Journal of Coastal Research | 12 | 4 | 1017–1023 | Fort Lauderdale, Florida | Fall 1996

Sand Grain Roundness and Transport in the Swash Zone

A. S. Trenhaile, L. V. Van Der Nol, and P. D. LaValle

Geography Department
University of Windsor
Windsor, Ontario N9B 3P4
Canada

ABSTRACT

TRENHAILE, A. S.; VAN DER NOL, L. V., and LAVALLE, P. D., 1977. Sand grain roundness and transport in the swash zone. *Journal of Coastal Research*, 12(4), 1017–1023. Fort Lauderdale (Florida), ISSN 0749-0208.

This study considered the effect of particle roundness on the movement of sand grains in the swash zone. A wave tank was used to investigate the transport of a sample of quartz grains of fairly uniform size up an inclined ramp. A similar procedure, using fluorescently dyed grains, was used in the field in southern Lake St. Clair, Ontario. It was found that rounder grains were preferentially transported towards the upper part of the swash zone in the laboratory and field. Round grains may congregate on the berm and upper foreshore because of their higher settling velocities or their greater ease of entrainment compared with more angular grains.

ADDITIONAL INDEX WORDS: *Sand grain shape, beaches, sorting.*

INTRODUCTION

Cross-shore and longshore changes in beach sediment characteristics may be attributed to several possible mechanisms, including mechanical and chemical breakdown, more rapid transport of grains of one size than another, longshore variations in wave energy, the addition or loss of sediment, and mixing of two or more distinct sediment populations. Sediments are sorted through the modification of grain populations by selection, breaking, and mixing, as the result of a number of variables working together, or independently, to separate grains according to their shape, size, and density.

Many workers have studied the effect of grain size on sand entrainment thresholds, transportation rates, and sorting mechanisms, and the resulting changes in grain size parallel and perpendicular to the shore (MCLAREN, 1981; CARTER, 1988). There have also been a number of studies on the role of grain density in sediment sorting, and particularly on the concentration of the heavy mineral component on quartz- and feldspar-dominated beaches (SLINGERLAND, 1977; TRASK and HAND, 1985; LI and KOMAR, 1992; FRIHY and KOMAR, 1993). Although it is generally acknowledged that grain shape and roundness are also important hydraulic characteristics, their effect on beach dynamics and sedimentation has not been investigated, and there have only been a few studies of their relationship to longshore and cross-shore sorting patterns. MACCARTHY (1933) found that the proportion of angular grains increases in the direction of longshore sediment transport between Delaware and Chesapeake Bays. This could be the result of the lower settling velocities of angular grains, which allow them to remain in suspension longer, so that they are carried further and at higher rates than more rounded grains. The sphericity, and especially the roundness of sand grains also decrease in the direction of longshore transport on a spit in Lake Erie (PETTIJOHN and LUNDAHL, 1943). On the other hand, grain rounding increases with longshore transport on Long Island (WILLIAMS and MORGAN, 1988). SHEPARD and YOUNG (1961) suggested that waves selectively transport rounder grains up beaches, and berm sand is therefore rounder than on foreshores, although less than in dunes. There has been more interest in the effect of particle shape on grain movement by wind than by waves, but the precise nature of the relationship has not been determined and the experimental results are often contradictory (WILLIAMS, 1964; STAPOR *et al.*, 1983; JENSEN and SØRENSEN, 1986; WILLETTS and RICE, 1986; RICE, 1991).

Irregular, asymmetrical sand grains spin, oscillate, or tumble as they fall through water, and their settling velocity is therefore less than for perfect spheres. The settling velocity of irregular coral sand, for example, can be considerably lower than for less angular quartz, although coral density may also be a little lower (VAN RIJN, 1989). Small differences in the shape of angular grains may have far greater hydraulic significance than small differences in the shape of nearly spherical grains (BRIGGS *et al.*, 1962). The effect of particle shape on the settling velocity and drag coefficient of ellipsoidal and disc-shaped quartz grains was investigated by KOMAR and REIMERS (1978). This study was extended by KOMAR (1980) to consider the settling velocity of cylindrical grains, which are characteristic, for example, of several types of heavy mineral. BABA and KOMAR (1981a,b) found a number of relationships between the settling velocity of natural grains and spheres with diameters equal to the intermediate diameter of the natural grains, and they derived equations for the settling velocity of irregularly shaped grains. HALLERMEIER (1981) also investigated the settling velocity of

---

95075 received 30 May 1995; accepted in revision 9 February 1996.

natural quartz grains, but although they were assumed to be somewhat angular, their precise shape was not considered.

There has been little work on the effect of particle shape on sandy beaches, but much more is known of its role on coarse clastic beaches. The shape sorting of clasts reflects their varying suspension and pivotability potentials. Pronounced shape sorting produces distinct, shore-parallel zones or frames, which are dominated by particular clast shapes. Although it may be difficult to separate the interrelated effects of clast size, disc- and blade-shaped clasts are generally concentrated towards the back of beaches, with rods and especially spheres lower down (BLUCK, 1967; POSTMA and NEMEC, 1990). The degree of shape sorting may vary with wave energy (ORFORD, 1975). WILLIAMS and CALDWELL (1988) concluded that when swash zone processes are at the critical transport threshold during periods of berm buildup, the more easily suspended oblate material is thrown forward during the brief energy peak of the uprush. Spherical and prolate material is then winnowed down the beach by the longer, weaker backrush. Mass rather than shape becomes the dominant factor in determining net cross-shore transport when energy levels are high, and entrainment forces are much greater than the threshold values. Grain size may also affect the degree of shape sorting. MASSARI and PAREA (1988), for example, found that the degree of shape sorting increases with grain size, and is weakest in less responsive, finer-grained clasts.

Many indices have been developed to describe the overall form or some specific aspect of the shape of coastal sediments (WINKELMOLEN, 1971; KING, 1972; KOMAR, 1980; WHALLEY, 1981; WILLETTS and RICE, 1983; MAZZULLO *et al.*, 1986; ILLENBERGER, 1991). Although the sphericity and other aspects of the shape of coarse clasts can be determined fairly easily, direct measurement has generally proven to be too time consuming for sand and other small grains. The shape of large numbers of sand grains is therefore usually estimated visually, by comparing them with a set of standard grain images with known characteristics.

METHODOLOGY

This paper describes a field and laboratory study that attempted to determine how variations in the roundness of sand grains, which is a measure of the smoothness of their surface, influence their movement in the swash zone. Medium-grain sand samples were collected from Tremblay Beach, on southern Lake St. Clair, Canada (Figure 1). To reduce the effect of variable grain size on sediment transport, the samples were sieved and all experiments were conducted on one of the three largest size fractions. To eliminate or reduce the effects of variable particle density on grain transport, all measurements were conducted on quartz grains.

A wave tank, 0.6 m wide, 0.9 m deep, and 15.9 m long, was used in the laboratory experiments. Monochromatic waves were generated by a plunger, and experiments were conducted with a water depth of 21.5 cm. An adjustable artificial ramp was built to simulate foreshore slopes of 4, 6, and 8°. The surface of the ramp was covered by a piece of cork to provide enough friction to allow the grains to stay on it. All laboratory experiments were conducted on the 355–425 μm and 425–500 μm grain size fractions. In the first series of experiments, wave heights of 5 and 8 cm (with periods of 1.8 and 1.6 s, respectively) were generated and propagated up the three slopes. In the second series of experiments, which were designed to examine the effects of small differences in wave size, 8 and 8.5 cm high waves (with 1.6 s periods) were propagated up the slopes. The use of two sets of waves and three slope gradients therefore provided six possible maximum uprush distances for each experimental series. Three sampling points, 40 cm apart, were aligned down the centre of the ramp. Sediment was placed at the still water line at the bottom of the ramp, and four uprush and backrush cycles were allowed to disperse it over the slope. The resulting grain distribution was sampled using an 8 by 12 cm, water resistant pad with adhesive paper lining the underside. To remove the surface grains, the pad was centered over each sampling point and pressed onto the ramp (Figure 2a).

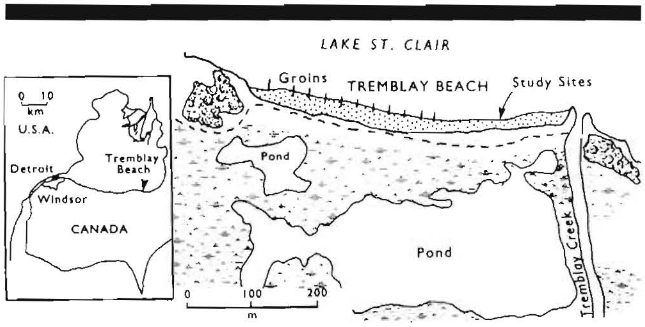

Figure 1. The study area.

Two experimental sites, approximately 5 m apart, were selected in the swash zone of Tremblay Beach. Each site consisted of three surveyed profile lines, spaced 2 m apart, one sample release point located below the still water line in the centre of each site, and fifteen sample points (Figure 2b). Two samples of sieved sediment (500–425 μm and 355–300 μm) were treated with fluorescent Anthracene dye. For the first three days, portions of the coarser sample were placed at the release points at the two sites and allowed to disperse over four uprush-backrush cycles. Field assistants then used the adhesive pad technique to simultaneously collect sand at each sample point. The procedure was repeated for the next three days using the finer grain sample. Wave heights ranged from 0.37 to 0.17 m and periods from 2.66 to 1.85 s during the study period. The slope of the beachface varied from 8.3 to 6.3° at site I, and 8.7 to 7.8° at site II, and the depth of the water table, measured daily at each site in shallow wells at the top and foot of the foreshore, was from 0.46 to 0.21 m over this period.

The grains were washed and removed from the pads, and microscopic slides were made of each of the samples. A fluorescent lamp was used to identify and remove dyed grains from the pads used in the field. Twenty grains, if present, were analysed from each laboratory slide, using a microscopic grid and random number selection, whereas all the recovered dyed grains were included from the field. About 1,000 grains

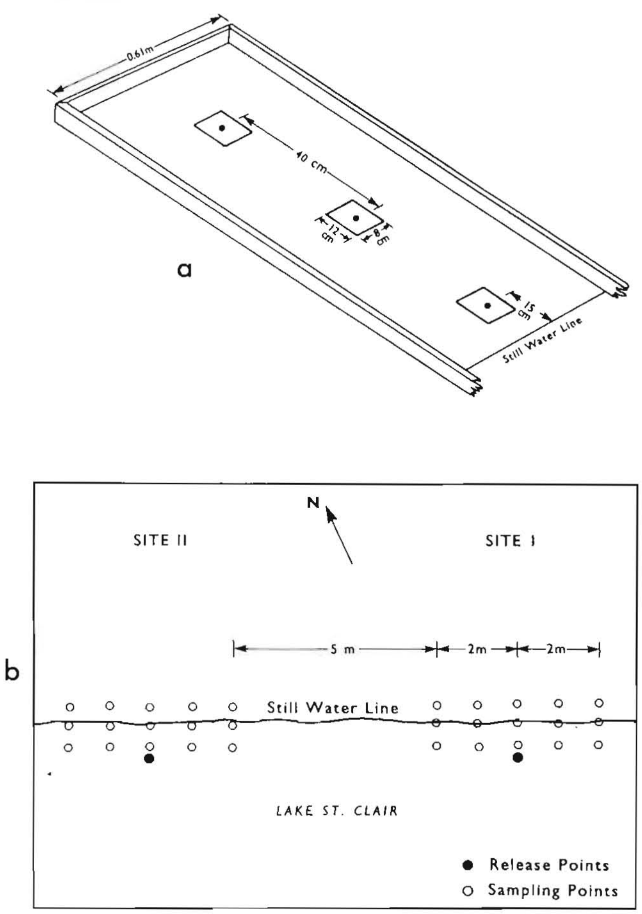

Figure 2. Artificial ramp and sample sites in the laboratory (a), and samples in the field (b).

were analysed in the laboratory experiments and 700 from the field. The length of the longest axis of each sampled grain in the laboratory and field experiments was measured under a microscope. This was done to determine the possible effect of slight variations in grain diameter within the sieved samples. The roundness of each grain was classified using POWERS' (1953) system, which is based on six roundness classes ranging from very angular to well rounded. Because of the small number of very angular and very round particles encountered in this study, however, the two most angular and the two most rounded classes were combined into a four-fold classification for the analysis of variance studies. The effect of grain roundness on settling velocities may be much less than the non-spherical shape of the grains (BABA and KOMAR, 1981b). An attempt was therefore made to investigate spatial variations in grain sphericity using POWERS' classification, which only makes the distinction between spherical and non-spherical grains. It soon became apparent, however, that there was no significant difference in grain sphericity, as determined by this method, within the swash zone. To assess the effect of sphericity and other aspects of grain shape on swash transport, it may be necessary to measure the length of grain axes, apply Fourier series (MAZZULLO *et al.*, 1986), or use grain "rollability" (WINKELMOLEN, 1971) or similar indices that are fairly easy to determine and less sensitive to operator error than visual comparison charts.

The distance of travel or displacement from the release point (d) to the sample location in the laboratory and field was determined for each grain. These displacement distances were averaged for each combination of roundness class (all six were used here), particle size class, beach slope, and mean breaker height used in the wave tank experiments. There was an average of seven grains per sampled group in the laboratory experiments, and a minimum of four grains constituted a group. These mean displacement distances served as the criterion or dependent variable in the study. A similar procedure was used in the field study to obtain mean displacement distances, using a minimum eleven particles to constitute a group. The uprush distance (x) from the still water line to the swash limit was also calculated using:

$$x = 2H_b \cot \beta$$

where H_b is breaker height and β is the beach slope (C.E.R.C. 1984). Although very few particles will travel this distance, it was hypothesized that as the uprush distance increases, the mean sediment displacement distances also increase for each sediment roundness class.

Three two way analyses of variance were run on the field and laboratory data to test the hypothesis that mean particle displacement distance per sample group was a linear function of roundness class (four were used here) and uprush distance class. The two way analysis of variance models were used to test the following null hypotheses:

(a) There would be no significant difference between the mean displacement distances between groups defined by a combination of uprush class and roundness class (Ho: $\mu_{11} = \mu_{12} \ldots \mu_{ru}$, where r = roundness class and u = uprush class);

(b) There would be no significant difference between the mean displacement distances (averaged over the uprush classes) for the roundness classes (Ho: $\mu_{1\cdot} = \mu_{2\cdot} = \ldots \mu_{r\cdot}$);

(c) There would be no significant difference between the mean displacement distances (averaged over the roundness classes) for the uprush classes (Ho: $\mu_{\cdot 1} = \mu_{\cdot 2} = \ldots \mu_{\cdot u}$);

(d) Mean displacement distances would not be significantly influenced by interaction effects between the uprush and roundness factors (Ho: $\Sigma\mu_{ru} - \Sigma\mu_{r\cdot} - \Sigma\mu_{\cdot u} + \Sigma\mu_{\cdot\cdot} = 0$, where $\mu_{\cdot\cdot}$ is the overall mean displacement distance).

Significant interaction would suggest that the slopes of the relationship between mean sediment displacement distance and wave uprush for each roundness class were not parallel, and the relationships would therefore be complex. Bartlett's tests, which were run before each analysis of variance, showed that there were no significant heteroscedasticity of variance effects in the laboratory or field data. After the analysis of variance, multiple regression analysis was used to test the hypothesis that sediment displacement distance is a linear function of mean roundness and maximum uprush distance.

RESULTS

In the first wave tank experiment, sediment movement up 4, 6, and 8 degree slopes was recorded for 5 and 8 cm high

Table 1. *Analysis of variance between sediment displacement, roundness and maximum wave uprush.*

a) waves 5 and 8 cm high—dependent variable d, n = 51, multiple R = 0.76, squared multiple R = 0.577. Bartlett's Chi Square = 11.09 with df = 11, not significant at the 0.05 level.

Source	Sum-of-squares	df	Mean-square	F-ratio	P
r	1.036	3	0.345	7.809	0.000
u	0.900	2	0.450	10.171	0.000
r*u	0.183	6	0.030	0.689	0.660
Error	1.725	39	0.044		

b) waves 8 and 8.5 cm high—dependent variable d, n = 48, multiple R = 0.711, squared multiple R = 0.506. Bartlett's Chi Square = 22.09 with df = 11, not significant at the 0.05 level.

Source	Sum-of-squares	df	Mean-square	F-ratio	P
r	0.904	3	0.301	5.925	0.002
u	0.810	2	0.405	7.964	0.001
r*u	0.088	6	0.015	0.288	0.939
Error	1.831	36	0.051		

c) Tremblay Beach—dependent variable d, n = 42, multiple R = 0.771, squared multiple R = 0.594. Bartlett's Chi Square = 13.51 with df = 11, not significant at the 0.05 level.

Source	Sum-of-squares	df	Mean-square	F-ratio	P
r	0.764	3	0.255	10.597	0.000
u	0.123	2	0.062	2.569	0.093
r*u	0.101	6	0.017	0.700	0.651
Error	0.721	30	0.024		

d = mean distance moved, r = roundness class, u = wave uprush class, r*u = roundness—uprush interaction term

Table 2. *Sediment displacement regressed against roundness and uprush level.*

a) waves 5 and 8 cm high—dependent variable d, n = 51, multiple R = 0.692, squared multiple R = 0.479, adjusted squared multiple R = 0.457, standard error of estimate = 0.211.

Variable	Coefft.	Std. Error	Std. Coefft.	T	P(2 TAIL)
Constant	−0.108	0.112	0.000	−0.967	0.338
r	0.834	0.173	0.505	4.846	0.000
u	0.174	0.039	0.462	4.428	0.000

Analysis of variance

Source	Sum-of-squares	df	Mean-square	F-ratio	P
Regression	1.954	2	0.977	22.030	0.000
Residual	2.129	45	0.044		

b) waves 8 and 8.5 cm high—dependent variable d, n = 48, multiple R = 0.627, squared multiple R = 0.393, adjusted squared multiple R = 0.366, standard error of estimate = 0.224

Variable	Coefft.	Std. Error	Std. Coefft.	T	P(2 TAIL)
Constant	−0.024	0.135	0.000	−0.180	0.858
r	0.757	0.188	0.467	4.022	0.000
u	0.153	0.042	0.420	3.615	0.001

Analysis of variance

Source	Sum-of-squares	df	Mean-square	F-ratio	P
Regression	1.458	2	0.729	14.588	0.000
Residual	2.249	45	0.050		

c) Tremblay Beach—dependent variable d, n = 42, multiple R = 0.717, squared multiple R = 0.515, adjusted squared multiple R = 0.476, standard error of estimate = 0.150

Variable	Coefft.	Std. Error	Std. Coefft.	T	P(2 tail)
Constant	−0.292	0.364	0.000	−0.804	0.426
r	0.850	0.152	0.661	5.599	0.000
u	0.116	0.034	0.445	3.372	0.002
l	0.009	0.005	0.253	1.854	0.072

Analysis of variance

Source	Sum-of-squares	df	Mean-square	F-ratio	P
Regression	0.913	3	0.304	13.436	0.000
Residual	0.861	38	0.023		

u = Wave uprush from still water line, r = geometric mean roundness, l = mean particle long axis length

waves. Two way analysis of variance showed that particle roundness and wave uprush accounted for a significant proportion of the variation in mean sediment displacement distances (Table 1a). The lack of significant interaction effects suggests that the slopes of the relationships between displacement distance and uprush levels for each roundness class were roughly parallel to each other. Overall, a linear combination of roundness and uprush accounted for 57.7 percent of the observed variation in sediment displacement distance. The experimental procedure was repeated in the wave tank for a second data set, using waves of 8.0 and 8.5 cm in height (Table 1b). Two way analysis of variance demonstrated that a linear combination of sediment roundness and wave uprush levels accounted for 50.6 percent of the variation in sediment displacement levels. The interaction term was again non-significant.

The relationship between sediment displacement and roundness and uprush levels was expressed in the form of regression models (Table 2). When mean sediment displacement was regressed against the geometric mean roundness and maximum uprush levels, a linear combination of the two factors accounted for 45.7 percent of the displacement distance variation for 5 and 8 cm waves, and 36.6 percent of the distance variation for 8 and 8.5 cm waves. Although the use of samples consisting of a single sieve size eliminated the effects of large variations in grain size, the movement and distribution of grains within the swash zone could still have largely reflected small differences in size within each sample. It was found that particle long axis length, however, did not contribute significantly to either equation. The relationship between sediment displacement and sediment roundness and wave uprush was therefore between moderately strong and strong in the two laboratory experiments, and the two factors made roughly equal contributions to the explanation of sediment displacement variations (Table 2—note the roughly equal standardized regression coefficients).

The Tremblay Beach field experiments and statistical analyses were similar to those conducted in the wave tank, although at a larger scale, and with less control over beach slope and wave parameters. Sediment displacement distances and sediment roundness were measured on six occasions in June and July 1988, and the maximum wave uprush from the still water line was calculated from the data. Two way analysis of variance produced similar results to those ob-

Table 3. *Regression equations obtained from the field and wave tank studies.*

Wave tank study using 5 and 8 cm waves	$d = 0.83\ r + 0.17\ u$
Wave tank study using 8 and 8.5 cm waves	$d = 0.76\ r + 0.15\ u$
Field study	$d = 0.85\ r + 0.12\ u$

tained in the wave tank. Although grain roundness made a significant contribution to the explanation of spatial variations in sediment displacement, uprush did not contribute significantly to the explanation, probably because of the lack of marked variations in slope, and to a somewhat lesser degree wave conditions, over the measurement period (Table 1). The interaction term was also non-significant. The multiple regression model showed that a linear combination of geometric mean roundness and maximum uprush accounted for 47.6 percent of the spatial variation in sediment displacement distance (Table 2). The wave uprush variable made a significant contribution to the proportion of explained variance in this model.

Statistical analysis of the field and wave-tank data produced surprisingly consistent results. In all three regression models, a linear combination of geometric mean roundness and maximum uprush distance accounted for 35.7 to 47.6 percent of the spatial variation in mean displacement distance (all significant at the 0.05 level). There was also a great deal of similarity in the regression equations, which suggest that sediment displacement is sensitive to particle roundness (Table 3; Figures 3, 4, and 5). The use of sieved samples and quartz grains, however, did not allow the relative importance

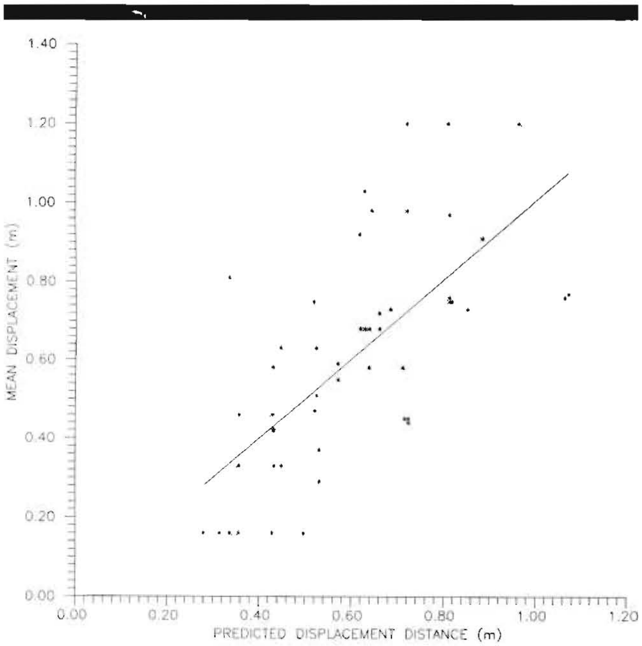

Figure 3. Wave tank experiment with wave heights of 5 and 8 cm: observed mean particle displacement versus estimated mean particle displacement based on the following combination of geometric mean roundness (r) and mean uprush distance (u): $d = -0.108 + 0.838r + 0.174u$.

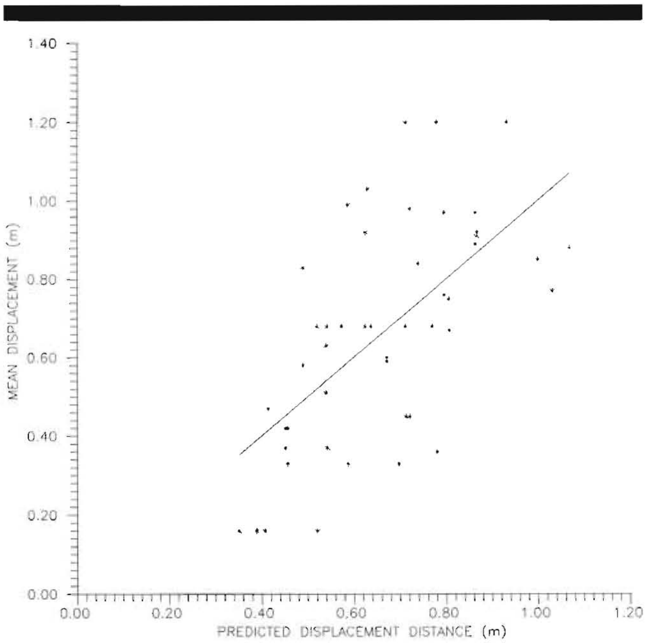

Figure 4. Wave tank experiment with wave heights of 8 and 8.5 cm: observed mean particle displacement versus estimated mean particle displacement based on the following combination of geometric mean roundness (r) and mean uprush distance (u): $d = -0.024 + 0.757r + 0.153u$.

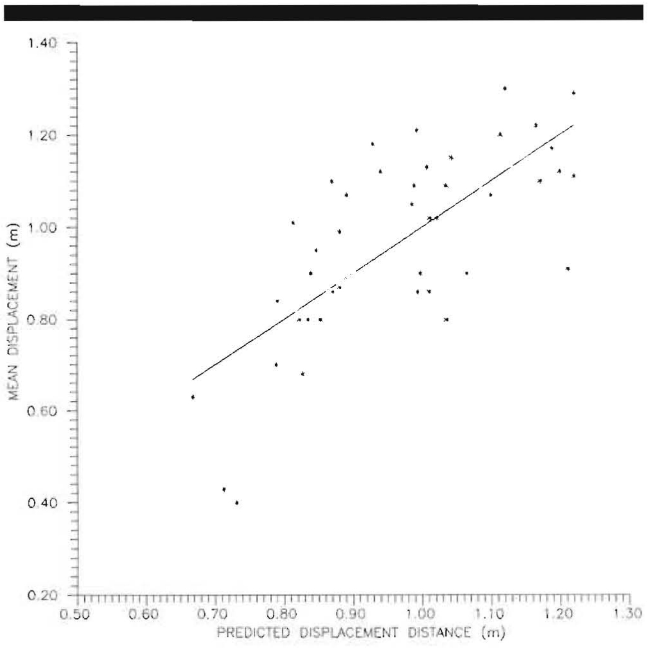

Figure 5. Tremblay beach observed mean particle displacement distance versus predicted mean particle displacement distance based on the regression model: $-0.292 + 0.850r + 0.116u + 0.009l$. r = Geometric Mean Roundness, u = mean uprush distance, l = Mean Particle Long Diameter, d = Mean Displacement Distance.

of grain roundness, compared with grain size and density, to be determined in the present study. Nevertheless, it was possible to compare the effect of a limited range of grain sizes on displacement patterns by running a t-test between the sediment displacement means for the 355–425 μm and 425–500 μm particle size groups used in the two laboratory experiments. The lack of significant differences between the mean displacement distances of the two size classes suggested that grain roundness is more important than grain diameter in determining displacement distance in the swash zone, over the limited range of grain sizes considered in this study.

DISCUSSION

One can only speculate at this stage on the possible reasons for the transport of more rounded sand grains towards the back of the swash zone. An increase in the proportion of angular grains with the distance of longshore transport (MacCarthy, 1933; Pettijohn and Lundahl, 1943) supports the conclusion that they generally travel further than rounded grains because of lower settling velocities. Rounded grains may therefore be deposited at the back of beaches by the uprush, while more angular grains remain in suspension and are carried back down the foreshore by the backrush. In the swash zone, however, sediment is moved in dense suspended concentrations and in sheet flow (highly concentrated layers of grains shearing over each other, with an intrusive depth of several millimetres) (Horikawa *et al.*, 1982; Dibajnia and Watanabe, 1992; Asano, 1992). The effect of variable settling velocities under these conditions is unclear, and in any case, the general occurrence of finer, and therefore more mobile, grains towards the upper portion of foreshores suggests that the more mobile angular grains should also congregate towards the higher parts of the slope. The alternate explanation, that rounder grains are more easily entrained in water than angular grains, remains to be determined. Lower entrainment thresholds could explain why dune sands tend to be more rounded and spherical than beach sands -although it may also be due to selective transport by wind (MacCarthy, 1935; Beal and Shepard, 1956; Shepard and Young, 1961; Bigarella, 1972; Mazzullo *et al.*, 1986).

CONCLUDING REMARKS

Although it has been recognized that grain size and mineralogy generally change in somewhat predictable ways on beaches, the role of shape and roundness needs to be determined. The degree of roundness or shape sorting in the swash zone, and its importance relative to grain size and mineralogy, probably vary according to such factors as the beach state, the depth of the water table, the rate of sediment accumulation, grain size, density, and packing, and the shear velocity, turbulence, and depth of the uprush and backrush (Steidtmann, 1982). It has already been noted, for example, that shape sorting on coarse clastic beaches is less pronounced where there are high energy levels (Orford, 1975; Williams and Caldwell, 1988), and it is possible that a similar relationship occurs on sandy beaches.

The results of this study provide support for Shepard and Young's (1961) suggestion that particle roundness can have a significant effect on cross-shore sediment transport and sorting in the swash zone. The importance of grain roundness may have significant implications for the formulation of sediment transport equations and beach equilibrium models, which have generally only considered the variable size of quartz grains (Horikawa, 1988; van Rijn, 1989; Hardisty, 1990; Horn, 1992; Fredsøe, 1993). Nevertheless, more work is necessary to determine whether, or under what conditions, grain roundness sorting is a significant factor on beaches, and to assess its role in sediment entrainment and transport in the littoral zone.

LITERATURE CITED

Asano, T., 1992. Observations of granular-fluid mixture under an oscillatory sheet flow. *Proceedings of the 23rd Coastal Engineering Conference*, pp. 1896–1909.

Baba, J. and Komar, P.D., 1981a. Measurements and analysis of settling velocities of natural quartz sand grains. *Journal of Sedimentary Petrology*, 51, 631–640.

Baba, J. and Komar, P.D., 1981b. Settling velocities of irregular grains at low Reynolds numbers. *Journal of Sedimentary Petrology*, 51, 121–128.

Beal, M.A. and Shepard, F.P., 1956. A use of roundness to determine depositional environments. *Journal of Sedimentary Petrology*, 26, 49–60.

Bigarella, J.J., 1972. Eolian environments —their characteristics, recognition and importance. *In*: J. K. Rigby and W. K. Hamblin (eds.), *Recognition of Ancient Sedimentary Environments*. Tulsa, Oklahoma: Society Economic Paleontologists Mineralogists, Special Publication, 16, pp. 12–62.

Bluck, B.J., 1967. Sedimentation of beach gravels: Examples from south Wales. *Journal of Sedimentary Petrology*, 37, 128–156.

Briggs, L.I.; McCulloch, D.S., and Moser, F., 1962. The hydraulic shape of sand particles. *Journal of Sedimentary Petrology*, 32, 645–656.

Carter, R.W.G., 1988. *Coastal Environments*. London: Academic Press, 617p.

C.E.R.C., 1984. *Shore Protection Manual*. Volume 2. Washington, D.C.: U.S. Army Corps of Engineers, fourth edition.

Dibajnia, M. and Watanabe, A., 1992. Sheet flow under nonlinear waves and currents. *Proceedings of the 23rd Coastal Engineering Conference*, 2015–2028.

Fredsøe, J., 1993. Modelling of non-cohesive sediment transport processes in the marine environment. *Coastal Engineering*, 21, 71–103.

Frihy, O.E. and Komar, P.D., 1993. Long-term shoreline changes and the concentration of heavy minerals in beach sands of the Nile Delta, Egypt. *Marine Geology*, 115, 253–261.

Hallermeier, R.J., 1981. Terminal settling velocity of commonly occurring sand grains. *Sedimentology*, 28, 859–865.

Hardisty, J., 1990. *Beaches Form and Process*. London: Unwin Hyman, 324p.

Horikawa, K., 1988, (ed.). *Nearshore Dynamics and Coastal Processes*. Tokyo: University Tokyo Press, 522p.

Horikawa, K.; Watanabe, A., and Katori, S., 1982. Sediment transport under sheet flow condition. *Proceedings of the 18th Coastal Engineering Conference*, pp. 1335–1352.

Horn, D.P., 1992. A review and experimental assessment of equilibrium grain size and the ideal wave-graded profile. *Marine Geology*, 108, 161–174.

Illenberger, W.K., 1991. Pebble shape (and size!). *Journal of Sedimentary Petrology*, 61, 756–767.

Jensen, J.L. and Sørensen, M., 1986. Estimation of some aeolian saltation transport parameters: A re-analysis of Williams' data. *Sedimentology*, 33, 547–558.

KING, C.A.M., 1972. *Beaches and Coasts*. London: Edward Arnold, 570p.

KOMAR, P.D., 1980. Settling velocities of circular cylinders at low Reynolds numbers. *Journal of Geology*, 88, 327–336.

KOMAR, P.D. and REIMERS, C.E., 1978. Grain shape effects on settling rates. *Journal of Geology*, 86, 193–209.

LI, M.Z. and KOMAR, P.D., 1992. Longshore grain sorting and beach placer formation adjacent to the Columbia River. *Journal of Sedimentary Petrology*, 62, 429–441.

MACCARTHY, G.R., 1933. The rounding of beach sands. *American Journal of Science*, 24, 205–224.

MACCARTHY, G.R., 1935. The rounding of beach sands, a comparison. *American Journal of Science*, 25, 204–224.

MASSARI, F. and PAREA, G.C., 1988. Progradational gravel beach sequences in a moderate- to high-energy, microtidal marine environment. *Sedimentology*, 35, 881–913.

MAZZULLO, J.; SIMS, D., and CUNNINGHAM, D., 1986. The effects of eolian sorting and abrasion upon the shapes of fine quartz sand grains. *Journal of Sedimentary Petrology*, 56, 45–56.

MCLAREN, P., 1981. An interpretation of trends in grain size measures. *Journal of Sedimentary Petrology*, 51, 611–624.

ORFORD, J.D., 1975. Discrimination of particle zonation on a pebble beach. *Sedimentology*, 22, 441–463.

PETTIJOHN, F.J. and LUNDAHL, A.C., 1943. Shape and roundness of Lake Erie beach sands. *Journal of Sedimentary Petrology*, 13, 69–78.

POSTMA, G. and NEMEC, W., 1990. Regressive and transgressive sequences in a raised Holocene gravelly beach, southwestern Crete. *Sedimentology*, 37, 907–920.

POWERS, M.C., 1953. A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology*, 23, 117–119.

RICE, M.A., 1991. Grain shape effects on aeolian sediment transport. *In*: BARNDORFF-NIELSEN, O.E. and WILLETTS, B.B. (eds.), *Aeolian Grain Transport 1 Mechanics*. Wien: Springer-Verlag, Acta Mechanica Suppl. 1, 159–166.

SHEPARD, F.P. and YOUNG, R., 1961. Distinguishing between beach and dune sands. *Journal of Sedimentary Petrology*, 31, 196–214.

SLINGERLAND, R.L., 1977. The effects of entrainment on the hydraulic equivalence relationships of light and heavy minerals in sands. *Journal of Sedimentary Petrology*, 47, 753–770.

STAPOR, F.W.; MAY, J.P., and BARWIS, J., 1983. Eolian shape-sorting and aerodynamic traction equivalence in the coastal dunes of Hout Bay, Republic of South Africa. *In*: BROOKFIELD, M.E. and AHLBRANDT, T. (eds.), *Eolian Sediments and Processes*. Amsterdam: Elsevier, pp. 149–164.

STEIDTMANN, J.R., 1982. Size-density sorting of sand-size spheres during deposition from bedload transport and implications concerning hydraulic equivalence. *Sedimentology*, 29, 877–883.

TRASK, C.B. and HAND, B.M., 1985. Differential transport of fall-equivalent sand grains, Lake Ontario, New York. *Journal of Sedimentary Petrology*, 55, 226–234.

VAN RIJN, L.C., 1989. *Handbook Sediment Transport by Currents and Waves*. Delft, The Netherlands: Delft Hydraulics Report. H 461.

WHALLEY, W.B., 1981. Physical properties. *In*: GOUDIE, A. (ed.), *Geomorphological Techniques*. London: Allen and Unwin, pp. 80–103.

WILLETTS, B.B. and RICE, M.A., 1983. Practical representation of characteristic grain shape of sands: A comparison of methods. *Sedimentology*, 30, 557–565.

WILLETTS, B.B. and RICE, M.A., 1986. Collision in aeolian transport: The saltation/creep link. *In*: NICKLING, W.G. (ed.), *Aeolian Geomorphology*. London: Allen and Unwin, pp. 1–17.

WILLIAMS, A.T. and CALDWELL, N.E., 1988. Particle size and shape in pebble-beach sedimentation. *Marine Geology*, 82, 199–215.

WILLIAMS, A.T. and MORGAN, P., 1988. Quartz grain S.E.M. textural variations of the beach/dune interface, Long Island, U.S.A. *Journal of Coastal Research*, Special Issue No. 3, pp. 37–45.

WILLIAMS, G., 1964. Some aspects of the eolian saltation load. *Sedimentology*, 3, 257–287.

WINKELMOLEN, A.M., 1971. Rollability, a functional shape property of sand grains. *Journal of Sedimentary Petrology*, 41, 703–714.