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Beach nourishment with coarse sediments: An in-situ investigation on the issues of abrasion and chipping

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A R T I C L E I N F O

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A B S T R A C T

The use of coarse sediments for beach nourishment represents an alternative solution to structural interventions for the protection of coasts that are exposed to energetic waves. Predicting the mass loss of fill material due to abrasion and scouring is crucial for proper nourishment design, as it has implications for the littoral sediment budget and sediment stability under extreme wave conditions. The present study aims at characterising the typical abrasion and chipping of coarse sediments used for beach nourishments, providing insights into their correlation with the wave energy flux incident on the coast. Estimation of weight loss and roundness variability is obtained through RFID (Radio Frequency IDentification) sediment tracking technology, 3D scanning techniques, and Los Angeles tests. The 1 year and 7 months in-situ investigation was carried out at Marina di Pisa (Italy), an artificial beach where the size of supplied pebbles was significantly reduced after few months of typical wave climate, jeopardizing the sediment stability and the lifetime of the nourishment. The methodology could be applied to other beaches and lithologies to establish a database of weight loss useful for coastal managers and engineers.

1. Introduction

Beach nourishment, i.e. the artificial addition of suitable sediment to a coastal area that has a sediment deficiency (National Research Council, 1995), is a well-established solution for the protection of the coasts against erosion and flooding (Karasu et al., 2016; Ruol et al., 2020; de Schipper et al., 2021). The general recommendation is to use fill material with a median grain size equal to or slightly coarser than the native sediment (Capobianco et al. 2002; Hanson et al. 2002; Li et al., 2022).

On highly energetic sandy beaches, coastal managers are testing nourishments with coarser sediments (up to pebbles or cobbles) to increase the design life of the projects (Buscombe and Masselink, 2006; D'Elisoet al., 2009). However, where coastal erosion is somewhat limited using coarse sediments as fill material, other issues arise that tend to reduce the stability of the pebbles and therefore of these beaches. In the case of gravel and mixed sand and gravel beaches (Jennings and Shulmeister, 2002), the hydrodynamic regime is controlled by swash processes, resulting in the formation of cusps on the beach face. Indeed, these types of beaches exhibit a reflective nature throughout the tidal cycle, due to their steeper active profile slopes. Furthermore, the reflective nature of these beaches affects their long-term stability. As previously highlighted by Soloy et al. (2022), coarse sediment beaches are subject to a range of modifications, including rotation, migration and overturning. The causes of sediment mobility can be attributed to a number of factors, including abrasion and chipping, which result in a reduction in average size, as well as alterations in shape. Abrasion occurs as a consequence of the dynamics of intergranular friction, which also gives rise to corner chipping. In the event of an extreme storm, breakage may also occur. As a result of these processes, the fill material becomes lighter and more unstable under the influence of wave action, and the abraded fraction of the original pebbles is lost from the sediment budget (Dornbusch et al., 2002; Chen and Stephenson, 2015). From an engineering perspective, the design of coarse beach nourishment should therefore take into account the effects of abrasion and chipping to ensure greater stability and a longer lifetime.

The loss of volume/weight of coarse sediments along beaches can be

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investigated with different methodologies, such as laboratory studies with steel drum or field tracking experiments. The former allow for a rapid characterization of the pebbles resistance (Hemmingsen, 2001; Dornbusch et al., 2004), however, the results are challenging to relate to natural abrasion. The latter can be carried out by marking the pebbles with numbers/colours or by using a more effective Radio Frequency IDentification (RFID) technology (Periyasamy et al., 2020). In this case, native or non-native pebbles are tagged with RFID tags, released on the beach under investigation, and tracked after a certain period with an RFID reader. Tracking experiments are in general used to analyze the coastal dynamics, recording the displacements during the campaign (e.g. Young et al. 2023), but few authors provided results in terms of abrasion and chipping due to the difficulties of recovering individual pebbles for reweighing. Dornbusch et al. (2002) released on the East Sussex coast (England) quartzite and limestone pebbles similar in size and shape to the natural flint shingle and estimated a mean relative weight loss due to abrasion between 5.7 % for quartzite and 18.6 % for limestone in one year. Allan et al. (2006) investigated the cobble transport on a mixed sand and gravel beach on the Oregon coast. The estimated average decrease in the tracer weights was only 0.003 % over 17 months due to the pebble lithology (basalt) and especially to a low exposure to waves. In a similar investigation, Dickson et al. (2011) found that, on the east coast of New Zealand, after 207 days the median loss was 1.8 % of total initial weight. Bertoni et al. (2016) found high abrasion rates of marble pebbles (of the order of 61 % relative weight loss) on the Marina di Pisa beach within a 13-month timespan.

As pointed out by Dickson et al. (2011), the mass loss rate should be linked with the wave energy flux (a proxy of longshore sediment transport), acting on the coast, as this could provide valuable insights for the design of coarse sediment nourishments. The literature review indicates that the timescale of abrasion and chipping is approximately one or two years, which is relevant to the expected service life of a beach nourishment project. Indeed, knowledge of the abrasion trend could be incorporated into the sediment budget losses, thereby enabling the selection of an appropriate fill sediment diameter to extend the project lifetime.

The aim of the present study is to establish a correlation between the wave energy flux and the weight loss of marble pebbles in an engineered beach. The research benefits from a multidisciplinary approach, encompassing the fields of coastal engineering, geology, and electronic measurements. The investigation is based on in situ RFID tracking experiments and makes use of 3D scanning technologies and Los Angeles laboratory tests. A novel statistical index – "significant weight loss" – is proposed, borrowing from the concept of significant wave height, to emphasise that waves are a crucial driver. The analysis is applied to coarse clastic sediment sampled at Marina di Pisa (Italy). The chosen beach is highly engineered and several seasonal maintenance operations are performed for tourist purposes. This choice does not compromise the results since both natural and human-induced mass variations are relevant for the analysis. The methodology can be replicated for other types of lithologies to establish a database of abrasion as a function of the forcing mechanism behind sediment transport, i.e. the wave energy flux. The ultimate objective of the research is to develop a predictive tool for assessing the impact of this process on the duration of beach nourishment. This paper includes four main sections and a concluding paragraph. In particular, the second section presents the details of the experimental methodology. The third section describes in details the investigation carried out at Marina di Pisa beach. The fourth section presents the results of the investigation focusing on the correlation between waves and abrasion. Finally, discussion and conclusions are drawn.

2. Methods

The experimental methodology consists of an in situ long-time RFID tracing of coarse sediments collected from a beach. A pocket beach is a appropriate candidate for this type of methodology since the pebble movements are constrained between the elements that bound laterally the beach. This allows easier recovery campaigns during the in-situ experiments.

The preliminary phase of the study involves the collection and characterisation of a sample of pebbles. Each pebble is weighed and scanned using a 3D structured-light scanner which enables accurate digital reconstruction of the shape of each pebble. The 3D scanning paves the way for additional observations about the shape evolution of the coarse sediments. Based on the 3D scanning results, the morphometric analysis (Bagheri et al., 2015) can be performed to evaluate the pebble longest axis (L), the intermediate axis (I), the shortest axis (S), the spherical equivalent diameter d_{EQ} (defined as the diameter of the sphere with the same volume V as the pebble) and the averaged geometrical diameter of the equivalent ellipsoid $d_G = \sqrt[3]{LIS}$ (i.e. an ellipsoid with same tri-axial dimensions as the pebble form dimensions). The d_{EQ} and d_G can however be considered proportional to each other. As highlighted by Bagheri et al., 2015, several procedures can be followed for the L, I and S, such as the protocol named Minimum Bounding Box (MBB) of Blott and Pye (2008). This protocol, shown in Fig. 1, allows to evaluate the smallest enclosing box of the 3D volume and consequently to compute the L, I and S axes. The Zingg (1935) diagram can be used to verify the initial and abraded shape, since it categorizes the elements on the basis of the ratios S/I and I/L.

One fundamental property of pebbles (and, indeed, of particles in general) is angularity, i.e. the sharpness of corners. This can be quantified by a parameter called roundness (R). Using two-dimensional projections of particles, Wadell (1932) defined roundness as the ratio of the average radius of curvature of the corners of a particle (black circles in Fig. 1) to the radius of the maximum inscribed circle (red circle in Fig. 1): $R = \sum_{i=1}^{N} r_i / N r_{mic}$ where r_i is the radius of the i th corner circle, N is the total number of corner circles and r_{mic} is the radius of the maximum inscribed circle in two-dimensional particle projection. The Wadell roundness should be evaluated for several 2D projections, with the final value being the mean value among those evaluated. Li et al. (2023) proposed the use of three perpendicular projections as the optimal compromise between estimation accuracy and computation time for the estimation of 2D Wadell roundness. Powers (1953) established a shape classification based on the degree of roundness, whereby a particle with a well-rounded shape is characterised by an R greater than 0.7. Zheng & Hryciw (2015) proposed a calibrated algorithm to detect the corner of the 2D projection of a particle based on computational geometry and is available for open access (www.mathworks.com/matlabcentral/fileexchange/60651-particle-roundness-and-sphericity-computation, accessed on 22 November 2024). In the present analysis, this algorithm is applied to three 2D projections extracted from the 3D scanning of the pebbles.

The tracing experiments follow the methodology proposed by Bertoni et al. (2010). The first phase consists of marking the collected coarse sediments using the Radio Frequency Identification Technology (RFID), which is a reliable method to mark and identify individual samples both in subaerial environments and underwater. The distinctive identification of pebbles permits the tracking of their evolution in terms of weight and shape variation. RFID is a radio system composed of two different devices: the reader and the transponders ("tags"). The reader is the device used to perform the actual identification operation: it generates an electromagnetic field used to interrogate the tags. The tags are the smart devices inserted inside the pebbles to be identified. To allow marine water data transmission, Low-Frequency technologies are employed. One of the readers is customized to operate underwater by providing it with waterproof housing. The tags are fully passive and their unique hexadecimal code, stored in the memory of the transponder, allows the univocal recognition of the pebbles.

In the second phase, the tagged pebbles are placed in three positions (underwater, at the shoreline, and at half of the berm height) along

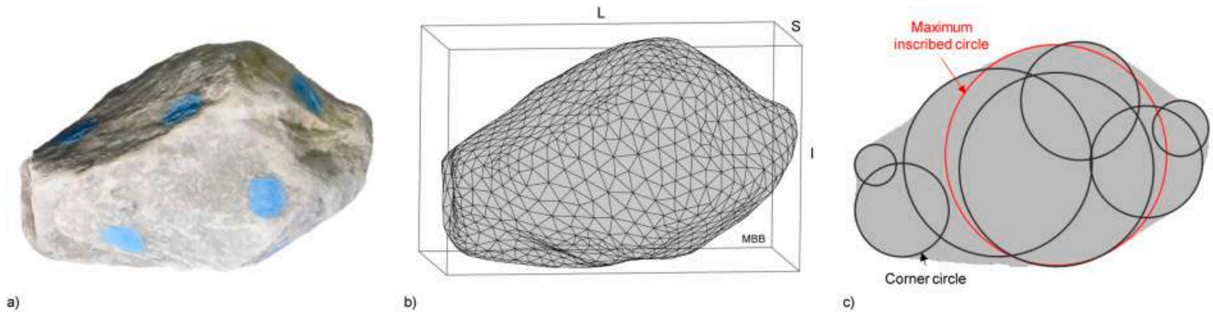

Fig. 1. a) Photograph of a pebble. b) Example of application of the Minimum Bounding Box protocol to a scanned pebble with the longest (L), intermediate (I) and shortest (S) axes highlighted. c) Example of the procedure for estimating the Wadell roundness.

several cross-shore sections of the beach. The position of each pebble is recorded by a GPS instrument. The third phase consists of the recovery campaigns, that should be carried out to cover at least 1-year timespan, during which tagged sediments are found and recovered. The recovery campaign requires an effort since the pebbles have to be dug from beneath the surface, sometimes at several centimetres depth. Each pebble is weighed, 3D scanned (as for the initial step) and (if feasible) its position collected, to create a measurement database.

The abrasion parameter is the relative weight loss $w_L = (W_0 - W_t)/W_0$, where W_t is the weight after the recovery campaigns at time t and W_0 is the initial weight. Similarly, the relative diameter loss is $d_L = (d_0 - d_t)/d_0$. Given that the weight is proportional to the volume and therefore to the cube of the diameter, $w_L = 1 - (d_T/d_0)^3$.

A new index, named “significant weight loss” w_{L_s}, is proposed using the same methodology as for the evaluation of the significant wave height. Accordingly, the relative weight loss of each pebble is evaluated, these values are sorted in descending order (from the most abraded to the least abraded) and the average value of the upper third is calculated, thus obtaining w_{L_s}. This w_{L_s} is a statistical descriptor useful to understand in-situ abrasion and chipping mechanisms since it does not take into account the small variations and, focusing only on the largest ones, highlights the behaviour of the pebbles that undergo long exposure to the wave action and are not buried.

Abrasion and chipping can be related to the incident wave energy flux, that is also the driver of longshore sediment transport, which in gravel beaches is proportional to grain size. For instance, Tomasicchio et al. (2023) proposed a longshore sediment transport procedure specifically designed for coarse-grained beaches, where the medium sediment diameter is included in the formula. Van Wellen et al. (2000) present a comprehensive review of longshore sediment transport equations, focusing on formulas that can be applied to coarse-grained beaches. Approaches to estimating longshore sediment transport can be classified into three categories: 1) energy methods (which are further subclassified into energy-flow and power-flow based approaches); 2) equilibrium of forces; and 3) dimensional analysis (which has been developed mainly from laboratory experiments). Van Wellen et al. (2000) found that energy-based equations provide reasonable predictions of coarse sediment transport.

The present study seeks to establish a correlation between abrasion and roundness and the forcing mechanism underlying sediment transport (namely the wave energy flux). A time series of wave data in the vicinity of the investigated beach is necessary to evaluate the incident wave energy flux $F = \rho g H_S^2/16 c_g \cos\alpha$, where ρ is the density of salt water, g is the gravitational acceleration, H_S is the significant wave height, c_g is the group celerity and α the wave obliquity. The wave energy flux is evaluated for the monitored period, taking into account the actual sequence of storms (Oo et al., 2022), and can be normalized with its yearly average value (Eq. (1)) to obtain a time-variable value representative of the typical wave climate, i.e. $F^* = 1$ is 1 year of typical wave climate.

$$F^* = \frac{\sum_{t=T_1}^{t=T} \rho g H_{St}{}^2 \Big/ 16 c_{g_t} \cos\alpha_t}{\langle F_y \rangle} \tag{1}$$

where T_1 is the date of the initial placement, T is the date of the recovery campaign and F_y is the yearly value of the wave energy flux.

A complementary laboratory investigation is suggested. The tumbling Los Angeles (LA) machine is a test used to determine the resistance of aggregates to abrasion. As pointed out by Eikaas & Hemmingsen (2006) tumbling experiments can be used to imitate the motion of sediments in coastal environments. The LA machine consists of a steel rotating drum (diameter of 70 cm), mounted on a base frame. The drum rotates around its horizontal axis and an internal shelf facilitates the abrasive mechanism, lifting up the aggregates. The cylinder rotates at a speed of 31 - 33 rpm and the machine is equipped with an automatic digital counter which can be pre-set to the required number of revolutions of the drum. Usually, the tests are performed with abrasive charges (steel spheres) placed in the tumbler together with the pebbles, however, to mimic the natural abrasion, the steel spheres are not inserted in the tumbling machine. In fact, the abrasion and chipping mechanisms that occur on a beach are due to collision or friction between pebbles of the same material induced by the wave run-up and run-down along the shoreface. The LA tests may be conducted by immersing the pebbles in water. For the present analysis, it was decided not to use water to simulate collisions in the subaerial environment during the strongest high-energy events.

The total number of revolutions depends on the pebble lithology and its abrasion resistance; in general, >2500 revolutions are required to characterize the abrasion trend of 1 year. As for the in situ investigation, before the tests, the pebbles (rounded and angular) are weighed, 3D scanned and painted for easier identification. At the end of each series of revolutions, the single pebbles are identified with the colours, and their weight and scan are registered. The w_L is computed as the ratio between the weight after each series of revolutions and the initial weight. As noted by Dickson et al. (2011), the physical mechanism of natural abrasion and chipping is probably through wearing (i.e. particles rubbing against each other) rather than fracturing. Since the LA machine induces several breakages, this suggests subdividing the behaviour of the non-fractured pebbles from the broken ones in the tumbling tests.

3. Investigation

3.1. Study area

The presented method is applied to 239 pebbles collected at the Marina di Pisa beach (Italy), a touristic small coastal village located along the Southern sector of the Ligurian Sea (Fig. 2b). In accordance with the classification proposed by Short (2020), Marina di Pisa is a wave-dominated beach, characterised by waves exceeding 0.5–3 m in height and the presence of micro-tides (30 cm in tidal range). During the

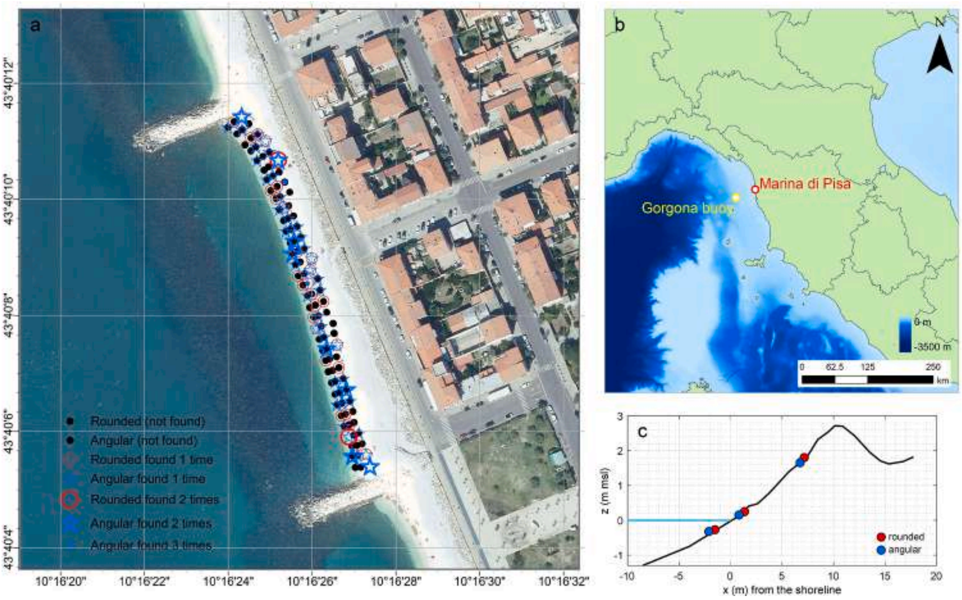

Fig. 2. Investigated area: Marina di Pisa (Italy). a) The map shows the pocket beach where the pebbles were injected. The dots indicate the position of the release and the colours/symbols indicate if the pebbles are recovered or not. b) The map shows the location of the Marina di Pisa beach along the Tuscany coast and the position of the Gorgona wave buoy. c) The figure shows a bathymetric profile with the location of pebble initial placement.

last 90 years, a serious erosive trend affected this area of the Tuscany coast, mainly caused by the decrease of the major sediment source, the River Arno sediment supply. To counteract the erosion processes, the local authorities created a series of artificial pebble beaches using waste from the Carrara marble quarries. For this reason, these beaches can be classified as a mixed sand and gravel beaches, where the two sedimentary types are entirely intermixed, although some surficial sorting may occur. This results in a reflective nature and a cuspate morphology. The beaches are confined by groins at both edges, by a submerged breakwater at the offshore limit, and by a rubble mound seawall at the onshore limit that separates the beaches from the adjacent street. During extreme storm events, several pebbles overtop the seawall ending up on the street and causing large deposits of pebbles on the road and even damage to the houses and parked vehicles. These "pocket" beaches are the ideal setting for a sediment tracing experiment to understand whether the abrasion and chipping mechanisms are critical in reducing the pebbles weight that become unstable under the wave action.

The pocket beach where the tagged pebbles are collected (and released) is shown in Fig. 2a. It is 200 m long and about 18–25 m wide. The main wave direction is from the southwest (220° - 260° N) and in fact, the longshore sediment transport in the whole area is directed towards the South, diverging from the Arno River mouth (Cipriani et al., 2001).

3.2. Data preparation and collection

The 239 pebbles were selected based on a minimum size that was verified to guarantee sufficient space for the drilling operations to insert the transponder (a disk with a diameter of 30 mm). The drilling process consists of carving a cylinder from the pebble, with a height of approximately 2 cm and a diameter that is slightly larger than that of the tag (35 mm). Once the tag has been inserted into the hole, the cylinder is then reinserted and sealed with cement. This method ensures that the pebble's density remains almost unchanged and that the cement component is minimal. The research group's experience of utilising RFID within the pebbles led to the observation that, in comparison to silicone, cement exhibits enhanced strength and displays a reduced tendency to abrade, in line with the properties of the material from which the selected pebbles are made.

The collected pebbles have a weight ranging between 0.4 and 2 kg, the d_{EQ} ranges between 75 and 125 mm and their density is approximately 2560 kg/m^3. Since the marble pebble density can be assumed constant the relative weight loss is proportional to the relative volume loss. The dimension of the selected pebbles is representative of the sediments that were originally used to fill the beach. Two populations of pebbles were collected and sorted by roundness: according to Wadell (1932) classification, half were angular, and half were well-rounded, i.e. representative of the pebbles that had already undergone some abrasion processes on the beach.

The 239 pebbles are subdivided into two samples, one for the in-situ campaign (204) and one for the tumbling tests (35). Before the experiments, all the pebbles were weighed with a digital scale (0.1 g of instrument error) and 3D scanned. The 3D scanning system comprises a low-cost 3D scanner, a wooden structure mounted on a tripod, and a camera crane. The low-cost 3D scanner is a Structure Sensor ST01, which employs laser technology to measure the distance between the ST01 and the object to be scanned. Additionally, the structured light technique is utilised to retrieve the surface and depth of the object. The wooden structure, which has a parallelepipedal base measuring 25×25 cm and a height of 60 cm, is equipped with a net made of fishing lines, allowing the pebble to be suspended. By moving around the pebble and scanning it from all angles, the ST01 is capable of acquiring a closed textured mesh acquired by a computer. The full system is described in Bertoni et al. (2023a).

3.3. Test programme

The sample for the tracing experiments is formed by 204 pebbles released on October 12th, 2022. The beach was characterized by high and steep storm berm (as visible in the cross-shore profile in Fig. 2) and the tagged pebbles were injected along 40 transects orthogonal to the coastline. Pairs of rounded and angular pebbles (Fig. 3a) were placed on three spots along each transect: one underwater, one at the shoreline, and one at half of the berm height (Fig. 2c). Four recovery campaigns were performed after approximately 4, 7, 12 and 19 months. Four 125 kHz readers are used, one customized to operate underwater by providing it with waterproof housing (Fig. 3b). Concerning the detection capabilities of the reader, the burial of the pebble does not reduce the

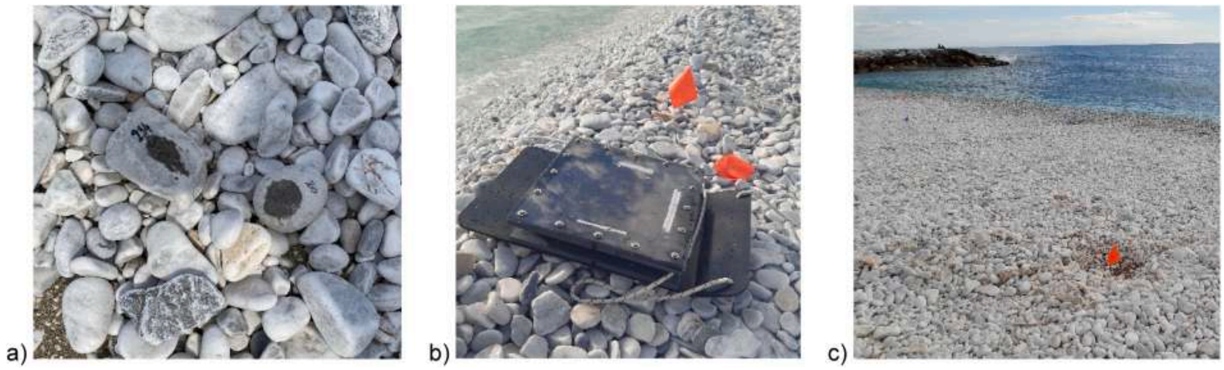

Fig. 3. a) Pairs of angular and rounded tagged pebbles injected in the beach. b) 125 kHz reader used to trace the tagged pebbles, customized to operate underwater by providing it with waterproof housing. c) Hole dug (up to 50 cm of depth) to find the tagged pebbles.

reading range: however, the actual reading range is strictly dependent on the tag typology (Benelli et al., 2011). For the 30 mm diameter disc tags used in this research, the reading range is approximately 60 cm outside water reducing to 50 cm underwater (Benelli et al., 2011). The readers are equipped with a Bluetooth data transmission channel able to send the code retrieved by detecting a marked pebble directly to a smartphone held by the operator. The Bluetooth transmitter was placed outside the water together with the 12 V lead-acid battery powering the reader. Once a tracer particle is detected, a message appears directly on the smartphone of the operator. After the localization, an effort is required to find the tagged pebbles, by digging holes up to 50 cm of depth (Fig. 3c). The DGPS-RTK instrument was employed to record the positions of the pebbles. However, this measurement was only feasible during the release and the initial recovery campaign, due to the lack of satellite coverage during subsequent campaigns.

The wave data were collected from two different sources: *i*) a time series recorded at an offshore wave buoy located in the vicinity of the Gorgona island (Lon. 9°57′25.20″ E Lat. 43°34′12.00″ N) at a depth equal to 150 m, owned by the "Centro Funzionale della Regione Toscana" and *ii*) a hindcast numerical time series (point next to the wave buoy, Lon 10°1′0.12′' E, Lat 43°35′24.00′' N) carried out by Lira-Loarca et al. (2022) with the wave model WAVEWATCH III v6.07 on an unstructured mesh over the whole Mediterranean Sea. This second source is the result of a research that validated (Cavaleri et al., 2022; Mentaschi et al., 2013) and analyzed the performance of the wave model (Mentaschi et al., 2015). The two data sources demonstrate a high degree of concordance during the period of overlap (coefficient of determination $R^2 = 0.77$), thereby enabling the utilisation of either source in the intervals of wave buoy downtime. Since the data are available offshore, a nearshore transformation to a depth equal to 10 m (∼ 1 km far from the beach) is carried out by applying the refraction and shoaling coefficients.

The tumbling tests are performed at the University of Padova and the sample comprises the remaining 35 pebbles that were painted for rapid recognition (as shown in Fig. 1). The pebbles share a similar weight, with an average of approximately 1.2 kg. The sample is subdivided into 5 sub-samples (7 pebbles each): 1 with only rounded pebbles, 1 with only rough angular pebbles and 3 mixed (Bertoni et al., 2023b).

For one of the mixed samples, the maximum number of revolutions was set equal to 500, weighing the pebbles every 20 revolutions up to 200 and then every 50 revolutions. This allows to characterize the first phases of the abrasion and chipping. For the other 4 samples, the maximum number of revolutions was set equal to 5000, weighing the pebbles every 100 or 200 revolutions. Only one sub-sample per type (1 mixed, 1 rounded and 1 angular) was 3D scanned.

4. Results

4.1. In-situ campaign results

The first recovery campaign was performed on February 7th, 2023, about 4 months after the injection campaign. The retrieved pebbles were 36 (13 rounded and 23 angular) plus 2 tags (i.e. two pebbles experienced fracture). The majority of the pebbles (∼ 85 %) were found in the southern part of the pocket beach, in the rear portion beyond the crest of the berm. The beach was characterized by a high and steep storm berm typical of coarse beaches after big storms. During the second campaign (May 2nd, 2023), the retrieved pebbles were 22 (9 rounded and 13 angular) less than in the first campaign since between the first and the second recovery some dumpers reshaped the beach for the tourist season probably burying several tagged pebbles. Moreover, 10 tags were found (5 belonging to rounded pebbles and 5 to angular pebbles) probably because the dumper operations induced breakage. 4 pebbles were found both during the first and the second campaigns. During the third recovery (October 17th, 2023), the retrieved pebbles were 18 (5 rounded and 13 angular). The majority of the pebbles were found landward of the berm crest. 3 pebbles were found both during the first and the third campaign. During the fourth recovery (May 15th, 2024), the retrieved pebbles were 19 (4 rounded and 15 angular) plus 3 tags. During the four recovery campaigns, some pebbles were located underwater. However, due to the difficulties encountered during the underwater excavation, it was not possible to recover all of them.

Based on the MBB protocol, the d_G is computed from the 3D scanner results. The ratio between d_{EQ} and d_G is approximately 1 (0.9 – 1.1) for all the scanned pebbles, therefore the selected pebbles have in general a spheroid shape. Fig. 4 shows the representative diameters (d_{EQ} and d_G) for the initial sample and the recovered samples. The initial indication of abrasion and chipping is a reduction in the median diameter over time, which suggests that the pebbles recovered are typically smaller than the original ones. It is evident that the graph is affected by the type of pebbles found, i.e. whether they were initially large or small. This also demonstrates the importance of using the RFID technology, which guarantees the recognition of each individual pebble and allows for the following analyses.

Table 1 summarizes the results of the in-situ investigation; after the four recovery campaigns a total of 81 pebbles were found (12 of these found two times and 2 found three times), i.e. ∼ 40 % of the initial sample (81 out of 204). The total number of rounded pebbles recovered is 29 out of 95 (30 %), whereas the total number of angular pebbles recovered is 52 out of 109 (48 %). The w_{L_s} is 22.1 % after 4 months, 33.1 % after 7 months, 34.8 % after 12 months and 43.7 % after 19 months. Due to the highly energetic environment that induces huge beach reworking, no clear correlations are observed between the initial position along the cross-sections and the measured rate of relative weight loss.

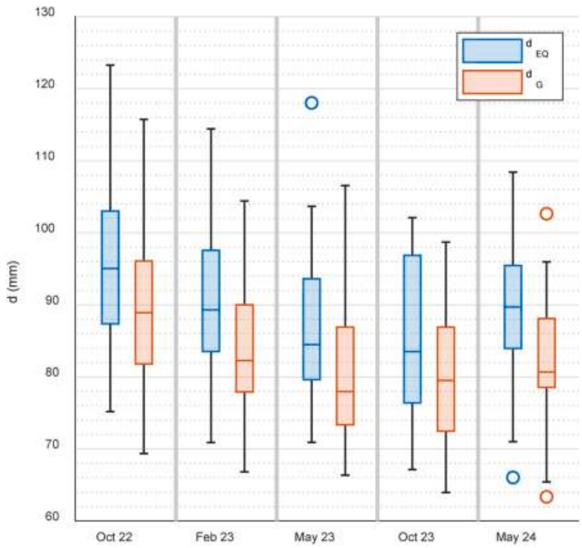

Fig. 4. Boxplot of the spherical equivalent diameter d_{EQ} and the averaged geometrical diameter of the equivalent ellipsoid d_G, for the initial sample and for the recovered samples. The line inside each box is the sample median, the top and bottom edges of each box are the 0.25 and 0.75 quartiles and the whiskers connects the quartiles to the non-outlier maximum and minimum (circles outside whiskers are outliers).

4.2. LA test results

The pebbles of the 5 subsets inserted in the LA machine were checked after the revolutions, subdividing the broken and unbroken ones. Table 2 presents the average rate of relative weight loss $< w_L >$ and the number of unbroken pebbles after 500, 1000, 2000 and 5000 revolutions (in the following N_R = number of revolutions) for the 5 subsets inserted in the tumbler. The average weight variation after 2000 revolutions is about 39–43 % and after 5000 revolutions is about 64–70 %. No different behaviours in terms of relative weight loss are observed for unbroken angular and rounded pebbles.

The relative weight loss obtained during the LA test is shown in Fig. 5. The figure shows the w_L trend for both broken and non-broken pebbles together with the average variation evaluated only for non-broken pebbles. As for the in situ investigation, the rate of relative weight loss decreases over time due to a decrease of the pebble volume. In fact, the weight loss in grams after each revolution decreases from 0.48 g/rev during the first 200 revolutions to 0.2 g/rev between 200 and 1000 revolutions and finally to 0.1 g/rev after 1000 revolutions. The "powder" produced by the abrasion during the LA tests was collected and weighed after 20–50 revolutions and the mean grain size d_{50} of this resulting material was 0.25–0.33 mm (Bertoni et al. 2023b).

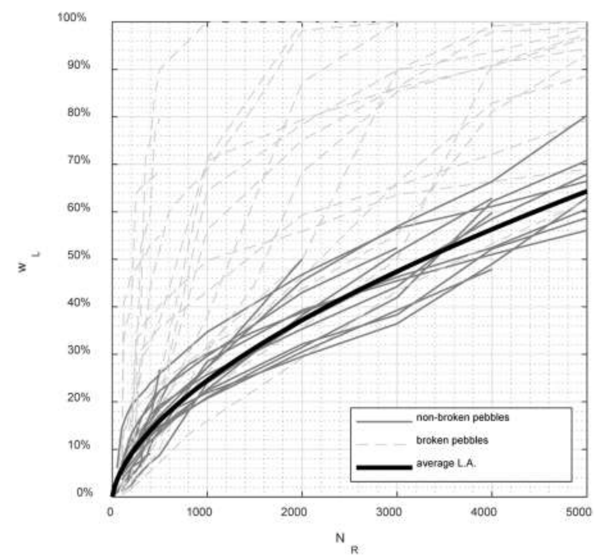

Fig. 5. Rate of relative weight loss function of the number of revolutions (N_R) during the LA tests for both broken and non-broken pebbles.

Table 1
Results of the in-situ campaign. In the column that indicates the number of pebbles recovered, the numbers of rounded (r) and angular (a) recovered pebbles are also reported in parentheses. Broken pebbles were not considered.

Recovery	Date	Months	No. pebbles recovered	% pebbles recovered	Range of weights	No. storms with Hs > 2 m between the recovery campaigns	$< w_L >$	w_{L_s}
start	12/10/2022	–	204 (r:95, a:109)	100 %	462 – 2036 g	–	0	0
1st	07/02/2023	3.87	36 (r:13, a:23)	17.6 %	387 – 1628 g	10	0.099	0.221
2nd	02/05/2023	6.64	22 (r:9, a:13)	10.8 %	387 – 1787 g	7	0.180	0.331
3rd	17/10/2023	12.16	18 (r:5, a:13)	8.8 %	329 – 1157 g	7	0.191	0.348
4th	15/05/2024	19.09	19 (r:4, a:15)	9.3 %	313 – 1385 g	33	0.245	0.437

Table 2
Results of the LA test: number of unbroken pebbles and average weight for the 5 subsets (broken pebbles were not considered).

N_R	set A (mixed)		set B (mixed)		set C (mixed)		set D (rounded)		set E (angular)	
	unbroken	$<w_L>$	unbroken	$<w_L>$	unbroken	$<w_L>$	unbroken	$<w_L>$	unbroken	$<w_L>$
100	7	0.05	7	0.07	7	–	7	0.01	7	0.05
200	4	0.1	7	0.12	7	0.08	6	0.05	7	0.09
500	2	0.22	5	0.24	6	0.12	5	0.16	7	0.17
1000	–	–	3	0.34	6	0.24	3	0.31	7	0.25
2000	–	–	3	0.43	5	0.36	2	0.43	7	0.39
3000	–	–	3	0.51	4	0.51	1	0.47	6	0.53
4000	–	–	3	0.57	2	0.57	1	0.59	5	0.58
5000	–	–	3	0.64	2	0.66	1	0.68	3	0.7

4.3. Pebble roundness behaviour

Fig. 6 illustrates three 3D scanning of pebbles employed in the in-situ campaign, along with two pebbles employed for the LA tests. Both the natural environment and the LA revolutions tend to result in the rounding of pebbles, as highlighted also in Fig. 7, where the ratio S/I is plotted against the ratio I/L. This figure shows also the lines of equal maximum projection sphericity $\Psi_P = \sqrt[3]{S^2/IL}$ (a perfect sphere has $\Psi_P = 1$).

Nevertheless, the analysis of the 3D scanning data indicates that LA experiments tend to produce slightly more rounded pebbles than those observed in the in-situ investigation. This is supported by the observed trend over time of the Wadell roundness parameter R, as illustrated in Fig. 8, for both in-situ and LA tests (where N_R represents the number of revolutions). The red-shaded area above $R = 0.7$ denotes pebbles with a well-rounded shape. For the LA tests, the roundness R for pebbles with an angular shape increases rapidly after a few revolutions (200–400 N_R). After 3000 N_R, almost all the pebbles are well rounded.

From the LA tests, it was observed that the rounded pebbles experienced more breakage than angular ones because they had already undergone some abrasion in the natural environment that probably caused internal fractures. In fact, during the test performed only on rounded pebbles, only one pebble remained intact after the 5000 revolutions, whereas during the test performed only on angular pebbles, about half of them remained intact at the end of the test. This may be the reason why a larger proportion of angular pebbles were recovered during the four campaigns than rounded ones. As illustrated in Fig. 8, a greater quantity of pebbles with an angular original shape (blue markers) was identified in the four recovery campaigns than those with an original rounded shape (red markers). It is likely that the rounded pebbles were broken during the swells and therefore not detected.

5. Discussion

The pebbles analysed in this study exhibited a markedly lower resistance to abrasion than that observed by other Authors (Table 3). This can be explained by the different influencing factors. In fact, the abrasion and chipping that occur in coarse sediment beaches are a function of the sediment characteristics (hardness, weight, density, size and shape) and of the beach characteristics (size, shape, wave energy).

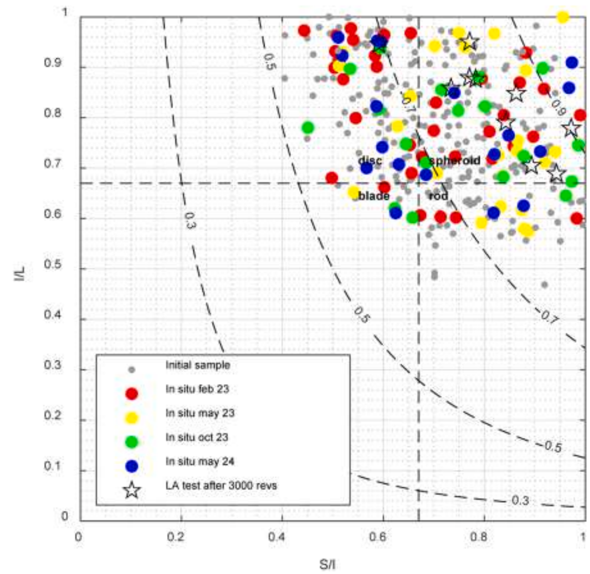

Fig. 7. Zingg diagram of the scanned pebbles showing lines of equal Maximum projection sphericity $\boldsymbol{\Psi_P} = \sqrt[3]{\mathbf{S}^2/\mathbf{IL}}$.

The larger abrasion found in this study is likely to be related to the type of lithology used for nourishment (marble) and to the extreme wave conditions experienced on this stretch of coast. This agrees with Dornbusch et al. (2002) suggestion that a critical factor influencing beach abrasion is the wave energy incident the coast. The waves are responsible for berm building and onshore migration (Pedrozo-Acuna et al. 2006) which are consequences of sediment movements (mainly saltation, bedload and sheetflow, Buscombe and Masselink, 2006).

In order to corroborate the dependence between abrasion and waves, the wave energy flux between two consecutive measurement campaigns was quantified, thereby obtaining the results presented in Fig. 9. This figure shows the trend of w_{L_s} during the in-situ campaign as a function of the cumulative normalized wave energy flux F* (Eq. (1)). Based on the numerical wave time series (Lira-Loarca et al., 2022), the yearly average wave climate at Marina di Pisa is $F_y = 3.26\times10^7$ W/m. The small black

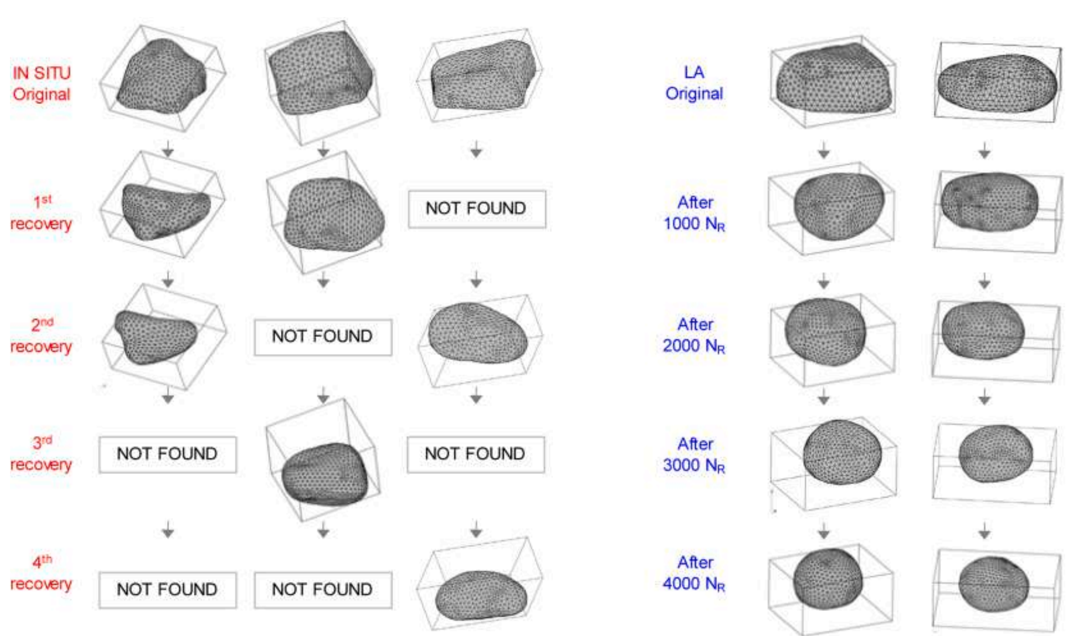

Fig. 6. Shape variation through 3D scanning of three pebbles used in the in-situ campaign and of two pebbles used in the LA tests.

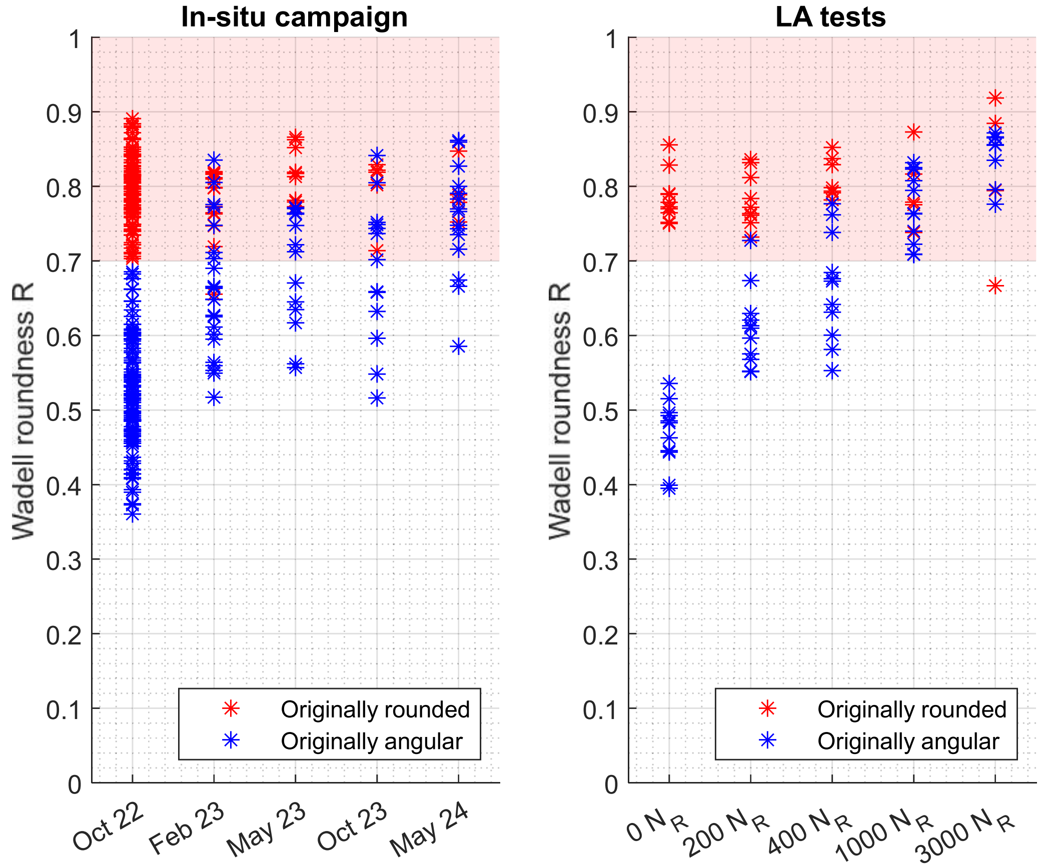

Fig. 8. Wadell roundness R for the in-situ campaign and for the LA tests.

Table 3
Abrasion results for different lithologies. Data collected from different studies.

Reference	Lithology	Months	$<w_L>$	Initial d_{50}
Present study	Marble	3.87	9.9 %	~96 mm
Present study	Marble	6.64	18.0 %	~96 mm
Present study	Marble	12.2	19.1 %	~96 mm
Present study	Marble	19.1	24.5 %	~96 mm
Dornbusch et al. 2002	Quarzite	10	0.36 %	~65 mm
Dornbusch et al. 2003	Limestones	10	1.44 %	~65 mm
Allan et al. 2006	Resistant basalt	17	0.003 %	~91 mm
Dickson et al. 2011	Greywacke	2.1	0.40 %	~60 mm
Dickson et al. 2011	Greywacke	6.8	1.80 %	~60 mm
Chen and Stephenson, 2015	Greywacke	1.38	2.69 %	~80 mm

dots are the w_L for all the retrieved tracers whereas the red dots are the w_{L_s} after each recovery campaigns. The results show that the relative weight loss rate is high during the first phases (i.e., the line slope is steep) and then decreases as the volume of the pebbles decreases (i.e., the line slope is gentler). This is due to corner chipping that occurs mainly during the first wave impacts and then diminishes. In the following periods, the abrasion mechanism becomes more relevant than chipping. Fig. 10 illustrates the ratio of Wadell roundness related to the four recovery campaigns (R_t) to the initial Wadell roundness (R_0) as a function of the normalised wave energy flux. A ratio greater than 1 indicates that the pebble has undergone a rounding process and has lost its corners. The mean trend of this ratio for pebbles with an original angular shape demonstrates that, during the initial period, corner chipping occurs. In the long term, the pebbles become well rounded, exhibiting no further evidence of corner chipping. This latter long-term behaviour is consistent with that observed in pebbles with an original rounded shape, which exhibited no evidence of corner chipping throughout the entire observation period.

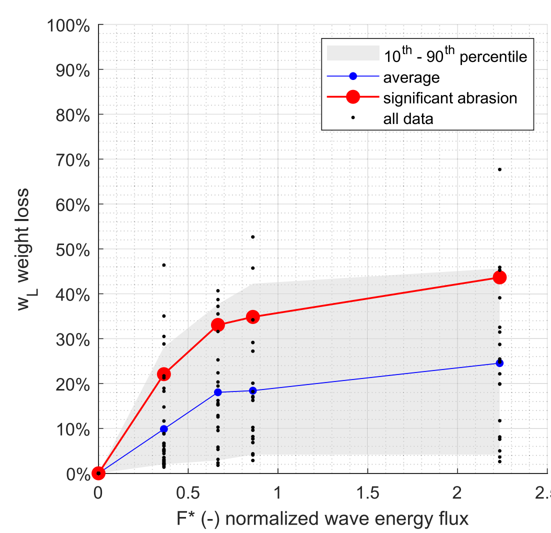

Fig. 9. Significant weight variation as a function of the normalized wave energy flux incident the coast for marble pebbles in Marina di Pisa.

The trend of the significant abrasion shown in Fig. 9, derived from the in-situ investigation results, is comparable to that observed during the LA test. This observation allows for the establishment of a preliminary predictive relation between the number of revolutions and the normalized wave energy flux, which can be expressed as $F^* = a\, N_R{}^b$. In detail, the significant abrasion identified during the in-situ tests (w_{L_s} in Table 1) can be entered into the LA test graph (Fig. 5), and the corresponding numbers of revolutions can be derived. The pairs formed by F^* and N_R thus identified can be used to fit the equation. The final fitting is

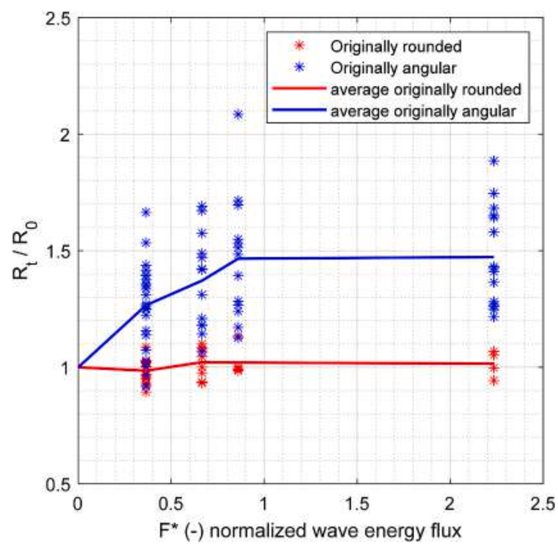

Fig. 10. Ratio of Wadell roundness related to the four recovery campaigns (R_t) to the initial Wadell roundness (R_0) as a function of the normalized wave energy flux incident the coast for marble pebbles in Marina di Pisa.

$F^* = 1.56 * 10^{-8} N_R^{2.39}$ (coefficient of determination $R^2 = 0.98$). Given that F^* is approximately 2.3 for the fourth campaign, this equates to 3000 N_R. Consequently, the effects in terms of roundness and weight loss after this number of revolutions (shown in Fig. 6, Fig. 7 and Fig. 8) can be related to those observed during the fourth campaign. Based on this simple equation, customized for the marble pebble in Marina di Pisa, 3700 N_R correspond to approximately 5 years of typical wave climate, which would result in an expected abrasion of 50 %. However, it is not reasonable to assume that the observed abrasion can be applied to the entire volume of the nourishment or to other lithologies. In fact, the grey region in Fig. 9 indicates the values between the 10th and 90th percentiles. The variability is notably high, as the pebbles situated in the superficial layers of the beach profile are the sole ones affected by a higher relative weight loss. It is reasonable to assume that the buried pebbles are protected from the effects of wave action and other sources of impact. However, the wave run-up and run-down processes induce mixing and therefore also buried pebbles can be exposed. A limitation of the present study is the lack of knowledge regarding the specific portion of the beach that experienced abrasion and chipping. Future research will require the use of active tags to monitor the movement of pebbles daily, highlighting therefore the post-event behaviour. This will facilitate the determination of whether the pebbles are subject to wave action or have been buried, thereby enabling an estimation of the volume affected by abrasion and a more precise prediction of the lifetime of the nourishment. Additionally, the results of abrasion are influenced by the recovery rate, which is related to the initial size of the marked sample and the characteristics of the beach. The site of Marina di Pisa exhibits a small tidal range, thereby precluding the recovery of submerged pebbles. In locations with large tidal range, it may be feasible to wait for low tides to conduct recovery campaigns and even identify submerged pebbles.

These findings are a step towards deriving a more precise understanding of abrasion on coarse nourished beaches to be accounted as an input to the sediment budget and as a feature for the nourishment design. The results are consistent with previous studies suggesting that abrasion is critical to beach volume and stability and should be considered when optimising nourishment design, as diameter reduction may be significant after only a few wave storms. Van der Meer and Pilarczyk (1986) suggested calculating the stability number $N_s = H_s / (\Delta\ d_{50})$ (where Δ is the relative mass density) for gravel and sandy beach nourishments. The former typically has N_s between 15 and 500, the latter $N_s > 500$. The high N_s value indicates that the gravel is rather unstable. Nevertheless, despite the inherent instability of the individual gravel units, it is desirable for the beachfront to attain a dynamically stable configuration. A comparable behaviour, dynamic stability, is observed for rocks forming berm breakwaters (typically, $N_s < 20$). For the site under investigation, with a typical $H_s = 2.5\ m$ at the toe of the nourishment, $\Delta = 1.5$, and an average sediment diameter of $d_{50} = 0.09\ m$, the stability number is $N_s \sim 18$. The reduction in sediment size due to abrasion and chipping ($d_{50} = 0.07\ m$) results in a decrease in stability, with an estimated N_s value of $\sim$24. It is important to note that a large rate of abrasion is dangerous, since the material becomes too fine and movable, reaching a level that results in the complete removal of the units from the beachfront.

The rate of weight loss is expected to be higher in the first period after the nourishment and to decrease as the volume of the pebbles decreases. The weight loss is partially transformed into finer gravel and partially into fine abraded material. The abraded material, constituted by medium-fine sand, hardly deposits in the nearshore because of the high energy of this environment at Marina di Pisa; furthermore, as the powder derives from marble pebbles, it is mainly composed of calcium carbonate, which may be also dissolved into salt water. Furthermore, the pebbles could also experience breakage as a result of the dumper's seasonal operations, thus representing an additional source of instability.

In fact, the mass variation has two main effects on the management of coarse nourished beaches: 1) to reduce the lifetime of the nourishment since the beach volume decreases with time, and 2) to make the pebbles more unstable under extreme waves, causing even damages to the areas behind the beach. The first issue is more related to planning mitigation strategies on a medium time scale, the second has consequences on the emergency management during extreme events.

6. Conclusions

The paper contributes to the practical issue of selecting the correct sediment characteristics for the design of nourishments with coarse material, up to 120 mm, which is a coastal protection mitigation strategy that is becoming increasingly of interest due to the considerable visual impact of structural interventions (e.g. groins, detached breakwaters). However, a major concern is the possible abrasion and chipping mechanisms, that may negatively affect the effectiveness and duration of the nourishment. A novel methodology is presented that evaluates the processes of abrasion and chipping in coarse nourished beaches, estimating the weight loss and the roundness as a function of the wave attacks impacting the coast. This methodology employs a field campaign that makes use of RFID technology, a 3D scanning procedure of the pebbles, and a set of laboratory tests with the LA machine.

The methodology is applied to the Marina di Pisa beach (Tuscany, Italy), where instability of the coarse nourished material was observed in the past. In fact, several extreme events occurred along this stretch of coast with the last one on November 3rd, 2023. During this event, the waves overtopped the rubble mound seawall causing extensive coastal flooding and a huge number of pebbles were thrown in the street behind the beach causing several damages and viability problems.

The selected pebbles used for the investigation are representative of the material used to fill the beach. For the Marina di Pisa marble pebbles, the significant sediment mass loss might exceed 35 % if exposed to 1 year of typical wave climate at Marina di Pisa, i.e. corresponding to a wave energy flux of about 3×10^7 W/m. The 3D scanning of the pebbles allows verification of the occurrence of corner chipping for angular sediment in the initial period, which corresponds to approximately one year of typical wave climate. Subsequently, pebbles become well-rounded, and the abrasion phenomenon becomes more relevant than chipping. This abrasion rate has a significant impact on the sediment stability, resulting in a notable reduction in the nourishment lifetime.

These findings have obvious consequences on the management of the nourished coast both for planning mitigation interventions and for emergencies during extreme events. Moreover, the weight loss should be accounted for in the design phase of nourishment since it is responsible for sediment instability and losses in the beach fill volume.

Further research is planned to apply the methodology to other coastal environments and different sediment lithologies in order to create a database useful for engineers and coastal authorities. Moreover, active tags are expected to measure the depth of beach layers affected by abrasion and chipping. The approach here presented is also suited for citizen science activities which can enhance the research outcomes and raise awareness among the local community about coastal processes and management.

CRediT authorship contribution statement

Chiara Favaretto: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Duccio Bertoni:** Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing. **Alessandro Pozzebon:** Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing, Supervision. **Luca Martinelli:** Conceptualization, Writing – review & editing. **Giovanni Sarti:** Conceptualization, Writing – review & editing. **Piero Ruol:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Additional Information

The authors declare no competing interests.

Data Availability

The datasets analyzed during this study are available from the corresponding author upon reasonable request.

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