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Mineralogy and morphology of sand: Key parameters in the durability for its use in artificial beach nourishment

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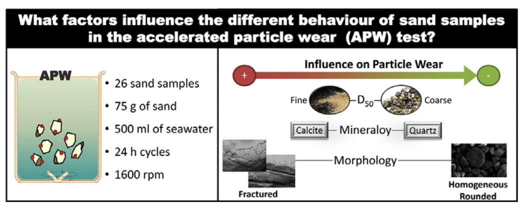
HIGHLIGHTS

- Median sediment size is not a decisive factor to explain the evolution of the shoreline
- Calcite sand content is related to the rapid wear of the samples
- Particle morphology can have either positive or negative influence on the sample wear

GRAPHICAL ABSTRACT



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ABSTRACT

Sand is the third most consumed material in the world, although it is a very scarce material. An exhaustive knowledge of sand and its behaviour against the waves is important for selecting the most suitable material to avoid shoreline erosion. To this end, a pattern of behaviour against accelerated wear test has been sought for 26 sand samples with different characteristics and origins (natural, dredged and quarried), with a focus on their mineralogy as well as a comparison of beach evolution carried out by other authors. Several techniques have been applied for characterization: granulometry, calcimetry, XRD and SEM. The results show that the different degrees of sand grain wear are not only due to their size and mineralogy, but also to the morphology of the particles.

1. Introduction

Coastal environment has been a growing concern among coastal engineers and researchers for many years. They work together to find ways of solving key problems that are visibly affecting the fragile shoreline, such as (i) the interaction between coastal defence structures and the sea, (ii) beach nourishment duration and its effect on marine biocenosis, and (iii) the consequence of sediment retention in dams and watercourse re-channelling, among others. It is a fact that the construction of certain structures, such as ports and dams, has a direct impact on the sediment contribution to beaches (Aragonés et al., 2016; Newton et al., 2012). Moreover, the scarce sand available from the contribution of rivers and ravines is widely used in the construction industry to produce concrete (Chaplot and Poesen, 2012).

In the last decade, there has been a trend towards soft interventions in coastal defence techniques, providing the endangered beaches with sand so as to mitigate the shoreline retreat (Burningham, 2006; Trembanis and Pilkey, 1998). Nevertheless, these soft techniques trigger an additional impact on the coastal environment, such as the significant degradation of the *Posidonia oceanica* (Aragonés et al., 2015; Pagán et al., 2016).

Anfuso et al. (2003) identified three major factors affecting the stability of the nourished beaches. The first factor is the designed beach profile. The second, the size, density, and porosity of the sediment (Román-Sierra et al., 2014). The third, the wave characteristics

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(Oliveira et al., 2017). Grain density and not grain size was found to have a decisive role in the durability of beach refill (Eitner, 1996; Roberts et al., 1998). Paterson and Hagerthey (2001) observed that the stability of the sediment is greatly affected by the activity not only of microorganisms, - bacteria, microalgae and fungi - but also of macro-organisms, such as worms, molluscs, and crustaceans in general. Such organisms act either as binders - increasing erosion resistance - or as degraders - through bioturbation (Karl and Novitsky, 1988). Other authors approach the study of seabed stability in terms of bed displacements in which grains of different sizes are taken into account. For instance, Van Ledden et al. (2004) and Hir et al. (2008) suggested that the relative size of coarse and fine particles in a mixture contributes to stabilizing the fine fraction. In this line, Bartke et al. (2013) conducted some erosion experiments with sand and silt, proving that seabed stability increased with the presence of small amounts of silt, and erosion shear stresses tended to occur at high flow velocities. However, the addition of fine particles to a thicker seabed does not always ensure stabilization. When the fine-grain content exceeds a certain percentage, the fine particles form a network around the coarser grains, interrupting intergranular contact. Then, the seabed erosion may be said to be predominantly carried out by the fine-grain fraction; in other words, the fine-grain fraction facilitates seabed erosion by transporting coarser sediments (Houssais and Lajeunesse, 2012; Iseya and Ikeda, 1987; Jackson and Beschta, 1984; Venditti et al., 2010a; Venditti et al., 2010b; Wilcock et al., 2001). Seabed stability, however, can also be influenced by some other parameters, such as grain shape (Komar and Li, 1986), mineralogy (López et al., 2016) and the wear of sediment particles (López et al., 2016).

The process of beach erosion and sand grain abrasion initiates when a particle gets dislocated by the force of the waves, which takes place when the fluid's upsurge force is greater than the counteracting resistance of the particle, which is a function of its weight, its angle, and the waves' lifting and dragging force (Allen, 1970; Komar, 1987; Van Rijn, 2007). The different processes by which particles are abraded are as follows: (i) particle wear by shock, (ii) particle breakdown into its different mineral fractions, and/or (iii) particle dissolution carbonate fraction (López et al., 2016). This last process may be aggravated by ocean acidification due to the increase in CO_2 emissions (Steinfeldt et al., 2009).

The large number of factors that influence the retreat of the coastline complicate its precise modelling (Williams et al., 2017). It is known wave energy erodes beaches faster if the sand grains are smaller (same density). This paper examines a wide range of grain parameters that are not typically studied. The grain parameters that control the reduction of the grain size (abrasion and dissolution) are analysed. The aim of the study is to optimise the selection of sand (size, composition, texture) to avoid a rapid reduction in the size of the sand and the consequent erosion of the beach in feeding projects. For this purpose, the behaviour of different sediment samples in relation to wear is studied, and their relationship with the granulometry, mineralogy and morphology of the sand grains is analysed.

2. Materials and methods

2.1. Materials

Table 1 shows the names and origins of 26 sand samples, of which most (19) came from beaches located in the province of Alicante (Spain). We added 2 more beaches from Mallorca (Spain) and 5 more from other countries (Fig. 1) to extend our analysis and compare results. The sand beach samples feature different origins – from natural beaches, from dredging, and from quarry.

All the analysed samples were taken directly from the beach. For sampling, the top 10 cm layer of sand was removed, and then a sample of 500 g of sand was taken. Four samples were taken at evenly distributed points along the beach (3 from the shoreline - centre and ends - and 1 from the centre of the dry beach). The samples were homogenised and divided by quartering for each test in the laboratory. In addition, the granulometry of the 4 samples from the same beach was compared and it was found to be very similar.

Table 1
Name of the beach and origin of the sand samples collected in this study. Origin of the sample: i) natural, beach nourished in a natural way; ii) quarry, beach artificially nourished by aggregate from a quarry; iii) dredging, beach artificially nourished by dredging nearby area.

Name of the beach	Sand origin	Municipality (province)/country
1 Acapulco	Natural	/Mexico
2 Aguamarina	Natural	Orihuela (Alicante)/Spain
3 Albir	Natural	Alfaz del Pi (Alicante)/Spain
4 Arenal	Dredging	Calpe (Alicante)/Spain
5 Arenales del Sol	Natural	Elche (Alicante)/Spain
6 Bol Nou	Natural	La Vila Joiosa (Alicante)/Spain
7 Caló des Moro	Natural	Santanyí (Mallorca)/Spain
8 Caribe	Natural	/Dominican Republic
9 Carrer la Mar	Dredging	El Campello (Alicante)/Spain
10 Deveses	Quarry	Dénia (Alicante)/Spain
11 El Conde	Natural	Pilar de la Horadada (Alicante)/Spain
12 El Cura	Natural	Torrevieja (Alicante)/Spain
13 Fustera	Quarry	Benissa (Alicante)/Spain
14 Guardamar	Natural	Guardamar del Segura (Alicante)/Spain
15 Krabi	Natural	/Thailand
16 La Caleta	Dredging	Cádiz (Cádiz)/Spain
17 Levante	Natural	Benidorm (Alicante)/Spain
18 Marineta Cassiana	Dredging	Dénia (Alicante)/Spain
19 Molinos y Palmeras	Quarry	Dénia (Alicante)/Spain
20 Portet de Moraira	Dredging	Teulada (Alicante)/Spain
21 Phi Phi	Natural	/Thailand
22 Playa Centro	Dredging	Benidorm (Alicante)/Spain
23 Playa Lisa	Dredging	Santa Pola (Alicante)/Spain
24 S'Amarador	Natural	Santanyí (Mallorca)/Spain
25 San Juan	Dredging	Alicante (Alicante)/Spain
26 Sottomarina	Natural	Chioggia (Venice)/Italy

When we refer to the origin of the sand (natural, dredged or quarry sand) we are referring to the origin of the sand prior to dumping it on the beach, since as indicated above all the analysed samples were taken on the beach.

2.2. Experimental methodology

We conducted five tests on the sand samples for their characterization: (i) particle size distribution, (ii) Calcimetry, (iii) accelerated particle wear (APW), (iv) X-ray diffraction (XRD), (v) scanning electron microscopy (SEM). In addition, we applied the SPSS 22.0 code (from SPSS Inc.) for a statistical analysis (vi) of large numbers of data.

(i) Particle size distribution of the sediment sample

We performed the particle size distribution tests following the UNE 103101 standards and complemented them with the UNE 7050-2 and the UNE 103100 codes. The particle size (in mm) was obtained at the beginning of each APW test cycle. However, the median sediment size (D_{50}) together with the specific surface area of each bulk sediment sample were acquired in two different ways: (i) from the whole sample, and (ii) after removing the finer particles (sizes <0.063 mm) from the sample before and after the APW tests were carried out.

(ii) Calcimeter analysis

We measured the percentage increase of $CaCO_3$ content in the water resulting from the loss of carbonate in every sand sample undergoing the APW test applying the Bernard Calcimeter method (UNE 103200).

(iii) Accelerated particle wear (APW) test

We performed the APW test (López et al., 2016) to simulate the abrasion of the sand particle in the swash zone. For this purpose, we placed 75 g of the beach sand sample and 500 ml of seawater (from the beach of Cabo de las Huertas in Alicante) in a magnetic stirrer at 1600 rpm in 24-h cycles. We used the number of cycles applied to each sample needed to reduce the particle size to <0.063 mm as a reference for determining the particle's wear resistance.