however, has met with some criticism due to considerable variability in measurements among users. One important point to make regarding this measurement is that it is conducted using dry sand in a non-flexible box, conditions not normally exhibited in the field. In reality, sand is installed on slopes of various slope angles, with or without sub-surface drainage, and at depths often exceeding 3 inches. All of these factors affect sand moisture content and ultimately, performance.

Additionally, sand in a typical bunker would rarely be subject to the lateral confinement that exists in the "test box". Thus, if an individual were to take an *in situ* penetrometer measurement in a real bunker, the observed value would likely be softer than what was obtained under laboratory conditions. In response to this concern, alternative more quantitative methods are currently under evaluation at several research laboratories. These methods include using various impact hammers like the Clegg impact tester to test for sand firmness. It is our hope that a more reliable test can be developed and correlated with other sand physical properties.

Acknowledgements

The authors wish to thank the USGA's Turfgrass and Environmental Research Program for its support of this project.

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