

Particle Size Distribution and Mean Diameter Characterization of Beach Sand from Haffa, Salalah, Oman

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Abstract: Particle size distribution is an important physical characteristic of coastal sediments, influencing sediment transport, depositional behavior, permeability, packing characteristics, and particle–fluid interactions. The present study investigates the particle size characteristics of beach sand collected from Haffa Beach, Salalah, Sultanate of Oman, using sieve analysis and moment-based particle diameter calculations. A sand sample with an initial mass of 100 g was subjected to particle size separation using sieves with nominal apertures of 2.000, 1.000, 0.710, 0.500, 0.355, and 0.250 mm. The representative particle diameter of the pan fraction was taken as 0.180 mm based on the Tyler method. The recovered sample mass was 99.51 g, corresponding to a mass recovery of 99.51%. The particle size distribution revealed that the fractions retained on the 0.250 and 0.355 mm sieves accounted for approximately 83.08% of the recovered mass, indicating a pronounced concentration of particles within the intermediate size classes. Several moment-based mean particle diameters were evaluated, including the number–length mean ($\bar{D}_{10}$), surface mean ($\bar{D}_{20}$), volume mean ($\bar{D}_{30}$), volume–surface mean ($\bar{D}_{32}$), and volume–mass mean ($\bar{D}_{43}$). Their corresponding values were 0.2405, 0.2480, 0.2567, 0.2751, and 0.3078 mm, respectively. The cumulative particle size distribution was further analyzed to estimate characteristic percentile diameters. Logarithmic interpolation yielded d_{30} , d_{50} , d_{60} , and d_{90} values of 0.2865, 0.3355, 0.3640, and 0.4749 mm, respectively. The median particle diameter corresponded to medium sand according to the Wentworth grain-size classification. The findings provide a quantitative characterization of the investigated beach sand and demonstrate the relevance of different mean particle diameter definitions for engineering and sedimentological applications. Further analysis of finer particle fractions and grain morphology is recommended to improve sediment sorting assessment and support interpretation of coastal sediment transport processes.

Keywords: Beach sand; Haffa; Salalah; Sieve analysis; Mean diameter; Coastal sediments.

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Introduction

Coastal sediments represent an important component of shoreline environments and play a significant role in coastal morphology, sediment transport, shoreline stability, and interactions between terrestrial and marine processes [1]. The physical characteristics of beach sediments are influenced by several factors, including sediment origin, mineralogical composition, wave action, tidal currents, wind conditions, weathering, and depositional processes. Among these characteristics, particle size distribution is particularly important because it provides information about sediment texture and helps describe the physical behavior of granular materials [2-4].

Particle size characterization is widely employed in sedimentology, coastal engineering, geotechnical engineering, environmental science, and chemical engineering [5]. The distribution of particle sizes influences sediment mobility, permeability, porosity, packing density, settling velocity, and the interaction of particles with surrounding fluids [6]. Consequently, accurate determination of particle size distribution and representative mean diameters is essential for understanding the physical properties of sand and evaluating its suitability for various engineering and environmental applications [7].

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Importance of particle size distribution

Natural sand generally consists of particles with different sizes, shapes, densities, and mineralogical compositions. Therefore, a single particle diameter cannot completely represent the characteristics of a sand sample [8]. Particle size distribution provides a more comprehensive description by indicating the relative proportions of different particle size fractions [9].

Sieve analysis is one of the most commonly used methods for characterizing coarse-grained sediments [10]. In this technique, a known mass of material is separated into different size fractions using a series of sieves with progressively smaller openings. The mass retained on each sieve is measured and used to calculate the percentage retained, cumulative percentage retained, and cumulative percentage passing. The resulting distribution can be represented using frequency distribution plots and cumulative particle size distribution curves. These graphical representations facilitate identification of dominant particle size fractions and estimation of characteristic particle diameters.

Particle size distribution is particularly important in coastal environments because the transport and deposition of sediment

particles are influenced by their size and density [11]. Finer particles may remain suspended under conditions where larger particles are transported primarily as bed load. However, sediment transport also depends on hydrodynamic forcing, grain shape, bed roughness, and sediment availability. Therefore, particle size measurements provide useful evidence but cannot independently establish the transport mechanisms responsible for an observed sediment distribution.

Mean particle diameters and their engineering significance

The mean particle diameter is an important parameter used to represent the overall size characteristics of particulate materials [12]. Different definitions of mean particle diameter are employed depending on the intended application. The number–length mean diameter represents the arithmetic average of particle diameters when each particle is weighted equally. The surface mean diameter incorporates the second moment of the number distribution, while the volume mean diameter incorporates the third moment. The volume–surface mean diameter, commonly known as the Sauter mean diameter, is particularly important in particle technology because it relates the total particle volume to the total particle surface area. This parameter is frequently employed in studies involving fluidization, packed beds, filtration, and particle–fluid mass transfer. The volume–mass mean diameter, also referred to as the De Brouckere mean diameter, gives greater weight to larger particles and is useful for characterizing volume-dominated particle populations. For particles of similar density and shape, these mean diameters can be calculated using mass fractions obtained from sieve analysis. Their comparison provides additional information about the relative contributions of fine and coarse particles to the overall particle population.

Particle size characterization of coastal sediments

Coastal sediments are commonly characterized using grain-size classification systems and statistical parameters [13]. The Wentworth classification is widely employed to distinguish gravel, sand, silt, and clay according to particle diameter. Sand particles generally occupy the grain-size interval from 0.0625 to 2.0 mm. Within this range, sand can be further classified into very fine, fine, medium, coarse, and very coarse fractions. Statistical descriptions of sediment grain-size distributions may also include mean grain size, sorting, skewness, and kurtosis. These parameters provide complementary information about the central tendency, dispersion, asymmetry, and shape of the particle size distribution. Folk and Ward (1957) proposed graphical measures for characterizing grain-size distributions, while moment-based approaches are also widely used in sedimentological and particle engineering studies [14]. The selection of statistical descriptors depends on the available particle size measurements and the objectives of the investigation.

Study area and research significance

Haffa Beach is located in Salalah, within the Dhofar Governorate of southern Oman, along the Arabian Sea coast. The coastal environment of southern Oman is influenced by seasonal atmospheric and oceanographic conditions, including the southwest monsoon, locally known as the Khareef. Seasonal changes in wave conditions, coastal currents, and sediment supply can influence the distribution and redistribution of beach sediments. Characterization of sand particle sizes therefore provides baseline information that may support future studies of shoreline processes and sediment behavior. Although particle size analysis is an established technique, site-specific measurements remain important because sediment characteristics can vary considerably between coastal locations and across different sampling periods. The present investigation focuses on the particle size characteristics of sand collected from Haffa Beach using conventional sieve analysis and complementary mean particle diameter calculations.

Objectives of the study

The principal objective of this study is to characterize the particle size distribution and representative mean diameters of beach sand collected from Haffa Beach, Salalah, Oman. The specific objectives are to: (i) Determine the mass distribution of sand particles across different sieve size fractions; (ii) Calculate the mass fraction retained, cumulative percentage retained, and cumulative percentage passing; (iii) Evaluate number-, surface-, volume-, and mass-related mean particle diameters; (iv) Determine the Sauter mean diameter and discuss its engineering significance; (v) Estimate characteristic percentile diameters from the cumulative particle size distribution; (vi) Classify the dominant particle size characteristics using established sedimentological classification; and (vii) Discuss the implications of the measured particle size distribution for coastal sediment characterization and potential engineering applications.

Materials and Methods

Study location

The sand sample investigated in this study was collected from Haffa Beach, located in Salalah, Dhofar Governorate, Sultanate of Oman (Figure 1). Haffa Beach forms part of the southern Omani coastline facing the Arabian Sea. The region experiences seasonal climatic variations associated with the southwest monsoon, which can influence coastal hydrodynamics and sediment redistribution. The present study focuses on laboratory particle size characterization.

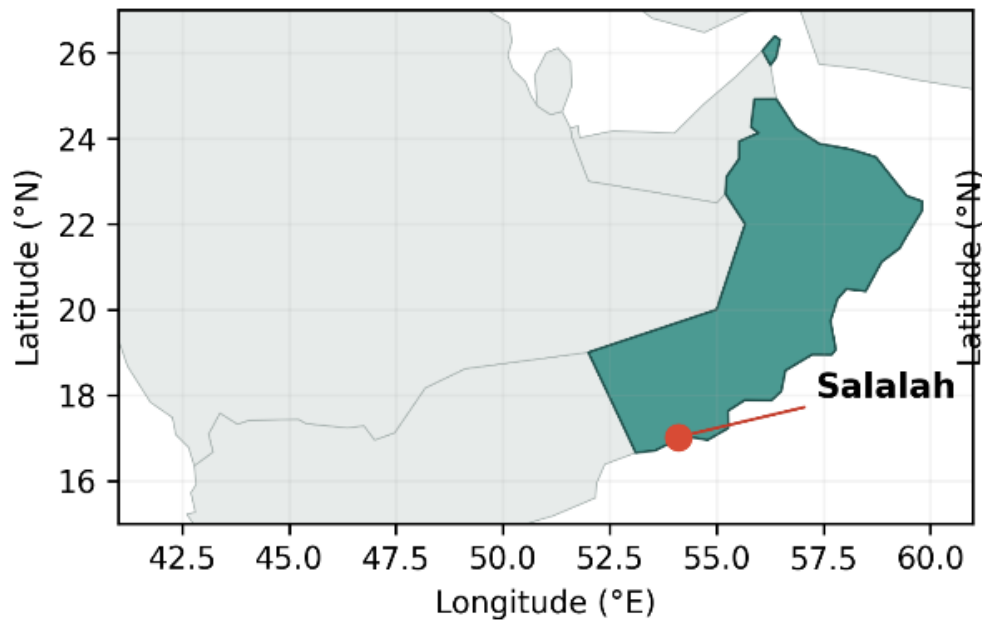


Figure 1. Study area of this research, Salalah in Oman.

Sand sample and sieve analysis

A sand sample with an initial mass of 100 g was used for particle size characterization. The sample was separated into different particle size fractions using a series of sieves with nominal openings of 2.000, 1.000, 0.710, 0.500, 0.355, and 0.250 mm, arranged in descending order. The mass retained on each sieve was measured and recorded. The material passing through the smallest sieve was collected in the pan. The representative particle diameter assigned to the pan fraction was 0.180 mm, estimated using the Tyler method. This value was used for calculating moment-based mean particle diameters. It was not treated as an additional experimentally measured sieve aperture. The total recovered mass after sieving was 99.51 g, corresponding to a mass loss of 0.49 g.

Calculation of mass fraction

The mass fraction of particles retained in each size class was calculated using Equation (1) [15]:

$$w_i = \frac{m_i}{M} \quad (1)$$

where w_i is mass fraction of size class i , m_i = mass retained in size class i , g, and i is number of size classes. The cumulative percentage mass retained was calculated by summing the percentages retained on successive sieves, beginning with the largest aperture.

Calculation of mean particle diameters

For a particle population containing n_i particles of diameter d_i , the generalized moment mean diameter is as given in Equation (2) [16]:

$$D_{pq} = \left[\frac{\sum_i n_i d_i^p}{\sum_i n_i d_i^q} \right]^{\frac{1}{p-q}} \quad (2)$$

where p and q represent the orders of the particle size moments.

Assuming constant particle density and comparable particle shape across the different size fractions, particle number is proportional to particle mass divided by the cube of particle diameter. Therefore, the generalized moment mean diameter can be expressed in terms of mass fractions as given in Equation (3) [16]:

$$D_{pq} = \left[\frac{\sum_i w_i d_i^{p-3}}{\sum_i w_i d_i^{q-3}} \right]^{\frac{1}{p-q}} \quad (3)$$

The mean diameters considered in this study are presented in Table 1 [17]. All mean diameters were calculated using the representative particle diameters supplied for the seven size fractions.

Table 1. Mathematical expressions used for calculating mean particle diameters

Mean particle diameter	Symbol	Equation
Number-length	d_{10}	$\left(\frac{\sum w_i / d_i^2}{\sum w_i / d_i^3} \right)$
Surface mean	d_{20}	$\left(\frac{\sum w_i / d_i}{\sum w_i / d_i^3} \right)$
Surface-length	d_{21}	$\left(\frac{\sum w_i / d_i}{\sum w_i / d_i^2} \right)$
Volume mean	d_{30}	$\left(\frac{1}{\sum w_i / d_i^3} \right)^{1/3}$

Volume-length	d_{31}	$\left(\frac{1}{\sum w_i / d_i^2} \right)^{1/2}$
Volume-surface (Sauter)	d_{32}	$\frac{1}{\sum w_i / d_i}$
Volume-mass (De Brouckere)	d_{43}	$\sum w_i d_i$

Determination of characteristic particle diameters

Characteristic particle diameters were estimated from the cumulative percentage passing distribution. The percentile diameter (d_x) represents the particle size at which (x)% of the sample mass is finer. Logarithmic interpolation between adjacent measured sieve openings was employed as given in Equation (4) [18]:

$$[\ln d_x = \ln d_L + \frac{x-P_L}{P_U-P_L}(\ln d_U - \ln d_L)] \quad (4)$$

where (d_L) and (d_U) are the lower and upper sieve apertures bounding the desired percentile, and (P_L) and (P_U) are their respective cumulative passing percentages. The characteristic

diameters (d_{30}), (d_{50}), (d_{60}), and (d_{90}) were determined using this procedure. The 10th percentile diameter could not be resolved because the entire fraction passing the 0.250 mm sieve was collected in a single pan fraction.

Grain-size classification

The median grain diameter was used to classify the sample according to the Wentworth grain-size classification [19]. The conventional boundaries used for sand are listed in Table 2. The classification was applied to the median grain diameter and interpreted alongside the experimentally measured mass distribution.

Table 2. Wentworth grain-size classification for sand

Classification	Grain diameter (mm)
Very coarse sand	1.000–2.000
Coarse sand	0.500–1.000
Medium sand	0.250–0.500
Fine sand	0.125–0.250
Very fine sand	0.0625–0.125

Results

Mass balance and particle size distribution

The experimental sieve analysis results are presented in Table 3 and Figure 2. The initial sand sample mass was 100 g, while the total mass recovered after sieving was 99.51 g. The corresponding mass recovery was 99.51%, indicating that only 0.49% of the original sample mass was unaccounted for after the experiment.

Table 3. Experimental sieve analysis and cumulative particle size distribution of Haffa Beach sand

Sieve aperture (mm)	Representative diameter (mm)	Mass retained (g)	Mass fraction	Retained (%)	Cumulative passing (%)
2.000	2.000	0.70	0.00703	0.70	99.30
1.000	1.000	0.61	0.00613	0.61	98.68
0.710	0.710	0.94	0.00945	0.94	97.74
0.500	0.500	1.93	0.01940	1.94	95.80
0.355	0.355	38.44	0.38629	38.63	57.17
0.250	0.250	44.23	0.44448	44.45	12.72
Pan	0.180	12.66	0.12722	12.72	0
Total	—	99.51	1.00000	100.00	—

The largest mass fraction was retained on the 0.250 mm sieve, accounting for 44.45% of the recovered mass. This was followed by the 0.355 mm sieve, which retained 38.63%. The combined contribution of these two fractions was 83.08%. The remaining material was distributed among the pan fraction (12.72%) and the coarser sieve fractions (4.20%). The frequency distribution demonstrates a pronounced concentration of particles within the two dominant sieve fractions. The comparatively small quantities retained on sieves of 0.500 mm and larger indicate that relatively coarse material constitutes only a minor proportion of the sample.

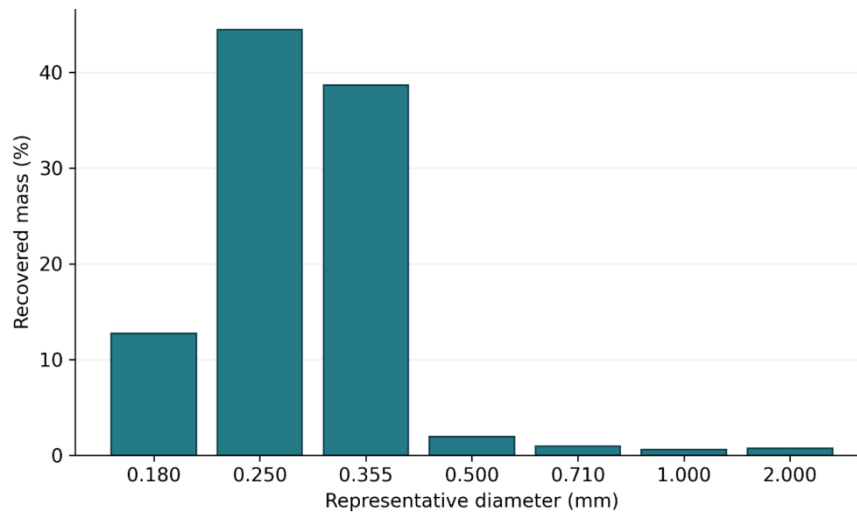


Figure 2. Mass percentage associated with each supplied representative diameter (mm). The pan fraction is represented by its Tyler-estimated mean diameter.

Cumulative particle size distribution

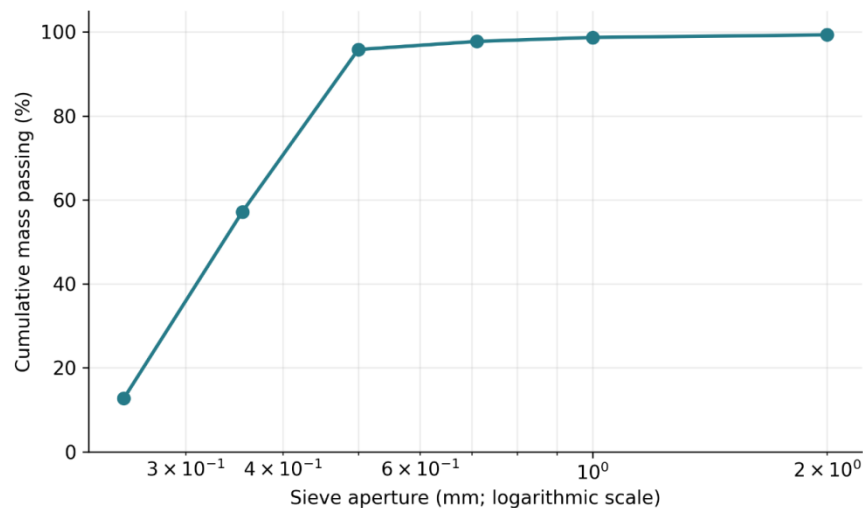


Figure 3. Cumulative mass passing distribution of beach sand in Haffa, Salalah, Oman. Sieve apertures are shown in millimeters. The corresponding publication figure should use a logarithmic horizontal axis.

The cumulative particle size distribution was evaluated using the percentage of recovered mass passing each sieve aperture. The cumulative passing percentage decreased from 99.30% at 2.000 mm to 12.72% at 0.250 mm. The most pronounced change occurred between the 0.355- and 0.250-mm sieve apertures, where cumulative passing decreased from 57.17% to 12.72%. The steep increase in cumulative passing between 0.250 and 0.500 mm indicates that a substantial proportion of the sample falls within this grain-size interval (Figure 3).

Characteristic particle diameters

The characteristic percentile diameters obtained from logarithmic interpolation are presented in Table 4.

Table 4. Characteristic particle diameters from the cumulative passing distribution

Parameter	Diameter (mm)
d ₁₀	Not resolved
d ₃₀	0.2865
d ₅₀	0.3355
d ₆₀	0.3640
d ₉₀	0.4749

The median particle diameter was 0.3355 mm, indicating that 50% of the recovered sand mass consisted of particles finer than this estimated size. The median diameter falls within the medium-sand category of the Wentworth classification. The 10th percentile could not be determined

from the available sieve apertures because 12.72% of the recovered mass passed the smallest sieve. Consequently, the uniformity coefficient and coefficient of curvature were not calculated.

Evaluation of mean particle diameters

The mean particle diameters were calculated using the mass fractions and representative particle diameters. The results are summarized in Table 5.

Table 5. Calculated mean particle diameters of Haffa Beach sand

Mean diameter	Symbol	Value (mm)	Value (μm)
Number–length	d_{10}	0.2405	240.5
Surface mean	d_{20}	0.2480	248.0
Surface–length	d_{21}	0.2558	255.8
Volume mean	d_{30}	0.2567	256.7
Volume–length	d_{31}	0.2653	265.3
Volume–surface	d_{32}	0.2751	275.1
Volume–mass	d_{43}	0.3078	307.8

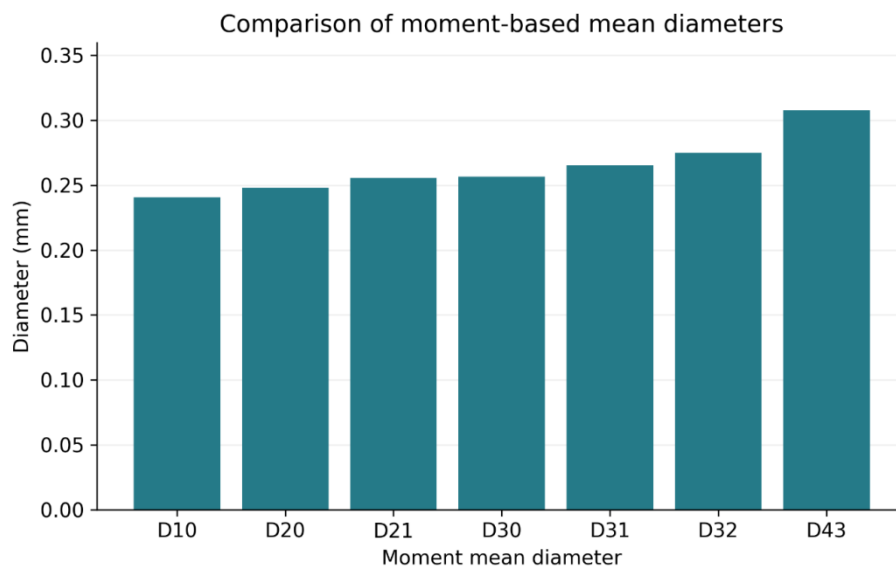


Figure 4. Comparison of moment-based mean diameters

The number–length mean diameter was the smallest among the calculated mean diameters, whereas the volume–mass mean diameter was the largest. The results indicate that the calculated mean diameter depends strongly on the mathematical definition used to represent the particle population (Figure 4).

3.6. Specific surface area estimation

The mass-specific external surface area of ideal spherical particles can be estimated using Equation (5):

$$[SSA = \frac{6}{\rho_p D_{32}}] \quad (5)$$

where (ρ_p) is the particle density. For illustration, assuming a particle density of 2650 kg/m³, commonly used as an approximate density for quartz: $SSA = 0.00823 \text{ m}^2/\text{g}$. The calculated value is a theoretical external geometric specific surface area, not an experimentally measured BET surface area. The assumed quartz density should not be interpreted as a measured

density or confirmed mineralogical composition of the Haffa Beach sand.

Discussion

Dominant particle size characteristics

The sieve analysis revealed that the investigated sand sample was dominated by material retained on the 0.250- and 0.355-mm sieves, which together accounted for approximately 83.08% of the recovered mass. This concentration indicates that most of the sample was distributed within a relatively restricted range of sieve fractions.

The median particle diameter of 0.3355 mm classifies the sample as medium sand according to the Wentworth classification. This result provides a useful central measure of grain size and supports the observation that intermediate-sized sand particles dominate the recovered material. However, the median grain-size

classification does not establish the mineralogical composition, sediment source, or depositional history of the sample.

Comparison of mean particle diameters

The calculated mean particle diameters varied from 0.2405 mm for the number–length mean diameter to 0.3078 mm for the volume–mass mean diameter. This difference arises because each moment-based mean emphasizes a different aspect of the particle size distribution.

The number–length mean diameter is influenced more strongly by the number of small particles, while higher-order moment means place greater emphasis on larger particles. The volume–mass mean diameter was approximately 28.0% greater than the number–length mean diameter, demonstrating the influence of particle size weighting on the resulting mean value. These findings highlight the importance of selecting an appropriate mean particle diameter for the intended engineering application rather than using a single mean value for all purposes.

Significance of the Sauter mean diameter

The Sauter mean diameter was determined as 0.2751 mm, lying between the number-based and volume–mass mean diameters. This parameter is particularly useful for engineering calculations involving particle surface area and volume. In packed-bed systems, particle diameter influences hydraulic resistance and pressure drop. In filtration processes, it affects the interaction between fluid flow and granular media. Similarly, particle size and surface area are important in heat and mass transfer applications involving particulate solids.

The Sauter mean diameter provides an appropriate equivalent diameter for representing the total external surface-to-volume relationship of the particle population, provided that particle shape assumptions are satisfied. However, natural sand particles are not perfectly spherical. Their irregular shapes, angularity, and surface roughness can influence actual surface area and hydrodynamic behavior. Consequently, the calculated Sauter mean diameter should be interpreted as an equivalent diameter based on the adopted particle model.

Implications for coastal sediment transport

Particle size is an important factor affecting sediment entrainment, transportation, and deposition in coastal environments. The dominance of medium-sized sand fractions at Haffa Beach may be consistent with sediment redistribution and sorting under wave- and current-driven coastal processes. During periods of increased hydrodynamic activity, sediment particles may be mobilized, transported, and redistributed according to the balance between hydrodynamic forces and particle resistance to motion.

The Dhofar coastline experiences seasonal changes associated with the southwest monsoon, which may influence nearshore wave conditions and sediment transport. Nevertheless, the present dataset represents a particle size characterization of the supplied sand sample. It does not include seasonal comparisons, wave measurements, sediment transport rates, or spatially distributed sampling. Therefore, specific conclusions regarding the influence of monsoon conditions, longshore transport, or sediment provenance cannot be established from these measurements alone.

Engineering relevance of the particle size distribution

The particle size characteristics determined in this study may be useful as preliminary information for several engineering applications. In granular filtration systems, particle size distribution influences permeability, hydraulic conductivity, and resistance to fluid flow. In packed beds, the particle size distribution affects packing arrangement, void fraction, and pressure drop. The Sauter mean diameter is frequently used as a representative particle diameter in models of fluid flow through granular media.

The results may also provide baseline information for evaluating sand in construction materials, although engineering suitability would require additional measurements, including mineralogical composition, particle shape, bulk density, moisture content, mechanical properties, and relevant material quality tests. Thus, particle size characterization represents an initial step toward broader evaluation of the physical and engineering properties of Haffa Beach sand.

Limitations of the study

The present analysis has several limitations that should be acknowledged: (i) The particle size distribution was obtained from a single supplied sieve analysis dataset. The representativeness of the sample across different beach locations and sampling periods has not been established.

(ii) The pan fraction accounted for 12.72% of the recovered mass. Although a representative particle diameter of 0.180 mm was assigned using the Tyler method, the internal particle size distribution of this fraction remains unknown. (iii) The moment-based mean diameters were calculated assuming constant particle density and comparable particle shape across size fractions. Natural sand may deviate from these assumptions. (iv) The absence of finer sieve measurements prevents independent determination of the 10th percentile diameter and limits the calculation of certain sedimentological sorting parameters. (v) The present investigation did not include mineralogical analysis, microscopic particle morphology, or seasonal sediment sampling. Future investigations incorporating finer sieving, image-based particle analysis, mineralogical characterization, and spatial and seasonal sampling would provide a more comprehensive understanding of the sediment characteristics of Haffa Beach.

Conclusion

The particle size characteristics of sand collected from Haffa Beach, Salalah, Oman, were investigated using sieve analysis and moment-based mean particle diameter calculations. The experimental sample had an initial mass of 100 g, of which 99.51 g was recovered after sieving, corresponding to a mass recovery of 99.51%. The particle size distribution indicated that the fractions retained on the 0.250 and 0.355 mm sieves accounted for approximately 83.08% of the recovered mass. The median particle diameter was estimated as 0.3355 mm, corresponding to medium sand according to the Wentworth classification. The calculated number–length, surface, volume, volume–surface, and volume–mass mean particle diameters were 0.2405, 0.2480, 0.2567, 0.2751, and 0.3078 mm, respectively. The variation among these mean diameters demonstrates the influence of particle size weighting and highlights the importance of selecting a representative diameter appropriate to the intended application. The Sauter mean diameter

of 0.2751 mm provides a useful parameter for describing the volume-to-surface-area relationship of the particle population and may support preliminary calculations involving packed beds, filtration, and particle–fluid interactions. The findings provide baseline quantitative information on the particle size distribution of the investigated Haffa Beach sand sample. Additional finer-size analysis, grain morphology characterization, and spatial and seasonal sampling are recommended to strengthen sedimentological interpretation and establish the broader representativeness of the results.

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