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The Cool Sand Phenomenon of Boracay Island: A Comparative Study of the Thermal Properties of Philippine Beach Sands

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ABSTRACT

Boracay Island is internationally recognized not only for its pristine white beaches but also for the remarkable sensation that its sands remain relatively cool even under intense tropical sunlight. Despite this well-known phenomenon, few scientific studies have investigated the thermal behavior of Boracay's beach sand using laboratory measurements. This study compared the thermal properties of Boracay white sand with beach sands from Panglao, Dakak, Pink Beach in Zamboanga, Ob-ob Black Beach in Aklan, and White Beach in Zambales. Elemental composition was determined using X-ray fluorescence (XRF), while calorimetric measurements and controlled heating experiments were conducted to evaluate specific heat capacity and heating response. Results indicate that Boracay sand possesses the highest specific heat capacity among the examined beach sands, largely due to its predominance of calcium carbonate derived from coral fragments and shells. In contrast, sands dominated by silica, volcanic minerals, and iron oxides exhibited lower specific heat capacities and warmed more rapidly under identical heating conditions. These findings provide a scientific explanation for Boracay's well-known "cool sand phenomenon" and demonstrate the influence of mineralogical composition on beach surface temperature. The study highlights the importance of preserving Boracay's unique carbonate beach ecosystem for sustainable coastal management and tourism.

Keywords: Boracay, beach sand, specific heat capacity, X-ray fluorescence, calcium carbonate, thermal properties, coastal geology, sustainable tourism

INTRODUCTION

Boracay Island, located in the province of Aklan in the central Philippines, has consistently been recognized as one of the world's premier beach destinations because of its exceptionally fine white sand, turquoise waters, and unique coastal landscape. Beyond its aesthetic appeal, visitors frequently observe an unusual characteristic of Boracay's beaches: even during periods of intense solar radiation, the white sand often remains comfortable to walk on barefoot. This observation contrasts markedly with many other tropical beaches where sand temperatures rapidly become uncomfortable during midday exposure. Although this phenomenon has become part of Boracay's identity, scientific explanations remain limited.

The thermal behavior of beach sand is governed primarily by its mineral composition, grain size distribution, porosity, moisture content, albedo, and specific heat capacity (Incropera et al., 2017). Among these properties, specific heat capacity plays a fundamental role because it represents the amount of heat energy required to raise the temperature of a material by one degree Celsius. Materials possessing high specific heat capacities absorb relatively large quantities of heat while exhibiting comparatively small increases in temperature. Consequently, beaches composed of minerals with higher heat capacities may remain cooler despite prolonged solar exposure.

The mineralogical composition of beach sediments varies considerably depending on their geological origin. Carbonate beaches originate primarily from biological materials including corals, mollusks, calcareous algae, foraminifera, and other marine organisms that produce calcium carbonate ($CaCO_3$). In contrast, siliciclastic beaches originate from weathering of continental rocks and consist predominantly of quartz, feldspars, volcanic fragments, and heavy minerals (Boggs, 2014). These contrasting mineral assemblages influence numerous physical properties, including density, reflectance, weathering resistance, and thermal behavior.

Racadio et al. reported in the Philippine Journal of Science that elemental and stable isotope techniques were successfully applied to trace nutrient sources in the neritic zone and determine the provenance of Boracay White Beach sand. Their study demonstrated that the white beach sand is predominantly biogenic, originating mainly from coral-derived calcium carbonate, supported by elemental composition, rare earth element patterns, principal component analysis, and stable isotope signatures. The authors further showed that algae were not the primary source of the white sand, reinforcing the interpretation that coral reef ecosystems are the principal contributors to Boracay's carbonate sediments. These findings provide strong geochemical evidence supporting the present study's XRF results and thermal analyses, as the predominance of calcium carbonate explains the higher specific heat capacity and slower heating response of Boracay sand. The integration of geochemical provenance analysis with thermal property measurements offers a more comprehensive understanding of the unique characteristics of Boracay's beach sediments.

Boracay's white sand is predominantly biogenic, originating from coral fragments and shell debris that have undergone extensive weathering and mechanical breakdown through wave action over geological timescales. Previous geological studies have identified carbonate sediments as the principal constituent of Boracay's famous White Beach, with calcium carbonate being the dominant mineral phase. Carbonate sands generally possess higher albedo than volcanic or quartz-rich sediments, allowing greater reflection of incoming solar radiation and reducing surface heating (Pilkey et al., 2011). However, albedo alone does not fully explain the observed cooling phenomenon. The intrinsic thermal properties of the sediment must also be considered.

The thermal characteristics of sediments have received increasing attention because of their ecological and environmental significance. Beach temperature influences microbial activity, nesting behavior of marine turtles, germination of coastal vegetation, evaporation rates, and human thermal comfort (Brown & McLachlan, 2002). As coastal tourism continues to expand globally, understanding the physical properties of beach sediments has become increasingly important for sustainable coastal management. Thermal comfort is now recognized as one of the environmental variables influencing tourist satisfaction and destination competitiveness.

Mineralogical composition strongly influences thermal conductivity, heat storage capacity, and radiative behavior of geological materials. Quartz-rich sands generally exhibit relatively low heat capacity compared with carbonate-rich sediments, while volcanic sands containing iron-bearing minerals frequently absorb solar radiation more efficiently because of their darker coloration and lower reflectance (Clauser & Huenges, 1995). Consequently, beaches composed predominantly of volcanic minerals frequently attain considerably higher surface temperatures than white carbonate beaches under identical environmental conditions.

The present study was undertaken to provide a scientific explanation for Boracay's cool sand phenomenon through laboratory characterization of thermal properties. Beach sands collected from Boracay were compared with sands from Panglao, Dakak, Pink Beach (Zamboanga), Ob-ob Black Beach (Aklan), and Zambales using X-ray fluorescence spectroscopy, calorimetric determination of specific heat, and controlled laboratory heating experiments. By integrating mineralogical and thermal analyses, this research seeks to identify the principal factors responsible for the unique thermal behavior of Boracay's beach sand.

Understanding the relationship between mineral composition and thermal properties extends beyond academic interest. The findings may contribute to coastal resource management, tourism planning, environmental conservation, and public awareness regarding the geological uniqueness of Boracay Island. As climate change continues to increase surface temperatures worldwide, preserving coastal environments with naturally favorable thermal characteristics becomes increasingly important.

Objectives

The general objective of this study was to investigate the thermal properties of Boracay beach sand in comparison with selected Philippine beaches.

Specifically, the study aimed to:

1. determine the elemental composition of beach sands using X-ray fluorescence spectroscopy;
2. compare the specific heat capacities of Boracay, Panglao, Dakak, Pink Beach, Ob-ob Black Beach, and Zambales beach sands;
3. evaluate the heating response of different beach sands under controlled laboratory conditions; and
4. identify the mineralogical factors responsible for the cool sand phenomenon observed in Boracay.

MATERIALS AND METHODS

Research Design

This study employed a comparative experimental design to investigate the thermal properties of beach sands collected from selected Philippine beaches. The investigation integrated three complementary analytical approaches: (1) elemental composition analysis using X-ray fluorescence (XRF) spectroscopy, (2) determination of specific heat capacity through calorimetry, and (3) controlled laboratory heating experiments. The combination of mineralogical and thermal analyses enabled the evaluation of factors influencing the unique cool-sand phenomenon observed in Boracay Island.

Study Sites

Beach sand samples were collected from six well-known Philippine beaches representing different geological origins and sediment compositions: Boracay White Beach, Aklan, Panglao Beach, Bohol, Pink Beach, Zamboanga, Dakak Beach, Zamboanga del Norte, Ob-ob Black Beach, Batan, Aklan, White Beach, Zambales. These sites are shown in the Philippine map in Figure 1.

Figure 1. Sites of the beach sand study sites

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These beaches were selected because they represent distinct sedimentary environments. Boracay and Panglao are dominated by biogenic carbonate sediments produced mainly from coral and shell fragments, whereas Ob-ob Black Beach consists primarily of volcanic materials. Dakak and Zambales contain larger proportions of quartz-rich and siliciclastic sediments, while Pink Beach contains a mixture of white carbonate sand and fragments of red corals. This diversity allowed comparison of sands possessing contrasting mineralogical characteristics and thermal behavior.

Sample Collection and Preparation

Representative sand samples were collected from the surface layer of each beach. Foreign materials such as shells, pebbles, plant debris, and other visible contaminants were removed manually prior to laboratory analysis.

The collected samples were air-dried and homogenized to obtain representative subsamples for elemental and thermal analyses. Portions designated for XRF analysis were finely ground and pelletized to produce uniform analytical specimens suitable for instrumental measurement.

The remaining samples were preserved in clean laboratory containers for calorimetric measurements and heating experiments.

Elemental Composition Analysis

The elemental composition of each beach sand sample was determined using X-ray fluorescence (XRF) spectroscopy, a well-established non-destructive analytical technique capable of simultaneously determining major and trace elements in geological materials.

Analysis was performed using a PANalytical Epsilon 5 Energy Dispersive X-ray Fluorescence Spectrometer equipped with: Scandium-Tungsten X-ray tube, Maximum X-ray tube power of 600 W, Germanium detector, Ten secondary targets for optimized elemental excitation

The XRF instrument identifies characteristic X-rays emitted by atoms after excitation by the primary X-ray beam. Each element emits unique X-ray energies, allowing qualitative and quantitative determination of elemental composition.

Prior to analysis, each sand sample underwent the following preparation: Drying, Grinding, Homogenization, Pelletization

The prepared pellets were analyzed under appropriate instrumental conditions to determine the relative abundance of major elements present in each sand sample.

The elemental data were used to compare the abundance of calcium-rich carbonate minerals and silica-rich or iron-bearing minerals among the different beaches

Determination of Specific Heat Capacity

Specific heat capacity was determined using calorimetric techniques.

Calorimetry measures the quantity of heat absorbed or released by a material during a controlled temperature change. In this study, a known quantity of heat was transferred to sand samples, and the corresponding temperature change was measured.

The specific heat capacity (c) represents the amount of heat required to increase the temperature of one unit mass of a substance by one degree Celsius.

The specific heat capacity is expressed mathematically as

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$Q = mc\Delta T$

where

Q = heat absorbed (J)

m = mass of the sample (g)

c = specific heat capacity (J g^{-1} $°C^{-1}$)

ΔT = change in temperature (°C)

Higher specific heat capacity indicates that a material requires more thermal energy before experiencing a temperature increase. Consequently, materials possessing higher specific heat generally remain cooler under identical heating conditions.

The measured specific heat capacities of the six beach sands were compared to determine whether Boracay sand possesses significantly greater thermal storage capacity than the other beaches.

Laboratory Heating Experiment

To evaluate the heating response of each sand type under controlled laboratory conditions, a heating experiment was conducted using a laboratory drying oven.

Sample Preparation

Each sand sample was placed inside an individual heat-resistant container. A laboratory thermometer was inserted approximately one inch below the sand surface to obtain representative internal temperatures while minimizing surface fluctuations.

Heating Procedure

The laboratory oven was initially maintained at 0°C. The oven temperature was then increased in 10°C increments until reaching 60°C. The heating sequence consisted of:

0°C

10°C

20°C

30°C

40°C

50°C

60°C

After each adjustment of oven temperature, the samples were allowed to equilibrate for approximately two hours before temperature measurements were recorded.

Maintaining identical equilibration periods ensured comparable thermal conditions among all sand samples.

Temperature Measurement

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At each oven setting, the internal temperature of every sand sample was measured using the inserted thermometer. Measurements were performed under identical experimental conditions for all beach sands. The recorded temperatures were subsequently compared to evaluate the relative rates of heating among the different sediment types.

Data Analysis

Elemental composition obtained through XRF spectroscopy was compared qualitatively among beaches to identify dominant mineralogical differences.

Particular attention was given to:

Calcium-rich carbonate minerals

Silicon-bearing minerals

Iron oxides

Thermal behavior was evaluated by comparing:

Specific heat capacities

Heating response during laboratory oven experiments

The mineralogical composition was subsequently interpreted together with thermal measurements to explain the observed differences in heating characteristics among beach sands.

The interpretation focused on determining whether higher calcium carbonate content was associated with higher specific heat capacity and reduced temperature increase during controlled heating.

Conceptual Framework

The study was guided by the hypothesis that the mineralogical composition of beach sand governs its thermal behavior. Figure 2 shows the conceptual framework.

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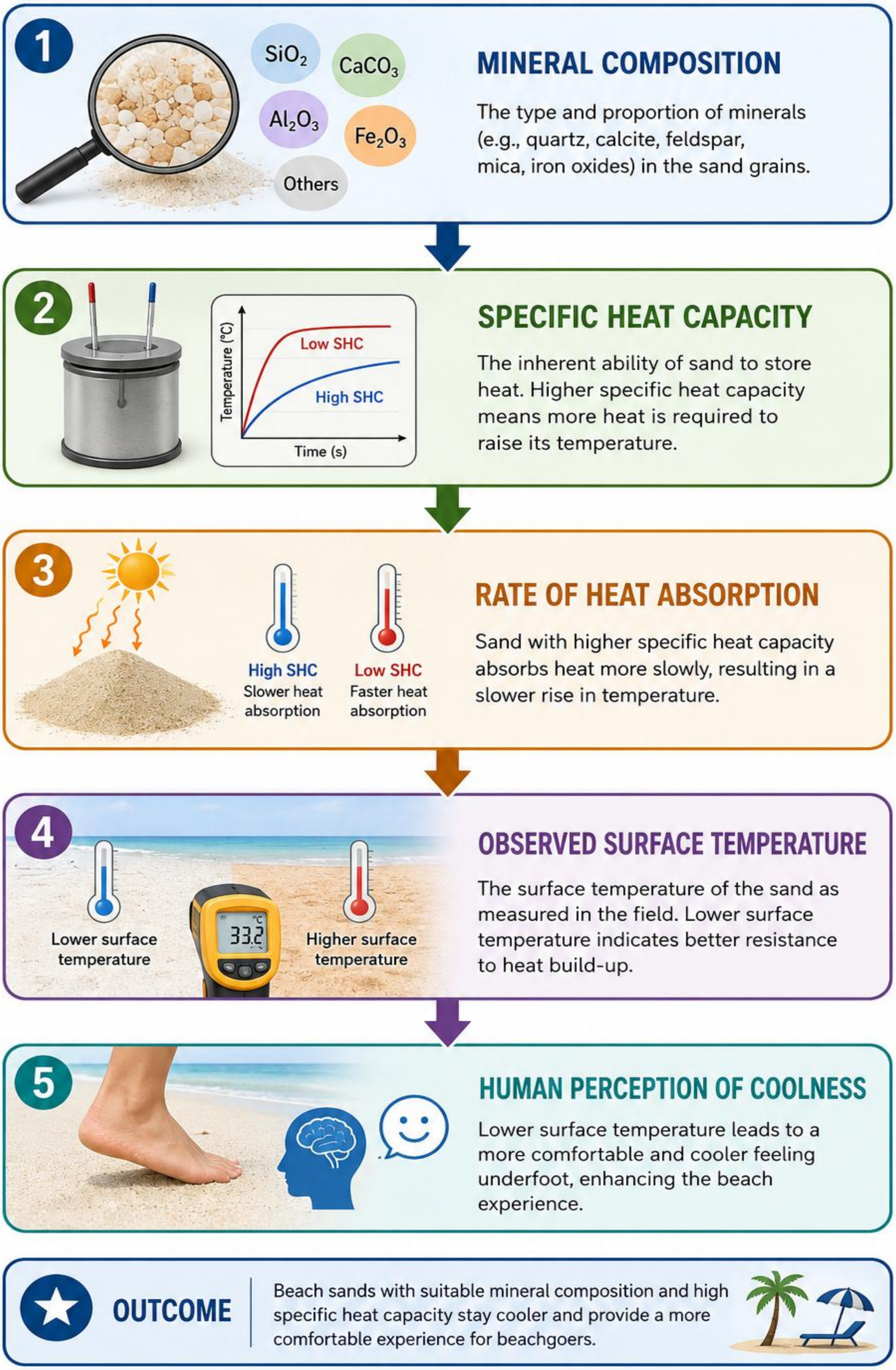

Figure 2. Conceptual framework illustrating the hypothesized relationship between mineral composition, specific heat capacity, rate of heat absorption, observed surface temperature, and human perception of coolness in beach sands.

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Carbonate-rich sands, such as those from Boracay, were expected to absorb larger quantities of thermal energy before increasing in temperature, whereas silica-rich and volcanic sands were expected to exhibit more rapid heating because of their lower specific heat capacities.

RESULTS

Elemental Composition of Beach Sands

X-ray fluorescence (XRF) spectroscopy revealed substantial differences in the elemental composition of the six beach sand samples, reflecting their contrasting geological origins (Table 1a-b). The analyses demonstrated that Boracay white sand is predominantly composed of calcium-rich minerals, whereas sands from volcanic and siliciclastic beaches contained greater proportions of silicon, iron, and other lithogenic elements.

The elemental composition of Boracay sand (Figure 3a) was characterized by a predominance of calcium, indicating that the sediment is primarily composed of calcium carbonate derived from fragmented corals and marine shells. This finding is consistent with the well-established carbonate origin of Boracay's famous white beaches.

In contrast, the Zambales white sand (Figure 3b) exhibited higher proportions of silica and iron-bearing minerals, reflecting its siliciclastic origin. Likewise, the Ob-ob Black Beach sample showed mineral characteristics typical of volcanic-derived sediments. The darker coloration of volcanic sands corresponds with their higher concentrations of iron-rich minerals, which possess different thermal properties from carbonate materials.

The mineralogical differences observed among the beaches suggest that geological origin is a primary factor controlling their thermal behavior.

Table 1 a. Elemental composition of Boracay beach sand determined using X-ray fluorescence spectroscopy.

Element/Compound	Chemical Formula	Typical Percentage (%)	Notes
Calcium Carbonate	$CaCO_3$	90-95	Main component; responsible for the cool properties of the sand.
Silica	SiO_2	<5	Present in smaller amounts compared to other beach sands.
Magnesium	Mg	Trace (<1%)	Found in association with marine calcite.
Iron	Fe	Trace (<0.5%)	Minor influence on sand coloration.
Aluminum	Al	Trace (<0.5%)	Present in minimal amounts.
Sodium	Na	Trace (<0.1%)	Part of minor mineral inclusions.
Potassium	K	Trace (<0.1%)	Present in trace quantities.
Organic Matter	-	Trace	Minor amounts from decayed marine organisms.

Table 1b Elemental composition of Zambales beach sand determined using X-ray fluorescence spectroscopy.

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Element/Compound	Formula	(%)	Notes
Silica	SiO_2	50-70	High due to quartz and volcanic glass; main heat absorber.
Iron Oxides	Fe_2O_3, Fe_3O_4	15-20	High iron content; responsible for dark, heat-absorbing sand.
Calcium Oxide	CaO	3-5	Present in minor amounts; from shells or coralline material.
Aluminum Oxide	Al_2O_3	5-8	Common in volcanic sand; found in alumino-silicate minerals.
Magnesium Oxide	MgO	2-4	Moderate levels from volcanic source material.
Titanium Dioxide	TiO_2	1-3	Found in volcanic sands; contributes to thermal properties.
Other Trace Elements	-	Trace	Includes manganese, nickel, and other trace volcanic elements.

Comparison of Specific Heat Capacity

Calorimetric measurements demonstrated clear differences in the thermal capacities of the investigated beach sands (Figure 3).

Among all samples analyzed, Boracay sand exhibited the highest specific heat capacity. This indicates that Boracay sand requires more thermal energy to increase its temperature compared with the other beach sands included in the study.

The remaining beaches exhibited progressively lower specific heat capacities. Sands collected from Panglao and Pink Beach showed intermediate thermal behavior, whereas Dakak, Ob-ob Black Beach, and Zambales displayed comparatively lower heat capacities.

The lower specific heat capacities of these beaches imply that their temperatures increase more rapidly when exposed to identical amounts of heat energy.

These findings provide the first experimental evidence supporting the commonly observed phenomenon that Boracay sand remains noticeably cooler under direct sunlight than many other Philippine beaches.

Beach Location	Specific Heat Capacity (J/g°C)
Boracay	0.80
Panglao (Bohol)	0.75
Dakak	0.70
Ob-ob Beach (Batan)	0.60
Pink Beach (Zamboanga)	0.78
Zambales (Lahar)	0.65

Figure 3. Comparison of specific heat capacities of beach sands collected from selected Philippine beaches.

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Heating Behavior Under Controlled Laboratory Conditions

The laboratory heating experiment further confirmed differences in thermal response among the beach sands.

As oven temperature was gradually increased from 0°C to 60°C, all samples exhibited corresponding increases in internal temperature. However, the rate at which temperature increased varied considerably among the different sands.

Boracay sand consistently demonstrated the slowest temperature increase throughout the heating experiment. Even after prolonged exposure at each heating interval, Boracay sand maintained comparatively lower temperatures than the other beach sands.

Conversely, Ob-ob Black Beach and Zambales sand exhibited the most rapid heating response. These samples reached higher internal temperatures under identical heating conditions, indicating greater susceptibility to heat accumulation.

Dakak and Pink Beach sands demonstrated intermediate heating characteristics between Boracay and the volcanic-derived samples.

The controlled heating experiment therefore corroborated the calorimetric measurements by demonstrating that sands possessing lower specific heat capacities warm more rapidly than carbonate-rich sands.

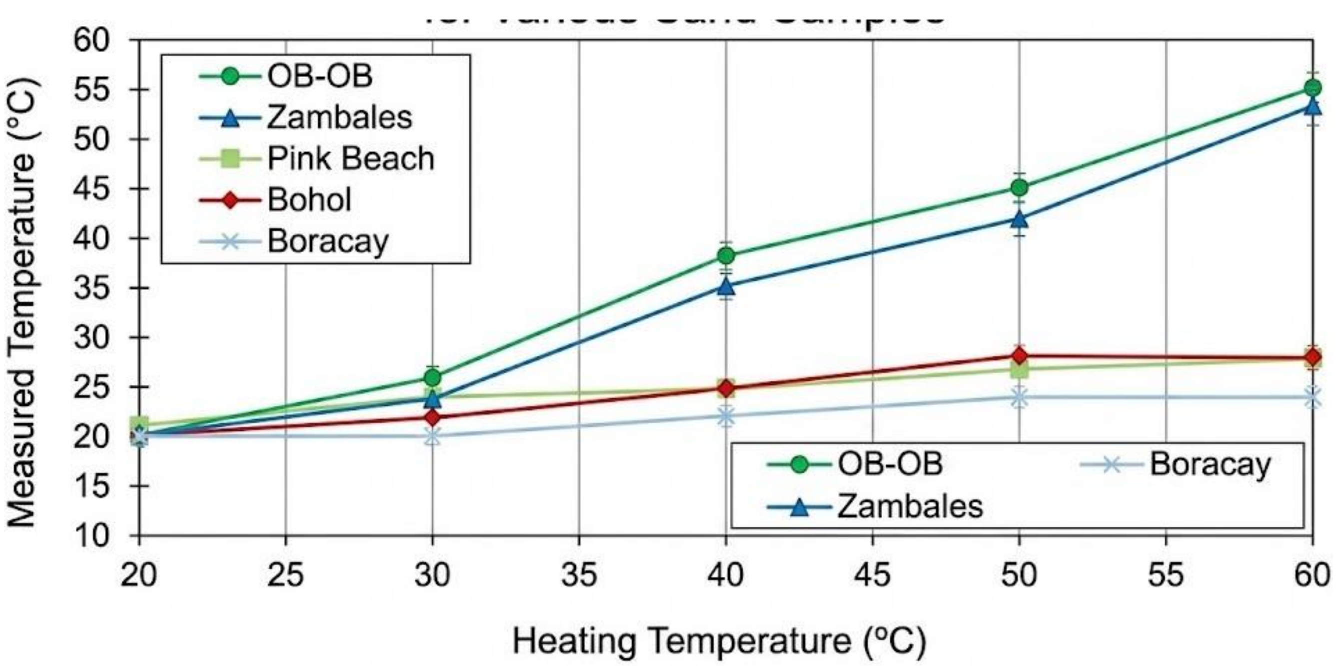

Figure 3. Heating response of beach sands subjected to increasing laboratory oven temperatures.

Relationship Between Mineral Composition and Thermal Properties

Comparison of the XRF results with the calorimetric measurements revealed a clear association between mineral composition and thermal behavior.

Boracay sand, which is dominated by calcium carbonate, exhibited the highest heat capacity and the slowest heating response.

In contrast, sands containing higher concentrations of silica and iron oxides displayed lower heat capacities and more rapid temperature increases.

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The observed relationship suggests that mineral composition exerts a strong influence on the ability of beach sediments to absorb and store thermal energy.

Carbonate minerals require greater quantities of heat before their temperatures increase substantially, whereas quartz-rich and volcanic minerals exhibit comparatively lower heat storage capacities.

The mineralogical characteristics therefore provide a scientific explanation for the unique thermal properties of Boracay's white sand.

Comparative Characteristics of the Six Beaches

The comparative analysis revealed distinct thermal characteristics among the six beaches investigated.

Boracay White Beach

Boracay exhibited the highest specific heat capacity and the slowest heating response. The sand is predominantly composed of calcium carbonate originating from coral fragments and shells. These characteristics collectively contribute to the well-known cool-sand phenomenon.

Panglao Beach

Panglao sand also originates largely from coral and shell materials. However, its thermal behavior indicates a lower specific heat capacity than Boracay, resulting in slightly warmer surface conditions.

Pink Beach

Pink Beach consists of a mixture of white carbonate sand and crushed red corals. The mixed mineral composition produced intermediate thermal characteristics, with heating occurring more rapidly than Boracay but more slowly than volcanic sands.

Dakak Beach

Dakak sand exhibited lower specific heat capacity than Boracay. Its mineral composition, consisting largely of quartz and feldspar, contributed to a relatively faster heating response.

Ob-ob Black Beach

Ob-ob Black Beach demonstrated one of the lowest specific heat capacities among the investigated samples. The volcanic origin of the sediment and its darker coloration resulted in rapid heat absorption and greater temperature increases during laboratory heating.

Zambales White Beach

Although visually white, the Zambales sand exhibited mineralogical characteristics distinct from Boracay. The XRF results indicated higher silica and iron oxide contents with comparatively lower calcium concentrations. Consequently, this sand displayed the lowest heat capacity and one of the fastest heating responses.

DISCUSSION

Scientific Basis of Boracay's Cool Sand Phenomenon

One of the defining characteristics of Boracay Island is the remarkable coolness of its white sand despite prolonged exposure to intense tropical sunlight. For decades, this phenomenon has been regarded largely as anecdotal evidence shared by tourists and residents. The present study provides experimental support for this observation by demonstrating that Boracay sand possesses a higher specific heat capacity than beach sands collected from Panglao, Pink Beach, Dakak, Ob-ob Black Beach, and Zambales.

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Specific heat capacity is a fundamental thermophysical property that describes the amount of thermal energy required to increase the temperature of a material by one degree Celsius. Materials possessing higher specific heat capacities require greater quantities of absorbed energy before their temperatures increase appreciably (Çengel & Ghajar, 2020). Consequently, Boracay sand can absorb more incoming solar energy while maintaining comparatively lower surface temperatures.

The laboratory heating experiment supports this explanation. During progressive heating under controlled laboratory conditions, Boracay sand exhibited a slower temperature increase than the other beach sands. Although all samples eventually warmed as oven temperatures increased, Boracay consistently displayed the least rapid response to heating. This behavior is entirely consistent with materials possessing relatively higher thermal inertia.

Thermal inertia, defined as the resistance of a material to temperature change, is controlled principally by specific heat capacity, density, and thermal conductivity (Incropera et al., 2017). The results therefore suggest that Boracay's distinctive thermal behavior arises not merely from visual whiteness but from the intrinsic thermal properties of its sediment.

Influence of Mineral Composition on Thermal Properties

The XRF analyses indicate that Boracay sand is dominated by calcium-rich minerals, whereas Ob-ob Black Beach and Zambales sands contain relatively larger proportions of silica and iron-bearing minerals. This mineralogical contrast provides the most plausible explanation for the observed thermal differences.

Calcium carbonate ($CaCO_3$), the principal constituent of coral-derived beach sands, possesses physical properties that differ substantially from those of quartz and volcanic minerals. Carbonate sediments generally exhibit greater reflectivity (albedo) and different heat storage characteristics compared with siliciclastic sediments (Boggs, 2014).

The predominance of calcium carbonate in Boracay sand enables the sediment to absorb larger quantities of thermal energy without experiencing large increases in temperature. In contrast, quartz-rich sands possess comparatively lower heat capacities and therefore exhibit greater temperature increases under equivalent heating conditions.

The present findings agree with previous geological investigations describing Boracay's beaches as predominantly biogenic carbonate systems formed through long-term fragmentation of corals, mollusks, calcareous algae, and other marine organisms (Pilkey et al., 2011).

The study therefore demonstrates that the famous coolness of Boracay sand is fundamentally a consequence of its carbonate mineralogy.

Carbonate Beaches Versus Volcanic Beaches

An interesting outcome of this investigation is the clear thermal distinction between carbonate beaches and volcanic beaches.

Boracay and Panglao are both carbonate beaches derived primarily from coral reef ecosystems. Although Boracay exhibited the highest specific heat among the investigated beaches, Panglao also demonstrated relatively higher thermal capacity than volcanic and quartz-dominated beaches.

Conversely, Ob-ob Black Beach displayed one of the most rapid heating responses. Black volcanic sands are composed primarily of basaltic minerals rich in iron and magnesium. These minerals are generally darker in color and absorb a larger proportion of incoming solar radiation than white carbonate sediments.

Similarly, the Zambales beach, despite appearing visually white, exhibited elemental characteristics indicating greater silica and iron oxide contents. Its comparatively rapid heating suggests that color alone does not determine thermal comfort. Rather, mineral composition exerts a more fundamental influence on heat absorption and storage.

These findings emphasize that beach temperature depends on both optical properties (reflectance) and intrinsic thermophysical characteristics.

Relationship Between Color and Temperature

Many visitors intuitively attribute Boracay's cool sand to its brilliant white color. Although color undoubtedly influences solar reflectance, the present study demonstrates that color alone cannot fully explain the phenomenon.

For example, the white sands from Zambales did not exhibit thermal behavior comparable to Boracay despite having similar visual appearance. XRF analyses revealed differences in elemental composition, particularly lower calcium concentrations and higher silica and iron oxide contents.

This observation illustrates that two visually similar beaches may possess markedly different thermal behaviors because of differences in mineral composition.

Consequently, thermal comfort cannot be predicted solely by beach color. Instead, the interaction among mineralogy, specific heat capacity, density, grain morphology, moisture retention, and solar reflectance collectively determines beach temperature.

Geological Origin Determines Thermal Behavior

Beach sediments preserve a record of their geological history.

Boracay represents a classic example of a carbonate beach produced by biological processes within coral reef ecosystems. Coral skeletons, mollusk shells, calcareous algae, foraminifera, and other marine organisms continuously produce calcium carbonate that eventually becomes fragmented into fine sand-sized particles through wave action and biological erosion.

In contrast, the sediments of Zambales originate primarily from weathering of continental rocks and volcanic deposits transported by rivers and coastal processes.

Ob-ob Black Beach derives from volcanic materials associated with basaltic parent rocks.

These contrasting geological histories produce sediments with markedly different mineral compositions, explaining the thermal differences observed during laboratory experiments.

The present study therefore illustrates how geological processes influence not only beach appearance but also human thermal perception.

Implications for Sustainable Tourism

Boracay's cool sand constitutes an important natural asset that enhances visitor comfort.

Walking barefoot on beach sand represents an essential component of the recreational experience. Excessively hot sand can discourage recreational activities, reduce visitor satisfaction, and increase the risk of thermal injury, particularly among children and elderly tourists.

The higher specific heat capacity of Boracay sand allows visitors to comfortably walk along the beach even during periods of intense solar radiation.

This natural advantage contributes to Boracay's international reputation as one of the world's premier tropical beach destinations.

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Understanding the scientific basis of this phenomenon strengthens the case for protecting Boracay's coastal ecosystems. Activities that alter sediment composition, including excessive dredging, shoreline modification, coral reef degradation, or artificial sand replacement, could potentially modify the thermal characteristics of the beach.

Consequently, conservation of Boracay's carbonate sediment system should be regarded not only as an ecological priority but also as an important component of sustainable tourism management.

The findings also have important implications for the sustainable management of Boracay's coastal environment. The high specific heat capacity of Boracay's carbonate-rich sand not only contributes to the island's unique thermal comfort but also represents a valuable ecosystem service that enhances the quality of the beach experience. Protecting the sources of carbonate sand, particularly coral reefs and shell-producing marine organisms, is therefore essential for maintaining both the ecological integrity and tourism value of the island. This is consistent with the Boracay Blue Economy Framework proposed by Delos Santos et al. (2024), which emphasizes that sustainable tourism must be founded on the protection of natural capital, science-based environmental management, stakeholder participation, and long-term ecosystem conservation. Preserving the thermal characteristics of Boracay's beach sand should therefore be recognized as part of the island's broader strategy for environmental stewardship and sustainable coastal development.

Implications for Coastal Resource Management

The findings of this study have broader implications beyond tourism.

Coastal managers frequently focus on shoreline erosion, water quality, and habitat protection. However, the thermal properties of beach sediments also influence ecological processes.

Beach temperature affects:

a. microbial activity within sediments;
b. incubation conditions for sea turtle nests;
c. survival of beach invertebrates;
d. evaporation rates;
e. coastal vegetation establishment; and
f. human thermal comfort.

Knowledge of sediment thermal behavior may therefore assist environmental planners in designing beach nourishment projects that preserve both ecological function and recreational quality.

Where artificial beach nourishment is necessary, consideration should be given not only to grain size and color but also to mineralogical composition and thermal properties.

Limitations of the Study

Several limitations should be recognized when interpreting the findings.

The benvironmental variables such as moisture content, grain-size distribution, wind velocity, relative humidity, solar radiation intensity, and seasonal variation were not reported in the presentation. These factors may also influence the thermal behavior of beach sediments under natural conditions.

The laboratory heating experiments cannot fully replicate complex field conditions where solar radiation, sea breeze, tidal processes, groundwater seepage, and evaporative cooling interact simultaneously.

Future studies incorporating detailed field measurements, thermal infrared imaging, mineralogical analyses by X-ray diffraction (XRD), grain-size distribution, and comprehensive statistical analyses would provide a more complete understanding of Boracay's unique thermal environment.

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SUMMARY

The findings of this study demonstrate that Boracay's cool sand phenomenon is not merely a subjective observation but is supported by measurable differences in thermal behavior. The predominance of calcium carbonate, together with the higher specific heat capacity observed in Boracay sand, provides a scientifically plausible explanation for its resistance to heating under tropical conditions. By linking mineralogical composition with thermophysical properties, this study highlights the importance of geological processes in shaping both the environmental characteristics and recreational value of coastal ecosystems. These results underscore the need to conserve Boracay's carbonate sediment system as an integral component of the island's natural heritage and sustainable tourism appeal.

CONCLUSIONS

This study investigated the thermal properties of beach sands from Boracay and five other Philippine beaches through elemental composition analysis using X-ray fluorescence (XRF), calorimetric determination of specific heat capacity, and controlled laboratory heating experiments. The integration of mineralogical and thermal analyses provides a scientific basis for explaining Boracay's well-known "cool sand phenomenon."

The results indicate that Boracay beach sand exhibits the highest specific heat capacity among the beach sands examined in this study. This characteristic allows the sand to absorb larger amounts of thermal energy while undergoing comparatively smaller increases in temperature. The controlled heating experiments further demonstrated that Boracay sand warms more slowly than the other beach sands under identical laboratory conditions.

Elemental analyses revealed that Boracay sand is predominantly composed of calcium-rich carbonate minerals derived from coral fragments and marine shells. In contrast, the sands collected from Zambales and Ob-ob Black Beach contained relatively greater proportions of silica and iron-bearing minerals characteristic of siliciclastic and volcanic sediments. These mineralogical differences explain the observed variation in thermal behavior among the beaches.

Collectively, the findings demonstrate that the coolness of Boracay sand is not simply a consequence of its white appearance but is closely associated with its mineralogical composition and higher specific heat capacity. The study highlights the importance of preserving Boracay's carbonate sediment system, not only for ecological conservation but also for sustaining the island's distinctive tourism value.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

Conduct quantitative mineralogical analyses. Future investigations should employ X-ray diffraction (XRD), scanning electron microscopy (SEM), and petrographic analyses to identify the mineral phases responsible for the observed thermal properties.

Perform field-based thermal monitoring. Continuous measurements of surface sand temperature under natural environmental conditions, including solar radiation, humidity, wind speed, and moisture content, would complement the laboratory experiments.

Assess seasonal variability. Sampling during both dry and wet seasons would help determine whether climatic variations influence the thermal behavior of Boracay sand.

Investigate grain-size effects. Grain size, particle shape, and porosity may also contribute to heat absorption and should be examined in future studies.

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Expand geographical coverage. Additional carbonate, volcanic, and siliciclastic beaches throughout the Philippines should be included to establish a broader understanding of the relationship between sediment composition and thermal behavior.

Evaluate ecological implications. Future research should investigate how sediment thermal properties influence beach ecosystems, including sea turtle nesting habitats, benthic organisms, and microbial communities.

Support sustainable tourism planning. Coastal managers should consider sediment composition and thermal properties when planning beach nourishment or restoration projects to preserve the natural thermal characteristics that contribute to visitor comfort.

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