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Analysis of the suitability of marble waste for beach nourishment

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ABSTRACT

Marble waste, as a subproduct of the exploitation of marble quarries, could be reused as a replacement for the scarce sand sediment supply for beach nourishment. This work studied the suitability of 4 different types of marble (Bateig, Ivory Cream, Imperial Brown and Niwala). The method consisted of generating 3 samples for each type of marble and preparing them (i) with jaw crusher and $D_{50} = 0.692$ mm; (ii) with jaw crusher and $D_{50} = 0.301$ mm; and (iii) with ball mill and $D_{50} = 0.268$ mm. These samples were analysed using the accelerated particle wear test, and the mineralogy and morphology of the particles were studied using X-ray diffraction and Scanning electron microscopy. Results indicate that if the particle size is larger than 0.4 mm, durability increases between 2 and 4 times compared to a usual sand sample. The jaw crusher generates a smaller number of fractures to the particles than the ball mill, increasing the durability of the sample. If these criteria are followed, marble wastes can be used in beach nourishment, becoming a circular economy asset, alleviating the adverse environmental impact, saving resources and energy and reducing the total cost of nourishments.

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1. Introduction

Sandy beach erosion is a worldwide problem, coupled with the scarcity of natural material for artificial beach nourishment becomes an even greater problem. To mitigate this problem, quarried materials are used recently to combat the shortage of natural sediments. Although due to the progress of science and the increase in global awareness for the protection of the environment, a new tendency to recycle industrial waste has emerged (Amin et al. 2019).

One of the materials to be used in artificial beach nourishment could be marble waste. In the last decade, the annual growth rate of marble production is about 15% in China (Secretariat of the China Stone Association 2017), 4–5% in Malaysia (Zainuddin et al. 2016), which is a large volume of material to be utilized. However, the marble waste generated after quarrying, cutting and polishing of the pieces (about 70% of the resources) are dumped in landfills due to the limited economic benefit they present (Gencel et al. 2012; Hebhoub et al. 2011). Currently, the larger marble residues (not the dust) are deposited near the mines or work and cutting areas and do not provide any benefit; moreover, their indiscriminate dumping pollutes the soil to such an extent that it is no longer suitable for cultivation, and can even reach the groundwater table, contaminating the water (Chávez et al. 2015). Recycling of marble waste is possible through the development of value-added products (Careddu, Marras, and Siotto 2014), which would also reduce ecological and health risks (Rizzo, D'agostino, and Ercoli 2008). Besides, recycling helps to both decrease pollution and reduce production costs (Amin et al. 2019).

In recent years, research on the use of marble waste has focused on its use in mortar mixes (Khyaliya, Kabeer, and Vyas 2017), concrete (Arel 2016; Ulubeyli, Bilir, and Artir 2016), concrete roof tiles (Aditya, Halim, and Putri 2014), ceramic wall and floor tiles (Bilgin et al. 2011), etc. For example, in the case of self-compacting concrete, marble powder showed excellent performance as a substitute for sand without the adverse effect on the hydration process (Sadek, El-Attar, and Ali 2016). Although, as noted, its most widespread use has been as coarse and fine aggregates in concrete and/or cement (Alyamac, Ghafari, and Ince 2017), it has also been studied for neutralizing acidic wastewater and removing harmful metals (Mehta, Mondal, and George 2016; Mlayah and Jellali 2015), with an efficiency of >85% by the zeolite adsorbent of marble dust (Javed et al. 2016). However, very few studies have been conducted for the reuse of marble waste for beach nourishment. Nordstrom et al. (2008) studied the impression of people towards the beach nourishment with marble pebble (0.8–200 mm), and the durability and rounding capacity versus other materials such as limestone and basalt. Other authors investigated the use of other types of waste such as glass in beach nourishment with favourable results (Edge, Cruz-Castro, and Magoon 2003; Makowski et al. 2007).

Finally, it is worth noting the economic advantage of using recycled material instead of marine dredged material.

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Figure 1. (a) Waste area of a marble company. (b) Waste collected from Ivory Cream and Imperial Brown. (c) Anvil and hammer. (d) Jaw crusher. (e) Ball mill. (f) Pestle and mortar.

The cost of a dredge (including the dredge, floating pipe, auxiliary vessels, and drilling equipment), assuming that the dredging area is less than 1 km from the coast, is approximately 87.5€/m^3 (this price does not include the transport of the dredge to the work area). However, according to Hinkel et al. (2018), among others, the existence of sand for dredging on the Spanish coast is very scarce (or almost non-existent) because the continental shelf is very narrow, so the cost would be even higher. On the other hand, the cost of dumping recycled material would be reduced only to the crushing and washing the rock and the subsequent dumping on the beach, which has a cost of about 16.72 €/m^3. Therefore, the cost would be about 5 times lower than dredging.

For all these reasons, this work studies the suitability of processed marble waste for beach nourishment. Tests of particle wear, granulometry, calcimetry, X-ray diffraction and electron microscopy were performed. All this to determine the most suitable granulometry and its level of durability in comparison with natural sediments.

2. Methodology

2.1. Sampling

The samples (Figure 1a) were collected from marble waste generated by companies in the province of Alicante (Spain). The province of Alicante produces 35% of the marble at national level, generating a medium-sized waste (non-dust) of 26,400–28,800 t/year (Data provided by Mármol de Alicante, Asociación de la Comunidad Valenciana, https://marmoldealicante.com/). Specifically, four different types of marble were used for this study: Bateig, Ivory Cream, Imperial Brown and Niwala.

Once in the laboratory, the samples (approximate dimensions of $0.4 \times 0.15 \times 0.05$ m) were broken to manageable sizes using a hammer and anvil (Figure 1c). The pieces obtained were crushed using: (i) Jaw crusher (Figure 1d) or (ii) Ball mill (Figure 1e). Finally, to achieve the established particle size after the first crushing (if necessary), a manual crushing with a mortar was performed (Figure 1f).

After crushing, three grain sizes were formed: 2 sand samples with grain sizes similar to the sediments found on the beaches of the province of Alicante (López et al. 2018; Pagán et al. 2018a) with median sizes of 0.268 mm (ball mill) and 0.301 mm (jaw crusher), and slightly coarser sand sample with sizes between 0.4 and 0.8 mm (jaw crusher) and a median size of 0.692 mm (Figure 2). To see the retained weight on each sieve used, see the supplementary material.

2.2. Accelerated particle wear test (APW)

The wear and durability of the marble particles were performed using the accelerated particle wear test (APW) proposed by López et al. (2016). In the test, 75 g of the sample together with 500 ml of seawater were stirred at 1600 rpm with a magnetic stirrer in 24-hour cycles. After each cycle, calcimetry of the water was done using the Bernard calcimeter method (UNE 103200), the sediment sample was dried in an oven and granulometry was performed following the UNE-EN ISO 17892-4:2019. The number of cycles applied is the number of cycles necessary to reduce 50% of the sample to sizes below 0.063 mm.

2.3. X-ray diffraction (XRD)

The mineral phases of the tested samples were determined by X-ray diffraction (XRD) using a Bruker D8-Advance diffractometer with a Göebel mirror. For this purpose, the sample was ground with a ball mill to a size of less than 0.063 mm. To analyse it, an accelerating voltage of 40 kV and a current of 40 mA and a scanning angle (2-Theta) of 4° to 60° were used. Through Rietveld analysis using PANalytical Highscore Plus 4.6 software, the mineral phase of the sample was quantitatively determined. The

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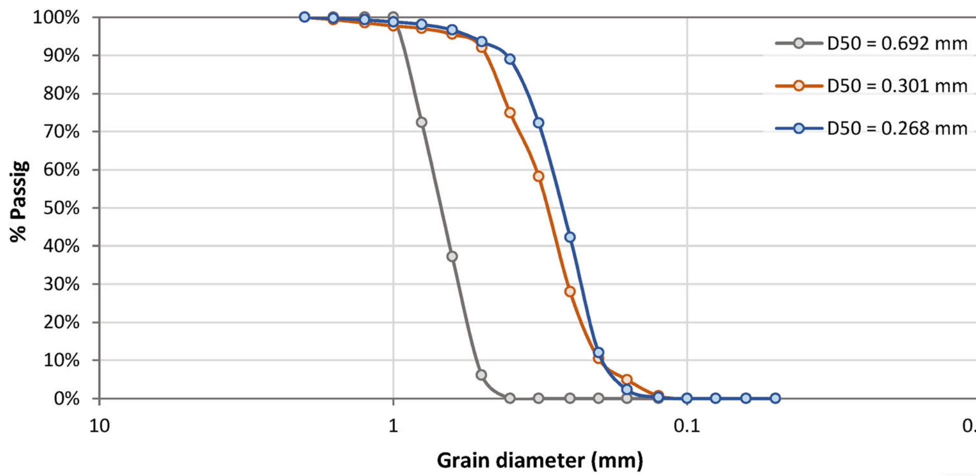

Figure 2. Granulometries used in APW test.

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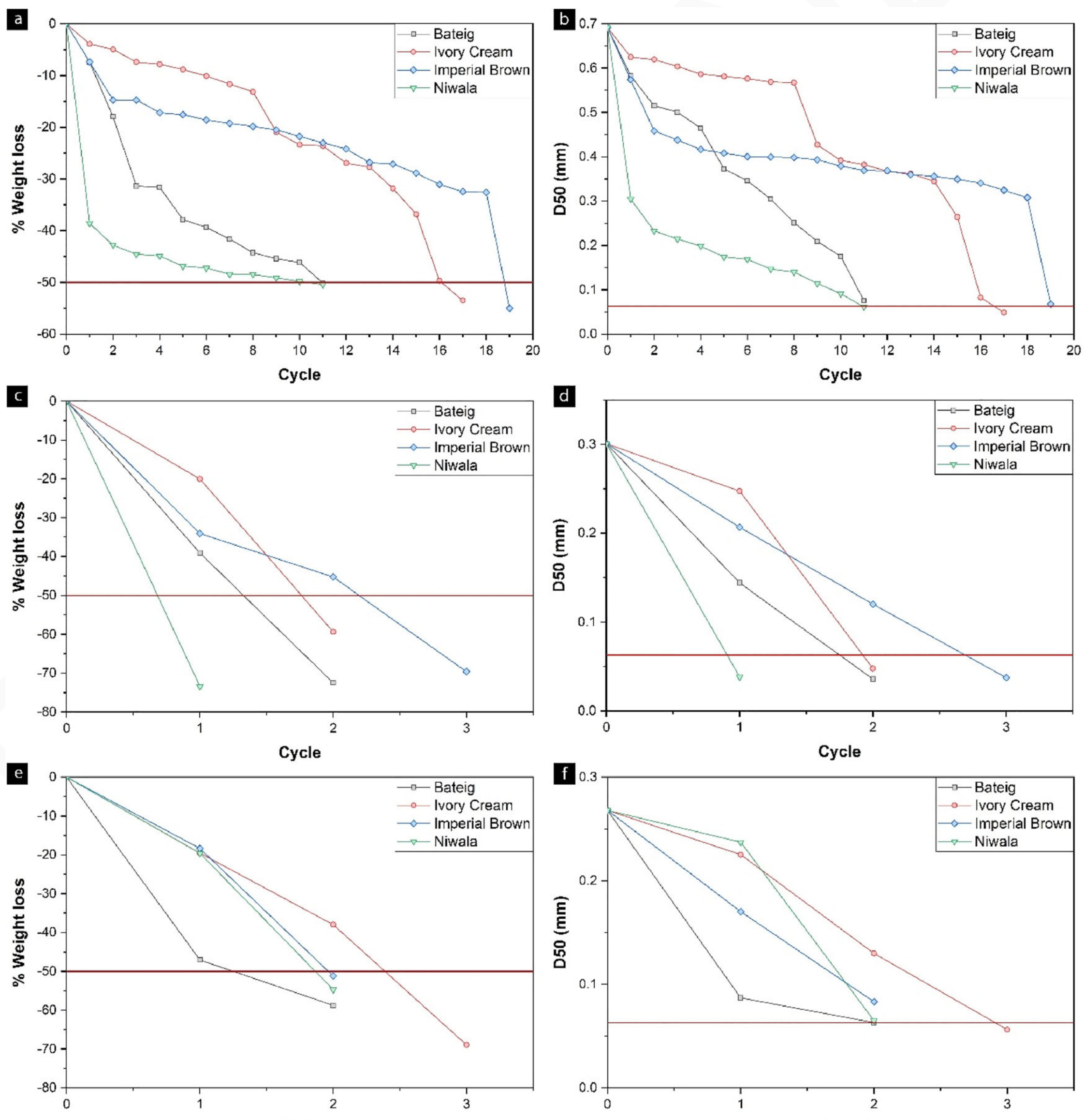

Figure 3. Percentage weight loss and median sediment size (D50) evolution for: samples prepared with jaw crusher and $D_{50} = 0.692$ mm (a and b); samples prepared with jaw crusher and $D_{50} = 0.301$ mm (c and d); and samples prepared with ball mill and $D_{50} = 0.268$ mm (e and f). The red horizontal line represents the 50% loss in the weight loss plots and the 0.063 mm size in the D_{50} evolution plots.

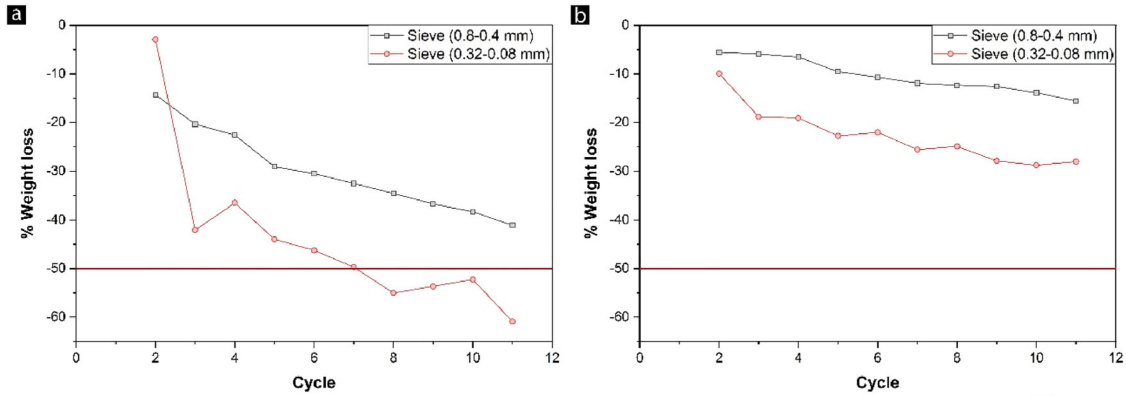

Figure 4. Percentage of weight lost for samples of median sediment size 0.692 mm, for sieves larger (0.8–0.4 mm sieves) and smaller (0.32–0.08 mm sieves) than 0.4 mm. (a) Bateig. (b) Niwala.

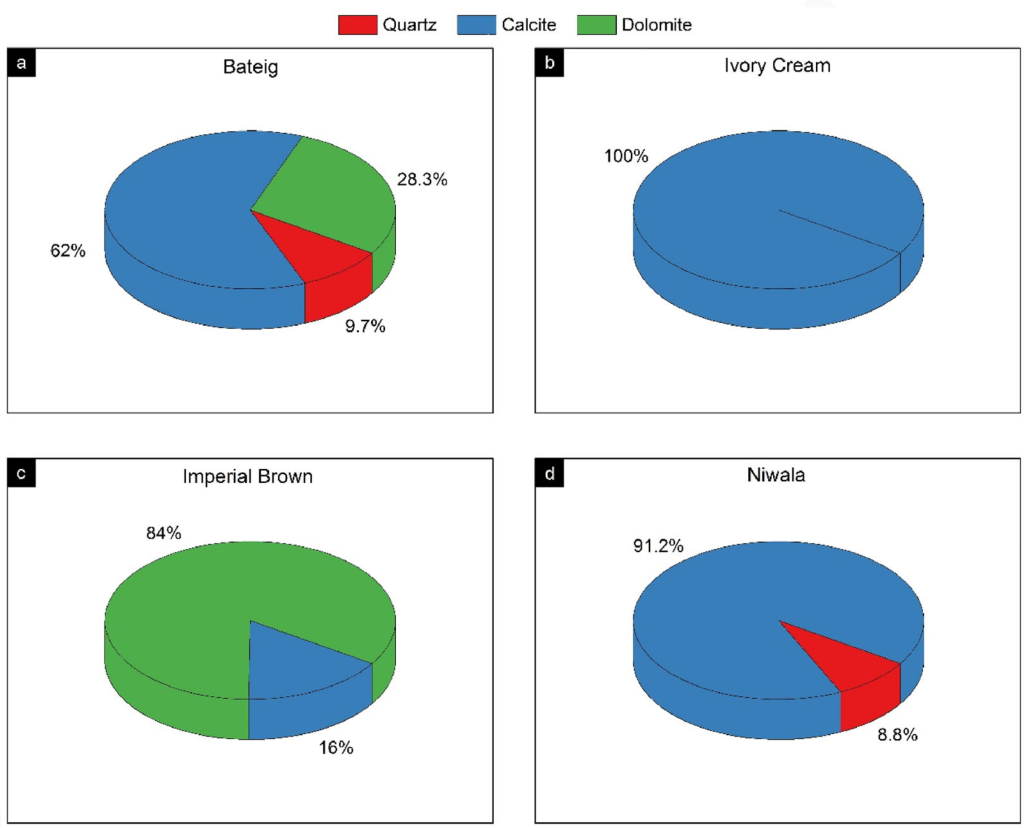

Figure 5. Mineralogical composition. (a) Bateig. (b) Ivory Cream. (c) Imperial Brown. (d) Niwala.

background was manually adjusted, the scale factor, cell parameters and peak parameter were refined.

2.4. Scanning electron microscopy (SEM)

Using a Hitachi S3000N scanning electron microscope (SEM) with an X-ray detector for microanalysis (EDS) and variable pressure mapping, the microstructure and morphology of the samples were examined.

3. Results and discussion

Figure 3 shows the results of the APW test. It is observed that the larger the particle size, the more cycles in the test they can withstand before converting to sizes below 0.063 mm. The size 0.063 mm is taken as a reference since, on natural beaches, particles with sizes at or equal to 0.063 mm are easily transported by waves, and when they exceed the depth of closure they can no longer return to the beach and the sand is lost (Aragonés et al. 2016). However, depending on the crushing method used, the behaviour of the samples differs. For example, in the case of the Niwala sample, when the sample preparation is done with the jaw crusher, in the first cycle there is a significant mass loss of 38.6% in the case of $D_{50} = 0.692$ mm and 73.4% in the case of $D_{50} = 0.301$ mm, while in the case of the ball mill after the first cycle only 19.6% is lost. The high mass loss experienced is consistent with that observed by Nordstrom et al. (2008), according to whom after 40 hours in a ball mill at a

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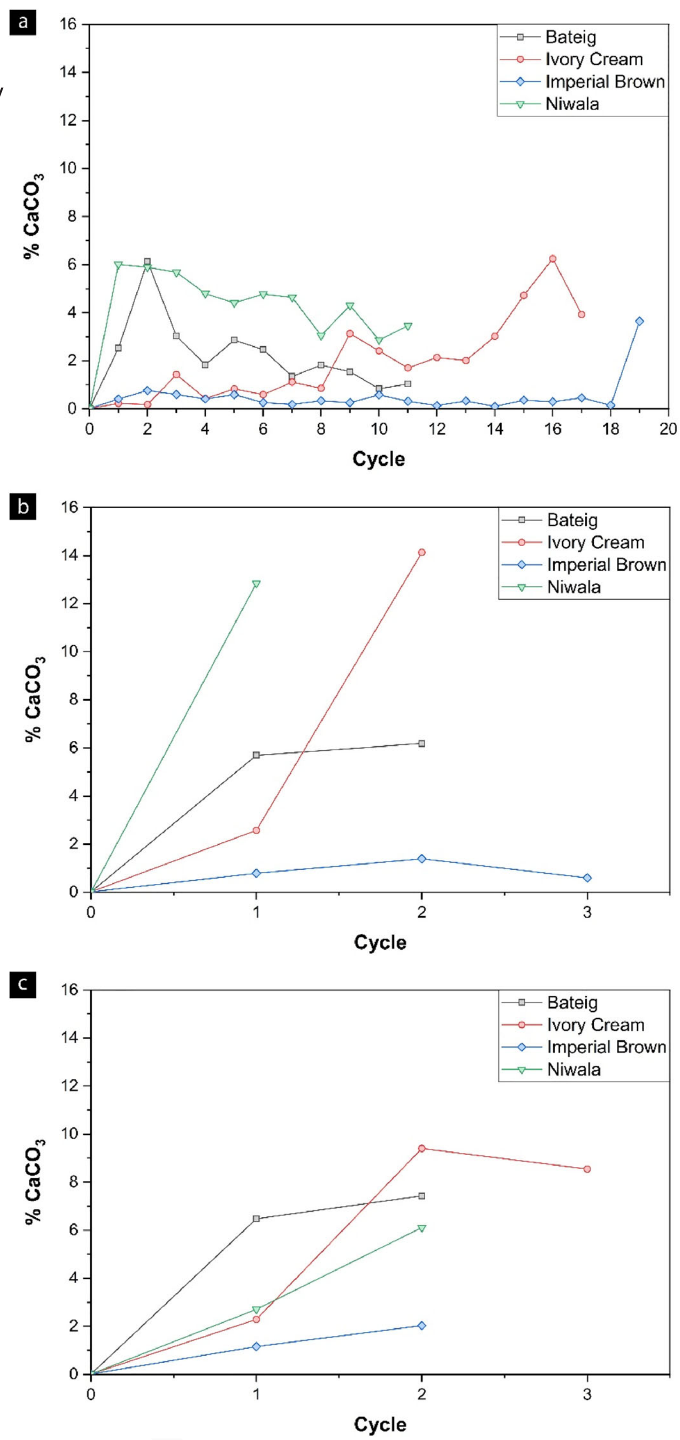

Figure 6. Evolution of $CaCO_3$ in suspension in the APW test water for: (a) samples prepared with jaw crusher and $D_{50} = 0.692$ mm; (b) samples prepared with jaw crusher and $D_{50} = 0.301$ mm; and (c) samples prepared with ball mill and $D_{50} = 0.268$ mm.

speed of 50 turns/min the grey marble suffered a 27% mass loss and the white marble a 52% mass loss.

When comparing the duration of the samples with the average duration of the sands in the province of Alicante—4.8 cycles—(Chiva et al. 2018; López et al. 2018; Pagán et al. 2018a; Pagán et al. 2018b) it is observed that the finer samples ($D_{50} = 0.301$ mm and $D_{50} = 0.268$ mm) last significantly less than the natural sands, while the coarser samples ($D_{50} = 0.692$ mm) last more than twice as long, with the Imperial Brown and Ivory Cream samples lasting up to almost 4 times longer. This indicates that the use of marble as a beach nourishment material is valid as long as a suitable granulometry is used. In this case, the particles that in cycle 0 were larger than 0.4 mm lasted on average 7.5 cycles, which indicates that a good sediment size for the use of marble could be at least 0.4 mm, which represents a sand size accepted by users on a sandy beach (Marin et al. 2009; Morgan 1999). The longer duration of sizes larger than 0.4 mm is also observed in Figure 4, which shows the percentage of weight lost for the Bateig and Niwala samples of median size 0.692 mm, for sieves larger and smaller than 0.4 mm. This is shown without considering the first cycle, since the material lost in the first cycle for sizes above 0.4 mm passes to the lower sizes producing an increase in the amount of material retained between 0.32 mm and 0.08 mm. Thus, it is observed that sizes larger than 0.4 mm lose much less mass than sizes 0.32–0.08 mm, producing a cumulative loss in the last cycle in the case of Bateig of 41.1% and 60.9%, respectively, and in the case of Niwala of 15.6% and 28.0%, respectively. Furthermore, if the durability results of marble are compared with those of quartz or limestone (Pagán et al. 2021), it is observed that for $D_{50} = 0.692$ mm the Bateig and Niwala samples have a similar durability to that of limestone ($D_{50} = 0.624$ mm; Duration at APW 10 cycles), while at well below that of quartz ($D_{50} = 0.565$ mm; Duration at APW 26 cycles), although the Ivory Crean and Imperiral Brown samples are somewhat more similar to quartz (17 and 19 cycles, respectively).

According to López et al. (2016) the weathering of sediment particles in the APW is due to particle collision, dissolution of carbonates and particle separation. Therefore, both mineralogical composition and particle morphology should be analysed. Thus, the analysis of the mineralogical composition of the samples (Figure 5) shows that all of them have a very high calcite content (more than 60%), except the Imperial Brown sample which only has 16% calcite, the rest being dolomite. This could explain the better APW behaviour of the Imperial Brown samples in practically all cases, since of the three minerals (quartz, calcite and dolomite), dolomite has higher resistance (Kushnir et al. 2015). On the other hand, particle weathering can be assessed by measuring the suspended $CaCO_3$ content in the test water after each cycle (Figure 6), as $CaCO_3$ is part of almost all minerals identified in the samples (Figure 5). Figure 6 shows that the Niwala and Bateig samples show the highest percentage of $CaCO_3$ in suspension after the first and second cycle in all cases. This could justify the abrupt weight loss that both samples show in the first cycle of the APW (Figure 3). It is noteworthy that the percentage of $CaCO_3$ in suspension in the water does not maintain a constant increase, but shows a cyclical behaviour of increases and decreases. This is because during the APW test part of the $CaCO_3$ sediments and part remains in suspension, which is consistent with the observations of López et al. (2016); López et al. (2018). In general, an increase in the percentage of $CaCO_3$ suspended in the water is observed in the final cycles, which coincides with a sharp decrease in both sample

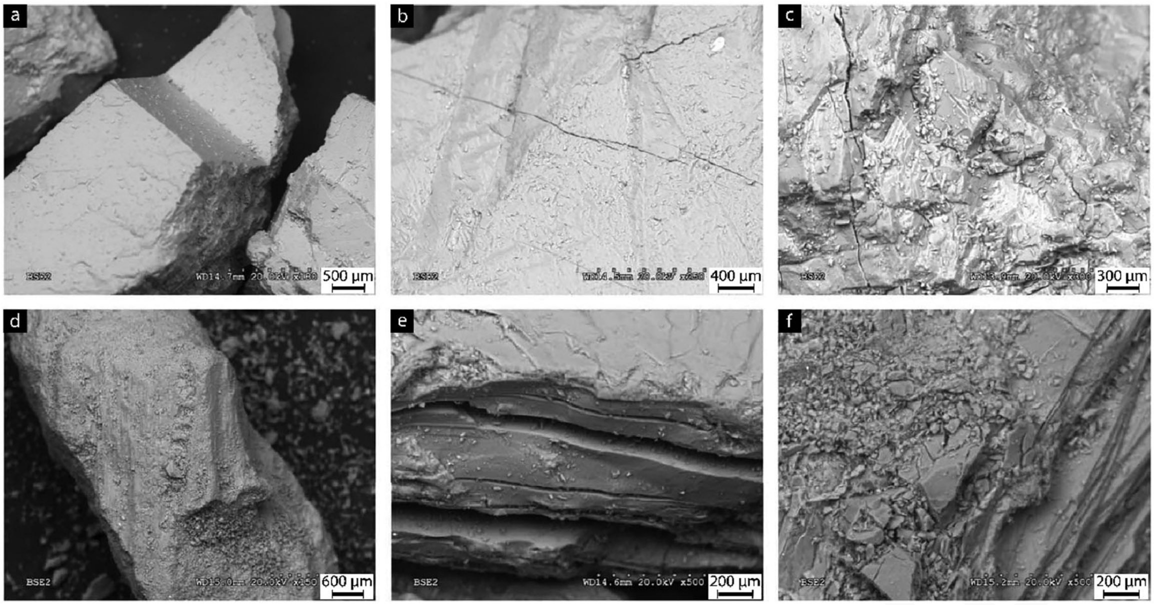

Figure 7. Particle morphology (SEM). (a–c) Samples prepared with jaw crusher. (d–f) Samples prepared with ball mill.

mass and median size. This may be because the decrease in median size causes an increase in specific surface area and therefore there is a larger contact area with the water, and part of the carbonates can pass into colloidal dispersion (Chiva et al. 2018).

Understanding the fundamental mechanisms contributing to abrasion and their link to the macroscopic behavior of granular assemblies is of vital importance both for understanding beach erosion and for solving other problems such as degradation of ballast performance, which translates into huge costs for rehabilitation and maintenance of railway infrastructure (De Bono, Li, and Mcdowell, 2020). Thus, micromechanics-based approaches provide some key answers to problems related to the performance of aggregates used in engineering projects (Li and Mcdowell 2020). In this regard interparticle-type experiments and indentation-based analyses comprise two of the most recent approaches employed in the study of aggregates and particulate materials (Kasyap, Li, and Senetakis 2021). To determine the influence of microstructure on the abrasion of marble particles, particle morphology has been studied in this work.

The study of the particle morphology (Figure 7) shows that the particles prepared with a jaw crusher (Figure 7a) show a higher angularity at the edges compared to the particles prepared with a ball mill (Figure 7d). However, it is observed that the samples prepared with a ball mill (Figure 7e and 7f) show numerous fracture planes and cracks, which may influence their rapid wear since, as indicated by López et al. (2016) the collision of the particles causes them to break through these fractured planes very easily. Meanwhile, the samples prepared with a jaw crusher show hardly any cracks in the grains (Figure 7b and 7c), so the initial size losses of the samples prepared with a jaw crusher in the initial cycles (Figure 3) may be due to the rounding of the particles as the more angular peaks become detached.

Although morphology is not related to particle size, it does influence particle lifetime. Since, for example, for two particles with cracks at approximately their center, the particle with larger size has a longer lifetime, as the particles become approximately half their size after the collision between them (Figure 3). Thus, the sample with smaller size (D_{50} = 0.301 mm) becomes sample of about D_{50} = 0.150 mm, while the sample with larger size (D_{50} = 0.692 mm) become samples of the order of D_{50} = 0.340 mm. And at a minimum the large sample will last twice as long as the small sample.

The strong relationship observed between weight loss and particle abrasion is supported by a number of studies published in the literature, which have shown that the behavior of geological materials is significantly affected by grain interactions, including grain-to-grain contacts as well as grain morphology (Kawamoto et al. 2018; Mollon et al. 2020). Friction and wear behavior is inherently linked and affects contact response with applications in industrial systems and geological processes (Sandeep, He, and Senetakis 2018). Yang et al. (2016) found that an important mechanism that can control the tribological behavior of sand grains is related to ploughing during shearing. Boneh and Reches (2018) found that the wear rate of rock interfaces is inversely proportional to the hardness of the material.

4. Conclusion

In this work, the suitability of marble waste beach nourishment was studied. After studying the mineralogy, morphology and APW test behaviour of 4 types of marble with three different particle sizes (D_{50} = 0.268 mm, D_{50} = 0.301 mm and D_{50} = 0.692 mm) prepared with jaw crusher or ball mill, it can be affirmed that: (i) The size of the marble particles to be used should be larger than 0.4 mm. These sizes will allow a duration in the APW test of double or even quadruple that of natural sands. (ii) It is preferable to crush by jaw crusher as it generates a smaller number of fractures to the particles and therefore improves the durability of the sample.

However, since marble has a carbonate composition, it is easy to cement under long-term immersion and compaction in seawater. Therefore, as future lines of research it is proposed to study the pressolution and compaction state of marble residues in the state of immersion in seawater.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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