

RESEARCH ARTICLE

Seawater Curing Effects on the Long-Term Performance of High-Volume Fly Ash Concrete (HVFAC)

Yohans Sunarno^{1*}, Savitri Prasandi Mullyani¹, Parea Rusan Rangan², Miswar Tumpu³

¹ Civil Engineering Department, Engineering Faculty, Bosowa University, Makassar, South Sulawesi, Indonesia

² Civil Engineering Department, Engineering Faculty, University of Christian Indonesia Toraja, Toraja Regency, South Sulawesi, Indonesia

³ Disaster Management Study Program, The Graduate School, Hasanuddin University, Makassar, Indonesia

* Corresponding author : yohanssunarno@gmail.com

Tel.: +62 81389038885

Received: May 24, 2026; Accepted: Sep 9, 2026.

DOI: 10.25299/jgeet.2026.11.3.22595

Abstract

As a maritime nation, Indonesia has many concrete buildings that interact directly with the marine environment. Concrete must be designed to withstand seawater's deteriorative effects on strength and durability of material. This study's objective was to analyze the influence of immersion in seawater on the performance of concrete with 50% fly ash as a supplementary binder material. Three variants of concrete mixes, Fc 22.5, Fc 25, and Fc 30, each with 50% fly ash, were formed into cylindrical specimens and treated by curing in fresh water and seawater. The compressive strength of each specimen was assessed at ages 28, 90, and 120 days. The compressive strength test results of Fc 22.5 with curing treatment in freshwater were 22.0, 26.3, and 27.9 MPa. Conversely, when subjected to seawater curing, the compressive strength values were recorded as 20.3, 25.9, and 27.6 MPa. The results of Fc 25 compressive strength in freshwater curing based on age are (MPa): 27.3, 30.3, and 31.5, while seawater curing produced compressive strengths of (MPa): 25.2, 28.2, and 29.9. In freshwater curing, the Fc 30 compressive strength values were (MPa): 30.1, 33.0, and 33.7, while in seawater curing, the Fc 30 compressive strength values were (MPa): 28.3, 30.1, and 31.3. It was concluded that the compressive strength of concrete with 50% fly ash treated with seawater curing method was lower than that of freshwater curing method at 28, 90, and 120 days. The substitution of cement content with 50% fly ash causes the compressive strength of concrete to continue to increase after 28 days until 120 days of age.

Keywords: Seawater curing, Fly ash, HVFAC, Long-term performance, Compressive strength

1. Introduction

Indonesia, as the world's largest archipelagic nation, possesses vast marine territories that necessitate robust infrastructure to support maritime activities. The durability of construction materials, particularly concrete, is critical for structures exposed to seawater, such as bridges, ports, and coastal defenses (Wegian, 2010). Concrete in marine environments must resist aggressive agents like chlorides and sulfates, which compromise its strength and longevity (Fraternali et al., 2014; Hosseini, 2022; Kurniawandy et al., 2025; Tandilino et al., 2024). The unique geospatial challenges of Indonesia's coastline, spanning over 54,000 km, amplify the need for durable concrete solutions to mitigate frequent degradation caused by saline exposure. Marine structures without protective measures can lose up to 30% of their compressive strength within a decade due to chloride ingress (Bachtiar et al., 2024), underscoring the urgency for advanced material technologies.

Seawater contains approximately 55% chloride, 31% sodium, and 8% sulfate, with chlorides—primarily sodium chloride (NaCl) and magnesium chloride (MgCl₂)—being particularly detrimental (Chrismaningwang et al., 2017; Dasar et al., 2020; Xiao et al., 2023). These compounds react with cement hydrates, forming expansive products like ettringite and gypsum, which degrade the concrete matrix and reduce its structural integrity (Wang et al., 2022; Xu et al., 2017).

The chlorides present in seawater, primarily sodium chloride (NaCl) and magnesium chloride (MgCl₂), contribute significantly to concrete deterioration. These compounds

react with cement hydration products, leading to the dissolution of gypsum and the formation of calcium sulfoaluminate (ettringite). Sulfate attacks occur when sulfates react with calcium hydroxide (Ca(OH)₂) in hydrated cement, producing calcium sulfate (CaSO₄) and calcium aluminate hydrate (4CaO·Al₂O₃·13H₂O), which subsequently form expansive ettringite. This expansion increases internal pressure, disrupting the bond between aggregates and the cementitious matrix, ultimately reducing the structural integrity and service life of concrete (Aswad et al., 2021; Chrismaningwang et al., 2017; Dasar et al., 2020; X. Li et al., 2024; Wang et al., 2022; Xiao et al., 2023).

Porosity is a crucial factor in determining the durability of concrete, particularly for structures exposed to marine environments or groundwater. In coastal areas, seawater containing sodium chloride (NaCl) penetrates concrete pores, accelerating degradation. When NaCl crystallizes upon evaporation, it exerts pressure on pore walls, leading to microcracking and eventual concrete spalling (Alterary & Marei, 2021). This mechanism underscores the importance of reducing permeability to enhance concrete longevity in aggressive environments. Several studies have shown that the permeability of concrete is inversely correlated with its compressive strength (Harmiyati et al., 2024; Moïnul Islam et al., 2012; Nelfia et al., 2025; Yunus, 2010).

To address these challenges, researchers have explored alternative concrete technologies, including the incorporation of fly ash—a byproduct of coal combustion—as a supplementary cementitious material (SCM). Seawater-induced concrete damage stems from chloride and sulfate interactions with cement phases. For instance, the reaction

$2\text{NaCl} + \text{MgCl}_2 + 2\text{Ca(OH)}_2 \rightarrow 2\text{CaCl}_2 + \text{Mg(OH)}_2 + 2\text{NaOH}$ releases calcium ions, increasing porosity and promoting crack formation due to expansive hydrates (Arsyad et al., 2023). Fly ash mitigates these effects by reacting with Ca(OH)_2 to form additional calcium silicate hydrate (C-S-H), a denser and more durable binder (Hosseini, 2022).

Fly ash offers several advantages over conventional Portland cement due to its physical and chemical properties. Its finer particle size improves packing density, reducing pore connectivity and permeability (Alterary & Marei, 2021; G. Li et al., 2022; Sunarno, Tjaronge, et al., 2024; Wirth et al., 2019). Chemically, fly ash contains reactive silica and alumina, which participate in pozzolanic reactions, enhancing long-term strength and durability (Indriyanto et al., 2020). Studies confirm that fly ash-modified concrete exhibits higher compressive strength beyond 28 days due to improved microstructure (Sunarno, et al., 2024a; Sunarno, et al., 2024b). However, at early ages (<28 days), seawater curing can reduce strength due to sulfate-chloride synergy, which disrupts hydration and induces expansion (Wegian, 2010). Chloride infiltration through capillary pores exacerbates these effects, leading to cracking and brittleness (Bachtiar et al., 2024; Kurniawandy et al., 2025).

Several previous studies have demonstrated that the application of fly ash as a supplementary cementitious material (SCM) enhances the compressive strength of concrete beyond 28 days of curing. This improvement is attributed to the finer particle size of fly ash, which mechanically densifies the mortar matrix, thereby increasing its compressive strength (Hosseini, 2022; G. Li et al., 2022; Yahya et al., 2021; Yunus, 2010). For instance, Sunarno et al. (2024) observed that high-volume fly ash concrete exhibited superior long-term strength due to the pozzolanic reaction, which consumes calcium hydroxide (Ca(OH)_2) and forms additional calcium silicate hydrate (C-S-H) gel, further refining the pore structure. However, at early ages (below 28 days), concrete cured in seawater often shows lower compressive strength compared to freshwater-cured specimens. This phenomenon is linked to sulfate attack and chloride ion infiltration, which are exacerbated by the presence of dissolved salts in seawater (Nasr et al., 2022). Chloride ions penetrate the concrete through pores formed by the leaching of Ca(OH)_2 during cement hydration, disrupting the hydration process and inhibiting strength development (Hosseini, 2022a). Additionally, the combined action of sulfates and chlorides can lead to expansive reactions, causing internal stresses, spalling, and cracking, ultimately resulting in brittle failure of the concrete (Bachtiar et al., 2024; Moinul Islam et al., 2012). Studies by Indriyanto et al. (2020) and Zahlim et al. (2022) further confirm that fly ash mitigates these detrimental effects over time by reducing permeability and enhancing the durability of seawater-cured concrete, though its benefits are more pronounced in later stages. Thus, while fly ash improves long-term performance, its early-age limitations under aggressive curing conditions necessitate careful consideration in mix design and curing practices.

However, it is important to note that real marine environments are characterized by complex and dynamic conditions, including variations in seawater chemistry, temperature fluctuations, tidal actions, and wet-dry cycles. (Kurniawandy et al., 2025). These factors significantly influence the durability and long-term performance of concrete structures. In this study, the experimental setup focuses on controlled immersion conditions using natural seawater to isolate the fundamental effects of seawater curing on HVFAC performance. While this approach enables a clearer understanding of the primary mechanisms, it does not fully replicate the complexity of actual marine exposure. Therefore, the findings of this study should be interpreted as

a baseline for further investigations under more realistic environmental conditions.

The purpose of this study is to analyse the effect of seawater curing on the performance of concrete with 50% fly ash as an additional binder in three concrete mix variations, namely fc 22.5, fc 25.0, and fc 30.0. Each specimen will be tested and evaluated for its performance based on the results of unit weight and compressive strength at the age of (days): 28, 90, and 120 days.

2. Material and Method

2.1 Cementitious Characteristic

This research uses type-1 cement or ordinary Portland cement (OPC) and fly ash type F. The use of OPC type in this study is with the consideration that OPC still has the opportunity to be given additional pozzolanic substances, namely, fly ash. A sample of OPC was obtained from a local cement factory around Maros, South Sulawesi, Indonesia. The results of testing the characteristics of OPC aim to obtain data on the physical and chemical properties that will be the basis for designing concrete mixtures. The quality of OPC used determines the quality of the resulting concrete mix. Local brand OPC has been used in several previous studies with satisfactory results and in accordance with technical specifications according to ASTM C150 standards (Sunarno, 2025a; Sunarno et al., 2025b; Sunarno, et al., 2024b). The test results are described in Table 1.

Table 1. Ordinary Portland cement characteristics

Properties	Unit	Result	Accepted
Chemical Properties			
MgO	%	1.53	Max. 6.00
SO ₃ if C ₃ A	%	2.30	Max. 3.50
Insoluble residue	%	2.49	Max. 5.00
Loss of Ignition	%	1.19	Max. 3.00
Equivalent Alkali	%	0.39	-
Physical Properties			
Autoclave expansion	%	0.24	Max. 0.80
Fineness/Blaine meter	m ² /kg	341	Min. 280
Initial setting time	minute	109	Min. 45
Final setting time	minute	248	Max. 375
Compressive strength			
- 3 days	kg/cm ²	190	Min. 135
- 7 days	kg/cm ²	270	Min. 215
- 28 days	kg/cm ²	362	Min. 300
False set, final	%	83.11	Min. 50
Air content	% vol.	4.49	Max. 12

Table 2. Fly ash chemical characteristics

Properties	Unit	Result
MgO	%	2.73
SO ₃	%	0.96
SiO ₂	%	50.36
Al ₂ SO ₃	%	26.12
Fe ₂ O ₃	%	6.30
CaO	%	5.90
Na ₂ O	%	3.48
K ₂ O	%	0.84
TiO ₂	%	0.95
MnO ₂	%	0.13
P ₂ O ₅	%	0.32
Cr ₂ O ₃	%	0.06
Loss on ignition	%	1.85

Fly ash was taken from the Unit 1 BSW Jeneponto power plant located Jeneponto regency, in South Sulawesi, Indonesia. Evaluated fly ash properties are also utilized to determine the mix design that will be prepared. Refer to the values listed in Table 2, the analysis indicates that the fly ash utilized in this research is classified as type F fly ash based on its composition, namely the concentrations of SiO₂, Al₂SO₃,

and Fe₂O₃, which total to 82.78%. (Alterary & Marei, 2021; Sunarno, 2024b; Suraneni et al., 2021; Wirth et al., 2019).

2.2 Aggregate Characteristic

This research uses two types of aggregates: coarse aggregate and fine aggregate/sand. Raw material for coarse aggregate is sourced from Bili-Bili area of Gowa Regency. The fine aggregate utilized in this study is derived from silica sand sourced from Pinrang, located in the South Sulawesi region of Indonesia. Table 3 presents empirical data demonstrating that the physical attributes of the aggregates employed satisfy the specifications outlined in ASTM C-33-03.

The aggregates used in this study have been tested and used in previous studies with satisfactory results.

Table 3. Physical characteristics of aggregate

Properties	Coarse Aggregate	Fine Aggregate
Colloid content (%)	0.77	4.79
Fineness modulus/FM	6.80	3.01
Water absorption (%)	1.09	2.99
Specific gravity, SSD	2.58	2.60

2.3 Mix Design

The mix design of this study consisted of 3 variations, namely fc 22.5, fc 25, and fc 30, each containing fly ash at 50% of the total binder. The selection of 50% fly ash content is based on the minimum content requirements that must be met as high volume fly ash concrete (HVFA), while the determination of three concrete grades namely fc22.5, fc25 and fc30 are 3 concrete grades that are often used for building construction exposed to seawater at the research site. This design specifies the quantities of each material used, including cement, fly ash, coarse aggregate, fine aggregate, water, and additives, per 1 m³ volume of concrete. There are two types of additives used, namely retarder (admix-1) and superplasticizer (admix-2). A retarder serves to slow down the set time of the mixture, while a superplasticizer serves to reduce water consumption and increase the workability of fresh concrete so that the design performance of concrete can be achieved. The production process was carried out on a laboratory scale using a mini mixer. The mix design of each specimen used in this study is described in Table 4.

The selection of three mix variations with a constant fly ash replacement level of 50% was intended to represent typical HVFA applications while maintaining experimental consistency. However, it is acknowledged that broader variations in mix proportions, including different fly ash contents and alternative supplementary cementitious materials such as slag or silica fume, could provide a more comprehensive understanding of performance variability. These aspects are recommended for future studies to improve the generalizability of the results.

Table 4. Mixed design composition of concrete (per m³)

Material	Grade		
	Fc22.5	Fc25.0	Fc30.0
Cement, kg	198	219	239
Fly ash, kg	198	219	239
Coarse Agg.	900	940	1020
Fine Agg., kg	910	850	770
Water, l	130	130	131
Admixture-1, l	1.19	1.31	1.43
Admixture-2, l	1.00	1.10	1.20

2.4 Workability Test of Fresh Concrete

The objective of conducting tests on fresh concrete is to assess its workability. Workability is a parameter of the ease

of casting process in the field. Workability tests are conducted by conducting slump tests that follow ASTM C1611 standards in their implementation, as Figure 1.



Fig. 1. Slump Test

Fig. 2 Seawater curing

The Subsequents step entails casting specimens using a 100-mm-diameter by 200-mm-high cylindrical mold. Pouring the mixture, kneading, compaction, and fresh concrete must refer to ASTM C31-19 standards. Specimens that have been molded and hardened are treated with the curing method of immersion in water, as Figure 2. In this experiment, the specimens were divided into two immersion media. Half of the specimens were immersed in a tub of fresh water; the other half were immersed in a tub of seawater.

2.5 Compressive Strength Test of Hard Concrete

The method of testing the compressive strength of specimens follows the rules and regulations in ASTM C39/C39M, which describe test preparation, test execution, and the calculation of compressive strength values. The compression strength of a cylindrical test sample is determined by dividing the highest load applied to the sample during the test by its average square area. The resulting value is expressed by rounding to one decimal point and reported in units of 0.1 MPa. The compression strength of concrete can be determined using Eq. 1

$$F_c = N/A \quad (1)$$

Definition:

F_c is compressive strength of cylindrical specimens, in MPa or N/mm²

N is axial compressive force, in Newtons (N);

A is specimen's cross-sectional area, in mm²

3. Results and Discussion

3.1 Workability of Fresh Concrete

Workability test is conducted with slump test in fresh concrete. According to the slump test results in Table 4 for each mix variation, the average slump values for fc 22.5, fc 25.0, and fc 30.0 were 109.5 mm, 124.5 mm, and 126.0 mm, respectively. According to this finding, all of the fresh concrete mixtures are categorized as normal concrete with a moderate level of workability. Visual observation of the fresh concrete showed that all mixes were adhesive, homogeneous, and avoided bleeding.

Table 5. Slump test result

Grade	Slump Result (mm)		
	Maximum	Minimum	Average
Fc22.5	112.0	107.0	109.5
Fc25.0	121.0	128.0	124.5
Fc30.0	123.0	129.0	126.0

3.2 Unit Weight Test Result

Figure. 3 shows the unit weight values for all specimen variations at 28, 90, and 120 days of age, respectively. Fc 22.5 has the smallest unit weight values, ranging from 2349 to 2417 kg/m³. Fc 25 has unit weight values (kg/m³) of 2361, 2400, and 2430, respectively. At Fc 35, the unit weight values (kg/m³) are 2380, 2405, and 2435. Based on all unit weight values obtained, all specimens can be grouped as concrete with a normal specific gravity category, refer to ACI 318-11.

The unit weight of concrete exhibits a positive correlation with its age, effective in concrete mixtures at the nano scale, providing positive effects on workability even at very low doses. Their dispersion properties facilitate the uniform distribution of aggregates within the mix, thereby reducing friction between cement particles and aggregates.

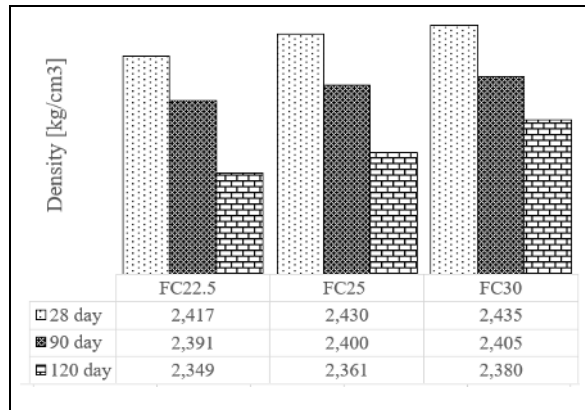


Fig. 3. Unit weight value of the test specimen

3.3 Compressive Strength

The compressive strength of the tested specimens was evaluated at 28, 90, and 120 days, covering all mixture variations, under two distinct curing conditions: freshwater and seawater. Table 6 presents a detailed summary of these findings. Under the freshwater curing regime, the specimens with design strength grade fc 22.5 exhibited compressive strengths of 22.0 MPa at 28 days, increasing to 26.3 MPa at 90 days, and further reaching 27.9 MPa at 120 days. For specimens with a target grade fc 25, the measured compressive strengths were 27.3 MPa at 28 days, rising to 30.3 MPa at 90 days, and slightly improving to 31.5 MPa at 120 days. Meanwhile, the higher strength grade fc 30 specimens showed compressive strengths of 30.1 MPa at 28 days, progressing to 33.0 MPa at 90 days, and achieving 33.7 MPa at 120 days.

In contrast, when cured in seawater, the compressive strength values generally lagged behind those cured in fresh water. For grade fc 22.5, the specimens recorded compressive strengths of 20.3 MPa at 28 days, 25.9 MPa at 90 days, and 27.6 MPa at 120 days. The grade fc 25 specimens, under seawater curing, showed strengths of 25.2 MPa at 28 days, increasing to 28.2 MPa at 90 days, and further to 29.9 MPa at 120 days. Similarly, grade fc 30 specimens displayed compressive strengths of 28.3 MPa at 28 days, 30.1 MPa at 90 days, and 31.3 MPa at 120 days.

Table 6. Compressive strength of concrete

Material	Compressive Strength, MPa		
	28 days	90 days	120 days
Fc22.5 FW	22.0	26.3	27.9
Fc22.5 SW	20.3	25.9	27.6
Fc25.0 FW	27.3	30.3	31.5
Fc25.0 SW	25.2	28.2	29.9
Fc30.0 FW	30.1	33.0	33.7
Fc30.0 SW	28.3	30.1	31.3

Figure 4 shows a comparison of the compressive strength of grade fc 22.5 specimens using two variations, namely freshwater curing against seawater. All tests show that the compressive strength of specimens with seawater curing is smaller than that with freshwater curing. The difference decreases as concrete ages. The compressive strength increases with the increasing age of the concrete.

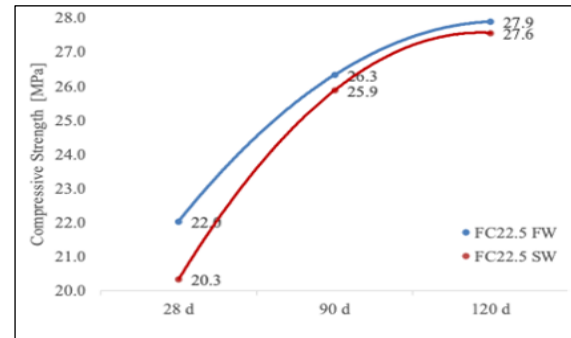


Fig. 4. Fc 22.5 sea water vs fresh water curing

Figure 5 describes a comparison of the compressive strength of grade fc 25 specimens using two variations. All tests show that the compressive strength results in specimens with seawater curing are smaller than in specimens with freshwater curing. The difference increases as concrete ages. The compressive strength increased with the increasing age of concrete, from 28, 90, and 120 days.

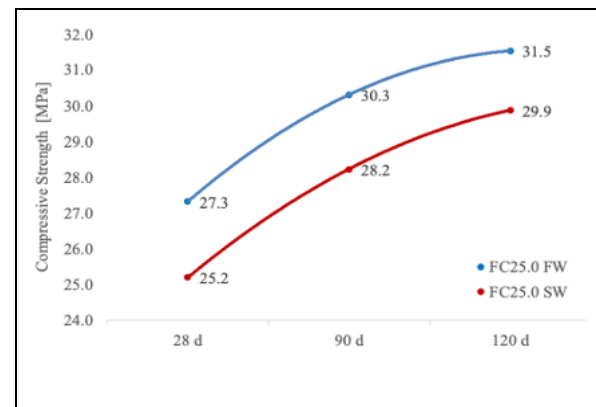


Fig. 5. Fc 25.0 sea water vs fresh water curing

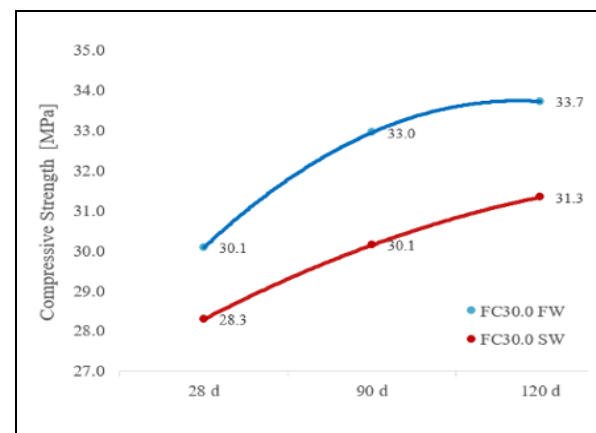


Fig. 6. Fc 35.0 sea-water vs freshwater curing

Then, from Figure 6, it can be seen that the comparison of the compressive strength of grade fc 30 specimens using two variations. All tests show that the compressive strength results in specimens with seawater curing are smaller than in specimens with freshwater curing. The difference that occurs is almost constant as the concrete ages. The compressive

strength increased with increasing concrete age, including at 28, 90, and 120 days.

All specimen tests showed that curing with seawater resulted in smaller concrete compressive strength values than curing with fresh water. This is due to the absorption of seawater into concrete, which causes concrete damage. The inclusion of 50% fly ash in the concrete sample led to a notable enhancement in its compressive strength following 28 days. Based on these findings, it is a consideration for structural designers to provide sufficient safety factors in designing concrete quality in buildings around the sea.

From a microstructural perspective, the lower compressive strength observed in seawater-cured specimens can be attributed to the interaction between chloride and sulfate ions with cement hydration products. These interactions may lead to the formation of expansive compounds such as ettringite and gypsum, which induce internal stresses and microcracking within the concrete matrix. Furthermore, chloride ingress can increase pore connectivity, thereby reducing the overall density of the hardened concrete. (X. Li et al., 2024; Xu et al., 2017)

On the other hand, the incorporation of high-volume fly ash contributes to long-term strength development through pozzolanic reactions, which gradually refine the pore structure and reduce permeability. Although this study does not include direct microstructural characterization such as SEM or XRD analysis, the observed macroscopic behavior is consistent with widely reported hydration and durability mechanisms of HVFAC in aggressive environments. Future studies incorporating microscopic analysis are necessary to validate these interpretations.

Compared to conventional curing methods, freshwater curing remains more effective in achieving higher early and long-term compressive strength. However, seawater curing presents a practical alternative in coastal and remote areas where freshwater resources are limited. In comparison with other durability enhancement techniques, such as the use of chemical admixtures, corrosion inhibitors, or fiber reinforcement, HVFAC offers a more sustainable solution due to its reduced cement content and improved long-term performance. Nevertheless, its relatively lower early strength under seawater exposure remains a limitation that must be addressed through optimized mix design or hybrid material approaches.

3.4 Practical Implications

The application of HVFAC with seawater curing presents several practical considerations. From an economic perspective, the use of fly ash as a partial cement replacement can significantly reduce material costs and lower carbon emissions associated with cement production. This makes HVFAC an attractive option for sustainable construction, particularly in developing countries.

In terms of constructability, the use of seawater for curing may offer logistical advantages in coastal regions by reducing dependency on freshwater resources. However, careful quality control is required to ensure consistent performance, particularly during early-age strength development.

Environmentally, the utilization of industrial by-products such as fly ash contributes to waste reduction and promotes circular economy practices. Nevertheless, long-term durability concerns under aggressive marine exposure must be addressed to prevent premature structural degradation.

Overall, while HVFAC cured in seawater shows promising potential, its implementation in real-world projects requires a balanced consideration of performance, cost, and environmental impact.

4. Conclusions

According to the research findings and discussion, the following can be concluded:

1. All specimens' unit weights can be categorized as normal-density concrete.
2. The results of the fresh concrete slump test indicated it to be a medium level workability concrete.
3. The compressive strength value of concrete with fly ash in seawater curing is smaller than freshwater curing at the ages of 28, 90, and 120 days. This is due to the influence of seawater containing chloride (Cl), which is absorbed into the concrete.
4. The substitution of cement content with 50% fly ash increases the compressive strength of concrete, which continues to increase after 28 days until 120 days of age.
5. This study is limited to controlled seawater immersion conditions and does not account for environmental variables such as temperature fluctuations, tidal actions, and wet-dry cycles. These factors should be considered in future research to better simulate real marine conditions.
6. Future studies are recommended to incorporate a wider range of mix compositions, include other supplementary cementitious materials, and conduct microstructural analyses to better understand the underlying mechanisms and improve the applicability of HVFAC in marine environments.

Acknowledgements

The author expresses sincere gratitude to all parties who have contributed to the successful completion of this paper. Special thanks are extended to the laboratory team of PT Bosowa Beton Indonesia, Makassar, South Sulawesi, Indonesia, for their invaluable support. Their dedication and commitment were instrumental in facilitating the research processes, and their assistance in data collection and analysis was essential to the achievement of this work's objectives.

References

- Alterary, S. S., & Marei, N. H. (2021). Fly ash properties, characterization, and applications: A review. In *Journal of King Saud University - Science* (Vol. 33, Number 6). Elsevier B.V. <https://doi.org/10.1016/j.jksus.2021.101536>
- Arsyad, F., Lakawa, I., Ilham, V. A., & Hakiman, H. (2023). Study Of Concrete Mixture Using Sea Sand With Fresh Water and Sea Water Cure. *Sultra Civil Engineering Journal*, 4(1). <https://doi.org/10.54297/sciej.v4i1.459>
- Aswad, N. H., Mustika, W., Tachrir, & Hartono, Y. D. (2021). The behaviour of self-compacting concrete (SCC) with nickel slag as fine aggregate towards seawater curing. *IOP Conference Series: Earth and Environmental Science*, 622(1). <https://doi.org/10.1088/1755-1315/622/1/012030>
- Bachtiar, E., Setiawan, A. M., Setiawan, A., & Fudlailah, P. (2024). Mikrostruktur, Porositas Dan Sifat Mekanik Beton Curing Air Laut. *Jurnal Talenta Sipil*, 7(1). <https://doi.org/10.33087/talentasipil.v7i1.492>
- Chrismaningwang, G., Basuki, A., & Sambowo, K. A. (2017). The Effect of Seawater Curing on the Correlation between Split Tensile Strength and Modulus of Rupture in High-strength Concrete Incorporating Rice Husk Ash. *Procedia Engineering*, 171. <https://doi.org/10.1016/j.proeng.2017.01.447>
- Dasar, A., Patah, D., Hamada, H., Sagawa, Y., & Yamamoto, D. (2020). Applicability of seawater as a mixing and curing agent in 4-year-old concrete. *Construction and*

- Building Materials, 259, 119692. <https://doi.org/10.1016/j.conbuildmat.2020.119692>
- Fraternali, F., Spadea, S., & Berardi, V. P. (2014). Effects of recycled PET fibres on the mechanical properties and seawater curing of Portland cement-based concretes. *Construction and Building Materials*, 61, 106–118. <https://doi.org/10.1016/j.conbuildmat.2014.03.019>
- Harmiyati, Al Ihsyan, N., & Syahputri, D. (2024). Analysis of the Effect of Bagasse Addition on Compressive Strength, Porosity, and Permeability of Pervious Concrete as Material for Green Building Program. *Journal of Geoscience, Engineering, Environment, and Technology*, 9(04), 420–425. <https://doi.org/10.25299/jgeet.2024.9.04.15093>
- Hosseini, S. A. (2022). Seawater curing effects on the permeability of concrete containing fly ash. *Advances in Concrete Construction*, 14(3), 205–214. <https://doi.org/10.12989/acc.2022.14.3.205>
- Indriyanto, L. A., Saputra, A., & Sulisty, D. D. (2020). Pengaruh Air Laut Pada Masa Perawatan Terhadap Infiltrasi Ion Klorida pada Beton Dengan Penambahan Fly Ash 12.5%. *Jurnal Riset Rekayasa Sipil Universitas Sebelas Maret*, 3(2), 61–67.
- Kurniawandy, A., Ismeddiyanto, Haekal, M., & Zikri, R. (2025). Study of the Mechanical Properties of Underwater Concrete in Seawater Environments. *Journal of Geoscience, Engineering, Environment, and Technology*, 10(1), 51–58. <https://doi.org/10.25299/jgeet.2025.10.1.20989>
- Li, G., Zhou, C., Ahmad, W., Usanova, K. I., Karelina, M., Mohamed, A. M., & Khallaf, R. (2022). Fly Ash Application as Supplementary Cementitious Material: A Review. In *Materials* (Vol. 15, Number 7). MDPI. <https://doi.org/10.3390/ma15072664>
- Li, X., Wang, Z., Zhang, M., Liu, R., Wang, Z., Zhang, C., Yan, J., Liu, Y., Zhang, Z., & Wu, W. (2024). Properties of the cement containing hybrid micro-fibers and polymer latex using the orthogonal test: A comparative study of freshwater and seawater curing conditions. *Construction and Building Materials*, 411, 134661. <https://doi.org/10.1016/j.conbuildmat.2023.134661>
- Moinul Islam, M., Saiful Islam, M., Al-Amin, M., & Mydul Islam, M. (2012). Suitability of sea water on curing and compressive strength of structural concrete. In *Journal of Civil Engineering (IEB)* (Vol. 40, Number 1).
- Nasr, A. A., Chen, S., Wang, Y., Jin, F., & Qiu, L. C. (2022). Strength evaluation of a new underwater concrete type. *Case Studies in Construction Materials*, 16, e00884. <https://doi.org/10.1016/j.cscm.2022.e00884>
- Nelfia, L. O., Rahman, M. R. F., Adijaya, K., & Sunarno, Y. (2025). Analysis of the Potential and Impact of Utilizing Nickel Slag Powder and Recycled Plastic on the Technical Properties of Concrete Blocks: In Terms of Strength and Cost Efficiency. *Journal of Geoscience, Engineering, Environment, and Technology*, 10(4), 478–485. <https://doi.org/10.25299/jgeet.2025.10.4.24979>
- Sunarno, Y. (2025a). The influence of fly ash characteristics as a supplementary cementitious material (SCM) on concrete's mechanical properties. *Materials Research Proceedings*, 48, 587–596. <https://doi.org/10.21741/9781644903414-64>
- Sunarno, Y., Abduh, N., Eka Yuniarto, Tumpu, M., & Nelfia, L. O. (2025b). Application of Carbon Nanotube (CNT) to Improve Mechanical Properties of Concrete: A Comparative Analysis with Superplasticizer. *Journal of Geoscience, Engineering, Environment, and Technology*, 10(1), 91–96. <https://doi.org/10.25299/jgeet.2025.10.1.19526>
- Sunarno, Y., Rangan, P. R., Ambun, E., Tumpu, M., Rinanti, A., & Nelfia, L. O. (2024a). Utilization of High-Volume Fly Ash As A Supplementary Cementitious Material In Environmentally Friendly Concrete. *Indonesian Journal of Environmental Technology*, 7(1), 106–118. <https://doi.org/https://doi.org/10.25105/urbanenvirotech.v7i1.19658>
- Sunarno, Y., Tjaronge, M. W., & Muhiddin, A. B. (2024b). Mechanical Properties of High-Volume Fly Ash Concrete With Varying Fly Ash Content. *ARNP Journal of Engineering and Applied Sciences*, 19(16), 1063–1068. www.arnpjournals.com
- Suraneni, P., Burris, L., Shearer, C. R., & Hooton, R. D. (2021). ASTM C618 Fly Ash Specification: Comparison with Other Specifications, Shortcomings, and Solutions. *ACI Materials Journal*, 118(1). <https://doi.org/10.14359/51725994>
- Tandilino, F., Hutabarat, L. E., & Simanjuntak, R. M. (2024). Bestmittel and Silicafume Effect on Concrete Compressive Strentgh with Seawater Curing. *Jurnal PenSil*, 13(1). <https://doi.org/10.21009/jpensil.v13i1.39103>
- Wang, C., Liu, Z., Zhang, T., & Zhang, Y. (2022). Influence of Seawater and Curing Conditions on the Hydration Performance of Portland Cement. *Cailiao Daobao/Materials Reports*, 36(10). <https://doi.org/10.11896/cldb.21010137>
- Wegian, F. M. (2010). Effect of seawater for mixing and curing on structural concrete. *IES Journal Part A: Civil and Structural Engineering*, 3(4). <https://doi.org/10.1080/19373260.2010.521048>
- Wirth, X., Benkeser, D., Nortey Yeboah, N. N., Shearer, C. R., Kurtis, K. E., & Burns, S. E. (2019). Evaluation of alternative fly ashes as supplementary cementitious materials. *ACI Materials Journal*, 116(4). <https://doi.org/10.14359/51716712>
- Xiao, S., Zhang, M., Zou, D., Liu, T., Zhou, A., & Li, Y. (2023). Influence of seawater and sea sand on the performance of Anti-washout underwater concrete: The overlooked significance of Mg2+. *Construction and Building Materials*, 374, 130932. <https://doi.org/10.1016/j.conbuildmat.2023.130932>
- Xu, X., Yang, J., Gu, M., & Li, X. (2017). Effect of Seawater Curing on Microstructure and Properties of Magnesium Potassium Phosphate Cement Paste. *Jianzhu Cailiao Xuebao/Journal of Building Materials*, 20(5). <https://doi.org/10.3969/j.issn.1007-9629.2017.05.003>
- Yahya, Z., Abdullah, M. M. A. B., Li, L. Y., Nergis, D. D. B., Hakimi, M. A. A. Z., Sandu, A. V., Vizureanu, P., & Razak, R. A. (2021). Behavior of alkali-activated fly ash through underwater placement. *Materials*, 14(22). <https://doi.org/10.3390/ma14226865>
- Yunus, A. (2010). Compressive Strength and Flexural Strength of Concrete with Added Material of Fly Ash as Material of Rigid Pavement. *Universitas Sebelas Maret Surakarta*.
- Zahlim, A., Bachtar, E., & Makbul, R. (2022). Efek Curing Air Laut Terhadap Kuat Tekan Beton Mutu Tinggi Yang Menggunakan Fly Ash Sebagai Substitusi Pasir. *Borneo Engineering: Jurnal Teknik Sipil*, 1(1). <https://doi.org/10.35334/be.v1i1.2161>

