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THE WATER CONTENT OF SAND REQUIRED FOR THE MAXIMUM STRENGTH FOR BUILDING SAND CASTLES

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Abstract: A sandy beach has a special attraction for people: building sand castles. The required ingredients are simply sand and water. But what about the mixing ratio to achieve the maximum strength of the wet sand? In this study the influence of the moisture content on the strength of sand was investigated. For the measurement of the strength at different values of the consolidation stress a ring shear tester was used. At small moisture contents up to 2% the strength strongly increased with the moisture content. Over a relatively wide range of the moisture content, almost from 2% to 17% the influence of the moisture content on the strength was relatively small. The maximum strength was measured at a moisture content of approximately 16%. In this moisture range maximizing the applied consolidation stress is of comparatively much higher importance for the strength of the wet sand than the finding the optimum moisture content. At higher moisture contents the strength decreased as saturation with water approached 100%.

Keywords: beach, sand castle, strength, sand, water content

1. INTRODUCTION

For holidays by the sea a sandy beach is a special attraction. This is not least due to the tempting possibility of building sand castles. The motivation of beach visitors for the construction of sand castles is even the subject of research (Obrador-Pons, 2009; Franklin, 2014). Books on how to build a sand castle were probably written for these people (Wierenga, 2005). The list of ingredients for building a sand castle is quite short: sand, water and a few tools. By experience, all builders of sand castles know that dry sand is not suitable. The sand has to be wet because the water sticks the grains together. According to The Guardian (2009) the rule is: “The fail-safe recipe for castle concrete is one part sand to one part water”.

From a particle technologist’s point of view sand is a bulk solid. When a low viscosity liquid, in this case water, is added to the solid particles and when the particles are wettable by the liquid, the liquid accumulates in the narrow gaps between particles and forms liquid bridges. The inter-particle adhesive forces are thereby increased due to the surface tension of the liquid and a possible negative capillary pressure (Mitarai & Nori, 2006). This results in increased strength of the bulk material. However, if too much liquid is added the voids within the bulk solid are totally filled with the liquid, which means that the granular material is saturated with liquid. As a consequence, the liquid-air surfaces disappear and the surface tension also vanishes. As soon as saturation is approached, the strength of the material decreases sharply, and the moist bulk solid is transformed into a slurry.

The flow characteristics of sand have been investigated by several researches. Longo and Lambert (2000) studied the continuous flow of sand in slowly rotating drums. Barabási et al., (1999) used the angle of repose of dry and wet sand to characterize the physics of building sand castles. Pakpour et al., (2012) compacted sand in plastic tubes with different diameter to determine the maximum possible height of columns of wet sand.

A more appropriate method is to use the yield limit of the consolidated sand, the yield locus, which can be determined by shear tests. The strength of a bulk solid can be characterized by the cohesion τ_c or by the unconfined yield strength σ_c. The cohesion is the shear stress at the intersection of the yield locus with the shear stress axis. Usually, the cohesion can only be determined by extrapolating the yield locus which is somewhat inaccurate because of the slightly curved shape of the yield locus. The unconfined yield strength results from the stress circle, which is tangential to the yield locus and runs through the origin (Fig. 1a). Since a yield locus is increasingly curved towards small stresses, the value of the cohesion cannot be determined very exactly this way and is usually less accurate than the unconfined yield strength. Therefore, in this study the unconfined yield strength was used for the characterization of the strength of the moist sand.

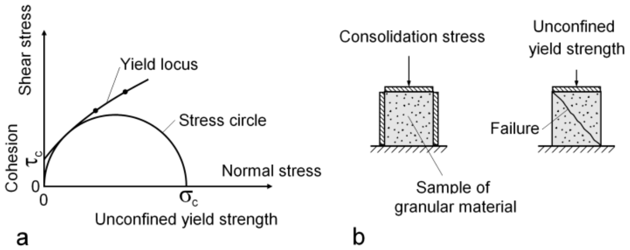

Figure 1. Yield locus with cohesion and unconfined yield strength (a); Uniaxial compression test (b)

The circumstances can be explained using the uniaxial compression test (Schulze, 2008). Figure 1b shows a hollow cylinder which is filled with a sample of granular material. The internal wall of the hollow cylinder is assumed to be frictionless. The granular material is loaded in the vertical direction by the consolidation stress and is thus compressed. Thereby, the bulk density as well as the strength of the granular material increases. Afterwards, the material is relieved of the consolidation stress and the hollow cylinder is removed. When the consolidated material is loaded subsequently with an increasing vertical compressive stress, the sample will break at a certain stress. The stress causing failure is called unconfined yield strength σ_c.

This situation is similar to the procedure of building a sand castle. First, a heap of the moist sand is compacted by applying vertical stress, for example by weight. Horizontal confinement is achieved by the surrounding sand. Afterwards, elements of the castle like walls, etc. are shaped by removing part of the sand. The unconfined yield strength of the remaining sand is then a reasonable measure for the stability of the castle.

In the literature, investigations of the influence of the moisture content on the properties of various bulk solids like gypsum, diary powders, pharmaceutical powders and glass powders using shear testers have been reported (Schulze & Schwedes, 1991; Emery et al., 2009; Fitzpatrick et al., 2007; Landi et al., 2011). However, for these industrial powders the opposite of strength, the tendency to flow was the subject of interest. Some results on the shear strength of unsaturated silty sand have been published by Schnellmann et al., (2013). However, the size distribution of the investigated sand was significantly wider (span of the size distribution: approximately 40) than what is expected for sand from a beach.

The aim of this study was to investigate the influence of the water content of sand from a beach on the strength of the material. For the investigation sand from an Italian beach was used. In the study sand-water mixtures with different water content were produced and tested using a ring-shear tester.

2. MATERIAL AND METHODS

2.1. Materials

The sand sample was collected from the beach of Bibione Pineda, Italy. In total, 10 kg of sand were collected from 10 different points at a distance of approximately 10 m from the water line. In the laboratory the sand was dried in a compartment drier for 24 hours. Afterwards, the sand was sieved using a 1mm sieve to remove foreign material like pieces of shells and wood.

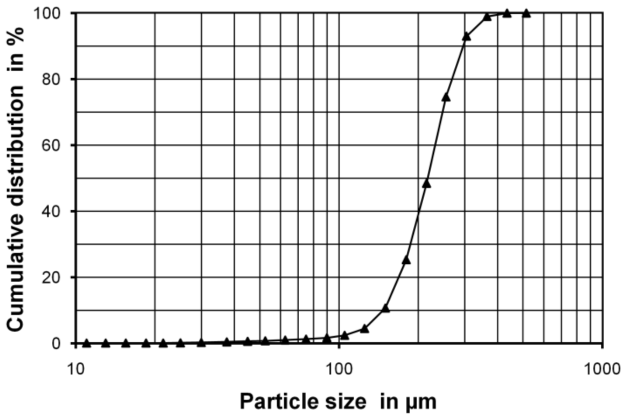

Figure 2. Particle size distribution of the sand

The particle size distribution of the sand is shown in Figure 2. The mass median diameter x_{50} of the sand was 217 µm. The size difference between the coarse and the fine particles was quite small, the value of the span was as low as 2.0. Figure 3 shows microscopic images of the sand. The shape of the sand particles is compact but far from spherical (Fig. 3a). A closer look reveals that the surface of the grains is not smooth (Fig. 3b).

The chemical composition obtained by SEM-EDX shows Ca, Si, Mg and Al as the main metals (Fig. 4). When Ca and Mg are assumed to be present as carbonates the calculation reveals a significant surplus of C. This is the result of some sample holder surface visible between the particles.

The measured bulk density of the dry sand was 1,490kg/m³ and the particle density was 2,830kg/m³. The resulting porosity of the dry sand was 0.47.

2.2. Methods

The particle size distribution of the sand sample was determined using a laser diffraction instrument with dry sample dispersion from Sympatec, type HELOS/RODOS. The calibration of the instrument was checked with a Sympatec SiC-P600'06 standard. The mass median diameter x50 of the particle size distribution was calculated by linear interpolation between the two measured values next to it. The x_{50} is the particle size with 50% of the mass of the sand consisting of particles smaller than this size and the remaining sand consisting of larger particles. The span of the size distribution was calculated as the quotient of x_{90} and x_{10}. The x_{10} and the x_{90} are defined in a similar way to the x_{50} (Rumpf, 1990).

Microscopic images of particles were taken with a scanning electron microscope TESCAN, type MIRA3. Further information was obtained in combination with energy dispersive X-ray spectroscopy (SEM-EDX).

The bulk density ρ_B of the sand was determined according to EN ISO 60. The bottom cover of a funnel is removed to allow 120cm³ of the sand stored in the funnel to flow by gravity into a coaxial 100cm³ measuring cylinder. The excess material is removed by drawing a straight, flat blade across the top of the measuring cylinder.

The density of the sand ρ_S was determined according to ÖNORM EN ISO 8130-3 using a 300cm³ liquid displacement pycnometer. For the displacement of the air n-heptane with a density of 0.681g/cm³ was used.

The moisture content of the sand samples was adjusted by mixing with tap water for 5 minutes in an Erweka AR 403/SW 1/S ploughshare drum mixer. The speed of the mixer was 300 rpm. The moisture content of the samples produced was measured gravimetrically using a moisture analyser from OHAUS, type MB 45. Thereby, the samples were dried at 105°C until constant weight.

For determination of the yield locus for the sand samples a RST-XS ring shear tester with a 30cm3 shear cell from Schulze was used. In order to do a shear test, the sample is loaded vertically at a certain normal stress and then a shear deformation is applied to the sample by moving the top plate at a constant rotation velocity. This results in a horizontal shear stress within the sample.

Each point of the yield locus is measured in two steps. Firstly, the sample is consolidated in the pre-shear step. In this way the point of steady-state flow is determined with the pair of values for the normal stress σ and the shear stress τ. Secondly, a point of the yield limit is determined at a reduced normal stress level.

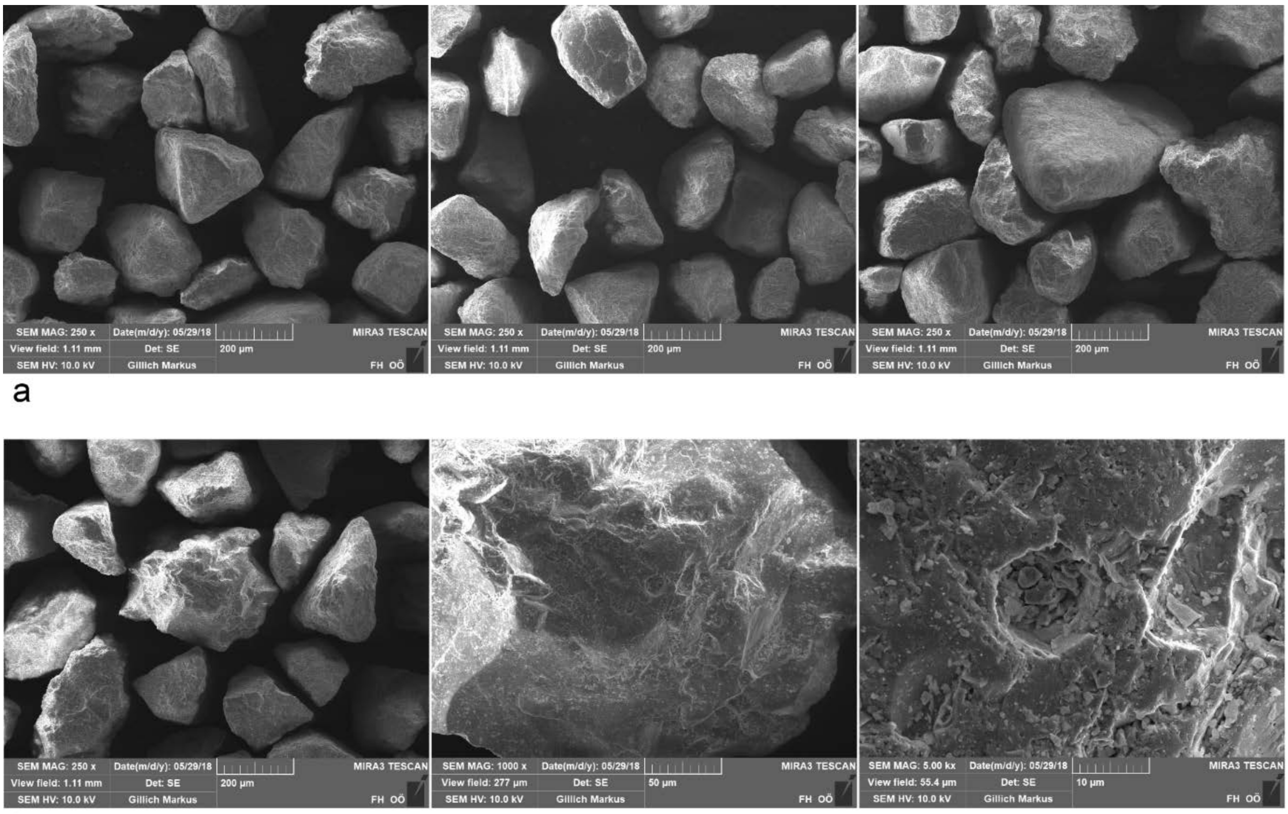

Figure 3. Microscopic images of the sand granules

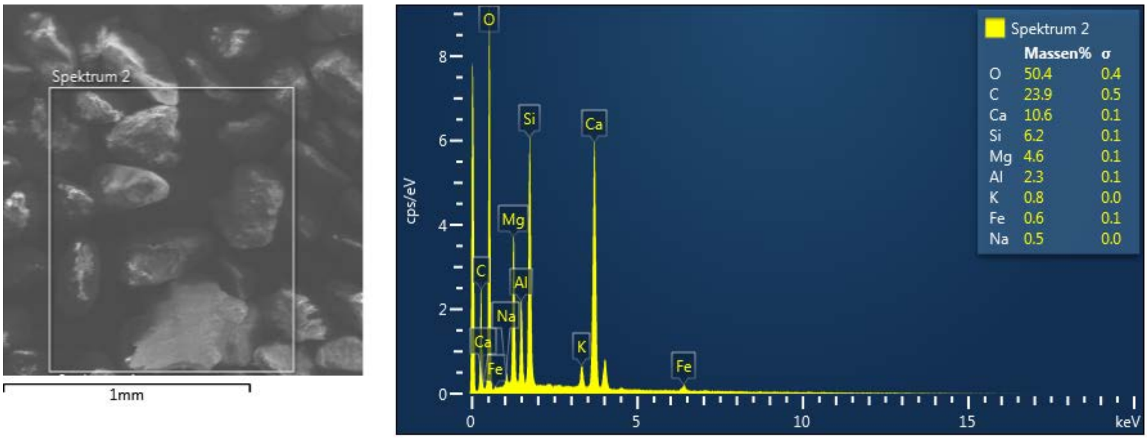

Figure 4. SEM-EDX analysis of the sand granules

The corresponding values for the normal stress and the shear stress deliver one point of the yield limit. Repeating the procedure produces the entire yield locus. The unconfined yield strength results from the stress circle, which is tangential to the yield locus and runs through the origin (Schulze, 2008). With four moisture contents the measurement was carried out in triplicate in order to check the precision. The results are summarized in Table 1. The standard deviation was typically less than 10% of the arithmetic mean. Only at the maximum moisture content of the sand the standard deviation was somewhat higher.

2.3. Calculations

The voidage or porosity ε of a packed bed of particles is defined by equation (1)

$$\varepsilon = \frac{V_P}{V_S + V_P} \quad (1),$$

where V_P is the volume of the pores and V_S is the volume of the solid particles (Seville et al., 1997).

For a packed bed containing some liquid the saturation S is defined by equation (2)

$$S = \frac{V_L}{V_P} \quad (2),$$

where V_L is the volume of the liquid water in the pores between the solid particles (Rushton et al., 1996). Equations (1) and (2) can be summarized. Using the density of the solid ρ_S, the density of the liquid ρ_L and X_{mL}, the ratio of the mass of the liquid to the mass of the solid, equation (3) results to

$$S = X_{mL} \cdot \frac{\rho_S \cdot (1-\varepsilon)}{\rho_L \cdot \varepsilon} \quad (3).$$

The bulk density ρ_B in the shear cell depends on the porosity of the material

$$\rho_B = \rho_S \cdot (1-\varepsilon) + \rho_L \cdot \varepsilon \cdot S \quad (4).$$

With increasing normal stress, the material is compacted, thus reducing the porosity and increasing the saturation. After elimination of the porosity by combining equations (3) and (4), the following equation for the saturation of the material in the shear cell is obtained.

$$S = \frac{\rho_B \cdot X_{mL}}{\rho_L \cdot \left(1 + X_{mL} - \rho_B / \rho_S\right)} \quad (5).$$

3. RESULTS AND DISCUSSION

3.1. Characterization of the wet sand

In Figure 5 the bulk density of the sand is shown as a function of the moisture content. Generally, the bulk density was higher for higher values of the consolidation stress. However, this difference was quite small for dry sand as well as when the value of the saturation got close to 1.0. Then the bulk density was nearly constant over a wide range up to a moisture content of approximately 14%. At higher moisture contents the bulk density increased significantly. At low moisture content in the range of 0-2% the bulk density decreased with increasing moisture content.

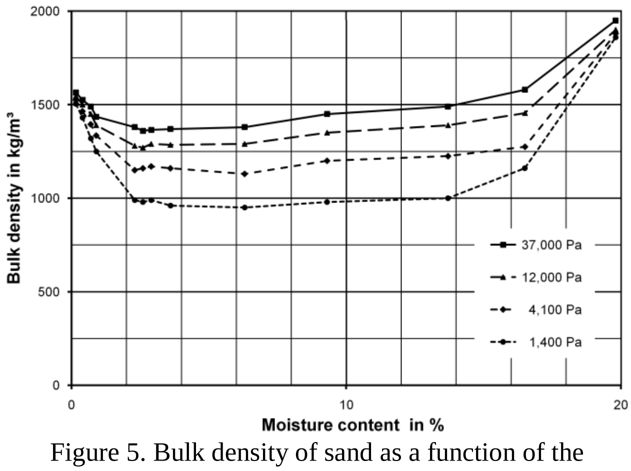

Figure 5. Bulk density of sand as a function of the moisture content

Table 1 Precision of the measurement of the unconfined yield strength in Pa (arithmetic mean ± standard deviation)

Moisture content in %	Consolidation stress			
	1.4 kPa	4.1 kPa	12 kPa	37 kPa
0.7	400±40	660±19	920±130	1800±110
2.3	1130±12	2440±18	4240±200	6880±280
6.3	1400±78	3210±120	5860±180	9930±230
19.8	1510±106	2710±280	4680±490	7630±1070

The course of the porosity showed an opposite behavior (Fig. 6). With increasing water content the porosity of the sand increased. Starting at approximately 0.47 for dry sand the porosity increased up to 0.69, 0.62, 0.57 and 0.54 at a consolidation stress of 37kPa, 12kPa, 4,100Pa and 1,400Pa, respectively.

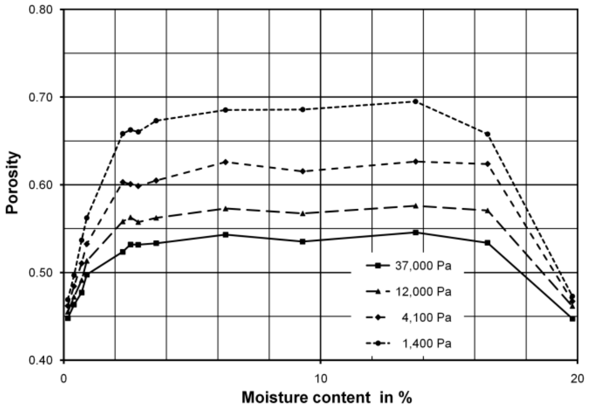

Figure 6. Porosity of the sand as a function of the moisture content

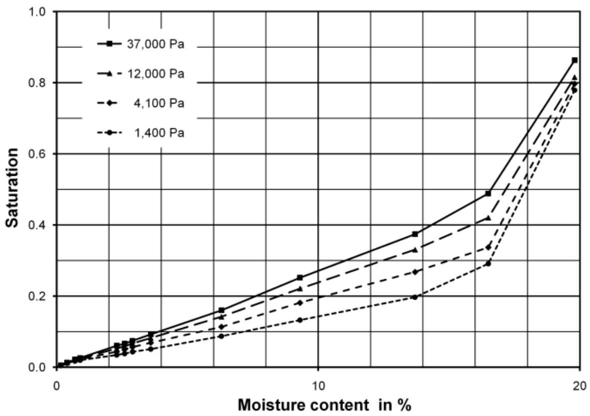

Figure 7. Saturation versus moisture content

At moisture content higher than 17% the porosity decreased again and reached practically the same porosity as dry sand when the moisture content was approximately 20%. Thus, the higher bulk density at this moisture content is a result solely from the water inside the pores and not from a higher packing density of the particles.

The sharp increase of the bulk density at moisture content above 17% (Fig. 5) and the simultaneous decrease of the porosity (Fig. 6) resulted in a steep increase of the saturation (Fig. 7). Total saturation would be reached at moisture content somewhat above 20%.

3.2. Dependence of strength on water content

Figure 8 shows the unconfined yield strength for four values of the consolidation stress as a function of the moisture content of the sand. The values of the consolidation stress of 37kPa, 12kPa, 4,100Pa and 1,400Pa correspond with a weight load per 1dm² during consolidation of 37.7kg, 12.2kg, 4.2kg and 1.4kg, respectively. Generally, higher values of the consolidation stress result in higher values of the unconfined yield strength.

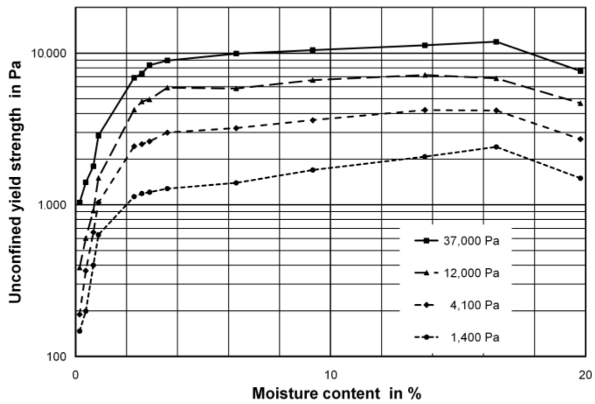

Figure 8. Unconfined yield strength of sand as a function of the moisture content

For dry sand the strength of the material is quite small. When the moisture content reaches 2% the strength of the sand is nearly ten times the strength of dry sand. Between 2% and 17% moisture content the strength of the sand increases only slightly with the moisture content. This increase is more pronounced when the consolidation stress is low. Between 16% and 17% the maximum values of the unconfined yield strength were measured for all values of the consolidation strength.

A wide range of moisture content with nearly constant strength is consistent with results published by Scheel et al., (2008). They investigated the tensile strength of beds of glass beads with a diameter of 280 µm applying a centrifugal measurement method and found only slightly increasing strength in the range of approximately 2% to 20% moisture content. In contrast, in a study by Møller & Bonn (2007) with various granular materials the maximum of the strength was found within a range of the moisture content of 1-

3%. This difference might be explained by the compaction method applied in this study with unmentioned consolidation stress, which resulted in a porosity of the sand of 0.37±0.01. Therefore, the porosity was much lower than the porosity obtained in this study even at the highest value of the consolidation stress applied. To achieve such low porosity would require unrealistic high values of the consolidation stress.

At a moisture content of 19.8% the strength of the sand was significantly reduced to values similar to those measured for a moisture content of approximately 2%. The recipe presented in The Guardian (2009) suggests a much higher amount of water in the mixture. The reason why this recipe might still be applicable can be assumed in the circumstances at the building site of a sand castle: some of the surplus water will be drained to the ground and some of the water will evaporate.

4. CONCLUSION

As well known by all builders of sand castles the strength of dry sand is small. At a moisture content up to 2% the strength of the sand greatly depends on the moisture content. Above a moisture content of approximately 2% the dependence of the strength on the moisture content is small. The maximum strength of the sand was measured at moisture content between 16% and 17%. At higher moisture content the strength decreased. Over a relatively wide range of moisture content the influence of the moisture content on the strength is relatively small. Therefore, tourists building sand castles do not have to worry much about finding the best mixing ratio of water and sand.

An important influence on the strength of the sand is given by the consolidation stress. Therefore, careful compaction of the moist sand is obligatory for building a strong sand castle.

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REFERENCES

Barabási, A.-L., Albert, R., Schiffer, P., 1999. *The physics of sand castles: maximum angle of stability in wet and dry granular media.* Physica A 266, 366-371.

Emery, E., Oliver, J., Pugsley, T., Sharma, J., Zhou, J., 2009. *Flowability of moist pharmaceutical powder.* Powder Technology 189, 409-415.

Fitzpatrick, J.J., Barry, K., Cerqueira, P.S.M., Iqbal, T., Neill, J.O., Roos, Y.H., 2007. *Effect of composition and storage conditions on the flowability of dairy powders.* International Dairy Journal 17, 383-392.

Franklin, A., 2014. *On why we dig the beach: Tracing the subjects and objects of the bucket and spade for a relational materialist theory of the beach.* Tourist Studies 14, 261–285.

Landi, G., Barletta, D., Poletto, M., 2011. *Modelling and experiments on the effect of air humidity on the flow properties of glass powders.* Powder Technology 207, 437–443.

Longo, S., Lambert, A., 2000. *Granular Streams Rheology and Mechanics.* Physics and Chemistry of the Earth, Part B 25, 375-380.

Mitarai, N., Nori, F., 2006. *Wet granular materials.* Advances in Physics 55, 1-45

Møller, P.C.F., Bonn, D., 2007. *The shear modulus of wet granular matter.* EPL (Europhysics Letters) 80, 38002.

Obrador-Pons, P., 2009. *Building Castles in the Sand: Repositioning Touch on the Beach*. The Senses and Society 4, 195-210.

Pakpour, M., Habibi, M., Møller, P., Bonn, D., 2012. *How to construct the perfect sandcastle.* Scientific Reports 2, 549.

Rumpf, H., 1990. *Particle Technology.* Chapman and Hall, London, pages 199, ISBN 0-412-35230-3.

Rushton, A., Ward, A.S., Holdich, R.G., 1996. *Solid-Liquid Filtration and Separation Technology.* VCH Verlagsgesellschaft, Weiheim, pages 538, ISBN 3-527-28613-6.

Scheel, M., Seemann, R., Brinkmann, M., Di Michiel, M., Sheppard, A., Herminghaus, S., 2008. *Liquid distribution and cohesion in wet granular assemblies beyond the capillary bridge regime.* Journal of Physics: Condensed Matter 20, 494236.

Schnellmann, R., Rahardjo, H., Schneider, H.R., 2013. *Unsaturated shear strength of a silty sand.* Engineering Geology 162, 88-96.

Schulze, D., Schwedes, J., 1991. *Das Fließverhalten und die Silolagerung von REA-Gips.* Chemie Ingenieur Technik 63, 256-257.

Schulze, D., 2008. *Powders and Bulk Solids – Behavior, Characterization, Storage and Flow.* Springer Verlag, Berlin, pages 511, ISBN 978-3-540-73767-4.

Seville, J., Tüzün, U., Clift, R., 1997. *Processing of Particulate Solids.* Blackie Academic & Professional, London, pages 372, ISBN 0-7514-0376-8.

The Guardian, 2009. *How to build the perfect sandcastle.* Retrieved from https://www.theguardian.com/lifeandstyle/2009/aug/01/how-to-build-perfect-sandcastle/ (2009, August 1). Accessed 24 January 2018

Wierenga, L., 2005. *Sandcastles Made Simple: Step-by-Step Instructions, Tips, and Tricks for Building Sensational Sand Creations.* Harry N. Abrams, New York, pages 128, ISBN 1-584-79408-9.

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