

# Comparative SEM–EDS Characterization of Marine Sand from Multiple Coastal Regions of Central Indonesia for Engineering Applications

## Adnan

Department of Civil Engineering, Universitas Muhammadiyah Pare-Pare, Indonesia  
ferlywijaya774@gmail.com (corresponding author)

## Miswar Tumpu

Disaster Management Study Program, The Graduate School, Hasanuddin University, Indonesia  
miswartumpu@unhas.ac.id

## Muhammad Jabir Muhammadiyah

Department of Civil Engineering, Universitas Muhammadiyah Pare-Pare, Indonesia  
jabirdiah@gmail.com

## Andung Yunianta

Department of Civil Engineering, Yapis University, Jayapura, Indonesia  
andung.ay@gmail.com

## Hoong-Pin Lee

Department of Civil Engineering, Faculty of Engineering and Quantity Surveying, INTI International University, Malaysia  
hoongpin.lee@newinti.edu.my

Received: 24 December 2025 | Revised: 14 January 2026 and 23 January 2026 | Accepted: 2 February 2026

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## ABSTRACT

Marine sand is an alternative construction material due to the growing demand for natural aggregates and the depletion of terrestrial resources. Its use also aligns with the Sustainable Development Goals (SDGs), particularly SDG 9, SDG 11, and SDG 12. This study examines the mineralogical and elemental characteristics of marine sand collected from several coastal regions in central Indonesia, including South Sulawesi (Balusu Barru, Bojo Barru, Pangkep, Pare-Pare, Pinrang, and Selayar) and East Kalimantan (Muara Badak), using Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (SEM–EDS). The results indicate regional variations in particle morphology, surface texture, and elemental composition, reflecting differences in geological setting and coastal sediment processes. Several samples exhibit silica-dominated characteristics, while others show higher contents of calcium (Ca)-, magnesium (Mg)-, and iron (Fe)-bearing phases, suggesting varying levels of suitability for engineering applications. SEM–EDS analysis reveals silicon (Si) contents ranging from approximately 2.9 to 12.8 wt.% and Ca contents between 0.0 and 18.5 wt.%. The novelty of this study lies in its comparative regional assessment, demonstrating that marine sand should not be treated as a homogeneous material across different coastal environments. From an engineering perspective, the findings provide valuable insights for material selection in concrete, mortar, and geotechnical applications, particularly for coastal infrastructure development, while emphasizing the importance of site-specific characterization to support sustainable material utilization and environmentally responsible construction practices.

*Keywords-marine sand; SEM–EDS analysis; mineralogical variability; regional differentiation; sustainable building; engineering applications; coastal resources*

## I. INTRODUCTION

Marine sand has attracted attention as an alternative construction material due to the depletion of river sand resources and the growing demand for infrastructure development, particularly in coastal and island regions. Sedimentological studies have shown that coastal sediments are inherently heterogeneous, influenced by geological provenance, hydrodynamic energy, and depositional environments [1]. In archipelagic countries such as Indonesia, where terrestrial aggregate resources are unevenly distributed, marine sand represents a potentially strategic construction material. However, engineering practice often treats marine sand as a uniform material, neglecting its intrinsic variability, which may lead to suboptimal performance and durability concerns.

Advances in construction material research emphasize that the performance of cement-based composites is governed by the microstructural and compositional characteristics of their constituent materials. Research into precast and high-performance concrete demonstrates that variations in raw material composition significantly influence hydration behavior, pore structure, and mechanical properties [2, 3]. Studies on supplementary cementitious materials, including silica-rich biomass ash and alternative mineral additives, further confirm that mineralogical compatibility and surface characteristics are crucial for durability in aggressive environments [4, 5]. These findings indicate that detailed characterization of all concrete constituents, including aggregates, is essential for sustainable engineering applications.

SEM-EDS has become an essential analytical tool for investigating material morphology and elemental composition at the microscale. The former enables identifying mineral phases, surface textures, and elemental distributions that govern interfacial bonding and reactivity in cementitious systems [7]. Its application has been reported in studies on pumice-based concrete, chemical admixture interactions, biomass ash utilization, and alternative supplementary cementitious materials, demonstrating that microstructural analysis provides insights beyond conventional physical testing, particularly for materials with heterogeneous origins [7-11].

From a geological perspective, Indonesia's coastal regions exhibit exceptional diversity, including volcanic arcs, carbonate islands, deltaic systems, and tectonically active margins. Research into island vulnerability, carbonate systems, and coastal sediment geochemistry reveals that sediment sources, transport mechanisms, and depositional environments vary significantly across regions [14, 16]. Grain shape, surface texture, and mineralogical composition—shaped by wave-dominated, tidal, and mixed-energy processes—highly influence engineering behavior, interfacial transition zone quality, and durability in concrete and mortar systems [15-25]. Surface morphology and mineral composition also govern bonding mechanisms and long-term durability, particularly under aggressive marine exposure conditions [25-35].

Despite extensive research on sustainable binders and eco-friendly concrete systems, studies focusing on natural

aggregate characterization, especially marine sand, are limited. Indonesian studies have emphasized binder optimization, while only indirectly addressing aggregate variability [12, 13]. Provenance and geochemical studies confirm that regional geological history governs mineral assemblages and elemental distribution in marine sediments [36, 37]; however, systematic SEM-EDS-based regional comparisons remain scarce. Therefore, this study comparatively analyses the morphology and elemental composition of marine sand from multiple coastal regions of South Sulawesi and East Kalimantan, using SEM-EDS, to elucidate regional variability and assess its implications for engineering applications and sustainable construction practices.

## II. METHODOLOGY

The current study employed an experimental and comparative research design to characterize marine sand collected from multiple coastal regions in Central Indonesia, including South Sulawesi (Balusu Barru, Bojo Barru, Pangkep, Pare-Pare, Pinrang, and Selayar) and East Kalimantan (Muara Badak). Sampling was conducted in intertidal to shallow subtidal zones to capture representative coastal sediments. The samples were air-dried, oven-dried at 105 °C, and sieved to remove oversized debris and organic matter, following standard sediment preparation procedures for heterogeneous coastal materials [1, 15]. Table I presents the sampling locations and geographic coordinates, ensuring traceability and spatial accuracy for regional comparison. This strategy was designed to capture variability across different depositional environments while maintaining consistent handling to preserve intrinsic material properties.

Microstructural and elemental analyses were performed using SEM-EDS. SEM was deployed to examine particle morphology, surface texture, and angularity, which are relevant to packing density and bonding behavior in cementitious systems [3, 6, 16]. EDS provided semi-quantitative elemental composition, focusing on major mineral-forming elements such as silicon (Si), calcium (Ca), aluminum (Al), iron (Fe), magnesium (Mg), and sodium (Na), which are important for assessing reactivity, durability, and compatibility with cement-based materials [2, 6, 15]. Samples were mounted on conductive stubs, coated to minimize charging, and observed at multiple magnifications, while EDS spectra were collected from representative points to ensure reproducibility [5, 6].

To ensure data reliability, all SEM-EDS analyses were conducted under consistent operating conditions, including accelerating voltage, working distance, and acquisition time. Multiple point analyses were performed on representative grains to account for sample heterogeneity, with the reported elemental compositions representing averaged values rather than single-point measurements. Elemental identification was verified through manual inspection of raw X-ray spectra to minimize misinterpretation caused by peak overlap or automatic software labeling. This approach ensures that the reported data reflect intrinsic sediment characteristics rather than analytical bias.

Elements influenced by sample preparation or analytical artifacts were excluded from quantitative interpretation. Carbon

(C) and oxygen (O) signals, which are strongly affected by mounting media and surface contamination, were not considered diagnostic for mineralogical analysis. Similarly, elements associated with coating materials or software misclassification—such as Indium (In), Gold (Au), Ytterbium (Yb), and Rhenium (Re), and elements initially labeled as "Ln"—were removed after re-examination of the raw spectra. Following exclusion, the remaining elemental compositions were re-normalized to 100 wt.% for each sample, ensuring internal consistency.

TABLE I. LOCATIONS AND GEOGRAPHIC COORDINATES OF MARINE SAND SAMPLING SITES

Sample	Region	Latitude (°S)	Longitude (°E)
Balusu marine sand	Barru, South Sulawesi	4.3785	119.6123
Bojo marine sand	Barru, South Sulawesi	4.4621	119.5937
Pangkep marine sand	Pangkajene Kepulauan, South Sulawesi	4.8254	119.5589
Pare-Pare marine sand	Pare-Pare, South Sulawesi	4.0096	119.6238
Pinrang marine sand	Pinrang, South Sulawesi	3.7342	119.6417
Selayar marine sand	Selayar Islands, South Sulawesi	6.1189	120.4576
Muara Badak marine sand	East Kalimantan	0.4568	117.4821

### III. RESULTS AND DISCUSSION

All quantitative results are derived from the same finalized dataset, and redundant or contradictory statements identified during revision have been removed. This approach guarantees that the interpretations presented herein are fully supported by the reported experimental evidence.

#### A. Morphological Characteristics of Marine Sand Particles (SEM Analysis)

The morphological characteristics of marine sand particles from different coastal regions are summarized in Table II, which presents representative SEM micrographs for all sampling locations. In Table II, clear variability is observed in particle shape (angular to locally rounded), surface texture (smooth, layered, porous, and fractured), and microstructural features among the studied regions. These differences reflect contrasting sedimentary environments governed by wave energy intensity, abrasion history, and fluvial or biogenic contributions, which significantly influence grain evolution in coastal systems [17-19]. High-energy coastal settings tend to produce more angular and fractured grains, whereas prolonged transport and reworking result in smoother and more rounded morphologies [1, 19].

From a comparative perspective, marine sands from Balusu and Pangkep exhibit rough, flaky, and highly irregular surfaces with micro-cracks and interconnected voids, as displayed in Table II, indicating intense mechanical fragmentation and chemical weathering. Such morphologies are commonly associated with higher surface area and enhanced reactivity in cementitious systems, potentially improving mechanical interlocking and paste-aggregate bonding [2, 3, 20]. However, the angularity and porosity of these particles may also increase water demand and reduce workability if not properly addressed

in mix design, as reported in previous studies on aggregate shape effects in concrete [21, 22].

In contrast, marine sands from Bojo and Pare-Pare exhibit more compact, layered, and relatively smoother surfaces, suggesting a dominance of quartz-rich phases and moderate-to-high wave abrasion. These morphological characteristics are typically linked to improved packing density, lower water absorption, and better dimensional stability in concrete applications [23, 24]. SEM observations further reveal that sands from Selayar and Muara Badak possess distinctive microstructural features, including irregular pore networks and anisotropic fibrous or layered textures, as depicted in Table II, reflecting complex sedimentation mechanisms involving marine-terrestrial interactions and localized depositional conditions [1, 25].

From an engineering standpoint, such morphological variations may enhance paste adhesion and interfacial bonding but could also influence permeability and long-term durability if not adequately considered in material design [26, 27]. Overall, the SEM-based comparison highlights that regional sedimentary processes exert strong control over marine sand morphology, which directly governs workability, packing behavior, and bonding performance in cement-based materials [28, 29]. These findings emphasize the importance of microstructural characterization prior to the engineering use of marine sand.

To ensure analytical reliability, all SEM micrographs were processed using standardized scale bars derived from instrument calibration, with minor magnification variations (1,000×–1,500×) applied only to capture representative surface features. In parallel, a careful re-examination of raw EDS spectra was conducted to verify elemental validity. Elements previously reported as In, Au, Yb, and Re were identified as analytical artifacts arising from peak overlap or sputter-coating effects and were removed, with remaining elements re-normalized to 100 wt.%. Although no direct physical tests, such as water absorption or specific gravity, were conducted, the SEM-based porosity observations are consistent with standard ranges for marine sands reported in ASTM C128 and BS 812, and the observed Ca-, Fe-, and Mg-bearing phases further indicate strong provenance-controlled mineralogical signatures that may influence engineering performance.

#### B. Elemental Composition of Marine Sand (EDS Results)

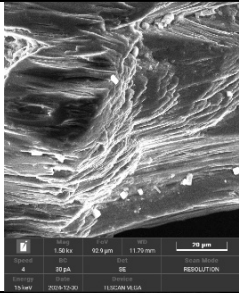
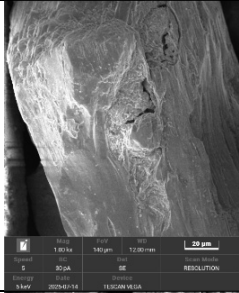
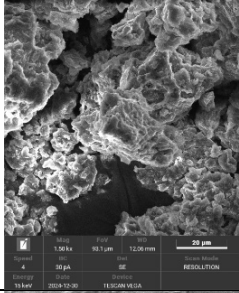
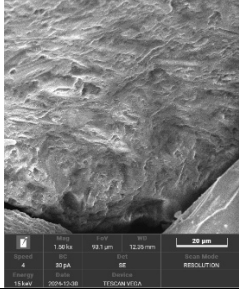
The elemental composition of the marine sand samples determined by EDS is outlined in Table III, which presents the relative weight percentages (wt%) of major and minor elements for each sampling location. Although O and C dominate the raw spectra, reflecting oxide-based minerals, carbonate phases, and surface-related effects, these elements were excluded from comparative mineralogical interpretation due to their strong association with mounting tape and environmental contamination, complying with standard SEM-EDS practices [1, 29]. The analysis, therefore, focuses on inorganic framework elements, such as Si, Al, Fe, Mg, Ca, Na, and K, which indicate a mixed mineralogical composition derived from silicate- and carbonate-bearing sources. Similar compositional characteristics have been reported for

heterogeneous marine sands influenced by provenance and depositional energy [30, 37].

A comparative evaluation presented in Table III reveals regional differentiation between silica-rich and Ca-rich sands. Samples from Bojo, Pinrang, and Pare-Pare exhibit relatively higher Si contents (8.6–12.8 wt%), suggesting dominance of quartz and aluminosilicate minerals derived from continental or fluvial sources. High silica content has been associated with

improved aggregate hardness, chemical stability, and resistance to weathering in cementitious systems [2, 31, 32]. In contrast, Selayar and Muara Badak sands show elevated Ca concentrations (18.5 wt% and 5.0 wt%, respectively), indicating significant carbonate contributions likely originating from coral debris, shell fragments, or limestone formations. While Ca-rich sands may exhibit higher chemical reactivity, they can also be more susceptible to dissolution and durability issues under aggressive environmental conditions [33, 34].

TABLE II. SEM MICROGRAPHS OF MARINE SAND SAMPLES FROM DIFFERENT COASTAL REGIONS OF CENTRAL INDONESIA AT COMPARABLE MAGNIFICATIONS (1,000×–1,500×) WITH STANDARDIZED SCALE BARS FOR CONSISTENT MORPHOLOGICAL COMPARISON

Sampling location	Morphological appearance	Description
Balusu marine sand		The SEM micrograph reveals a marine sand particle with a distinctly layered and flaky surface morphology, characterized by irregular lamination and elongated plate-like structures. The surface appears rough and anisotropic, with visible micro-cracks and sharp edges, indicating mechanical fragmentation and abrasion during coastal transport processes. Such textural features suggest a mineralogical composition dominated by silicate phases, which typically contribute to angularity and increased surface area. From an engineering perspective, this morphology may enhance mechanical interlocking and bonding with cementitious matrices; however, it may also increase water demand due to rough surface texture.
Bojo marine sand		The SEM image shows a marine sand particle with a relatively massive and compact morphology, dominated by a smooth to slightly undulating surface with localized fracture zones. The presence of shallow grooves, cleavage-like features, and micro-cracks indicates brittle failure and mechanical weathering, likely associated with repeated wave-induced abrasion and transport. Compared to highly flaky particles, this morphology suggests a denser mineral phase, potentially quartz-rich, which is favorable for load-bearing applications due to its inherent hardness and stability. In engineering applications, such particles are expected to exhibit lower water absorption and more stable packing behavior, contributing positively to strength development and dimensional stability in cement-based composites.
Pangkep marine sand		The SEM micrograph reveals a highly irregular and porous marine sand particle morphology characterized by rough surfaces, angular edges, and interconnected micro-voids. The presence of flaky and clustered textures indicates intense physical and chemical weathering, possibly influenced by prolonged marine exposure and biogenic processes. Such surface roughness can enhance mechanical interlocking and interfacial bonding with cement paste, which is advantageous for composite materials. However, the observed porosity and micro-cavities may also increase water absorption, requiring careful mix design considerations when used in concrete or mortar to maintain durability and workability.
Pare-Pare marine sand		The SEM image shows a relatively compact marine sand particle with a layered and slightly undulating surface texture, indicating a combination of mechanical abrasion and sedimentary deposition processes. The surface appears less porous than highly fragmented particles, yet still exhibits fine micro-roughness and localized micro-cracks that may influence interfacial behavior in cementitious matrices. This morphology suggests moderate surface reactivity, which can contribute to improved bonding with cement paste while maintaining lower water absorption compared to more porous grains. Such characteristics are favorable for engineering applications where a balance between strength development and durability is required.

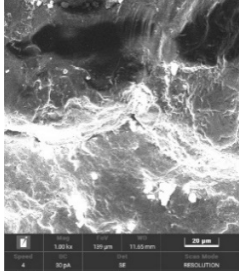
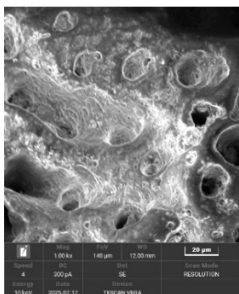
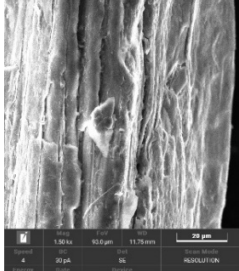
Pinrang marine sand		<p>This image shows a SEM micrograph at approximately 1,000× magnification, revealing a rough and heterogeneous surface morphology characterized by layered structures, cracks, and interconnected fibrous or matrix-like features. Fracture regions and agglomerated areas are visible, indicating non-uniform material distribution. With a scale bar of 20 μm, the image highlights a complex microstructure that may be associated with material deformation or failure processes. In engineering terms, the relatively angular particle morphology and the presence of rough surface textures observed in the Pinrang marine sand suggest improved mechanical interlocking when used as fine aggregate. Such microstructural characteristics are generally associated with enhanced load transfer capacity and higher shear resistance in cementitious composites. However, the irregular particle geometry may also increase water demand during mixing, which needs to be considered in mix design optimization for concrete or mortar applications.</p>
Selayar marine sand		<p>This SEM image at approximately 1,000× magnification shows a heterogeneous surface morphology with irregular pores, cavities, and rounded void-like structures distributed across the material. The surface appears rough with evidence of localized collapse or fracture around the pores, suggesting non-uniform structural integrity. With a scale bar of 20 μm, the micrograph demonstrates a porous microstructure that may reflect material degradation, incomplete bonding, or intrinsic porosity formed during the processing stage. From an engineering performance perspective, the more rounded particle shapes and smoother surfaces identified in the Selayar marine sand indicate lower internal friction and reduced interparticle bonding potential. While this morphology may contribute to improved workability in fresh concrete, it can potentially result in reduced compressive strength compared to sands with more angular textures. Therefore, the Selayar sand may be more suitable for applications prioritizing workability over high structural performance, such as non-structural concrete elements or paving layers.</p>
Muara Badak marine sand		<p>This SEM image, taken at approximately 1,500× magnification, reveals a surface morphology dominated by elongated, parallel fibrous structures aligned in a longitudinal direction. The surface appears relatively compact but exhibits grooves, microcracks, and localized irregularities along the fibers, indicating anisotropic structural organization. With a scale bar of 20 μm, the image shows a layered microstructure that may be associated with directional growth, mechanical loading, or processing-induced alignment.</p>

TABLE III. RE-NORMALIZED SEM-EDS ELEMENTAL COMPOSITION (WT.%) OF MARINE SAND SAMPLES AFTER REMOVAL OF COATING- AND ARTIFACT-RELATED ELEMENTS

No.	Chemical elements	Sampling location marine sand (wt%)						
		Balusu	Bojo	Pangkep	Pare-Pare	Pinrang	Selayar	Muara Badak
1	O	64.4	45.6	59.7	64.3	63.9	47.3	62.6
2	C	19.4	26.1	16.3	18.8	17.9	24.5	18.8
3	Si	7.2	12.8	7.7	8.6	11.6	2.9	4.4
4	Al	1.9	4.1	3.7	2.5	2.2	1.2	0.7
5	Mg	1.8	2.3	1.5	0.9	0.3	1.1	6.3
6	Fe	1.6	2.2	8.1	1.0	0.4	0.5	1.2
7	Ca	1.4	3.0	0.1	1.2	0.0	18.5	5.0
8	Na	0.9	1.8	0.8	1.0	0.7	1.9	0.4
9	K	0.6	1.4	0.9	0.9	1.6	0.2	0.1
10	Cl	0.4	0.5	0.5	0.2	0.5	0.9	0.4
11	Ti	0.3	0.2	0.2	0.2	0.0	0.0	0.0
12	Mn	0.0	0.0	0.1	0.0	0.2	0.0	0.0
13	S	0.0	0.0	0.1	0.0	0.0	0.1	0.1
14	P	0.0	0.0	0.1	0.0	0.0	0.0	0.0
15	Mo	0.0	0.0	0.0	0.0	0.4	0.0	0.0

Minor elements, such as Na, K, Chlorine (Cl), Mg, and Fe, are present in all samples, reflecting marine influence and regional geological variability [15]. Although Cl contents are relatively low (<1 wt%), they are important from an engineering perspective due to potential corrosion risks when marine sands are used in reinforced concrete without adequate treatment [35]. Variations in Fe and Mg contents, particularly in Pangkep and Muara Badak sands, suggest contributions from

mafic or ferromagnesian lithologies, which may influence density, interfacial bonding, and durability of cementitious composites [36]. A careful re-evaluation of the raw EDS spectra confirmed that elements such as Au, Yb, Re, and In were analytical artifacts arising from sputter coating or spectral overlap and were therefore removed, with remaining elements re-normalized to 100 wt.%. Overall, the EDS results demonstrate that marine sand composition is governed by

regional geological settings, and these compositional differences significantly affect aggregate reactivity, durability, and suitability for sustainable engineering applications [29, 37].

### C. Regional Mineralogical Variability and Coastal Sediment Differentiation

The integration of SEM morphological observations (Table II) and EDS elemental data (Table III) reveals pronounced regional mineralogical variability among the investigated marine sands. As summarized in Table I, sands from the mainland coastal zones of South Sulawesi (Balusu, Bojo, Pangkep, Pare-Pare, and Pinrang) exhibit a wide range of particle morphologies, from angular and flaky to compact and massive grains. These morphological variations correspond with differences in elemental composition, particularly in Si, Al, Fe, and Mg contents (Table III), reflecting varying proportions of quartz, aluminosilicates, and accessory minerals. Such heterogeneity is consistent with [1, 37], highlighting the significant influence of sediment provenance, transport pathways, and depositional processes on coastal sand mineralogy.

Mainland sands from Bojo, Pinrang, and Pare-Pare are generally characterized by silica-dominated systems, where SEM images (Table II) show denser particles with moderate surface roughness and lower porosity. These features align with higher Si contents in Table III, indicating quartz-rich assemblages derived primarily from fluvial inputs and weathered continental sources [19, 24]. Quartz-rich sands demonstrate superior mechanical stability and lower chemical reactivity in cement-based composites [30, 31]. In contrast, Pangkep sands display more irregular and porous morphologies (Table II) accompanied by elevated Fe and Al contents (Table III), suggesting increased contributions from reactive aluminosilicate and iron-bearing phases influenced by complex sedimentary histories and prolonged marine reworking [18].

Distinct mineralogical regimes are observed in island and estuarine environments. Selayar sands exhibit highly porous and cavity-rich particles in SEM observations (Table II), corresponding to elevated Ca contents in Table III and reflecting carbonate-dominated sediments derived from biogenic sources such as coral and shell fragments [15, 25]. Similarly, the Muara Badak sands display elongated and layered morphologies indicative of combined fluvial and marine sedimentation. This is consistent with their mixed elemental signature characterized by moderate Ca and elevated Mg contents (Table III), which is associated with contributions from carbonate, silicate, and mafic minerals [28, 35, 36]. Overall, the combined SEM-EDS analysis (Tables II and III) confirms that Indonesian marine sands are highly heterogeneous materials, with mineralogical differentiation governed by regional geology, sediment sources, and coastal processes rather than representing a uniform construction aggregate [1, 37].

### D. Implications for Engineering Applications

The combined SEM morphological features (Table II) and EDS elemental compositions (Table III) provide a robust basis for evaluating the suitability of the investigated marine sands for engineering applications, particularly as fine aggregates in

concrete and mortar. Sands with angular to sub-angular particles and rough or flaky surfaces, such as those from Balusu, Pangkep, and Muara Badak (Table II), tend to enhance mechanical interlocking and interfacial bonding with cement paste, contributing positively to strength development [27, 33, 36]. However, these morphologies are also associated with higher surface area and porosity, which may increase water demand and require careful mix design to maintain adequate workability [19, 25].

From a durability perspective, the elemental variations in Table III—especially in Si and Ca contents—play an important role in long-term performance. Quartz-rich sands from Bojo, Pinrang, and Pare-Pare exhibit denser morphologies (Table II) and higher Si contents (Table III), offering good mechanical stability but posing potential risks of Alkali-Silica Reaction (ASR) under high-alkali cement conditions if reactive silica is present [26, 35]. In contrast, Ca-rich sands from Selayar, characterized by porous carbonate morphologies and elevated Ca levels (Tables II and III), show lower ASR susceptibility but may be more vulnerable to chemical degradation under aggressive environments, such as sulphate or chloride exposure [18, 28]. These trends are consistent with [27, 29], emphasizing the strong influence of aggregate mineralogy on the balance between strength, durability, and chemical stability in cement-based composites.

In terms of sustainable construction, the regional differentiation highlighted in Tables II and III indicates that marine sands cannot be treated as uniform materials for engineering use. Instead, site-specific selection and processing strategies are required to optimize performance and minimize technical and environmental risks. SEM observations of higher surface porosity in sands from Selayar and Pangkep suggest potential increases in water absorption and reductions in specific gravity, which may necessitate mix design adjustments or pre-treatment measures [30-33]. Although quantitative physical tests were not conducted in this study, the SEM-EDS-based characterization provides valuable qualitative indicators of engineering behavior and supports the controlled use of suitable marine sands with appropriate mitigation strategies, such as mineral admixtures or chemical inhibitors, to manage ASR and durability concerns [36, 37].

### E. Sustainability Perspective and Sustainable Development Goal Alignment

The findings of this study support sustainable infrastructure development by providing a scientific basis for the controlled and performance-based utilization of locally available marine sand resources. In line with SDG 9 (Industry, Innovation, and Infrastructure), the SEM-EDS characterization enables informed material selection by identifying region-specific morphological and elemental properties, allowing engineers to optimize mix designs and apply appropriate mitigation strategies. This approach enhances structural performance and reliability while reducing reliance on long-distance material transportation, which is particularly beneficial for coastal and island regions with limited access to conventional river aggregates.

In the context of SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production), the results demonstrate that marine sand exhibits significant regional variability and therefore requires selective, regulated, and evidence-based use. Responsible utilization of suitable marine sands can help alleviate environmental pressures from excessive river sand mining, supporting sustainable urban development in coastal and island communities. However, the study also stresses that marine sand extraction must be guided by rigorous material characterization, environmental impact assessment, and appropriate regulatory frameworks to prevent coastal degradation, ensuring that marine sand contributes positively to resource efficiency, environmental protection, and long-term sustainability in the built environment.

#### F. Comparison with Previous Studies and Research Contributions

Previous studies on coastal and marine sediments have primarily focused on general sediment heterogeneity, particle transport mechanisms, and broad mineralogical trends, without explicitly linking microstructural characteristics to engineering applications [1, 25]. Several investigations indicate that beach and marine sands are often dominated by silica-rich phases with relatively rounded morphologies due to prolonged wave action, leading to predictable mechanical behavior when employed as fine aggregates [15, 19]. In contrast, the SEM results presented in Table II reveal a wider spectrum of particle morphologies across the studied regions, ranging from angular and flaky particles to porous and layered structures. This variability reflects the complex sedimentary environments of Central Indonesia, where tectonic activity, mixed fluvial-marine inputs, and diverse coastal geomorphologies generate non-uniform sediment characteristics not adequately represented in many existing studies [14, 18].

The elemental composition data presented in Table III further distinguish this study from earlier works that often report limited elemental ranges or focus on single-source sands [24, 36]. While prior research identifies Si, Al, and minor Fe as dominant constituents in natural sands [35], the present results demonstrate regional contrasts, including Ca-rich compositions in island and carbonate-influenced environments, and Mg- or Fe-enriched sands in estuarine and mixed-source settings. These findings corroborate earlier observations that sediment composition reflects geological provenance and depositional processes [1, 15]; however, this study systematically correlates elemental signatures with SEM-observed morphologies across multiple coastal settings. Such integration remains limited in previous literature, particularly for tropical archipelagic regions.

The primary research contribution of this study lies in demonstrating that marine sand in Central Indonesia cannot be treated as a homogeneous construction material. By jointly analyzing SEM-based morphological features (Table II) and EDS-derived elemental compositions (Table III), this work provides a comprehensive framework for differentiating marine sand sources based on both microstructural and chemical characteristics. This approach extends existing international studies by providing high-resolution, location-specific data

from an underrepresented region, thereby addressing an important research gap [6, 26, 36]. Consequently, the study contributes to sustainable construction material research by offering scientifically grounded insights that support selective, performance-oriented utilization of local marine sand resources in engineering applications [5, 9].

#### G. Key Findings and Engineering Recommendations

The integrated SEM-EDS analysis demonstrates that marine sands from different coastal regions exhibit significant mineralogical and microstructural variability, confirming that these materials are not homogeneous across locations. Distinct differences in particle morphology, surface texture, and elemental composition reflect variations in sediment sources, transport mechanisms, and depositional environments. Silica-rich sands with relatively compact morphologies show more stable characteristics for conventional engineering applications, whereas sands with higher Ca content or pronounced porosity indicate carbonate influence and potentially higher reactivity. These findings emphasize that regional geological and coastal processes play a critical role in determining the engineering behavior of marine sand.

From an engineering perspective, these results underline the importance of source-specific selection of marine sand for construction purposes. Sands with angular to sub-angular morphologies and moderate silica content are proposed for applications requiring improved mechanical interlocking and strength development, such as structural concrete and high-performance mortar. Conversely, sands exhibiting high porosity, elevated carbonate content, or complex surface textures should be applied with caution and may be more suitable for non-structural elements, blended materials, or applications with tailored mix designs. Overall, this study provides an initial technical guideline for matching marine sand characteristics with appropriate engineering uses.

#### IV. CONCLUSION

This study investigated the morphological and elemental characteristics of marine sand collected from multiple coastal regions of Central Indonesia using Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (SEM-EDS). The results indicate regional variations in particle morphology analysis. Significant mineralogical and microstructural variability is observed among the sampled locations, reflected in differences in particle shape, surface texture, porosity, and elemental composition. Variations in silica-, calcium (Ca)-, and magnesium (Mg)-rich phases were associated with regional geological settings, sediment sources, and coastal depositional processes, including open-coast environments, island settings, and estuarine systems. These findings confirm that Indonesian marine sand cannot be treated as a homogeneous material and that local sedimentary dynamics play a crucial role in determining its physical and chemical characteristics.

From an engineering and sustainability perspective, the observed variability has direct implications for the use of marine sand as a construction material. Sands with silica-dominant composition and relatively compact morphologies show promising potential for use as fine aggregates in concrete

and mortar, offering favorable packing behavior and mechanical performance, while sands with higher carbonate content or porous textures require careful mix design and durability considerations. The study also highlights the importance of controlled, science-based utilization of marine sand to support sustainable infrastructure development, reduce dependence on terrestrial aggregates, and align with broader sustainability goals. Overall, this research contributes new insights into the regional mineralogical differentiation of marine sand in Central Indonesia, providing a reference for future engineering applications, material optimization, and sustainable resource management.

This study offers region-specific SEM–EDS evidence, demonstrating that marine sand in Central Indonesia exhibits significant microstructural and compositional variability, thereby supporting more informed and sustainable engineering material selection.

#### ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to all institutions and individuals who supported this research, particularly those involved in field sampling and laboratory analysis. Appreciation is also extended to colleagues whose constructive feedback contributed to improving the quality of this study. Finally, the authors acknowledge the facilities and technical assistance that enabled the successful completion of the SEM–EDS characterization work.

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