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How they measure up

Lab study analyzes physical properties of bunker sand

Because of the high variability and artificiality of the test set-up regarding penetrometer resistance, a revised version of this study, first printed in the March '08 issue of GCI, is presented regarding physical analysis of sands. In light of new methods recently introduced to test surface penetration (Brame, B. 2008. Affirming firmness. USGA Green Section Record 46(2):17-20), it was decided the data regarding penetrometer resistance determined from the use of the pocket penetrometer test wasn't sufficiently robust.

A lab study at Purdue University evaluated the physical properties and visual characterisitcs of more than 20 bunker sand materials.

Most golf hole architectural designs incorporate sand bunkers to add dramatic visual contrast and enhance aesthetic beauty while also adding challenge and strategy for golfers. Technically, golf course bunkers are considered hazards. However, for many of the courses in the United States, the demand for manicured perfection throughout the entire golf course has resulted in unrealistic player expectations for perfect lies, even in areas defined as hazards. For golf course managers, this results in the pursuit of consistently firm, smooth bunker surfaces.

Many recently constructed courses contain a few smaller well-positioned bunkers and vast bunker expanses. At many golf facilities, the amount of maintenance resources spent on bunker management rivals that spent caring for putting greens. Where sand is installed on steep slopes, regular erosion repair costs can be substantial and are compounded when improperly selected, highly erodable bunker sands are chosen.

Numerous sand-sized materials are available commercially and marketed for use in golf course sand bunkers. Often a particular sand might be chosen based on subjective characteristics, such as aesthetic appearance (many golf course architects prefer bright white sands), or subjective functional characteristics such as how a particular golfer perceives the playability of the sand. Generally, firm sand is preferred because it allows the golf ball to sit on top of the sand surface, resulting in an easier play from the hazard.

Sometimes the long-term consequences of these decisions based on subjective criteria, such as color, might not be realized immediately. A sand that's the desired color but is too coarse or has a predominance of round particles might necessitate additional labor to maintain playability. From a golf course manager's perspective, an appropriate sand for golf course bunkers is one that maintains firmness, drains quickly and doesn't easily erode from slopes after moderate rainfall or irrigation. It's similar in size to that used for sand-based root zones, so when it's splashed onto putting surfaces, it does minimal damage to equipment when picked up during mowing and doesn't impact the composition of the sand-based root zone negatively over time.

Currently, there are no clear specifications for golf course bunkers sands, and the information that exists serves primarily as a guideline based mostly on sand particle size distribution and a measurement of surface firmness. In general, bunker sands particles should be mostly in the 0.25 to 1.0 millimeter range. In terms of sand mineralogy, silica sand is often preferred because silica resists weathering and retains its original shape longer. Other materials also might be suitable. Limestone sands, however, are more prone to weathering over time and might result in significant fine particles that 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. The authors suggest, when evaluating a particle size distribution based on its coefficient of uniformity, higher coefficient of uniformity values for sands are preferred, and the coefficient of uniformity could be adjusted by adding a small percentage of finer textured particles, such as native sandy-loam soil. In their studies, increasing the coefficient of uniformity value from 1.8 to 3.0 resulted in a doubling of the sand's bearing capacity – in essence, a much firmer sand root-zone surface. For bunker sands that need to infiltrate and drain rapidly, the addition of significant fines is risky, as it might 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 the relative sharpness of particle edges and the overall particle shape, referred to as angularity and sphericity (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 likely will stay in place on bunker faces. By contrast, a high-sphericity, rounded sand is more likely to be soft and 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 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 being used in golf course sand bunkers.

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 throughout the United States (Table 1). About one gallon of each sample was obtained, air-dried and well mixed before analysis. Subsamples (60 grams) from the center of each sand were removed and oven dried to determine particle size distribution using the pipette method and dry sieving on three replicate samples. The remaining sand was used to determine sand firmness, measured by resistance to penetration with a modified pocket penetrometer.

Each sample was placed into the standard measurement vessel (a rigid wooden box with interior dimensions of 11.4 centimeters by 12.7 centimeters) and compacted to a 7.6-centimeter depth. The modified penetrometer was inserted

www.golfcourseindustry.com/readerservice - #53 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 resmoothed and repacked.

To determine angle of repose, 20-gram samples of oven-dried sand were placed in a 26-millimeter-diameter plastic centrifuge tube with a 5-millimeter-diameter opening at the bottom, mounted perpendicular to a standard microscope stage. On the microscope stage, a circular pad marked with a measurement scale (marked in millimeters) 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 millimeter. This process was repeated three times, and the average radius and cone height were used to calculate angle of repose. Additionally, each sand was evaluated visually for overall particle shape and color using angularity/sphericity and Munsell color charts, respectively (data not presented).

The particle size distribution of each sand was used to calculate geometric mean diameter, coefficient of uniformity and gradation index. In addition to the bunker sand materials, three materials were included for general comparison; these

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

	Particle size distribution								Calculated property		
Sand	>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	1	79	261	375	217	27	29	11	0.66	3.63	2.00
Caylor White	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	1	59	198	337	263	76	48	17	0.59	2.85	6.23
Fine Topdressing	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	8	77	173	515	206	6	3	12	0.67	2.11	4.74
Kosse White	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	0	8	86	649	204	21	10	21	0.60	2.50	4.69
Putting Green	0	48	324	503	84	14	14	13	0.70	5.28	2.56
Shelby Bunker	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	0	0	0	350	555	40	14	41	0.50	1.53	2.53
Tan Bunker	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	0	35	220	495	194	19	10	27	0.63	2.35	8.41
White Bunker	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.

"standards" included a medium-coarse putting green root-zone sand, a medium-fine topdressing sand and rounded laboratory glass beads.

WHAT WE DISCOVERED

During 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 root-zone sand, a fine sand topdressing and laboratory glass beads. All sands were evaluated for visual characteristics, such as particle shape and color, and 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 determining the sand's particle 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, the coefficient of uniformity and gradation index – 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, which is one method for distilling a particle size distribution down into a single value and provides an overall sense for the relative coarseness or fineness of the sand, values ranged from 0.35 millimeter to 0.95 millimeter (Table 1). Although this is a convenient method for reducing a particle size distribution down into a single manageable value, it also can be somewhat misleading. For example, the laboratory glass beads had a very narrow particle size distribution with 100 percent of the particles in the 0.5-millimeter and 0.25-millimeter size classes, and a geometric mean diameter of 0.71. This value was similar to five other sand materials including the standard putting green sand (GMD equals 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's predicted this material would be rather unstable or soft, simply because of 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 minimum value greater than 0.5 millimeter is desirable. Below this value the sand might drain too slowly when installed in low lying bunker bottoms, resulting in wet or soft playing conditions.

For the coefficient of uniformity, which is a numerical expression of how uniform the particle sizes are and another value that could be used to predict how likely sand particles are to pack, the values ranged from 1.47 to 5.28. Some

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.

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

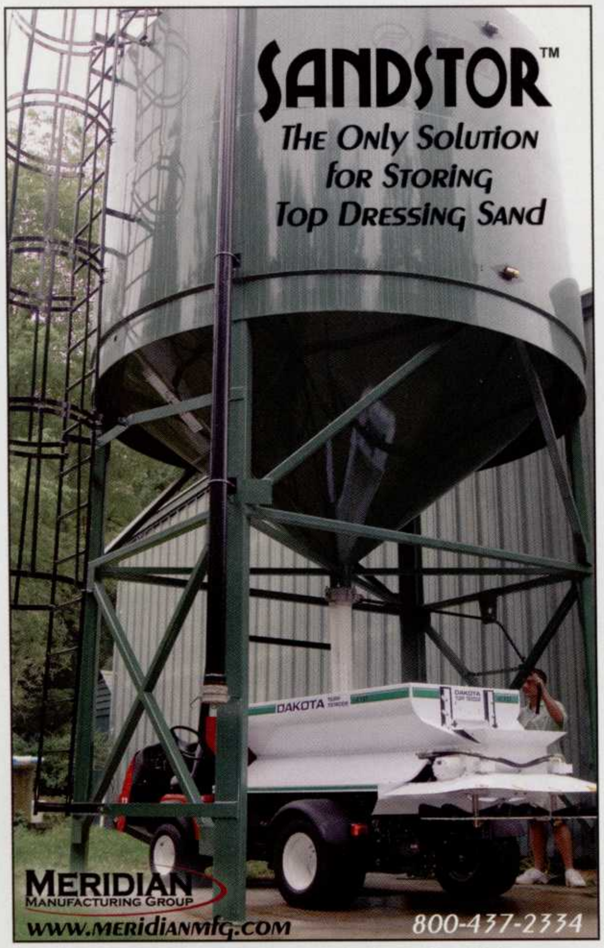
references suggest that "acceptable" coefficient of uniformity values are between 2 and 4. In general, a higher value suggests less uniformity and a greater range of particle sizes. Coefficient of uniformity values below 2 suggest a tendency for the particles to pack less tightly. Of the sands evaluated, 19 of the 26 sands fell within the "acceptable" range.

A similar calculated property is the gradation index, for which values ranged from 1.91 to 8.89. For gradation index 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, 11 of the 26 fell in the "acceptable" range, and only three were in the "preferred" range: Green Plus, Pro White and Sidley 1600.

In addition to analysis of data associated with the particle size distribution, 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 highly spherical. For angularity, the sands ranged from subangular to very angular, with the majority of sands possessing a subangular shape. In general, a more angular and less rounded sand tends to pack tightly and result in a desirable firm sand characteristic.

The data most helpful for determining surface hardness is the modified pocket penetrometer test.

One additional measurement that might help laboratories predict sand firmness is the angle of repose (Table 2). This calculation, expressed in 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 particle size distributions are more likely to stack higher, resulting 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 degrees to 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.



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PHYSICAL PROPERTIES AND SAND FIRMNESS

Besides the highly subjective characteristic, color, an important bunker sand property is firmness manifested as resistance to golf ball penetration. The values for the modified pocket penetrometer ranged from 1.22 to 3.31 kilograms per square centimeter, with values of 1.66 kilograms per square centimeter and 1.59 kilograms per square centimeter for the mean and median penetrometer values, respectively (data not presented).

In data interpretation, the scale most often used is presented in Table 3. This scale indicates that a lower threshold of 1.8 kilograms per square centimeter and below is the value most prone to producing a buried or plugged golf ball lie. Of the sands evaluated, 10 sands had a penetrometer value greater than 1.8 kilograms per square centimeter, but the majority of the sands were between 1.2 kilograms per square centimeter and 2.2 kilograms per square centimeter. As expected, the rounded laboratory glass beads with a narrow particle size distribution and spherical shape had the lowest penetrometer value of 0.1 kilograms per square centimeter and would be considered "softest." Generally, values greater than 2.2 kilograms per square centimeter are desirable because above this value the sand will 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., the coefficient of uniformity or angle of repose) was a strong indicator or predictor for penetrometer values. Although 10 sands had penetrometer values greater than 1.8 kilograms per square centimeter, which is the suggested threshold for an "acceptable" dry sand firmness value, only five sands were greater than 2.2 kilograms per square centimeter. In an attempt to relate these physical property data to penetrometer values, linear regression was conducted with the gradation index, coefficient of uniformity and angle of repose data. The results of these analyses resulted in R2 values of 0.0715, 0.0051 and 0.2566, for the gradation index, coefficient of uniformity and angle of repose data, respectively. In other words, because of 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 coefficient of uniformity and gradtion index value of 1.86 and 3.53, respectively. If one were to characterize this sand based solely on the coefficient of uniformity or gradation index data, they would predict this sand is less likely to pack because the coefficient of uniformity is less than 2.0 and that its surface instability is barely "acceptable" because of the gradation index value falling barely inside the 3 to 6 "suggested" range. Based on this information, it's apparent many properties likely influence sand surface hardness. These properties include particle size distribution, particle shape and other less quantifiable characteristics such as particle surface roughness.

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.

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

Mechanically crushing minerals into sand-sized products certainly affects surface roughness. This rough particle surface architecture might 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 also might have negative effects on turf health, as there might 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, it's highly recommended to enlist the assistance of an accredited testing laboratory when evaluating sands for golf course bunker use. 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 also can assess other properties like crusting potential, water retention and infiltration rate. Additionally, these laboratories probably are familiar with many of the existing regionally available sands, which might have been characterized already.

To date, the procedure most used for evaluating surface hardness is the modified pocket penetrometer test. But this test has met with some criticism because of considerable variability in measurements among users. One important point to make regarding this measurement is that it's conducted using dry sand in a nonflexible box, conditions not normally exhibited in the field. In reality, sand is installed on slopes of various slope angles, with or without subsurface drainage, and at depths often exceeding three 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 currently are under evaluation at several research laboratories. These methods include using various impact hammers, such as the Clegg impact tester, to test for sand firmness. It's the authors' hope a more reliable test will be developed and correlated with other sand physical properties. **GCI**

The sands analyzed in the study were variable in terms of all properties measured: particle size distribution, angularity, angle of repose, color and particle shape.

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