



SHORT-TERM MECHANICAL PROPERTIES OF GEOPOLYMER CONCRETE INCORPORATING SEA SAND

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Abstract. The depletion of natural river sand and the environmental effect of Portland cement production have motivated the search for green building materials. This study investigates the short-term mechanical properties of geopolymer concrete (GPC) incorporating sea sand as fine aggregate. Class F fly ash and ground granulated blast furnace slag were employed as aluminosilicate precursors, activated by a dry sodium silicate-based powder. Nine mixtures were designed by varying activator content (8%, 11.5%, and 15% by binder mass) and water-to-binder (W/B) ratios (0.30, 0.35, and 0.40). A total of 108 cylindrical specimens were tested for compressive strength at the age of 3, 7, 14, and 28 days. Flexural tensile strength, splitting tensile strength, and elastic modulus were evaluated at 14 days for the optimal mixture. Results indicate rapid early-age strength development, with 3-day strength reaching 50–60% of 28-day strength. Increasing activator content significantly improved compressive strength, while increasing W/B ratio reduced strength. The 28-day compressive strength reached 44.8 MPa under ambient curing. Flexural and splitting tensile strengths exceeded predictions from conventional concrete design models. The findings preliminary demonstrate that sea sand can be effectively utilized in geopolymer concrete providing a sustainable option for construction in coastal regions.

Keywords: geopolymer concrete, mechanical properties, fly ash, ground granulated blast furnace slag, sea sand, sustainable construction

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1. INTRODUCTION

The expanding demand for building materials has led to extensive exploitation of natural river sand, resulting in significant environmental concerns such as riverbank erosion, ecosystem degradation, and depletion of natural resources. At the same time, the production of ordinary Portland cement (OPC) remains a significant contributor to global carbon dioxide emissions, accounting for approximately 7–8% of total anthropogenic CO₂ emissions [1, 2]. Consequently, the construction industry has been actively exploring sustainable alternatives to both conventional cement binders and natural aggregates.

Geopolymer concrete (GPC), produced through the alkali activation of aluminosilicate materials including fly ash, ground granulated blast furnace slag (GGBFS), and metakaolin, has emerged as one of the most promising low-carbon alternatives to Portland cement concrete [3]. The geopolymerization process forms a three-dimensional aluminosilicate network, typically consisting of sodium aluminosilicate hydrate (N-A-S-H) or calcium aluminosilicate hydrate (C-A-S-H) gels, which provides high mechanical strength and improved chemical resistance [4].

In parallel with the development of geopolymer binders, researchers have investigated alternative sources of fine aggregates. Among these alternatives, sea sand has attracted increasing attention due to its abundance and accessibility in coastal regions. The use of sea sand in geopolymer concrete—commonly referred to as sea water sea sand geopolymer concrete (SWSS-GPC)—has been proposed as a sustainable solution to reduce freshwater consumption and river sand extraction. Recent studies have demonstrated that geopolymer concrete produced using sea water and sea sand can achieve satisfactory mechanical properties while offering environmental benefits and cost savings for coastal infrastructure development [5].

The mechanical performance of sea sand geopolymer concrete has been widely investigated through laboratory experiments in recent years. Key mechanical parameters include compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity.

Several studies have demonstrated that sea sand can be used as a complete replacement for river sand in geopolymer concrete without significant deterioration of mechanical properties [6]. In many cases, geopolymer concrete produced with marine aggregates exhibits mechanical strength comparable to that of conventional geopolymer concrete prepared with natural river sand.

Experimental results reported in recent literature indicate that the compressive strength of seawater sea-sand geopolymer concrete typically ranges between 35 MPa and 70 MPa depending on mixture proportions and curing conditions [5, 6]. Higher strengths can be achieved by optimizing the precursor composition and alkaline activator concentration.

One study investigating the mechanical properties of geopolymer concrete incorporating sea sand and seawater demonstrated that the replacement of river sand and freshwater with marine resources is feasible with respect to compressive strength [7].

In addition to compressive strength, researchers have also investigated the elastic modulus and tensile behavior of geopolymer concrete containing marine sand. The results indicate that the modulus of elasticity of sea sand geopolymer concrete is generally

comparable to that of conventional geopolymers concrete mixtures, suggesting that marine aggregates do not significantly compromise the stiffness of the material [8].

Furthermore, studies involving coral sand geopolymer concrete have shown that the compressive and flexural strengths increase with increasing proportions of slag or fly ash in the binder system. Importantly, these studies reported no significant difference was observed in the mechanical performance between geopolymer concrete produced with coral sand and that produced with conventional aggregates [6].

Vietnam has a coastline of more than 3,200 km and nearly 3,000 islands, creating an urgent demand for infrastructure development in coastal and island regions. However, construction in these areas is difficult and costly because essential materials such as cement, freshwater, sand, and aggregates must be transported from the mainland. Marine environments also accelerate corrosion and deterioration of reinforced concrete structures, leading to high maintenance costs that may account for 30–70% of total construction investment. In addition, the increasing scarcity of river sand has become a critical issue in many regions. The use of locally available marine sand can significantly reduce transportation costs and environmental impacts associated with aggregate extraction.

The transition from traditional river sand to marine resources in geopolymer production has shown significant technical viability in the Vietnamese context. Research conducted in the coastal regions of Thai Binh and Kien Giang indicates that the use of untreated sea sand and seawater does not adversely affect the compressive strength of geopolymer concrete. Specifically, SSSW-GPC specimens can achieve mechanical properties comparable to, or even slightly exceeding, those of traditional river sand geopolymers due to the catalytic effect of certain salts in seawater on the geopolymerization process [9, 10].

In terms of specialized applications, experimental results on pervious geopolymer concrete demonstrate that it can maintain a compressive strength of over 17 MPa with a porosity of 24%, making it a sustainable solution for coastal infrastructure such as pavements and parking lots [11]. Furthermore, microstructural analyses (SEM-EDS and XRD) have confirmed that the geopolymer matrix possesses a unique ability to "immobilize" chloride ions within its chemical framework. This characteristic significantly reduces the risk of steel reinforcement corrosion compared to ordinary portland cement concrete when exposed to saline environments [12, 13].

As the physicochemical characteristics of sea sand are inherently site-specific, the properties of the resulting concrete vary significantly depending on the geographical origin of the dredged materials. Consequently, it is imperative to evaluate the mechanical performance of geopolymer concrete synthesized from diverse raw material sources. Furthermore, given this inherent variability, a robust statistical analysis of the fluctuating properties of sea sand concrete carries substantial practical significance. To address these issues, the present study investigates the influence of varying compositions on the short-term performance of sea sand geopolymer concrete. Ultimately, this work provides preliminary insights into the sustainable and eco-friendly utilization of marine resources within the construction industry.

2. MATERIALS AND METHODS

2.1. Materials

Material characterization included chemical composition, particle size distribution,

mineralogical analysis, and compliance assessment with relevant standards.

2.1.1. Fly ash

The primary aluminosilicate precursor utilized in this study was low-calcium fly ash (FA), sourced from the Pha Lai thermal power plant (Hai Duong, Vietnam). To ensure high fineness and homogeneity, the material underwent air classification processing by Vina F&C. According to its chemical composition and loss on ignition (LOI), the FA is classified as Class F in accordance with ASTM C618 and TCVN 10302:2014.

Chemical composition of fly ash is presented in Table 1. Chemical analysis reveals a combined SiO₂ and Al₂O₃ content of 76.27 % (51.74 % SiO₂ and 24.53 % Al₂O₃), which significantly exceeds the 70% threshold required for effective geopolymerization. The low CaO content (0.81 %) confirms its siliceous nature, while a LOI (loss on ignition) of 8.98 % remains within the permissible limits for structural applications. Regarding physical properties, the FA exhibits a refined particle size distribution, with 95% of particles smaller than 30 μm. This high fineness, coupled with the characteristic spherical morphology of the particles, is expected to enhance both the workability (via the ball-bearing effect) and the reaction kinetics within the alkaline medium.

Table 1. Chemical composition of fly ash (wt.%).

Oxide	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	TiO ₂	SO ₃	LOI
Content	51.74	24.53	5.59	0.81	1.95	4.42	0.11	0.76	0.31	8.98

2.1.2. Ground granulated blast furnace slag (GGBFS)

Ground granulated blast furnace slag (GGBFS, grade S95), sourced from the Hoa Phat company (Hai Duong, Vietnam), was employed as a secondary aluminosilicate precursor in compliance with TCVN 11586:2016. The incorporation of GGBFS is strategically intended to accelerate early-age strength development under ambient curing conditions, leveraging its latent hydraulic reactivity and high calcium content.

Chemical composition of Hoa Phat GGBFS, grade S95, is presented in Table 2. The chemical composition of the GGBFS used in this study is predominantly composed of CaO (38.6 %) and SiO₂ (35.02 %), followed by Al₂O₃ (13.56 %) and MgO (8.18 %). The high calcium and silica content, along with a relatively low loss on ignition of 1.89 %, confirms the material's high potential for hydraulic reactivity. These constituents facilitate the formation of C-A-S-H gel, which is essential for achieving early-age mechanical strength in ambient-cured geopolymer systems.

Table 2. Chemical composition of GGBFS (wt.%).

Oxide	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	LOI
Content	35.02	13.56	1.41	38.6	8.18	0.31	0.80	0.23	1.89

The synergistic interaction between Class F fly ash and GGBFS facilitates a dual reaction mechanism: the geopolymerization of aluminosilicates alongside the formation of calcium aluminosilicate hydrate (C-A-S-H) gels. This hybrid binder system effectively promotes robust strength gain at room temperature, circumventing the necessity for conventional thermal curing.

2.1.3. Alkaline activator material (AAM)

A dry powdered sodium silicate-based activator (Na₂O.SiO₂.nH₂O) was employed. Unlike conventional liquid alkaline systems (NaOH + Na₂SiO₃ solutions), the dry activator

was pre-blended with solid precursors, simplifying handling and improving safety during mixing.

Upon contact with water, the activator dissolves exothermically, increasing local temperature and accelerating geopolymerization. The presence of soluble silicate enhances gel network formation and mechanical performance.

2.1.4. Coarse aggregate

Crushed basalt aggregate sourced from Hoa Thach quarry (Hanoi) was used. The aggregate was sieved and recombined to satisfy grading requirements of ASTM International C33. The selected maximum nominal size (D_{max}) was 19 mm.

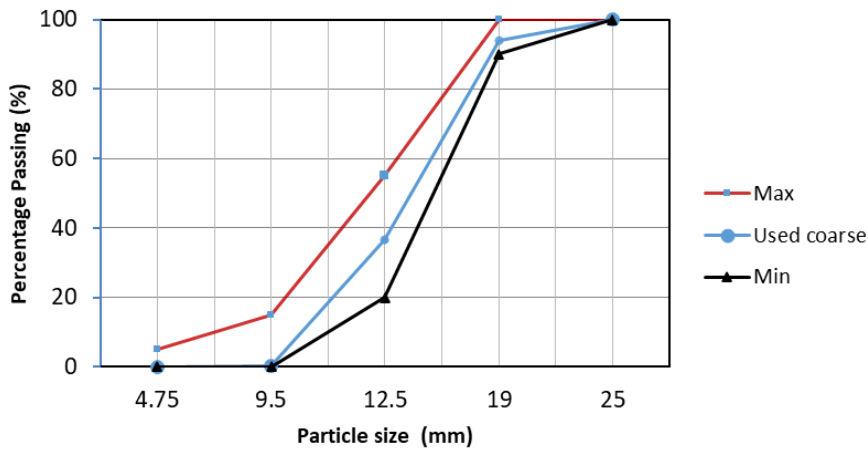


Figure 1. Coarse Aggregate Gradation Curve.

The grading curve falls within ASTM limits, ensuring adequate packing density and reduced void content.

2.1.5. Fine aggregate - sea sand

Marine sand from Cua Lo (Nghe An Province) was selected as fine aggregate. Particle size analysis was conducted according to ASTM C136 standard. The particle size distribution results are presented in Figure 2.

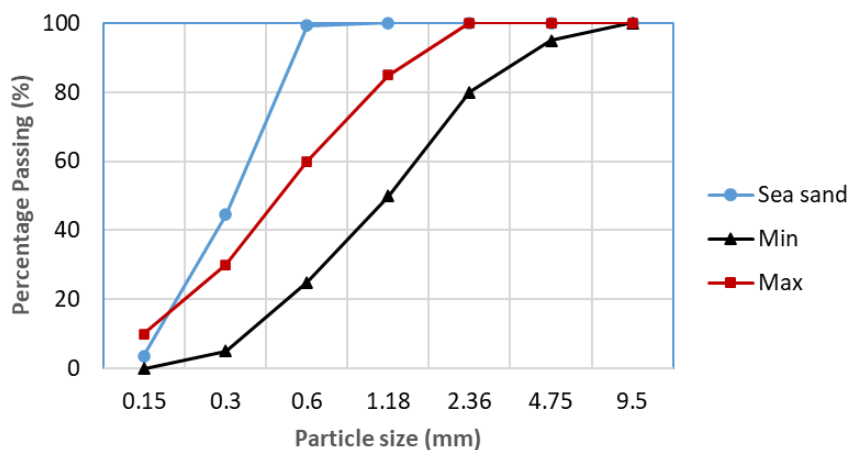


Figure 2. Sea Sand Gradation Curve.

Mineralogical analysis performed by the Vietnam Academy of Science and Technology. The results of the experiment determining the mineral composition of Cua Lo sea sand are presented in Table 3.

Table 3. Mineral compositions of used sea sand.

Analysis index	Illite	Kaolinite + Chlorite	Quartz	Feldspar	Goethite	Other minerals
Result (%)	4 – 6	3 – 5	78 – 80	6 – 8	1 – 3	Lepidocrocite

The high quartz content and low clay fraction indicate suitability for concrete production. The use of sea sand is particularly significant for coastal infrastructure development where freshwater and river sand resources are limited.

2.1.6. Mixing water

Water serves as the dissolution medium for the dry activator and facilitates geopolymerization without participating as chemically bound water in the hardened matrix.

2.2 Experimental design

The compressive strength of geopolymer concrete incorporating sea sand was determined using cylindrical specimens measuring 150 mm in diameter and 300 mm in height.. A total of 108 specimens were prepared, representing nine different mix designs. The mixtures were formulated with activator contents of 8%, 11.5%, and 15%, combined with water-to-binder (W/B) ratios of 0.30, 0.35, and 0.40. The experimental matrix was developed to systematically evaluate the effects of activator dosage and the W/B ratio on the compressive strength development of geopolymer concrete. Table 4 shows the mix design based on a target density of 2377 kg/m³. A total of nine mixes was synthesised.

Table 4. Geopolymer concrete compositions used in the study.

Designation	W/B	AAM content (%)	Coarse (kg)	Sea sand (kg)	Fly ash (kg)	GGBFS (kg)	AAM (kg)	Water (kg)
CP1	0.3	8	1080	680	262	175	38	142
CP2	0.4	8	1080	680	243	162	35	176
CP3	0.3	15	1080	680	242	161	71	142
CP4	0.4	15	1080	680	225	150	66	176
CP5	0.3	11.5	1080	680	252	168	55	142
CP6	0.4	11.5	1080	680	234	156	51	176
CP7	0.35	8	1080	680	252	168	37	160
CP8	0.35	15	1080	680	233	155	69	160
CP9	0.35	11.5	1080	680	243	162	53	160

The process of mixing geopolymer concrete using sea sand (summarized in Figure 3) takes place in two stages (dry mixing and wet mixing). The total mixing time is 480 seconds (8 minutes). Geopolymer mixtures require longer mixing times than conventional cement concrete due to their higher viscosity.

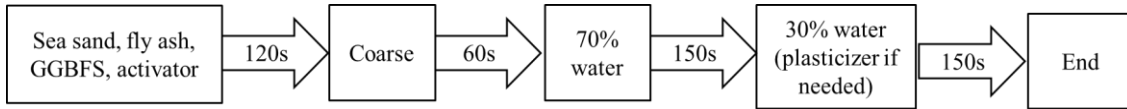


Figure 3. Geopolymer concrete using sea sand mixing process.

Flexural tensile strength, splitting tensile strength, and elastic modulus tests were conducted using the optimal mixture containing 15% activator content and a water-to-binder ratio of 0.30. All specimens were tested at the age of 14 days. Flexural strength was determined employing beam specimens with dimensions of 150 × 150 × 600 mm. In contrast, the splitting tensile strength and elastic modulus were determined using cylindrical specimens measuring 150 mm in diameter and 300 mm in height. All specimens were cured under ambient laboratory temperature prior to testing.

3. EXPERIMENT RESULTS AND DISCUSSION

3.1. Compressive strength testing

3.1.1 Compressive strength results of sea sand geopolymer concrete

The compressive strength of geopolymer concrete incorporating sea sand was determined in accordance with ASTM C39. A total of 108 specimens representing nine mixture proportions were prepared to investigate the effects of activator content and W/B ratio on compressive strength development.

To assess the influence of activator content, W/B ratio and age, an analysis of variance (ANOVA) was carried out from the experimental results using Minitab software. The summary of the factor information and analysis of variance from ANOVA are presented in the Tables 5 and Table 6.

Table 5. Factor information.

Factor	Type	Levels	Values
Activator content (%)	Fixed	3	8.0, 11.5, 15.0
W/B	Fixed	3	0.30, 0.35, 0.40
Age	Fixed	4	3, 7, 14, 28

Table 6. Analysis of Variance.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Activator content (%)	2	810.86	405.430	240.88	< 0.001
W/B	2	1020.51	510.255	303.16	< 0.001
Age	3	1074.68	358.228	212.84	< 0.001
Activator content (%)×W/B	4	66.62	16.654	9.89	0.001
Activator content (%)×Age	6	84.65	14.108	8.38	0.001
W/B×Age	6	162.24	27.039	16.07	<.001
Error	12	20.20	1.683		
Total	35	3239.75			

The ANOVA analysis was employed to investigate the influence of activator content, water-to-binder (W/B) ratio, and curing age on the compressive strength of concrete.. The results indicate that all main factors significantly influence compressive strength, including alkaline activator content, W/B, and curing age (Table 5) (P-value < 0.05). In addition to the main effects, all interaction terms are also statistically significant, including Activator content

× W/B, Activator content × Age, and W/B × Age (P-value < 0.05). These results indicate that the influence of each factor is not independent but depends on the levels of the other variables. Overall, the results demonstrate that reducing the water-to-binder ratio and increasing activator content significantly enhance compressive strength, particularly at later curing ages. This behavior can be attributed to the densification of the microstructure and the contribution of chemical reactions associated with activator, which become more pronounced over time.

Table 7. Tukey analysis of the interaction between activator content and W/B ratio on geopolymer concrete strength.

Activator content (%)*W/B	N	Mean	Grouping
15.0 0.30	4	34.300	A
11.5 0.30	4	31.800	A
15.0 0.35	4	28.175	B
8.0 0.30	4	27.050	B C
15.0 0.40	4	24.425	C D
11.5 0.35	4	21.350	D E
11.5 0.40	4	20.050	E
8.0 0.35	4	12.875	F
8.0 0.40	4	12.350	F

(Means that do not share a letter are significantly different).

The Tukey comparison results for the interaction between activator content and the W/B ratio on geopolymer concrete strength are presented in Table 7. The Tukey group analysis confirms that primary factors - activator content, W/B ratio - significantly influence the compressive strength of geopolymer concrete. The results showed that the compressive strengths depended significantly between the different W/B ratio and activator content mixtures.

3.1.2 Compressive strength development of sea sand geopolymer concrete

The compressive strength developments of sea sand geopolymer concretes are shown in the Figure 4.

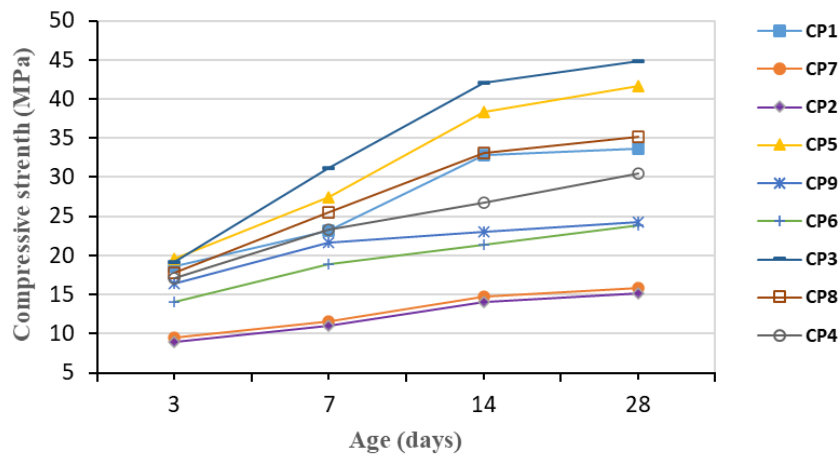


Figure 4. Compressive Strength Development Curves.

The compressive strength values recorded in this study, ranging from approximately 15 MPa to 45 MPa depending on mixture proportions, are consistent with those reported in

previous investigations on seawater sea sand geopolymer concrete. Several studies have shown that geopolymer concrete produced using marine sand can attain compressive strengths comparable to those of geopolymer concrete prepared with conventional river sand when appropriate mixture design parameters are used [5, 14].

The experimental data indicates that the compressive strength increased significantly with curing age for all mixtures. For example, at a W/B ratio of 0.30, the compressive strength increased from approximately 18 – 20 MPa at 3 days to 33.6 – 44.8 MPa at 28 days depending on the activator content. This rapid strength development during the early curing stage is a characteristic feature of alkali-activated materials and is attributed to the progressive geopolymerization reaction occurring within the binder matrix. During this process, aluminosilicate precursors dissolve in the alkaline solution and subsequently polymerize to form a three-dimensional aluminosilicate gel network, which provides the primary binding phase responsible for mechanical strength [15, 16].

The significant increase in compressive strength between 3 and 14 days observed in this study suggests that the geopolymerization reaction proceeds rapidly during the early curing period. After approximately 14 days, the rate of strength gain becomes less pronounced, indicating that most of the geopolymer gel network has already been formed and the microstructure is gradually approaching a stable state. Similar strength development behavior has been reported in previous studies on fly-ash-based geopolymer concrete and seawater sea-sand geopolymer systems [5, 14].

3.1.3 Influence of water-to-binder ratio

The water-to-binder ratio was another critical parameter affecting the compressive strength of geopolymer concrete. The experimental results reveal a clear inverse relationship between the W/B ratio and compressive strength. At an activator content (AC) of 15%, the 28-day compressive strength decreased from 44.8 MPa to 36.3 MPa and 30.5 MPa as the W/B ratio increased from 0.30 to 0.35 and 0.40, respectively. The influence of water-to-binder ratio on strengths of saline sand geopolymer concretes is shown in the Figure 5.

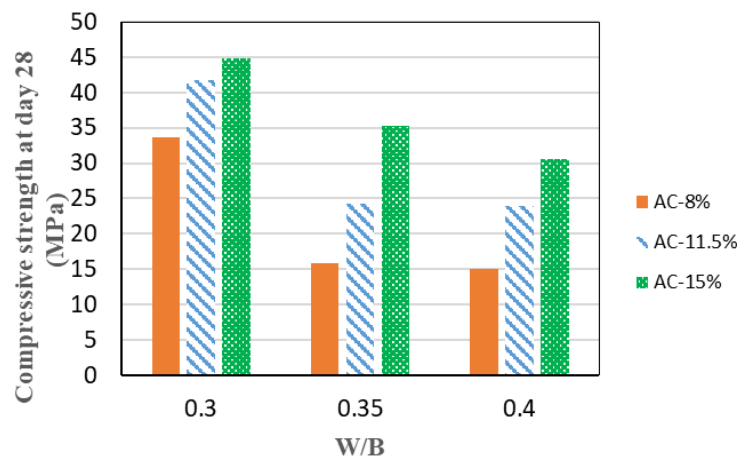


Figure 5. Influence of W/B ratio on Compressive Strength

This reduction in strength can be attributed primarily to the increase in capillary porosity within the geopolymer matrix caused by excess mixing water. A higher W/B ratio dilutes the alkaline activating solution and increases the amount of free water present in the mixture. During curing, this excess water gradually evaporates, leaving additional pores within the

hardened matrix. The formation of these capillary pores weakens the internal structure of the geopolymer binder and reduces its load-bearing capacity. Similar mechanisms have been reported in previous studies on alkali-activated materials, where the water content was found to strongly influence the microstructure and mechanical performance of geopolymer systems [14, 16].

Conversely, mixtures with lower W/B ratios tend to produce a denser and more compact geopolymer microstructure due to reduced porosity and improved gel formation. The lower water content facilitates closer packing of solid particles and enhances the formation of geopolymer gel phases, resulting in improved compressive strength.

The trend observed in this study is consistent with findings reported in recent research on seawater sea sand geopolymer concrete. For example, mixture optimization studies have shown that increasing the W/B ratio improves workability but significantly reduces compressive strength due to increased pore volume within the geopolymer matrix [5]. Similarly, Chen et al. reported that excessive water content in geopolymer mixtures leads to weaker gel structures and reduced mechanical performance [6]. These observations confirm that controlling the water-to-binder ratio is essential for optimizing the mechanical properties of geopolymer concrete manufactured with marine aggregates.

3.1.4 Influence of activator content

The activator content was found to significantly influence the compressive strength of geopolymer concrete. Increasing the activator dosage from 8% to 15% resulted in a substantial improvement in compressive strength at all curing ages. This trend indicates that the concentration of alkaline activator plays a crucial role in controlling the geopolymerization process and the development of mechanical strength. For example, at a W/B ratio of 0.30, the compressive strength at 28 days increased from 33.6 MPa for the mixture containing 8% activator to 41.7 MPa and 44.8 MPa for mixtures incorporating 11.5% and 15% activator, respectively. Similar trends were also observed for the mixtures with higher W/B ratios, confirming the consistent influence of activator dosage on strength development. The influence of activator content on strengths of sea sand geopolymer concretes is shown in the Figure 6.

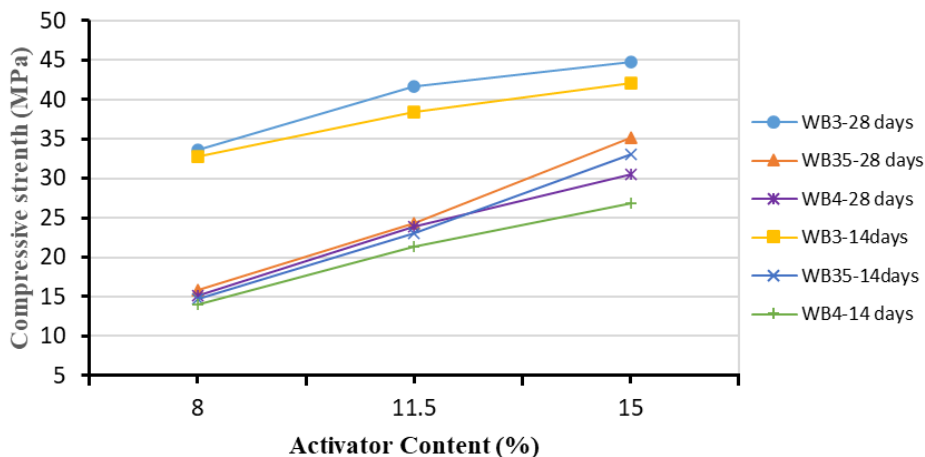


Figure 6. Influence of activator content on compressive strengths.

The improvement in compressive strength with increasing activator content can be explained by the enhanced dissolution of aluminosilicate precursors in the alkaline solution. A

higher concentration of hydroxide ions accelerates the breakdown of Si–O–Si and Al–O–Si bonds within the precursor materials, releasing a greater amount of reactive silicate and aluminate species into the solution. These species subsequently participate in polycondensation reactions, forming a three-dimensional aluminosilicate gel structure that constitutes the primary binding phase in geopolymer systems. As the activator concentration increases, the geopolymerization reaction becomes more efficient, leading to the formation of a denser and more continuous gel structure. This densification of the microstructure reduces internal porosity and improves the load-bearing capacity of the hardened geopolymer matrix.

In addition, the presence of sodium silicate in the activator solution provides additional soluble silicate species that facilitate the formation of a strongly cross-linked aluminosilicate framework. This results in a higher volume of geopolymer gel phases such as N–A–S–H or C–A–S–H gels, which contribute significantly to the mechanical strength of the material. Similar mechanisms have been widely reported in studies on alkali-activated materials, where the activator concentration strongly influences reaction kinetics and microstructural development [14, 16].

Comparable results were also reported by P. Cong and Y. Cheng, who found that increasing the alkalinity of the activator solution accelerated geopolymerization reactions and significantly improved the mechanical properties of geopolymer concrete produced with marine aggregates [17].

3.2. Flexural tensile strength

Flexural strength tests were conducted on $150 \times 150 \times 600$ mm beam specimens at the curing age of 14 days using the optimal mixture containing 15% activator content and a water-to-binder ratio of 0.30. For this mixture, the average compressive strength at 14 days reached 42Pa. A total of 09 geopolymer concrete samples incorporating sea sand were tested for flexural compressive strength at 14 days. The mean flexural tensile strength obtained from nine specimens was 4.6 MPa.

To investigate the mechanical performance of the geopolymer concrete incorporating sea sand, the experimental results were compared with the flexural tensile strength predicted for ordinary Portland cement (OPC) concrete according to ACI 318-19. The ACI model relates flexural strength to compressive strength and is widely used as a reference for conventional concrete design. The formula for determining the flexural tensile strength of cement concrete according to ACI 318-19 is described in the eq. (1).

$$f_r = 0.63\sqrt{f'_c} \text{ (MPa)} \quad (1)$$

The comparison between experimental and predicted values is presented in Table 8.

For OPC concrete with a compressive strength of 42 MPa, the ACI 318-19 equation predicts a flexural tensile strength of 4.1 MPa. The geopolymer concrete tested in this study exhibited a flexural strength approximately 12% higher than the predicted value for conventional OPC concrete. This improvement suggests that geopolymer concrete incorporating sea sand can provide enhanced resistance to tensile cracking under bending loads.

Table 8. Comparison of mechanical properties.

Mechanical properties	Sample size (mm)	Experimental value (MPa)	ACI 318-19 prediction (MPa)
Compressive strength	150 x 300	42	
Flexural strength	150 × 150 × 600	4.6	4.1
Splitting strength	150 x 300	3.77	3.63
Elastic modulus	150 x 300	28.4x10 ³	32.8 x10 ³

The superior flexural performance can be attributed to several microstructural characteristics of geopolymer binders. Unlike Portland cement systems, geopolymer concrete forms a three-dimensional aluminosilicate polymeric network (N-A-S-H or C-A-S-H gel) which contributes to improved stress transfer within the matrix [11]. This polymeric network structure tends to produce a denser matrix with lower microcrack density, which enhances tensile load transfer and crack bridging mechanisms.

Another important factor contributing to the improved flexural strength is the interfacial transition zone (ITZ) between aggregates and the geopolymer binder. Several studies have reported that geopolymer binders often produce a stronger and more compact ITZ compared with Portland cement systems, which results in improved tensile resistance and crack propagation control [18].

The results demonstrate that geopolymer concrete exhibits flexural performance comparable to or slightly better than conventional OPC concrete at similar compressive strength levels. When compared with recent international studies, the results obtained in this research is consistent with previous research findings [5, 19].

The improved flexural strength implies enhanced resistance to crack initiation and propagation under bending loads, which can be beneficial for structural members subjected to flexural stresses such as beams, slabs, and pavements.

3.3. Splitting tensile strength

A total of nine geopolymer concrete samples using sea sand were tested for splitting tensile strength at 14 days. The test results are the arithmetic mean of the 09 samples. The average splitting tensile strength obtained for the optimal mixture of sea sand geopolymer concrete was 3.77 MPa, corresponding to a compressive strength of 42 MPa.

To evaluate the tensile performance of the geopolymer concrete produced with sea sand, the experimental results were compared with the predictive equation specified in ACI 318-19 for OPC concrete. The formula for determining the splitting tensile strength of cement concrete according to ACI 318-19 is described in the eq. (2).

$$f_r = 0.56\sqrt{f'_c} \text{ (MPa)} \quad (2)$$

The comparison between experimental and predicted values is presented in Table 8. The experimentally measured value obtained in this study is therefore approximately 4% higher than the predicted value for OPC concrete.

The slightly higher tensile strength of geopolymer concrete can be attributed to the formation of a dense aluminosilicate polymeric network during the geopolymerization

process. The dissolution of aluminosilicate precursors in the alkaline environment releases reactive silicate and aluminate species that subsequently undergo polycondensation reactions to form a three-dimensional geopolymer gel structure. This polymeric network improves matrix cohesion and enhances the interfacial transition zone (ITZ) between aggregates and binder, which plays a critical role in resisting tensile stresses and delaying crack propagation [19, 16].

The results confirm that geopolymer concrete incorporating sea sand can achieve tensile performance comparable to or slightly better than conventional Portland cement concrete with similar compressive strength. This indicates that the use of marine sand does not significantly compromise tensile behavior and may even contribute to improved aggregate–binder bonding within the geopolymer matrix. Consequently, sea sand geopolymer concrete shows strong potential for sustainable construction in coastal and marine environments where natural river sand resources are limited.

3.4. Elastic modulus

The elastic modulus of geopolymer concrete incorporating sea sand was determined at the curing age of 14 days using 15 cylindrical specimens. The average experimental elastic modulus obtained from the tests was 28.4 GPa, corresponding to a compressive strength of 42 MPa.

To analyse the stiffness properties of the geopolymer concrete, the experimental results were compared with the empirical relationship between elastic modulus and compressive strength for OPC concrete specified in ACI 318-19 for geopolymer concrete. According to ACI 318-19, the elastic modulus of concrete can be predicted as a function of compressive strength and density, as proposed in the eq. (3).

$$E_c = 0,043\rho^{1,5}\sqrt{R_n} \quad (\text{MPa}) \quad (3)$$

The comparison between experimental and predicted values are summarized in Table 8. The results indicate that the experimentally measured elastic modulus is lower than the value predicted by ACI 318-19 for conventional OPC concrete. Recent studies have shown that geopolymer concrete generally exhibits a lower elastic modulus than OPC of the same strength grade, primarily due to differences in reaction products and increased matrix shrinkage that leads to microcracking [8, 20].

The lower modulus compared with OPC concrete suggests that geopolymer concrete generally exhibits slightly lower stiffness and greater deformability at equivalent compressive strength. This behavior can be attributed to differences in binder chemistry and microstructural characteristics between geopolymer systems and conventional cement hydration products. In geopolymer materials, the primary binding phase consists of a three-dimensional network of aluminosilicate gels (N-A-S-H or C-A-S-H gel), which differs significantly from the calcium-silicate-hydrate (C-S-H) gel formed in Portland cement systems [16, 20]. The polymeric gel structure tends to exhibit slightly lower stiffness, which contributes to the reduced elastic modulus observed in geopolymer concretes.

The elastic modulus of geopolymer concrete is also strongly influenced by aggregate characteristics and the microstructure of the ITZ. The incorporation of sea sand may affect the stiffness of the composite material due to differences in particle shape, mineral composition, and the presence of marine salts. In some cases, marine ions such as Mg^{2+} can lead to the

formation of secondary phases (e.g., hydrotalcite-type compounds) that influence matrix densification and mechanical properties [14, 16, 20].

Overall, the experimental results confirm that geopolymer concrete incorporating sea sand exhibits elastic modulus values slightly lower than those predicted for conventional Portland cement concrete, but still within the typical range reported for geopolymer systems with similar compressive strength. This slightly reduced stiffness suggests that geopolymer concrete may experience greater strain under applied loads, which could provide certain advantages in terms of improved deformation capacity and crack resistance in structural applications.

4. CONCLUSION

This study investigated the short-term mechanical performance of geopolymer concrete incorporating sea sand, with emphasis on compressive strength, flexural tensile strength, splitting tensile strength, and elastic modulus. The experimental results demonstrate that the developed geopolymer concrete achieved a compressive strength of up to 42 MPa at 14 days, indicating rapid early-age strength development under ambient curing conditions. The maximum compressive strength of geopolymer concrete was achieved at an optimal activator content of 15% and a water-to-binder ratio of 0.30, with the 28-day strength exceeding 45 MPa.

In terms of tensile behavior, the measured flexural strength (4.6 MPa) and splitting tensile strength (3.77 MPa) were slightly higher than the values predicted for ordinary Portland cement concrete according to ACI 318-19, suggesting improved resistance to crack initiation and propagation. The enhanced tensile performance is attributed to the dense aluminosilicate gel network and improved interfacial bonding between aggregates and the geopolymer binder.

The experimentally measured elastic modulus of 28.4 GPa was lower than the ACI prediction for conventional concrete with equivalent compressive strength but higher than empirical values reported for early fly ash-based geopolymer concrete. This result indicates that geopolymer concrete exhibits slightly lower stiffness but greater deformation capacity compared with conventional cement concrete.

Current research primarily focuses on evaluating the short-term mechanical properties of mixtures containing sea sand. To comprehensively assess the feasibility of utilizing saline sea sand in geopolymer concrete specifically, and in coastal construction structures in general, further extensive studies are required regarding durability characteristics. Future investigations should systematically address the durability of sea sand-based geopolymer concrete, specifically regarding sulfate resistance, chloride ion resistance, and long-term microstructural evolution as influenced by residual salts.

Overall, the results preliminary confirm that geopolymer concrete incorporating sea sand can provide adequate strength, improved tensile performance, and acceptable elastic stiffness, demonstrating its potential as a sustainable alternative construction material in coastal regions.

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