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Flexural and Microstructural Behavior of Reinforced Concrete Beams Using River and Beach Sand Aggregates

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ABSTRACT

This study investigates the effect of river sand and beach sand as fine aggregates on the flexural behavior, mechanical properties, and microstructure of reinforced concrete beams. Experimental tests were conducted using two fine aggregate types and two reinforcement configurations, namely plain and deformed steel bars. The investigation included compressive strength, flexural strength, water absorption, porosity, SEM, and XRD analyses. The results showed that concrete with river sand achieved higher compressive strength (24.85 MPa) and lower porosity than concrete with beach sand (17.69 MPa). Beams reinforced with deformed bars exhibited superior flexural performance compared to plain reinforcement. SEM analysis revealed that beach sand concrete had a more porous microstructure and weaker interfacial transition zones (ITZ), while XRD results indicated similar primary hydration products in both concrete types. Overall, beach sand has potential as an alternative fine aggregate, although additional treatment is necessary to improve concrete performance and durability.

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I. INTRODUCTION

Concrete is one of the most widely used construction materials in modern infrastructure due to its high compressive strength, ease of construction, economic efficiency, and adaptability for various structural applications [1–3]. The increasing demand for infrastructure development worldwide has significantly increased the consumption of concrete materials, particularly fine aggregates such as river sand [2–4]. In reinforced concrete structures, beams are essential structural elements designed to resist flexural loads and safely transfer forces to other structural components [5–7]. The flexural performance of reinforced concrete beams is strongly influenced by the mechanical properties of concrete, the quality of the bond between concrete and reinforcement, and the characteristics of constituent materials used in the concrete mixture [6–9].

Fine aggregate plays a critical role in determining the mechanical performance and durability of concrete. The physical characteristics of fine aggregates, including particle size distribution, particle shape, surface texture, and mineral composition, directly affect concrete workability, compressive strength, flexural strength, porosity, and water absorption [2–4, 10]. River sand has traditionally been used as the primary fine aggregate in concrete production because of its suitable gradation, relatively rough surface texture, and low chloride content, which contribute to good bonding characteristics between cement paste and aggregate particles [2, 4, 10, 11]. However, excessive extraction of river sand has caused severe environmental problems such as riverbank erosion, ecosystem degradation, groundwater depletion, and increasing construction costs due to material scarcity and transportation requirements [2, 4, 10, 11].

To address these environmental and resource limitations, alternative fine aggregates have been increasingly investigated. Among these alternatives, beach sand or sea sand has attracted considerable attention because of its abundant availability, especially in coastal and island regions [12–14]. The utilization of beach sand in concrete production has the potential to reduce dependence on river sand while supporting sustainable construction practices [3, 4]. Previous studies have reported that sea sand can be used as fine aggregate in concrete after appropriate treatment processes, such as washing to reduce chloride and salt contents [15, 16]. Nevertheless, the application of beach sand in reinforced concrete remains technically challenging because of its high chloride concentration, finer particle size, and rounded particle morphology, which may adversely affect cement hydration, concrete microstructure, and reinforcement durability [12–15].

Several studies have investigated the mechanical and durability performance of concrete incorporating sea sand or seawater materials. Pan et al. [12] reported that seawater and sea-sand concrete exhibited significant changes in mechanical and microstructural properties compared to conventional concrete. Wei et al. [13] found that replacing freshwater river sand with seawater sea-sand affected the compressive mechanical properties and pore structure of concrete. Gopinatha et al. [14] also highlighted that the incorporation of sea sand in self-compacting concrete influences packing density and concrete performance due to differences in particle gradation and morphology. Furthermore, Huang et al. [15] demonstrated that seawater sea-sand concrete showed variations in hydration products and microstructural characteristics, which could affect long-term durability and structural behavior.

Research on reinforced concrete beams containing sea sand has also shown varying structural responses. Chen et al. [16] observed differences in the flexural behavior of seawater sea-sand concrete beams due to changes in tensile stress distribution and cracking patterns. Tran et al. [5] emphasized that the flexural performance of reinforced concrete beams is governed not only by compressive strength but also by reinforcement interaction, crack propagation, and bond performance between concrete and steel reinforcement. Ignjatović et al. [8] found that concrete containing recycled and alternative aggregates influences flexural stiffness and cracking patterns. Other researchers reported that concrete containing sea sand tends to exhibit higher porosity and permeability, which may accelerate chloride penetration and reduce structural durability [9, 17, 18].

Sea sand concrete limitations have led to extensive research on FRP-reinforced seawater sea-sand concrete beams [19–21]. FRP reinforcement systems such as GFRP, BFRP, and CFRP have been widely studied due to their corrosion resistance and structural efficiency [22–24]. Hybrid reinforcement systems, including steel–FRP composites, also improve structural reliability in aggressive environments [25, 26]. Advanced concrete systems such as UHPC, geopolymer concrete, and composite beams have been developed to enhance flexural and durability performance [27–29]. Sustainable reinforcement alternatives such as bamboo, aluminum alloy, and textile-reinforced systems have also been proposed [30–32]. Other studies have explored steel fiber reinforcement, seawater-mixed concrete, and corrosion effects in marine environments [16, 33, 34]. Fracture mechanics and numerical simulations have been applied to evaluate crack propagation in recycled and seawater concrete systems [35, 36]. Bio-based materials such as biochar have also been investigated for sustainable concrete development [37].

Despite numerous studies on seawater sea-sand concrete, most previous investigations primarily focused on compressive strength, durability performance, corrosion resistance, or FRP-reinforced systems [16, 19–26]. Limited studies have specifically evaluated the flexural behavior of reinforced concrete beams using untreated beach sand as fine aggregate in direct comparison with conventional river sand concrete under identical loading conditions [16, 17, 38]. Furthermore, integrated analyses combining flexural performance, water absorption, porosity, and microstructural characterization using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) remain relatively scarce [15, 35, 36]. As a result, the relationship between aggregate characteristics, internal pore structure, interfacial transition zone (ITZ), and the structural behavior of reinforced concrete beams has not been comprehensively clarified [12, 13, 15].

Accordingly, this study addresses the following research questions:

(1) How does the use of untreated beach sand as fine aggregate influence the compressive strength,

flexural behavior, water absorption, and porosity of reinforced concrete beams compared to conventional river sand concrete [16, 17]?

(2) How do the microstructural characteristics observed through SEM and XRD analyses explain the differences in mechanical and structural performance between beach sand concrete and river sand concrete [15, 35, 36]?

This study proposes an experimental investigation on the flexural behavior of reinforced concrete beams incorporating river sand and beach sand as fine aggregates. The research evaluates compressive strength, flexural strength under two-point loading, water absorption, porosity, and microstructural characteristics using SEM and XRD analyses [35, 36]. The proposed approach aims to provide a comprehensive understanding of how beach sand affects the mechanical performance and durability-related properties of reinforced concrete beams.

The novelty of this research lies in the comprehensive and integrated evaluation of reinforced concrete beams containing untreated beach sand as alternative fine aggregate through combined mechanical, physical, and microstructural investigations [16, 19, 33]. Unlike previous studies that mainly focused on durability issues, compressive strength, or FRP-reinforced seawater sea-sand concrete systems [20–26], this study directly compares untreated beach sand concrete and conventional river sand concrete using conventional steel reinforcement under flexural loading conditions [16, 17, 38]. In addition, this study establishes a direct correlation between flexural performance, porosity, water absorption, SEM-observed interfacial transition zone (ITZ) characteristics, and XRD diffraction patterns to explain how aggregate morphology and internal pore structure affect the structural behavior of reinforced concrete beams [15, 35, 36]. The findings provide new scientific insight into the feasibility of untreated beach sand as sustainable fine aggregate for reinforced concrete applications, particularly in coastal regions with limited river sand resources [2–4, 40].

Therefore, the objective of this study is to analyze the influence of river sand and beach sand as fine aggregates on the flexural behavior, mechanical properties, and microstructural characteristics of reinforced concrete beams [16, 17].

II. LITERATURE REVIEW

2.1. Flexural Behavior of Reinforced Concrete Beams

The flexural behavior of reinforced concrete beams is governed by the interaction between concrete compressive resistance, tensile reinforcement performance, and bond characteristics between steel and concrete [5–8]. Under flexural loading, concrete primarily resists compressive stresses, while steel reinforcement carries tensile stresses developed in the tension zone of the beam section [5, 6]. The overall structural response of reinforced concrete beams is affected by crack initiation, crack propagation, stiffness degradation, reinforcement interaction, and failure mechanisms [6–9].

Previous studies reported that the flexural performance of reinforced concrete beams is highly influenced by the quality of constituent materials and internal concrete microstructure [5, 8]. Tran et al. [5] emphasized that flexural behavior depends not only on compressive strength but also on bond interaction and tensile stress transfer between reinforcement and concrete. Ignjatović et al. [8] further demonstrated that alternative aggregate materials can influence cracking behavior, stiffness, and ultimate flexural capacity of reinforced concrete beams.

2.2. Characteristics of River Sand and Beach Sand

Fine aggregate is one of the main constituents affecting concrete performance and durability [2–4]. River sand has traditionally been used in concrete production because of its favorable gradation, rough surface texture, and relatively low chloride content, which contribute to strong bonding characteristics between aggregate particles and cement paste [2, 10, 11]. However, excessive river sand extraction has caused environmental problems such as riverbank erosion, ecosystem degradation, and depletion of natural resources [2, 4].

Beach sand or sea sand has been increasingly considered as an alternative fine aggregate because of its abundant availability in coastal areas [12–14]. Nevertheless, beach sand generally contains finer particles, smoother morphology, and residual chloride salts that may adversely affect concrete performance [12–15]. Previous studies reported that beach sand may increase porosity, permeability, and chloride penetration, thereby reducing mechanical strength and long-term durability [13–18].

Pan et al. [12] reported that seawater and sea-sand concrete exhibited different microstructural and mechanical characteristics compared to conventional concrete. Wei et al. [13] found that the use of seawater sea-sand influenced pore structure and compressive behavior due to differences in aggregate properties. Huang et al. [15] further demonstrated that sea-sand concrete may alter hydration characteristics and internal microstructure, which consequently affect concrete performance.

2.3. Reinforcement Bond Behavior

The bond interaction between concrete and reinforcement significantly influences the structural behavior of reinforced concrete beams [6, 8, 16]. Reinforcement bars transfer tensile stresses from concrete through adhesion, friction, and mechanical interlocking mechanisms [6]. Plain reinforcement bars mainly rely on adhesive and frictional resistance, whereas deformed reinforcement bars provide stronger mechanical interlocking due to surface ribs and irregularities [6, 16].

Several researchers reported that deformed reinforcement improves crack control, flexural stiffness, and ultimate load-carrying capacity of reinforced concrete beams [6, 8]. Chen et al. [16] observed that improved reinforcement bonding contributes to more stable flexural behavior and better stress distribution in sea-sand concrete beams. Therefore, reinforcement configuration is an important parameter affecting beam performance, particularly in concrete containing alternative fine aggregates with weaker interfacial bonding characteristics.

2.4. Microstructural Analysis Using SEM and XRD

Microstructural characterization is essential for understanding the internal behavior of concrete materials and explaining the relationship between pore structure and mechanical performance [15, 35]. Scanning Electron Microscopy (SEM) is commonly used to observe hydration products, pore distribution, crack formation, and interfacial transition zone (ITZ) characteristics between aggregate particles and cement paste [15, 35, 36]. SEM analysis provides detailed information regarding concrete density and internal bonding quality.

Meanwhile, X-Ray Diffraction (XRD) analysis is widely applied to identify crystalline phases present in concrete materials, including calcium silicate hydrate (C–S–H), calcium hydroxide ($Ca(OH)_2$), and quartz (SiO_2) [15, 35]. XRD analysis is useful for evaluating hydration mechanisms and determining the influence of material composition on concrete performance. Previous studies reported that seawater sea-sand concrete may exhibit differences in hydration products and pore characteristics, which directly affect mechanical behavior and durability performance [12–15].

2.5. Theoretical Framework and Operational Variables

The flexural behavior of reinforced concrete beams is influenced by the interaction between concrete compressive properties, reinforcement characteristics, and the internal microstructure of the concrete matrix [5–8]. In reinforced concrete systems, the bond mechanism between concrete and steel reinforcement plays an important role in resisting tensile stresses and controlling crack propagation under flexural loading conditions [5, 6]. The quality of this interaction is strongly affected by the physical and chemical characteristics of the constituent materials, particularly fine aggregates used in concrete mixtures [2–4].

Fine aggregates contribute significantly to the density, pore structure, and interfacial transition zone (ITZ) characteristics of concrete [10–15]. River sand generally possesses rougher surface texture, better gradation, and lower chloride content, which contribute to improved bonding between aggregate particles and cement paste [2, 10, 11]. Conversely, beach sand commonly contains finer particles, smoother morphology, and residual chloride salts that may increase porosity and reduce concrete durability and mechanical performance [12–15]. These differences in aggregate characteristics may directly influence compressive strength, flexural strength, water absorption, porosity, and crack development in reinforced concrete beams [16, 17].

In addition to aggregate characteristics, reinforcement type also significantly affects beam behavior. Plain reinforcement bars primarily rely on adhesive bond resistance, whereas deformed reinforcement bars provide stronger mechanical interlocking with concrete, resulting in improved stress transfer, crack control, and flexural capacity [6, 8, 16]. Therefore, the combination of aggregate type and reinforcement configuration is expected to influence the overall structural response of reinforced concrete beams.

The present study evaluates the relationship between material characteristics and structural performance through integrated mechanical and microstructural analyses. Mechanical performance is represented by compressive strength and flexural strength, while durability-related properties are evaluated through water absorption and porosity tests [11, 36]. Furthermore, Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) analyses are employed to observe pore distribution, interfacial transition zone (ITZ) conditions, and hydration products within the concrete matrix [15, 35].

The operational variables used in this study are presented in Table I. The variables consist of independent variables, namely fine aggregate type and reinforcement type, as well as dependent variables related to mechanical, physical, and microstructural performance.

Table I. Operational Definition of Variables

Variable Type	Variable	Operational Definition	Indicator
Independent Variable	Fine Aggregate Type	Type of fine aggregate used in concrete mixture	River sand and beach sand
Independent Variable	Reinforcement Type	Type of steel reinforcement used in beam specimens	Plain bar and deformed bar
Dependent Variable	Compressive Strength	Maximum compressive stress resisted by concrete cylinders at 28 days	MPa
Dependent Variable	Flexural Strength	Maximum flexural stress resisted by reinforced concrete beams under two-point loading	MPa
Dependent Variable	Water Absorption	Percentage of water absorbed by concrete specimens after immersion	%
Dependent Variable	Porosity	Volume percentage of voids within concrete specimens	%
Dependent Variable	Microstructural Characteristics	Internal morphology, pore structure, ITZ condition, and hydration products observed using SEM and XRD	SEM and XRD observations

2.6. Research Hypotheses

Based on the theoretical background and findings from previous studies, the research hypotheses proposed in this study are formulated as follows:

H1: The use of beach sand as fine aggregate reduces the compressive and flexural strength of reinforced concrete beams compared to river sand concrete due to differences in particle morphology and pore structure [12–17].

H2: Reinforced concrete beams using deformed reinforcement bars exhibit better flexural performance than beams using plain reinforcement because of improved bond interaction and mechanical interlocking [6, 8, 16].

H3: The differences in mechanical performance between river sand concrete and beach sand concrete are associated with variations in porosity, interfacial transition zone (ITZ) quality, and microstructural characteristics observed through SEM and XRD analyses [15, 35, 36].

III. METHODS

This study employed a laboratory experimental method to evaluate the influence of river sand and beach sand as fine aggregates on the flexural behavior, mechanical properties, and microstructural characteristics of reinforced concrete beams [1, 2]. The experimental program consisted of material characterization, specimen preparation, curing process, mechanical testing, and microstructural analysis [3, 6]. The overall research procedure adopted in this study is illustrated in Figure 1.

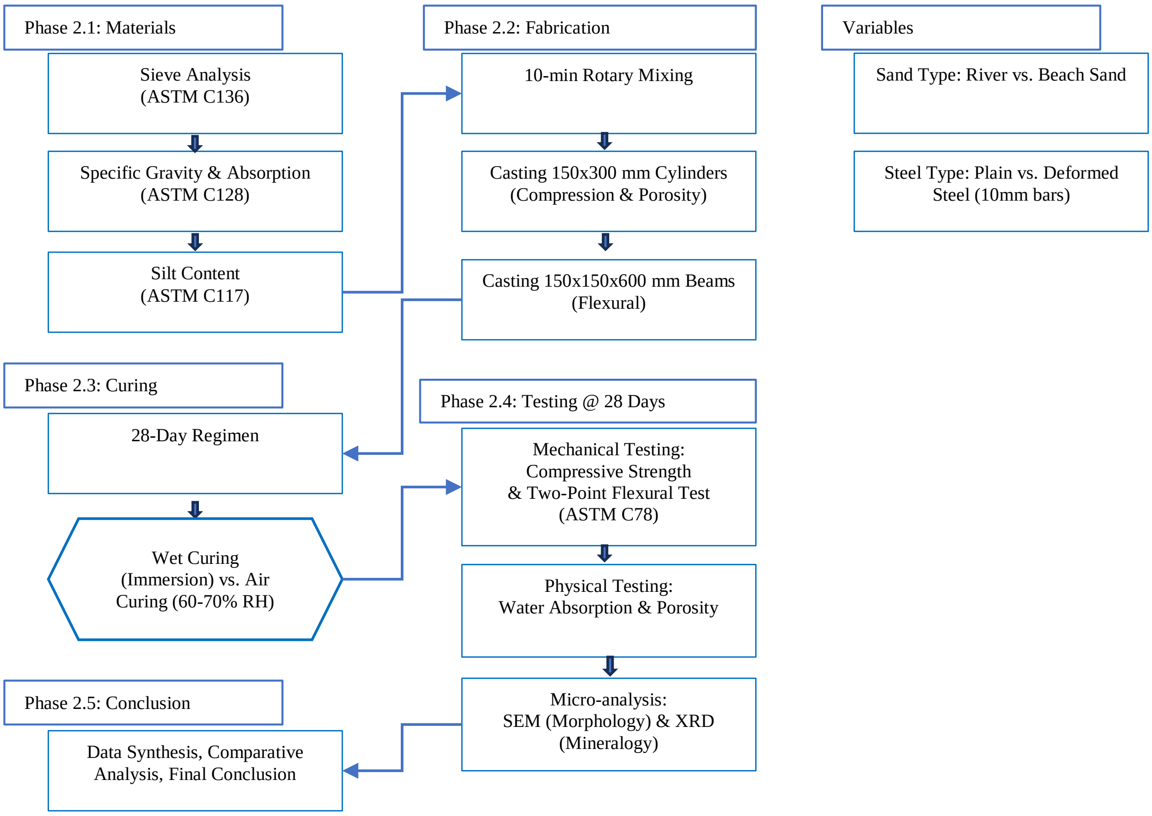


Figure 1. Research Flowchart of Experimental Program

The experimental variables used in this study consisted of two types of fine aggregates, namely river sand and beach sand, and two types of reinforcement bars, namely plain bars and deformed bars [8, 9]. The specimen variations are presented in Table II.

Table II. Experimental Variables and Specimen Codes

Specimen Code	Fine Aggregate Type	Reinforcement Type
PS-P	River sand	Plain bar
PS-D	River sand	Deformed bar
PP-P	Beach sand	Plain bar
PP-D	Beach sand	Deformed bar

2.1. Material Characterization

The first stage of the research involved characterization of the constituent materials used in the concrete mixture. The fine aggregates consisted of river sand and beach sand obtained from different sources. Material characterization was conducted to determine the physical properties of the aggregates and to ensure compliance with standard concrete requirements [2, 4, 10].

Sieve analysis was carried out to determine the particle size distribution of the aggregates using standard sieves ranging from 4.75 mm to 0.075 mm. The percentage passing through each sieve was recorded to generate the gradation curve of the aggregates. Specific gravity testing was performed using a pycnometer to determine the density characteristics of the aggregates. In addition, the mud content test was conducted using the sedimentation method to evaluate the amount of fine particles that could affect the bond quality between cement paste and aggregate particles [4, 10, 11, 30]. The compressive strength of concrete was determined using cylindrical specimens with a diameter of 150 mm and a height of 300 mm [7, 9]. The compressive strength was calculated according to Equation (1).

$$f'c = \frac{P}{A} \tag{1}$$

Where:
f'c = compressive strength of concrete (MPa)
P = maximum applied load (N)

A = cross-sectional area of specimen (mm^2)

Equation (1) was used to evaluate the compressive strength performance of all concrete mixtures at the age of 28 days.

In addition to physical characterization, the beach sand used in this study was collected from a coastal area located approximately 15 m from the shoreline to ensure representative exposure to marine environmental conditions. Prior to use, the beach sand was air-dried and visually inspected to remove organic impurities and oversized particles. The material was used without chemical washing treatment in order to evaluate the actual performance of untreated beach sand as an alternative fine aggregate in reinforced concrete applications.

To evaluate material quality and chloride-related characteristics, preliminary observations were conducted on the beach sand. The beach sand exhibited finer particle gradation and a smoother surface texture compared to river sand. These characteristics were expected to influence pore structure, interfacial transition zone (ITZ) quality, and concrete durability performance [12–15]. The presence of chloride contamination in beach sand was considered an important parameter because chloride ions may accelerate reinforcement corrosion and influence hydration behavior in concrete [15–18]. Therefore, the untreated beach sand used in this study represents natural field conditions for evaluating its feasibility as an alternative fine aggregate material.

2.2. Specimen Preparation

The specimen preparation stage involved the fabrication of reinforced concrete beams and cylindrical concrete specimens for mechanical and durability testing [2, 3]. Two types of reinforcement bars were used, namely plain and deformed steel bars with a diameter of 10 mm, to evaluate differences in bond performance and structural response [6, 8]. This variation was intended to assess the influence of steel–concrete interaction on flexural behavior.

The concrete mixture consisted of cement, coarse aggregate, water, and fine aggregate variations using river sand and beach sand as alternative materials [4, 11]. These fine aggregates were selected to investigate the effect of natural sand substitution on concrete performance and sustainability aspects [12–14]. All materials were proportioned according to the mix design and mixed using a mechanical mixer at constant speed for approximately 10 minutes to ensure uniformity.

After mixing, the fresh concrete was cast into cylindrical molds for compressive strength, water absorption, and porosity tests, as well as beam molds for flexural testing. The beam specimens had dimensions of 150 mm × 150 mm × 600 mm [6, 8]. The beam dimensions were selected to satisfy laboratory-scale experimental limitations while maintaining representative flexural behavior under two-point loading conditions. Reinforcement cages were placed inside the molds according to the designed configuration before casting. The concrete was then compacted using mechanical vibration to reduce air voids and improve density and homogeneity.

The concrete mix design used in this study was developed based on the ACI 211.1 method for normal concrete mixtures, with adjustments to laboratory material conditions and target compressive strength requirements. The selected water–cement ratio of 0.50 was intended to achieve moderate workability while maintaining adequate mechanical performance for reinforced concrete beam specimens. The mix proportions were maintained constant for all specimen variations to ensure that the observed differences in mechanical and microstructural behavior were primarily influenced by the type of fine aggregate and reinforcement configuration.

The use of identical mix proportions for both river sand and beach sand concrete mixtures allowed direct comparative evaluation of aggregate characteristics on compressive strength, flexural behavior, porosity, water absorption, and microstructural properties. The mix design parameters adopted in this study are presented in Table III.

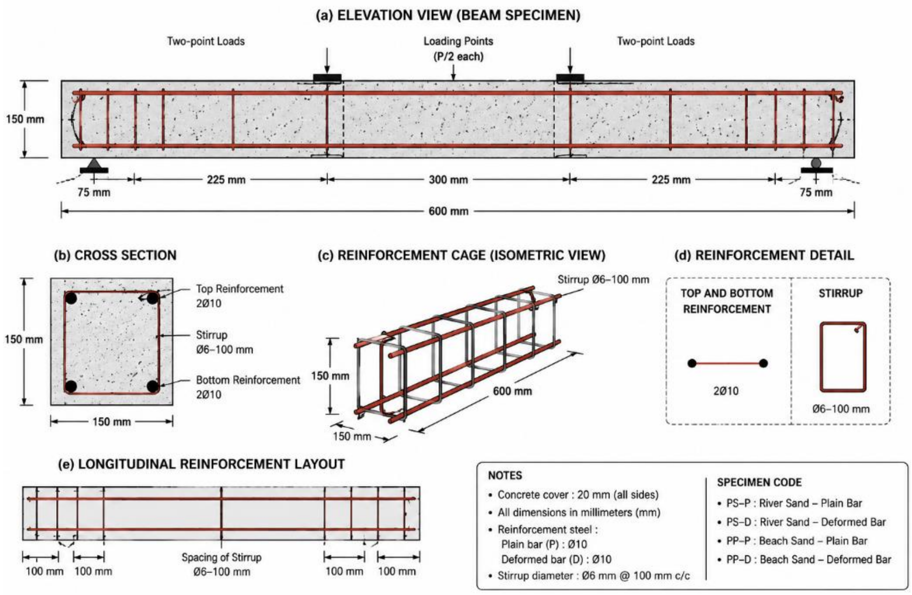


Figure 2. Reinforcement Detailing and Dimensions of Reinforced Concrete Beam Specimens

Table III. Concrete Mix Proportions

Material	Quantity (kg/m³)
Cement	400
Water	200
Coarse Aggregate	1050
River Sand / Beach Sand	650
Water-Cement Ratio	0.5

2.3. Curing Procedure

After casting, all specimens were covered with plastic sheets to prevent rapid moisture evaporation during the initial setting period. The specimens were demolded after 24 hours and subsequently cured using the wet curing method [15, 18]. The curing process was conducted by immersing the specimens in a water tank with a controlled temperature ranging from 20°C to 25°C for 28 days in accordance with ASTM C192 standards [15, 18]. The curing water level was periodically monitored to maintain constant moisture conditions throughout the curing period. The wet curing process was selected because it provides optimal hydration conditions for cement hydration reactions, resulting in improved concrete strength and durability. Proper curing also minimizes early-age cracking caused by rapid drying and enhances the formation of dense hydration products within the concrete matrix [15, 37]. The curing procedure adopted in this study is illustrated in Figure 3.

Figure 3. Wet Curing Process of Concrete Specimens

2.4. Mechanical Testing

Mechanical testing was conducted after the specimens reached 28 days of curing age. The tests included compressive strength testing, flexural strength testing, water absorption testing, and porosity testing [8, 9, 36]. The compressive strength test was conducted according to ASTM C39, while the flexural test generally followed ASTM C78 procedures using a two-point loading configuration. Water absorption and porosity tests were carried out in accordance with ASTM C642 procedures.

The flexural behavior of reinforced concrete beams was evaluated using a two-point loading test setup [16, 19]. The beam specimens were simply supported at both ends, while two concentrated loads were applied symmetrically at the loading points to create a constant bending moment region at the mid-span section. The flexural testing setup used in this study is illustrated in Figure 4.

The flexural behavior of reinforced concrete beams was evaluated based on the maximum load-carrying capacity obtained during the two-point loading test. The nominal flexural stress was calculated using Equation (2).

$$fr = \frac{PL}{bd^2} \quad (2)$$

Where:
fr = flexural strength (MPa)
P = maximum applied load (N)
L = span length (mm)
b = beam width (mm)
d = effective depth (mm)

The loading process was continued until flexural failure occurred, indicated by significant crack propagation and reduction in load-carrying capacity. Water absorption testing was conducted to evaluate the permeability characteristics of the concrete specimens [11, 36]. The specimens were oven-dried until constant mass was achieved and then immersed in water for 24 hours. The water absorption value was calculated using Equation (3).

$$WA = \frac{W_s - W_d}{W_d} x100\% \quad (3)$$

Where:
WA = water absorption (%)
Ws = saturated weight (g)
Wd = dry weight (g)

Porosity testing was performed to determine the volume of voids within the concrete matrix [11, 36]. The porosity value was calculated using Equation (4).

$$P = \frac{W_s - W_d}{V x \rho_w} x 100\% \quad (4)$$

Where:
P = porosity (%)
Ws = saturated specimen weight (g)
Wd = dry specimen weight (g)
V = specimen volume (cm^3)
ρw = density of water (g/cm^3)

2.5. Microstructural Analysis

Microstructural characterization of concrete specimens was performed using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) analyses [15, 35]. SEM analysis was conducted to observe the morphology of hydration products, pore distribution, and the interfacial transition zone (ITZ) characteristics between aggregate particles and cement paste [27, 34]. This provided detailed insight into microcrack development and bonding quality within the concrete matrix.

Meanwhile, XRD analysis was carried out to identify the crystalline phases present in the concrete specimens, including calcium silicate hydrate (C-S-H), calcium hydroxide ($Ca(OH)_2$), and quartz (SiO_2) [15, 37]. These phases were analyzed to understand the hydration process and the influence of material composition on concrete performance. The SEM observation process and XRD testing procedure are illustrated in Figure 5.

All experimental results were analyzed comparatively to evaluate the influence of fine aggregate type and reinforcement type on the flexural behavior, mechanical performance, and microstructural characteristics of reinforced concrete beams [12, 13, 36]. The comparison also aimed to correlate microstructural features with observed macroscopic mechanical responses, particularly in terms of strength development, crack propagation, and failure modes. This integrated analysis provides a comprehensive understanding of how material selection affects both the internal structure and overall structural performance of concrete.

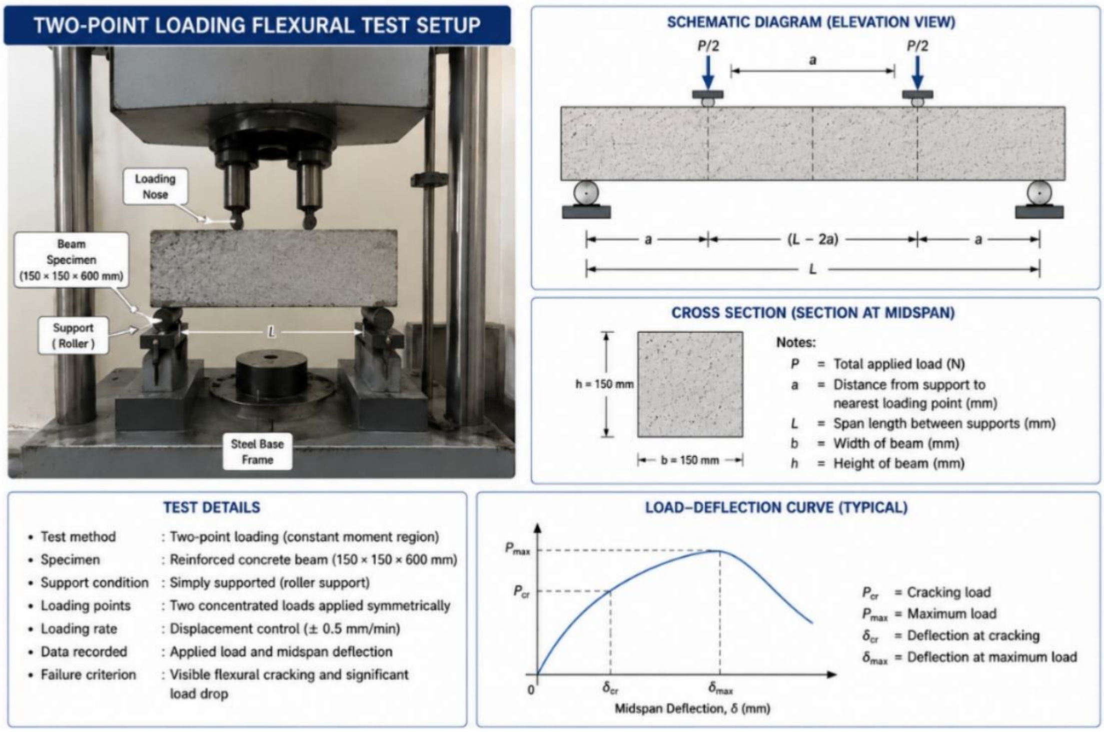


Figure 4. Two-Point Loading Flexural Test Setup

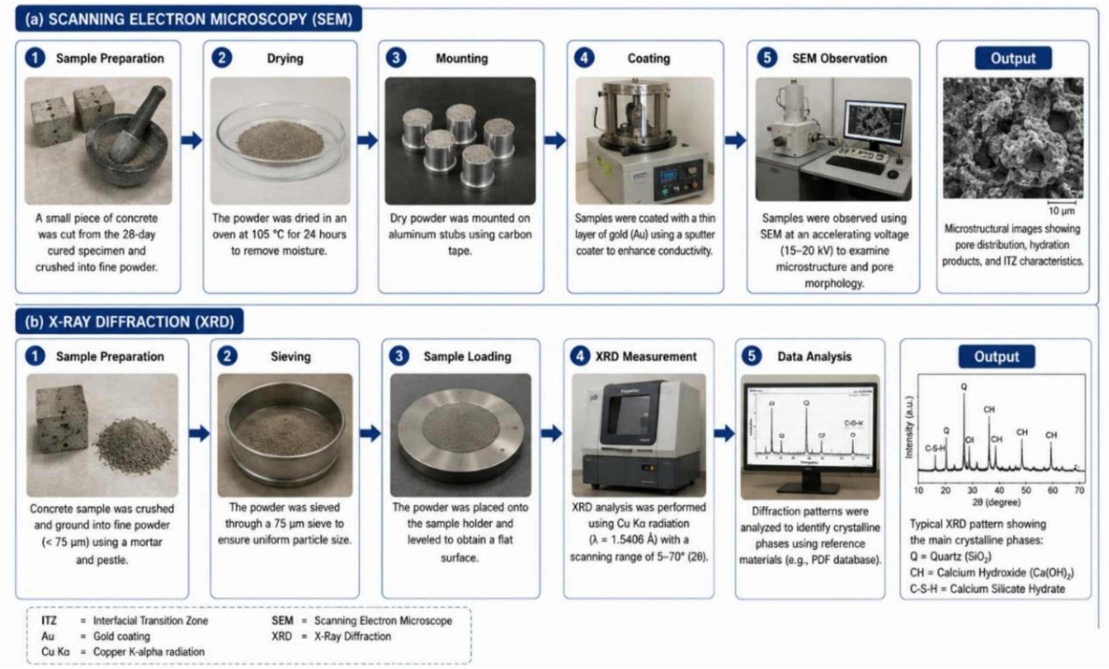


Figure 5. SEM and XRD Testing Procedures

IV. Result And Discussion

3.1. Compressive Strength of Concrete

The compressive strength test was conducted at the age of 28 days to evaluate the mechanical performance of concrete containing different fine aggregates, namely river sand and beach sand. The compressive strength results are presented in Table IV, while the comparison of average compressive strength values is illustrated in Figure 6.

Table IV. Compressive Strength of Concrete

Specimen	Compressive Strength (MPa)			Average Compressive Strength (MPa)
	1	2	3	
Concrete with River Sand (PS)	24.54	25.24	24.78	24.85
Concrete with Beach Sand (PP)	18.31	17.15	17.61	17.69

The results in Table III indicate that the concrete containing river sand achieved a higher average compressive strength compared to the concrete containing beach sand. The average compressive strength of concrete with river sand reached 24.85 MPa, while concrete with beach sand only achieved 17.69 MPa. This reduction in compressive strength may be attributed to the physical and chemical characteristics of beach sand, including smoother particle surfaces, finer gradation, and the possible presence of chloride salts that influence cement hydration and weaken the interfacial transition zone (ITZ) between aggregate and cement paste.

The compressive strength reduction observed in beach sand concrete in this study reached approximately 28.8% compared to river sand concrete. This finding is consistent with the results reported by Pan et al. [12] and Wei et al. [13], who observed compressive strength reductions ranging between 15% and 30% in seawater sea-sand concrete mixtures depending on chloride content, aggregate gradation, and curing conditions. The similarity of these trends indicates that untreated beach sand significantly affects concrete density and internal pore structure.

Previous studies reported that chloride ions contained in sea sand may accelerate early hydration reactions but simultaneously increase concrete porosity, leading to lower compressive strength at later ages. Furthermore, the morphology and grading distribution of beach sand particles can reduce the packing density of concrete, resulting in weaker internal bonding and lower load-bearing capacity.

The comparison shown in Figure 6 confirms that the use of beach sand negatively affected the compressive strength of concrete. Although beach sand can potentially be utilized as an alternative fine aggregate, additional treatment such as washing and gradation control is required to improve its performance and minimize adverse effects on concrete strength.

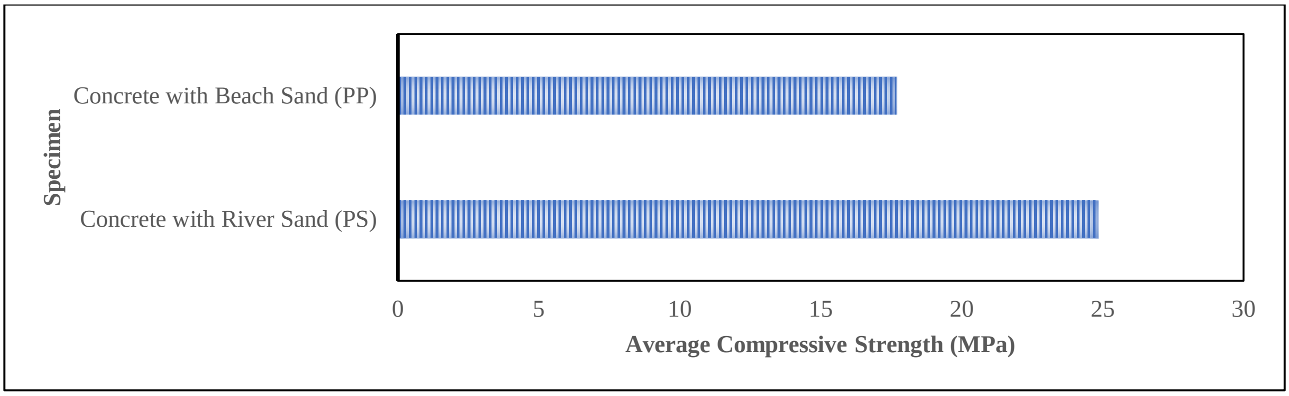


Figure 6. Comparison of Compressive Strength of Concrete

3.2. Flexural Strength of Reinforced Concrete Beams

To evaluate the significance of differences among specimen groups, a comparative statistical analysis was conducted based on the average flexural strength values and standard deviation results. The relatively high standard deviation observed in the PS beam with plain reinforcement (SD = 3.44 MPa) indicates greater variability in crack initiation and bond interaction during loading. In contrast, specimens reinforced with deformed bars exhibited lower variability and more consistent structural behavior.

Although the number of specimens in each group was limited, the overall trend clearly demonstrated that reinforcement type significantly influenced flexural performance. The use of deformed reinforcement bars consistently produced more stable flexural responses and higher average strength values compared to plain reinforcement specimens. These findings are consistent with previous studies reporting that improved mechanical interlocking between deformed bars and concrete contributes to enhanced stress transfer and crack control behavior [6, 8, 16].

Furthermore, the reduction in flexural performance observed in beach sand concrete beams is consistent with the higher porosity and weaker interfacial transition zone (ITZ) observed in SEM analysis. Similar trends were reported by Chen et al. [16] and Ganesan et al. [17], who found that sea-sand concrete beams generally exhibit lower flexural stiffness and more pronounced crack propagation due to weaker internal bonding characteristics.

The flexural behavior of reinforced concrete beams was evaluated using the two-point loading method to determine the influence of aggregate type and reinforcement configuration on beam performance. The experimental results are summarized in Table V, while the comparison of flexural strength values is presented in Figure 7.

Table V. Flexural Strength of Reinforced Concrete Beams

No	Beam Specimen Variation	Flexural Strength (MPa)			Average Strength (MPa)	SD
		1	2	3		
1	PS Beam – Plain Reinforcement	17.881	15.66	11.037	14.86	3.44
2	PS Beam – Deformed Reinforcement	14.62	16.548	15.46	15.543	0.96
3	PP Beam – Plain Reinforcement	9.881	14.193	16.119	13.398	3.14
4	PP Beam – Deformed Reinforcement	16.31	13.28	15.5	15.03	1.63

Based on the results presented in Table IV, the reinforced concrete beams containing river sand and deformed reinforcement exhibited the highest average flexural strength of 15.543 MPa. Meanwhile, the lowest flexural capacity was observed in beams containing beach sand with plain reinforcement, which achieved an average strength of 13.398 MPa.

To evaluate the consistency of the experimental results, the standard deviation (SD) values of flexural strength were also analyzed. The beam specimens containing river sand with plain reinforcement showed relatively higher variability compared to other specimens. This variation may be attributed to differences in crack initiation, local aggregate distribution, minor casting inconsistencies, and variations in bond interaction between concrete and reinforcement during loading. In reinforced concrete beam testing, flexural failure is highly sensitive to internal microcracks and interfacial transition zone (ITZ) conditions, which may cause fluctuations in measured flexural capacity even within identical specimen groups.

The specimens reinforced with deformed bars exhibited more stable flexural behavior due to improved mechanical interlocking and bond performance between steel reinforcement and concrete. The enhanced bond mechanism contributed to more uniform stress distribution and reduced variability in structural response during loading.

The findings indicate that the flexural performance of reinforced concrete beams is strongly influenced by both the type of fine aggregate and the reinforcement characteristics. Beams with beach sand generally showed more fluctuating flexural behavior compared to those with river sand. This condition is associated with the lower bonding quality between beach sand particles and cement paste, which affects crack propagation and tensile stress distribution within the beam section.

In addition, the use of deformed reinforcement significantly improved the flexural performance of beams due to the enhanced mechanical interlocking between steel reinforcement and concrete. Improved bond performance contributes to higher cracking loads, increased flexural stiffness, and better stress transfer after crack initiation. Therefore, the application of deformed bars can partially compensate for the reduction in concrete quality caused by the use of beach sand.

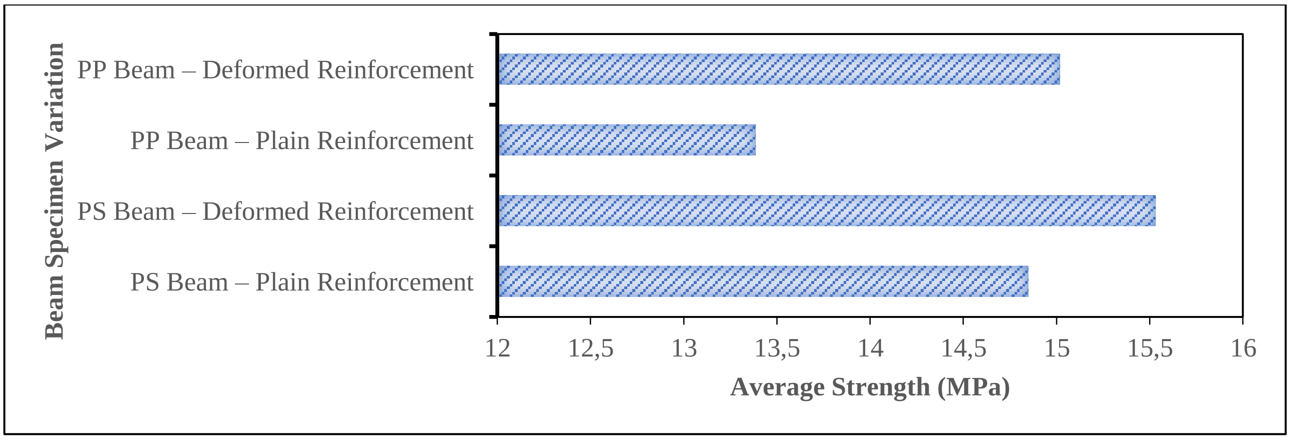


Figure 7. Comparison of Flexural Strength of Reinforced Concrete Beams

Figure 7 illustrates that the flexural strength of beams containing beach sand with deformed reinforcement approached the performance of beams with river sand. This result demonstrates the important role of reinforcement bonding in maintaining the structural performance of reinforced concrete beams.

3.3. Water Absorption of Concrete

The water absorption test was performed to evaluate the permeability characteristics and internal pore structure of the concrete specimens. The test results are presented in Table VI, while the graphical comparison is shown in Figure 8.

Table VI. Water Absorption of Concrete

Specimen	**Water Absorption (%)**			**Average Water Absorption (%)**
	1	2	3	
Concrete PS	1.75	1.19	1.52	1.49
Concrete PP	1.76	1.37	1.45	1.53

The results in Table V show that concrete containing beach sand exhibited slightly higher water absorption than concrete containing river sand. The average water absorption value for river sand concrete was 1.49%, whereas beach sand concrete reached 1.53%.

The slightly higher absorption observed in beach sand concrete indicates a more open pore structure and lower internal density. This behavior is related to the finer and smoother texture of beach sand particles, which may increase capillary pores within the concrete matrix. Increased pore connectivity allows water to penetrate more easily into the concrete structure.

However, the difference between the two concrete types was relatively small, approximately 0.04%, and both values remained below 3%, indicating that the concrete still possessed relatively good compactness and low permeability. These findings suggest that beach sand may still be considered as an alternative fine aggregate if proper processing and quality control are applied.

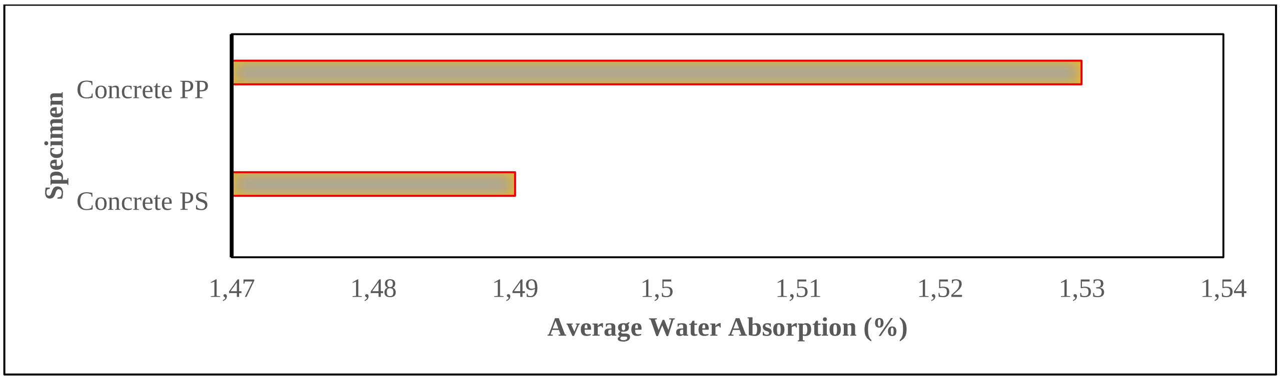


Figure 8. Comparison of Water Absorption Results

Figure 8 further demonstrates that the variation in water absorption between river sand concrete and beach sand concrete was relatively minor, although beach sand concrete consistently showed slightly higher absorption values.

3.4. Porosity of Concrete

The porosity test was conducted to evaluate the internal void structure of the concrete specimens and its relationship with mechanical performance. The porosity results are presented in Table VII, while the comparison graph is shown in Figure 9.

Table VII. Porosity of Concrete

Specimen	Porosity (%)			Average Porosity (%)
	1	2	3	
Concrete PS	10.12	10.87	7.2	9.4
Concrete PP	15.08	14.65	13.27	14.33

The results in Table VII indicate that concrete containing beach sand had significantly higher porosity compared to concrete with river sand. The average porosity value increased from 9.40% in river sand concrete to 14.33% in beach sand concrete.

Higher porosity indicates a more open internal pore structure and lower concrete density. This condition directly affects the mechanical performance of concrete because the presence of excessive pores reduces the effective load-bearing area within the concrete matrix. Consequently, concrete with higher porosity tends to exhibit lower compressive and flexural strength.

The higher porosity observed in beach sand concrete is associated with the particle characteristics of beach sand, including finer gradation and rounded particle shape, which may reduce particle interlocking and packing density. Increased porosity may also increase permeability and accelerate the penetration of aggressive agents such as chloride ions, thereby reducing the durability of reinforced concrete structures.

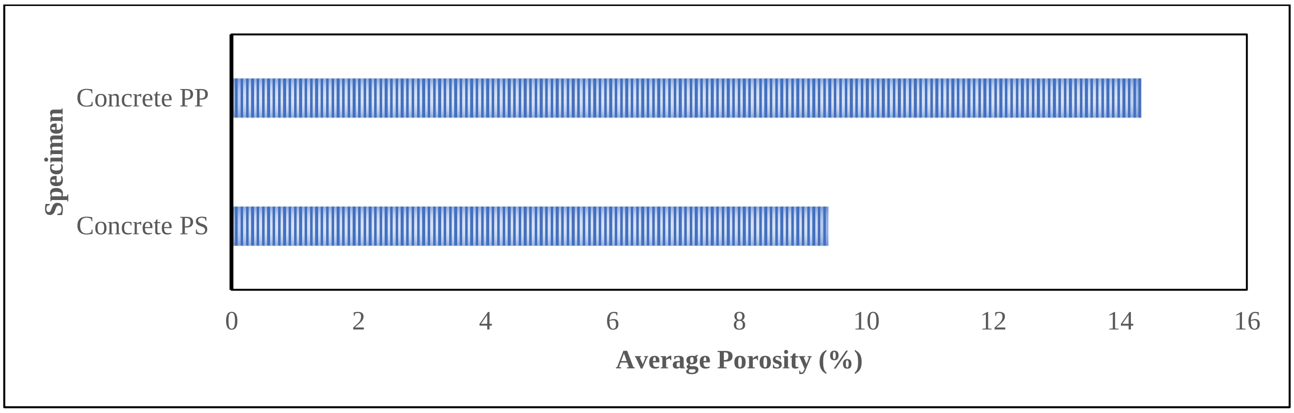


Figure 9. Comparison of Concrete Porosity Results

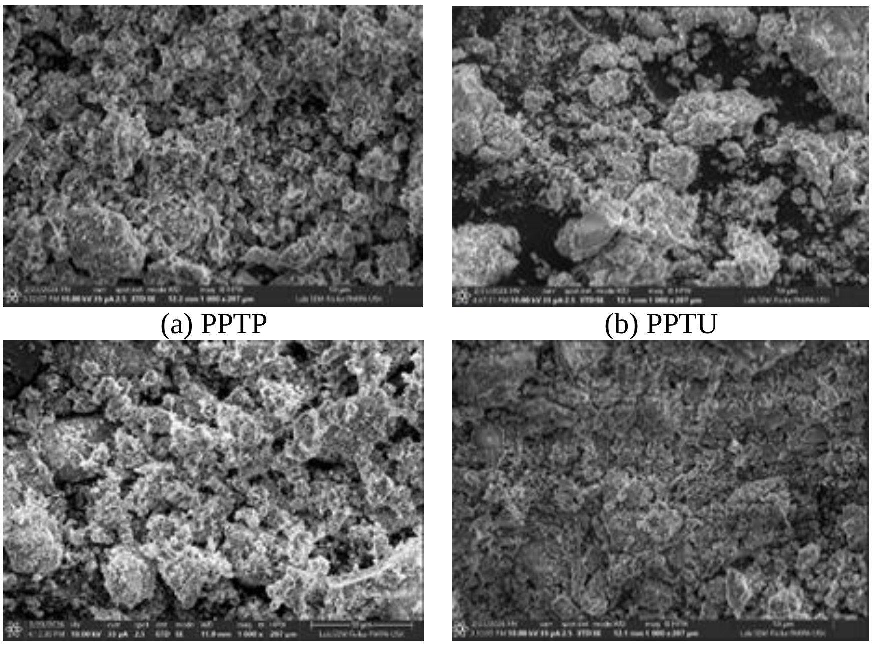
Figure 9 clearly shows the significant increase in porosity in concrete containing beach sand compared to river sand concrete, confirming the influence of aggregate characteristics on the internal structure of concrete.

3.5. Microstructural Analysis Using SEM

Scanning Electron Microscope (SEM) analysis was conducted to observe the morphology and pore distribution of the concrete specimens. The SEM observations are presented in Figure 10.

The SEM results revealed clear differences in the microstructure of concrete containing river sand and beach sand. Concrete with beach sand exhibited a more porous microstructure with less homogeneous hydration products and a more visible interfacial transition zone (ITZ) between aggregate particles and cement paste.

The presence of more open pores in beach sand concrete supports the results obtained from water absorption and porosity tests. The weaker bonding within the ITZ region may contribute to crack initiation and reduce the mechanical performance of concrete under compressive and flexural loading conditions. The weaker ITZ observed in beach sand concrete may be associated with the smoother surface texture and finer particle morphology of beach sand, which reduce mechanical interlocking between aggregate particles and cement paste. In addition, residual chloride salts may influence hydration kinetics and contribute to the formation of a more porous microstructure.



(a) PPTP (b) PPTU

(c) PSTP (d) PSTU

Figure 10. SEM Images of Reinforced Concrete Specimens

Conversely, concrete containing river sand demonstrated a denser microstructure with more uniformly distributed hydration products and a relatively compact ITZ. This denser structure contributed to improved compressive strength and flexural performance.

The specimen coding system used in the SEM and XRD analyses was defined based on the type of fine aggregate and reinforcement configuration. The code PPTP refers to beach sand concrete with plain reinforcement, while PPTU represents beach sand concrete with deformed reinforcement. In addition, PSTP indicates river sand concrete with plain reinforcement, whereas PSTU refers to river sand concrete with deformed reinforcement. This coding system was consistently applied throughout the microstructural analysis to distinguish the influence of aggregate type and reinforcement characteristics on the behavior and internal structure of the concrete specimens.

3.6. XRD Analysis of Crystalline Phases

X-Ray Diffraction (XRD) analysis was carried out to identify the crystalline phases formed in the concrete specimens after the hydration process. The XRD diffraction patterns are presented in Figure 11.

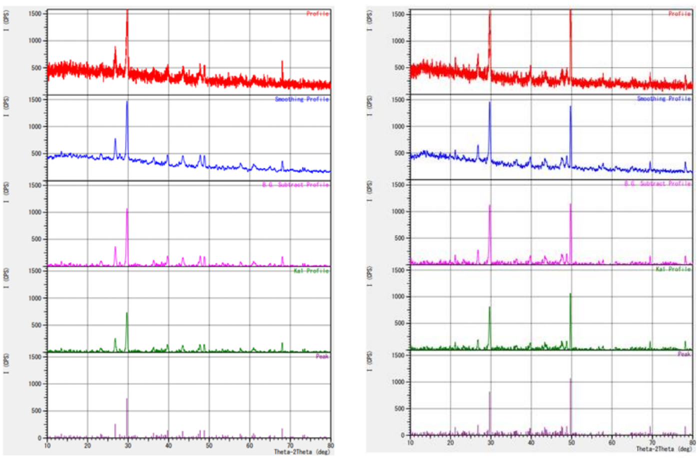
The XRD analysis identified the major hydration products in both concrete types, including calcium silicate hydrate (C–S–H), calcium hydroxide ($Ca(OH)_2$), and quartz (SiO_2). The diffraction peaks observed in the beach sand concrete showed relatively higher quartz intensity, indicating the contribution of silica-rich fine aggregates to the mineral composition of the concrete.

No significant new harmful crystalline phases were detected in the beach sand concrete, indicating that the use of beach sand did not fundamentally alter the cement hydration mechanism. The differences mainly occurred in the intensity of diffraction peaks, which reflects variations in microstructural density and aggregate composition.

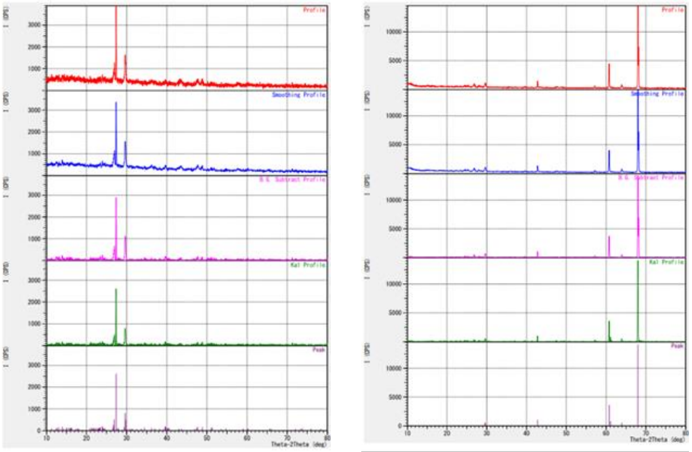
These findings suggest that the reduction in mechanical performance of beach sand concrete is more closely related to physical and microstructural characteristics rather than changes in the primary hydration products.

3.7. Research Limitations

Several limitations should be acknowledged in this study. First, the experimental investigation was limited to laboratory-scale reinforced concrete beam specimens under monotonic two-point loading conditions. Long-term structural behavior, fatigue performance, and cyclic or seismic loading effects were not evaluated. Second, the beach sand used in this study was applied without chemical treatment or chloride removal processes; therefore, the long-term corrosion behavior of steel reinforcement was not investigated. Third, the number of specimen replications in each variation was limited, which may influence statistical robustness and variability interpretation. In addition, advanced statistical analyses such as ANOVA or regression modeling were not comprehensively performed due to the limited sample size. Future studies are recommended to include larger experimental datasets, long-term durability evaluations, chloride penetration analysis, and reinforcement corrosion monitoring to provide more comprehensive validation of beach sand utilization in reinforced concrete structures.



(a) PPTP (b) PPTU



(c) PSTP (d) PSTU

Figure 11. XRD Diffraction Patterns of Concrete Specimens

V. CONCLUSIONS

Based on the experimental investigation conducted in this study, it can be concluded that the use of beach sand as fine aggregate significantly influences the mechanical performance, physical characteristics, and microstructural behavior of reinforced concrete beams. Concrete containing river sand achieved a higher average compressive strength of 24.85 MPa, whereas concrete containing beach sand only reached 17.69 MPa, indicating a compressive strength reduction of approximately 28.8%. In terms of flexural behavior, reinforced concrete beams with river sand and deformed reinforcement exhibited the highest average flexural strength of 15.543 MPa, while beams containing beach sand with plain reinforcement showed the lowest average flexural strength of 13.398 MPa. These findings confirm that both aggregate characteristics and reinforcement type strongly influence structural performance.

The water absorption and porosity results further demonstrated that beach sand concrete possessed a more porous internal structure. The average porosity increased from 9.40% in river sand concrete to 14.33% in beach sand concrete, while water absorption slightly increased from 1.49% to 1.53%. SEM observations confirmed that beach sand concrete exhibited a more porous microstructure and weaker interfacial transition zone (ITZ) compared to river sand concrete. Meanwhile, XRD analysis showed that both concrete mixtures produced similar primary hydration products, indicating that the differences in performance were mainly associated with physical and microstructural characteristics rather than changes in hydration mechanisms.

The results obtained in this study are consistent with the research objectives and hypotheses presented in the Introduction and Literature Review sections. The integrated mechanical, physical, and microstructural analyses successfully demonstrated the relationship between aggregate characteristics, pore structure, and flexural behavior of reinforced concrete beams.

Although beach sand has potential as an alternative fine aggregate for sustainable construction, additional treatment and quality control are necessary to improve its structural performance and durability. Washing treatment to reduce chloride and salt contamination is strongly recommended prior to concrete production. For practical applications, the chloride content of beach sand should be reduced to acceptable limits according to concrete material standards before use in reinforced concrete structures. Gradation optimization and the incorporation of supplementary cementitious materials (SCMs) such as fly ash, silica fume, or slag are also recommended to improve density, reduce porosity, and enhance long-term durability performance.

Several limitations should be acknowledged in this study. The experimental program was limited to laboratory-scale specimens under monotonic loading conditions, and long-term durability behavior such as reinforcement corrosion, chloride penetration, fatigue loading, and seismic performance were not evaluated. In addition, the number of specimen replications was limited, which may influence statistical robustness. Therefore, future studies are recommended to investigate long-term corrosion behavior, cyclic loading response, chloride diffusion characteristics, and advanced treatment methods for beach sand concrete in marine environments..

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