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How they measure up

Lab study analyzes physical properties of bunker sand

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**	**.25**	**.15**	**0.1**	**.05**	**<.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	1	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 1	4	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	3.06	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.

Most golf hole architectural designs incorporate sand bunkers to add dramatic visual contrast and enhance aesthetic beauty while adding challenge and strategy for golfers (1). Bunkers are considered hazards, yet, 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 demand results in the pursuit of consistently firm, smooth bunker surfaces.

At many golf facilities, the amount of the maintenance resources spent on bunker management rivals what's spent caring for putting greens. Where sand is installed on steep slopes, regular erosion repair costs can be substantial, and are compounded when improper, highly erodable bunker sands are selected.

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 sand's playability. Generally, firm sand is preferred because it allows a golf ball to sit on top of the sand surface, resulting in 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 bunkers would be one that maintains firmness, drains quickly, doesn't erode from slopes easily after moderate rainfall or irrigation, and is sized similar to those used for sand-based root zones (8). The latter is so that when it's splashed onto the putting surface it does minimal damage to the mowing 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 bunker sands, and the information that exists serves primarily as a guideline, which is based mostly on sand particle size distribution and a measurement of surface firmness. Generally, it's suggested bunker sands should have a large majority of the particles in the 0.25 to 1.0 mm range (7). 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, however, limestone sands are more prone to weathering and might result in significant fine particles over time, which can affect drainage and playability.

In terms of sand particle size distribution, research documents particle size distribution greatly influences sand strength and, specifically, the quantity and ratio of fine textured particles can have a strong influence on strength (2, 3). 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. Increasing the Cu value from 1.8 to 3.0 resulted in the

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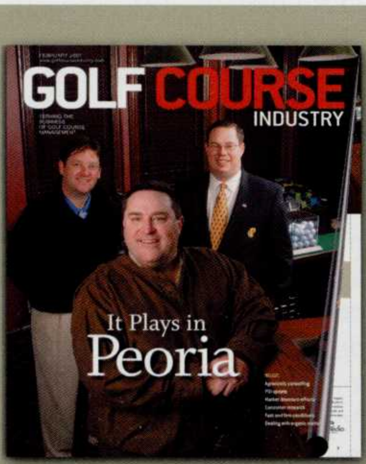

TABLE 2. Sand particle shape characteristics, calculated physical properties, angle of repose and modified pocket penetrometer values of commercially available sand materials from various regions in the United States.

Sand	Sphericity	Angularity	GMD†	Cu‡	GI§	Angle of repose	Penetrometer
		mm				degrees	kg cm^{-2}
Autumn Gold	Medium	Subangular	0.60	2.00	3.24	30.3	1.78
Bunker Sand	Medium	Subangular	0.66	3.63	2.00	31.1	1.79
Caylor White Sand	Low	Angular	0.66	1.82	3.323	2.5	1.44
Crushed Limestone	Medium	Angular	0.95	1.86	3.53	34.9	3.32
Extra Firm Bunker Sand	Medium	Subangular	0.59	2.85	6.23	31.6	1.80
Fine Topdressing Sand	Medium	Subrounded	0.35	3.60	2.40	30.4	1.57
Glass beads	High	Rounded	0.71	1.61	2.57	21.8	0.10
Gray Walreth Double Wash	Medium	Subangular	0.63	2.22	3.83	34.4	2.12
Green Plus	Medium	Subangular	0.71	2.38	5.24	33.1	1.38
Holliday (Banner Springs)	Medium	Subangular	0.63	3.94	2.24	32.0	1.64
Holliday (Miss. River)	Medium	Subangular	0.70	3.70	1.91	31.4	1.64
Klassic White Sand	Low	Angular	0.67	2.11	4.74	34.8	1.80
Kosse White B.S.	Medium	Rounded	0.54	1.47	2.41	30.8	1.72
Orlando White	Medium	Subangular	0.55	2.20	3.87	31.6	1.44
Pro Angle	Medium	Very angular	0.72	3.33	7.78	33.1	2.84
ProWhite Bunker Sand	Low	Very angular	0.60	2.50	4.69	33.4	2.07
Putting Green Sand	Medium	Subangular	0.70	5.28	2.56	32.2	1.65
Shelby Bunker Sand	Medium	Subrounded	0.71	2.00	3.79	31.6	1.30
Sidley # 1600	Medium	Subangular	0.56	2.25	4.17	32.4	1.64
Stone White Sand	Medium	Subangular	0.50	1.53	2.53	32.9	1.20
Tan Bunker Sand	Medium	Subangular	0.71	2.43	3.96	34.2	1.52
Tour Grade 50/50	Medium	Subangular	0.68	2.72	8.89	35.4	1.94
Tour Grade 535	Medium	Subangular	0.57	1.82	2.76	30.7	1.24
Tour Grade Signature	Low	Angular	0.71	3.06	8.89	33.9	1.59
USGA Bunker Sand	Medium	Subrounded	0.63	2.35	8.41	30.9	0.98
White Bunker Sand	Medium	Subangular	0.63	4.76	2.65	34.6	2.80

† 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, optimumvalue = 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.

doubling of the sand's bearing capacity or a much firmer sand root zone surface (2, 3). For bunker sands that need to infiltrate and drain rapidly, the addition of significant fines would be risky because 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, 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 are subjective qualitative characteristics, such as color or immediate cost, which 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 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 mixed well before analysis. Subsamples (60 grams) from the center of each sand were removed and oven-dried to determine particle size distribution using the pipet method and dry sieving on three replicate samples. The remaining sand was used to determine firmness as measured by resistance to penetration with a modified pocket penetrometer.

Each sample was placed in a 15-cm-diameter round plastic vessel and compacted to a 10-cm depth. The modified penetrometer was inserted using even and steady pressure until one-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, the sand surface was resmoothed, and the test vessel was repacked to the desired depth between measurements.

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 that 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 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 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, coefficient of uniformity and gradation index (4, 5, 6). In addition to the bunker sand materials, three materials were included for general comparison. These standards included a medium-coarse putting green root zone sand, a medium-fine topdressing sand and rounded laboratory glass beads.

WHAT WE DISCOVERED

In the 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, but also for their general phical 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 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 GMD, which is one method for distilling a 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 to 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 percent of the particles in the 0.5 and 0.25 mm size classes and a GMD of 0.71. This value was identical to four other sand materials with dramatically different PSDs.

Based on the very narrow PSD of the glass beads, it would be 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. Generally, however, for a bunker sand, a minimum value greater than 0.5 mm would be desirable because below this value the sand may drain too slowly when installed in low-lying bunker bottoms.

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 references suggest acceptable Cu values are between 2 and 4 (5). Generally, 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 similarly calculated property is the gradation index, for which values ranged from 1.91 to 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, 11 of the 26 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 highly spherical. For angularity, the sands ranged from subangular to very angular, with the majority of sands possessing a subangular shape. Generally, 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 might 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. Coarser textured, more angular sands with wider PSDs 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 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.

PHYSICAL PROPERTIES AND 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 0.1 to 3.32 kg cm^{-2}, with higher values being more desirable (Table 2).

When interpreting this data, the scale most often used is presented in Table 3. Of the sands evaluated, only five sands had a penetrometer value greater than 2.0 kg cm^{-2}, while the majority of the sands were between 1.2 and 2.0 kg cm^{-2}. As expected, the rounded laboratory glass beads with a narrow particle size distribution produced a penetrometer value of 0.1 kg cm^{-2} and was softest. Generally, a value greater than 2.2 kg cm^{-2} would be desirable as it's purported to have only a slight tendency to produce a buried golf ball lie.

NO STRONG INDICATOR

When evaluating all the physical data for these bunker sands, no single measured or calculated property was a strong indicator or predictor that could be correlated with penetrometer values. Although five sands had penetrometer values greater than 2.0 kg cm^{-2}, the GMD, Cu, GI and angle of repose data was highly variable. For example, crushed limestone had the highest penetrometer value, 3.32, but a Cu that was less than 2.0 and a GI of 3.53. This indicates that other properties might influence sand surface hardness such as particle surface roughness. The two firmest sand products, crushed limestone and Pro Angle with penetrometer values of 3.32 and 2.84 kg cm^{-2}, respectively, were mechanically crushed products. This process might affect surface roughness and allow the particle surface architecture to bridge or link with adjacent particles better than naturally mined materials.

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 tests and be extremely helpful during the selection process. In addition to the tests run in this study, these laboratories can also assess other properties like crusting potential and infiltration rate. Additionally, these laboratories probably are familiar with many of the existing, regionally available sands that might already have been characterized.

To date, data most helpful for determining surface hardness is the modified pocket penetrometer test. This test, however, has met with some criticism because of perceived reliability and variability in measurements among users. Other quantitative methods are under evaluation at several research laboratories. **GCI**

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