JKAU: Eng. Sci., **Vol. 2**, pp. 65-79 (1410 A.H. / 1990 A.D.)

An Investigation of the Influences of Particle Size, Size Gradation and Particle Shape on the Shear Strength and Packing Behavior of Beach Sands in Saudi Arabia

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ABSTRACT. This investigation is a study of the shear strength and packing behavior of Dammam and Abhur Beach Sands in Saudi Arabia in terms of the geometric particle characteristics of size and shape. A large number of uniform size sands and a limited number of improved gradations are studied. Particle size is defined by mechanical sieving and particle shape is quantified in terms of sphericity and roundness. Surface texture is recognized to be a significant variable as is particle mineralogy. Packing behavior is studied with respect to the maximum and minimum limiting void ratios and void ratio spreads. Shear resistance is investigated in terms of the angle of internal friction. Results indicate that both packing behavior and shear behavior are influenced significantly by particle roundness and surface texture. The uniform sands tested were normalized into a linear strength-packing-shape relationship at a given relative density. Changes in grading affect packing behavior more than strength behavior and the normalizations are rather sensitive to changes in void ratio spread. Normalizations appear significant in that they include surface texture variations and afford a possible technique for a more comprehensive approach to sand behavioral formulation in terms of the variables of particle size, size gradation, shape, surface texture, mineralogy and relative density.

Introduction

In the field of geotechnical engineering, the behavior of sands is dependent on quantities and characteristics such as relative density, confinement, particle size, particle size distribution, particle shape, surface texture, mineralogy, and type of test conducted to determine sand response[1-4]. Given a particular type of test in which, ideally, relative density and confinement can be controlled, the behavior of a given sand will then depend on the above sand characteristics. If it were possible to evaluate these characteristics for a given sand, it is conceivable that its behavior could be predicted if sufficient test results in terms of all quantities and characteristics were available to establish functional relationships. Thus, in order to differentiate one sand from another, a system of designating particle size, particle size distribution, particle shape and surface texture is necessary.

Particle size and size distribution are reproducible by the common sieve analysis. However, a close look at any of the specific groups obtained by sieve analysis will reveal that no two particles are exactly alike in shape or surface texture[5,6]. Hence, shape and texture can play a major role in the behavior of particulate materials.

Waddel[7,8] showed that particle shape essentially consisted of two distinct characteristics, sphericity and roundness. Sphericity, after Krumbein[9], is the ratio of the volume of the particle to the volume of the smallest circumscribing sphere. Perfect sphericity (perfect circularity in two dimensional views) gives a ratio of 1.0. Roundness is the ratio of the curvature of the corners and edges of the particle to the average curvature of the particle. A particle which gives a perfect circle as a projection has a roundness of 1.0. It will be shown that any given sieve portion of any sand does not have singular values of sphericity and roundness but rather has distributions of each. Therefore, in order to study sands realistically, the behavioral variations of different size ranges must be studied first and compared in terms of particles shape and texture to formulate sand behavior in terms of these characteristics.

Surface texture of sand grains is an extremely difficult property to formulate, if not an impossible one. The magnitudes of the surface features attributable to surface texture are subordinate in size to those features included in particle shape determination. For a given particle size, size distribution and particle shape, surface texture can be defined only in terms of its effects on sand behavior.

Another property of sands is the mineralogy. It is important since (1) absolute density in terms of specific gravity depends on the relative contributions of the various minerals comprising the sand particles, (2) tendencies of different minerals to cleave and/or fracture in different ways and the geological history of each particle influence the shape and textural features of the particles, and (3) grain-to-grain frictional phenomena are influenced by the types and relative amounts of the various minerals involved.

It is intended to determine, as far as possible, the relative order of magnitude of the influences of particle size, particle size gradation, particle shape and surface texture on the behavioral response of sand, to determine the significance of each of these characteristics on such response, to seek possible correlations among them, and to establish the feasibility of such an approach to sand behavior. This investigation is not concerned with information on particle formation, its interest is only in the geometrics and surface features of particles as they exist at present in nature. However, the study will assist the reader in understanding the complexity of any attempt to accurately describe a grain of sand.

Laboratory Investigation

Sand Properties

The materials studied in this investigation were derived from three sands obtained from Ottawa (USA), Dammam Beach on the eastern coast, and Abhur Beach on the western coast of the Kingdom of Saudi Arabia. Sands were sieved into several uniform sizes with a uniformity coefficient, C_u, of 1.2.

Mechanical sieving, though artificial in nature, is an adequate classification test for defining uniform particle size ranges and uniform size gradation in terms of the uniformity coefficient, however this coefficient is generally inadequate for describing particle size gradations. The range of particle size investigated extended from 0.84mm (No. 20) to 0.10mm (No. 140), plus two special mixes 1 and 2 as shown in Table 1.

TABLE 1. Materials investigated.

Sand	U.S. Sieve Size	Size of Opening (μm)	Mean Shape Values		Specific Gravity	Void Ratio			Porosity			Friction Angle**		Uniformity Coefficient
			Sphericity*	Roundness*		e_{max}	e_{min}	Δe	n_{max} (%)	n_{min} (%)	Δn (%)	Loose	Dense	
Ottawa	20-30	850-600	0.87	0.65	2.66	0.768	0.462	0.306	43.4	31.6	11.8	30.5	37.9	1.2
	35-45	500-355	0.85	0.59	2.66	0.821	0.478	0.343	45.1	32.3	12.8	32.9	40.4	1.2
	60-70	250-212	0.84	0.52	2.66	0.888	0.528	0.360	47.0	34.5	12.5	31.7	38.5	1.2
	70-100	212-150	0.83	0.50	2.66	0.915	0.537	0.378	47.8	34.9	12.9	32.3	39.2	1.2
	100-140	150-106	0.82	0.50	2.66	0.915	0.535	0.380	47.8	34.9	12.9	32.5	39.0	1.2
Dammam	20-30	850-600	0.85	0.65	2.69	0.880	0.580	0.300	46.8	36.7	10.1	32.7	47.5	1.2
	35-45	500-355	0.82	0.58	2.67	0.900	0.550	0.350	47.4	35.5	11.9	32.5	45.1	1.2
	60-70	250-212	0.79	0.52	2.67	0.980	0.610	0.370	49.5	37.9	11.6	31.5	40.0	1.2
	70-100	212-150	0.79	0.48	2.70	1.000	0.610	0.390	50.0	37.9	12.1	30.0	36.5	1.2
	100-140	150-106	0.79	0.47	2.72	1.010	0.610	0.400	50.2	37.9	12.3	30.0	36.0	1.2
Abhur	20-30	850-600	0.82	0.62	2.70	0.920	0.620	0.300	47.9	38.3	9.6	35.0	51.0	1.2
	35-45	500-355	0.81	0.55	2.70	1.000	0.609	0.391	50.0	37.8	12.2	34.0	48.5	1.2
	60-70	250-212	0.80	0.52	2.71	1.030	0.620	0.410	50.7	38.3	12.4	31.0	41.0	1.2
	70-100	212-150	0.81	0.51	2.72	1.100	0.680	0.420	52.4	40.5	11.9	28.5	39.5	1.2
	100-140	150-106	0.80	0.51	2.74	1.120	0.700	0.420	52.8	41.2	11.6	27.5	38.5	1.2
Mix 1	Ottawa: (20-30), (35-45), (50-70).		–	0.59	2.66	0.702	0.417	0.285	41.2	29.4	11.8	–	39.1	2.0
Mix 2	Ottawa: 20-30 (75%), 35-45 (10%), 50-70 (5%), 70-100 (5%), 100-140 (5%)		–	0.62	2.66	0.622	0.358	0.264	38.4	26.3	12.1	–	38.7	3.35

* Each number of sphericity and roundness shown in the table is the representative mean value of 100 grains as shown in Table 3.

** Average of 5 to 10 tests depending on the availability of certain sizes.

Dammam Beach sands are found to be primarily quartz as shown in Table 2, very pale brown and appear rounded to subrounded to the naked eye. The carbonate percentage for size 20-30 is 5 percent with little or no heavy minerals. The percentages of carbonate and heavy minerals increase as sieve size decreases to reach 19.5 and 4.5 percent for size 100-140, respectively.

TABLE 2. Minerals of the investigated sands.

Sand	Sieve Size	Carbonate (%)	Quartz (%)	Heavy Minerals (%)
Dammam Beach	20- 30	5.1	94.9	-
	35- 45	7.5	92.5	-
	60- 70	10.2	88.6	1.2
	70-100	14.2	82.6	3.2
	100-140	19.5	76.1	4.5
Abhur Beach	20- 30	88.4	11.1	0.5
	35- 45	67.7	30.8	1.5
	60- 70	62.4	34.9	2.7
	70-100	58.1	35.0	6.9
	100-140	43.2	41.2	15.6

Abhur Beach sands are brown in color, appear rounded to subrounded to the naked eye, partly quartz and partly carbonate with some percentage of heavy minerals. For size 20-30, the percentage of carbonate, quartz, and heavy minerals are 88.4, 11.1 and 0.5 percent, respectively. As the sieve size decreases, carbonate decreases, and quartz and heavy minerals increase. For size 100-140, the percentages of carbonate, quartz, and heavy minerals become 43.2, 41.2, and 15.6, respectively. This explains the increase in the specific gravity values for Abhur in Table 1.

Sphericity and Roundness

The individual grains were viewed through a microscope for estimations of sphericity and roundness using Rittenhouse Charts[10] and the Krumbein System[9]. The eyepieces were 10 × and the objective lenses varied from 10 × to 40 ×. Representative samples from each sieve portion were obtained by quartering. A minimum of 100 grains from each sieve portion were viewed in groups of 25 grains from each sand size over a period of 6 months.

Table 3 shows the individual sphericity and roundness determinations for 100 grains of the 70-100 Dammam Beach sand sieve size tested, where ψ is the spericity and R is the roundness. This is a typical testing procedure for all of the sands investigated. Figure 1 presents the results in a histogram form that illustrates the shape distribution variations, grains of a certain sieve size exhibit, indicating that the mean values of the shape terms are adequate to describe behavioral relationships.

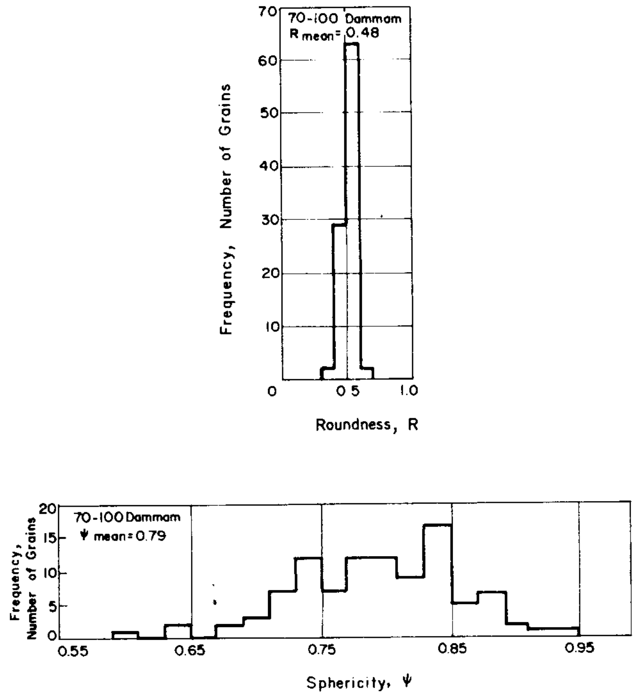

FIG. 1. Histograms of sphericity and roundness of 70-100 Dammam Beach sand.

Limiting Densities and Shear Resistance

The behavioral response was investigated in terms of limiting absolute densities (packing behavior). Loose specimens were prepared similar to ASTM D2049 by placing a glass funnel of 953mm stem and 7.6mm inside diameter, into 654mm mold, and pouring the sand in a steady stream and spiral motion while at the same time adjusting the free fall to 25mm. The top was then carefully levelled with a soft brush.

Dense specimens were prepared by emplacing the sand in three equal layers in a 60mm ×60mm shear box. Each layer was tapped 50 times by 6mm diameter glass rod and vibrated for 8 minutes under a surcharge load of 0.036 kg/cm^2. Both loose and dense specimen preparation techniques were found to be consistent and reproducible within reasonable limits.

The shear resistance is investigated in terms of the angle of internal friction obtained from testing 60mm × 60 mm specimens in the direct shear box. The limiting void ratios, porosities, void ratio spread, porosity spread, and the angle of internal friction for loose and dense specimens for all sieve sizes are given in Table 1.

TABLE 3. Typical test data for shape determinations of (70-100) Dammam beach sand.

Grain No.	Group 1		Group 2		Group 3		Group 4	
	ψ	R	ψ	R	ψ	R	ψ	R
1.	0.83	0.50	0.83	0.50	0.81	0.40	0.84	0.50
2.	0.79	0.50	0.74	0.50	0.79	0.45	0.72	0.50
3.	0.73	0.40	0.79	0.45	0.93	0.60	0.87	0.50
4.	0.81	0.45	0.80	0.50	0.87	0.55	0.85	0.45
5.	0.73	0.45	0.77	0.55	0.49	0.45	0.77	0.55
6.	0.83	0.50	0.79	0.50	0.71	0.45	0.88	0.55
7.	0.74	0.50	0.77	0.40	0.72	0.50	0.74	0.50
8.	0.76	0.40	0.79	0.50	0.89	0.50	0.73	0.45
9.	0.67	0.50	0.75	0.50	0.78	0.45	0.70	0.50
10.	0.77	0.50	0.79	0.30	0.84	0.50	0.87	0.55
11.	0.83	0.30	0.79	0.50	0.76	0.45	0.72	0.45
12.	0.83	0.30	0.79	0.50	0.81	0.50	0.76	0.50
13.	0.83	0.50	0.73	0.45	0.85	0.55	0.88	0.60
14.	0.73	0.50	0.85	0.50	0.76	0.50	0.79	0.55
15.	0.67	0.50	0.77	0.55	0.83	0.55	0.71	0.50
16.	0.73	0.50	0.77	0.50	0.77	0.50	0.83	0.55
17.	0.75	0.45	0.87	0.50	0.77	0.55	0.79	0.45
18.	0.83	0.60	0.81	0.50	0.87	0.55	0.79	0.45
19.	0.81	0.50	0.85	0.50	0.83	0.45	0.75	0.45
20.	0.077	0.50	0.81	0.30	0.81	0.50	0.78	0.55
21.	0.83	0.50	0.77	0.55	0.63	0.500	0.70	0.55
22.	0.89	0.50	0.80	0.40	0.82	0.50	0.82	0.50
23.	0.91	0.60	0.83	0.45	0.84	0.50	0.85	0.45
24.	0.69	0.45	0.64	0.45	0.71	0.55	0.77	0.45
25.	0.83	0.45	0.83	0.45	0.73	0.50	0.74	0.50
Sum	19.59	11.85	19.68	11.8	19.72	12.5	19.65	12.25
Mean	0.78	0.47	0.79	0.47	0.79	0.5	0.79	0.49
Standard Deviation	0.063	0.069	0.046	0.064	0.077	0.045	0.059	0.044
For 100 Grains Tested: ψ_{mean} = 0.79 , R_{mean} = 0.48								

Discussion

Values of mean roundness ranged from 0.65 (well rounded, 20-30 Ottawa and Dammam Beach) to 0.47 (subrounded, 100-140 Dammam Beach) which represents a significant range as shown in Figure 2. The larger the particle size, the more rounded it tends to become through natural processes. Since the average sphericities ranged only from 0.79 to 0.87 for the sands tested, sphericity was not considered a primary variable in this investigation.

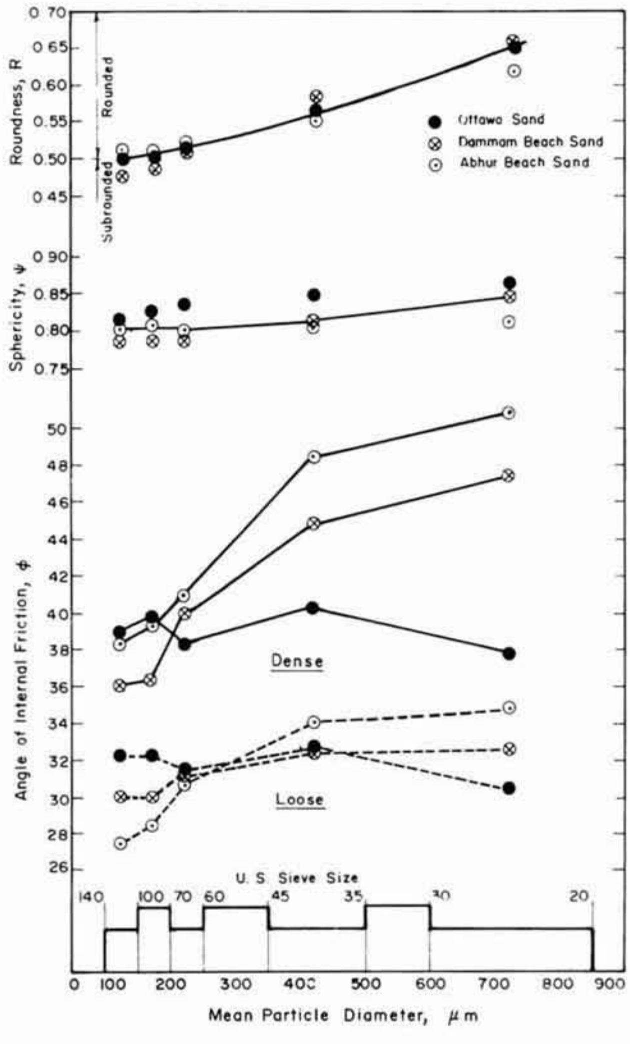

FIG. 2. Mean particle diameter versus roundness, sphericity and angle of internal friction.

Packing behavior, in terms of maximum and minimum void ratios and void ratio spreads, was investigated for the sands tested. These parameters increase as particle roundness and size decrease. Thus, for a given sand, the limiting densities tend to decrease with the increase of particle size because of the shape factor; data plotted in Figures 3 and 4 follow this trend for each type of sand.

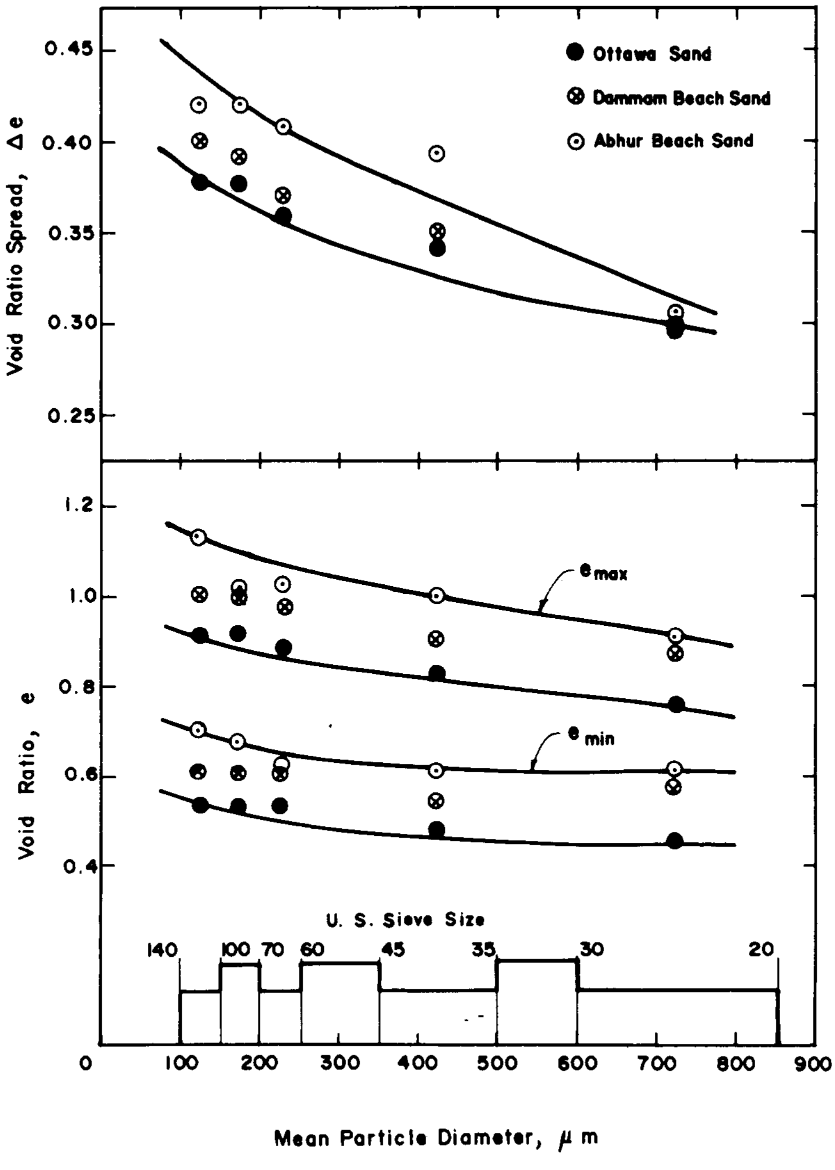

FIG. 3. Mean particle diameter versus void ratio and void ratio spread.

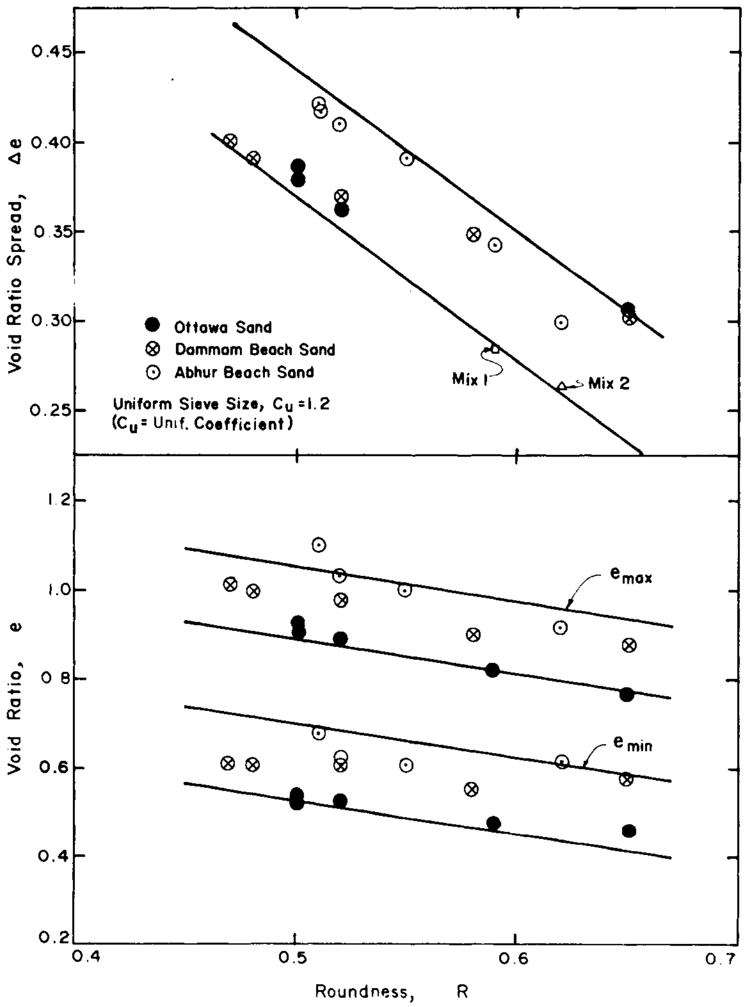

FIG 4. Void ratio and void ˜atio spread versus roundness.

Figures 5 and 6 are examples prepared using electron scanning microscopy technique to manifest the effect of surface texture on sand behavior. The figures are self-explanatory and indicate the smoother surface texture of Dammam Beach sand compared to Abhur Beach sand. A comparison between these photographs and values in Table 1 indicates that smoother surface texture results in decreased packing limits, decreased void ratio spread and decreased shear resistance at a given relative density.

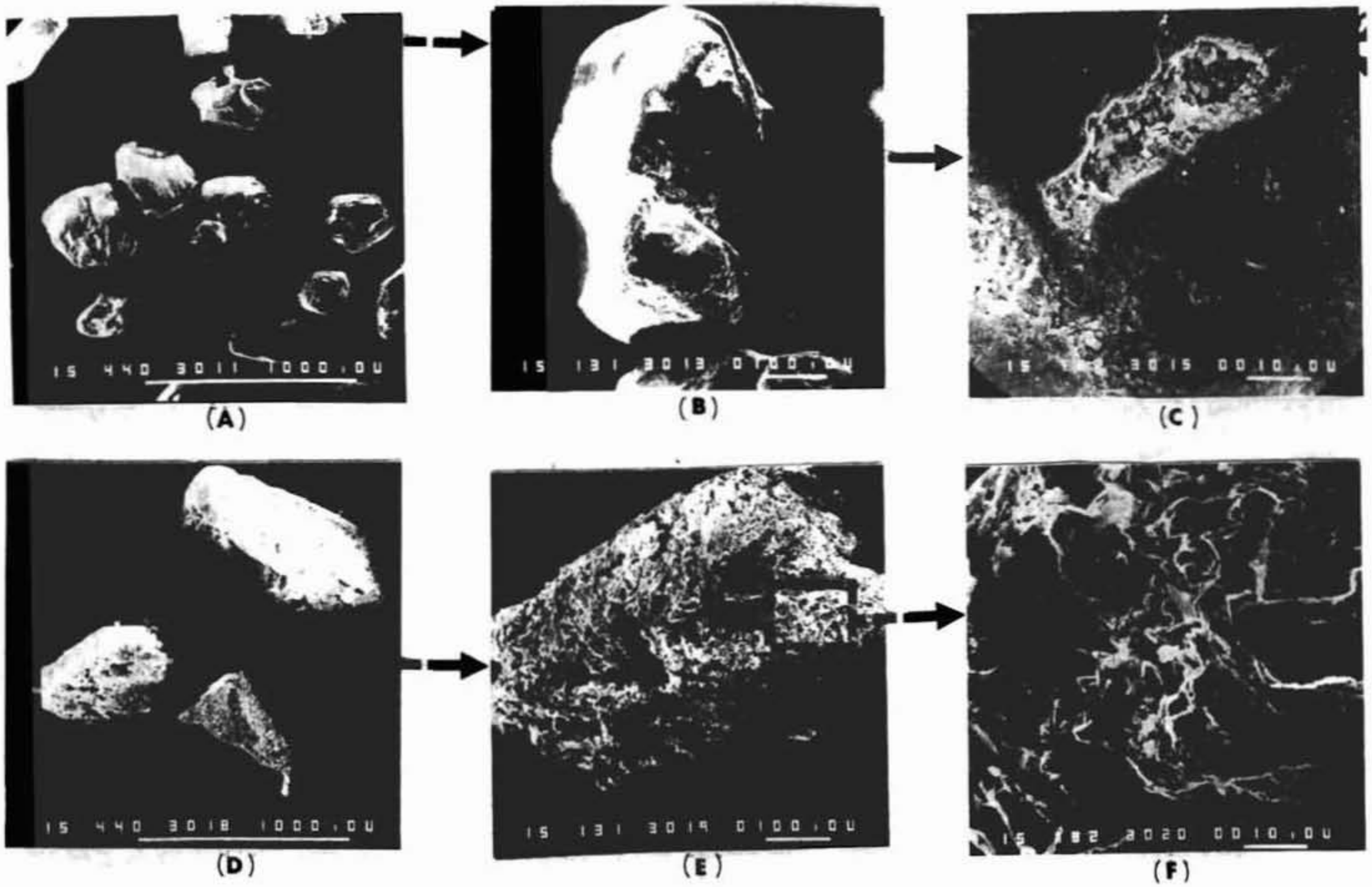

FIG. 5. Smoother surface texture of (35-45) Dammam Beach sand in A, B, and C, compared to the surface texture of (35-45) Abhur Beach sand in D, E, and F. Scale is in μm.

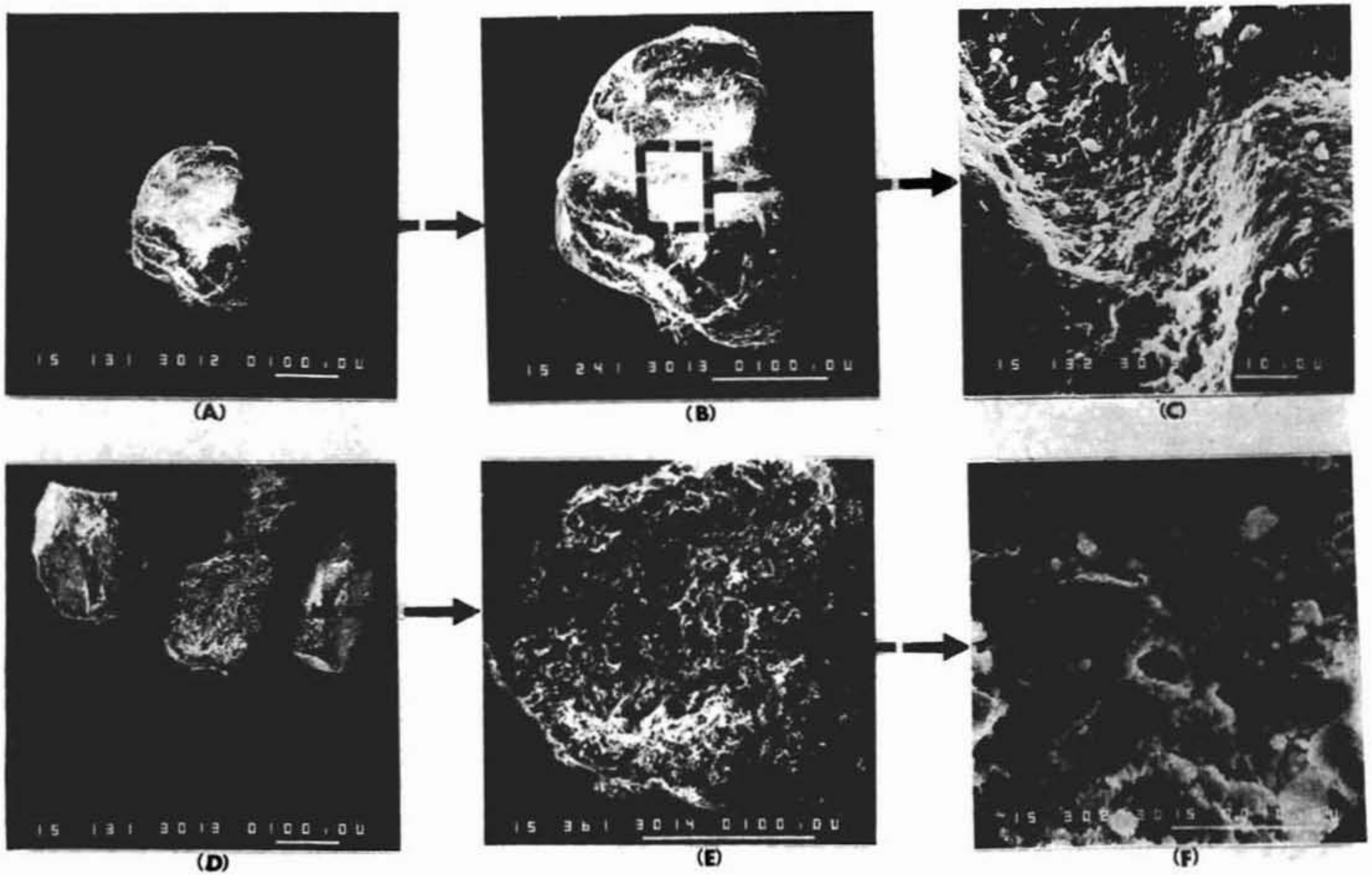

FIG 6. Smoother surface texture of (70-100) Dammam Beach sand in A,B, and C, compared to the surface texture of (70-100) Abhur Beach sand in D,E, and F. Scale is in μm.

Strength behavior in terms of the angle of internal friction increases significantly with the increase of particle roundness and size for Dammam and Abhur Beach sands as shown in Figures 2 and 7. However, the influences of particle size on Ottawa sand strength response were indeterminate either because they are small compared to the influences of particle shape and were masked by scatter or because the ranges of particle size investigated were limited (which is doubtful since the sands tested ranged from fine to medium coarse according to M.I.T. classification). Improved particle size gradation represented by Mixes 1 and 2 in Table 1 results in reduced packing limits and reduced void ratio spreads. Conversely, its influence on strength behavior is minor as compared to roundness and surface texture.

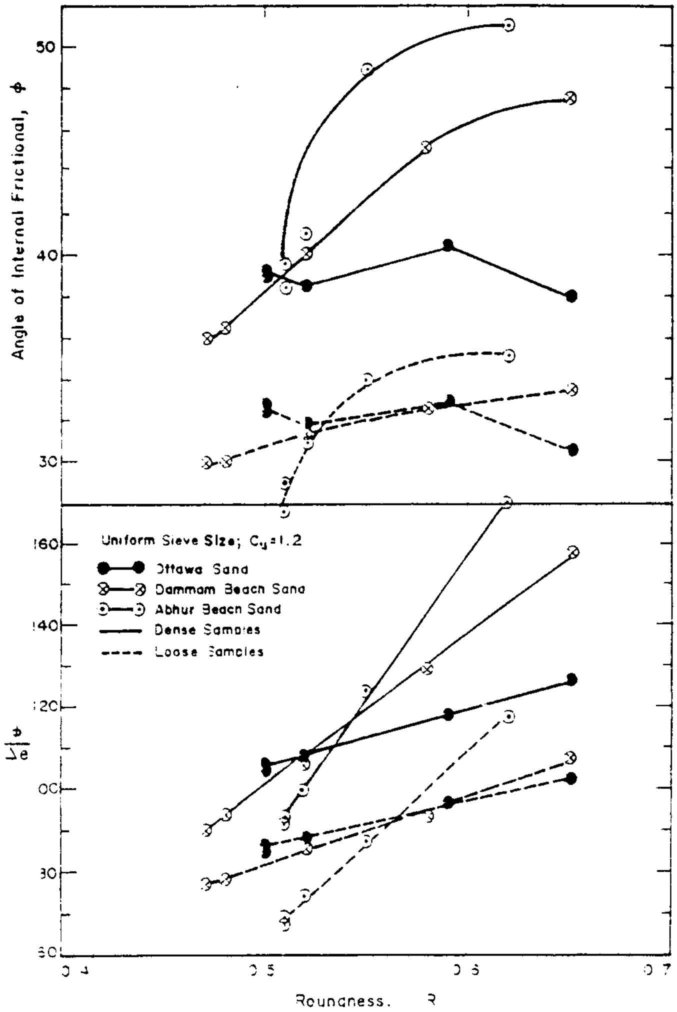

FIG. 7. Angle of internal friction and $\phi/\Delta e$ versus roundness.

Qualitative appraisals of surface texture are inadequate for behavioral description. An investigation of texture requires control of particle size, shape and mineralogy. Hence, the fact that particle roundness and surface texture packing behavior and strength behavior of the sands tested led to the process of dividing ϕ by Δe for each individual sand. This process resulted in a normalization relationship as a function of particle roundness that could be represented by a simple linear relationship.

$$\frac{\phi}{\Delta e} = A + B(R) \tag{1}$$

where A is an intercept on the stiength-packing parameter axis and B is the slope of the normalization. Figure 7 shows the normalizations for the present investigation with a minimum coefficient of determination, R^2, equal to 0.984 and for uniform sizes ($C_u = 1.2$), which appear promising in that the strength-packing parameter ($\phi/\Delta e$) appears to include surface texture variations.

Conclusion

This investigation has considered, for the first time, the comprehensive range of variables necessary to determine the quantitative measures of the influences of particle characteristics, relative to each other, on the behavior of some local sands. The particle characteristics included particle shape, particle size, surface texture, particle size gradation and mineralogy. Although it is difficult to isolate the absolute influences of these characteristics, the results of this investigation have conclusively demonstrated the orders of magnitude of the contributions which each characteristic makes to the overall response behavior of sands. The conclusions obtained were:

1. Particle roundness has a significant influence on both packing and shear strength behavior. Decreasing particle roundness (increasing angularity) results in increasing maximum and minimum void ratios, increasing void ratio spreads and decreasing frictional shear resistance at a given relative density.

2. Particle size has less influence on both packing behavior and strength behavior, compared to the significance of particle shape. However, as the particle size decreases, roundness decreases, maximum and minimum void ratio increase, void ratio spread increases in all the sands tested, and the frictional shear resistance decreases in Dammam Beach and Abhur Beach Sands.

3. Surface texture significantly influences both packing behavior and shear behavior. After roundness has been evaluated, surface texture is considered to comprise the features which are subordinate in size to those utilized to determine roundness, *i.e.*, surface texture is one order of magnitude or more below roundness. Smoother surface texture results in decreased packing limits, decreased void ratio spread, and decreased shear resistance at a given relative density.

4. Improved particle size gradation results in reduced packing limits and a reduced void ratio spread, all with regard to the respective packing behavior of the uniform constituent sizes. Its influence on packing is equivalent to that of roundness or texture. Conversely, its influence on strength behavior, at a given relative density, is minor as compared to roundness or texture.

5. Particle mineralogy significantly influences strength behavior, but it has little or no effect on packing behavior. Hence, a study of sand behavior based on such a characteristic, without recourse to particle shape information, can only lead to contradictions of response. Consideration must be given to all of the above particle characteristics in order to validly attribute a particular effect to any one of them. The importance of particle roundness in the present investigation intimates that particle roundness should influence the measurement of the particle-to-particle mineral friction characteristic.

6. Normalizations of the above phenomena in terms of the ratio of the friction angle to the void ratio spread as a function of roundness are of significant value in expressing strength-packing-shape interrelationships. This normalized form of representation is independent of surface texture but is a function of particle mineralogy, relative density, and particle size gradation.

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دراســة تأثــير حجم الحبيبـات ، وتـدرجهـا الحجمي ، وشكلهـا على مقاومــة القص والتصرف التعبوي لرمـال السواحـل في المملكة العربية السعودية

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يقـوم البحث بدراسـة مقاومة القص والتصرف التعبوي لرمال سواحل أبحر والدمام في المملكة العربية السعودية بدلالة حجم الحبيبات وشكلها . وقد تمت دراسة عدد كبير من الأحجـام الـرملية المنتظمة وعدد محدود من التدرج المحسَّن ، وتقييم الحجم من التدرج المنخلي وتقييم الشكل من الاستدارة والتكوّر . وتبين أن النسيج السطحي والتركيب المعدني من المتغـيرات المهمـة في هذا الموضوع . كما تمت دراسة التصرف التعبوي بدلالة نسب الفـراغـات الصغـرى والكـبرى وانتشـار نسبة الفراغات ، ومقاومة القص بدلالة زاوية الاحتكاك الداخلي .

ولقـد دلت النتـائـج على أن مقاومة القص والتصرف التعبوي كليهما يتأثر تأثُّراً كبيراً باستـدارة الحبيبـات والنسيج السطحي . ثم تمت مناظمة الرمال المنتظمة المفحوصة إلى علاقة خطية بين المقاومة والتعبئة والشكل لتلك الكثافة النسبية . وكما دلت النتائج على أن تغير التدرج يؤثر على التصرف التعبوي أكثر منه على مقاومة القص ، وأن المناظمة حساسة لتغيرات انتشار نسبة الفراغات وتأتي أهميتها باحتضان تغيرات النسيج السطحي في الحبيبات .