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PERMEABILITY AND COMPRESSIVE STRENGTH OF NORMAL CONCRETE SUBMERGED IN SEA AND BRACKISH WATER

Chatarina Niken*, Masdar Helmi, Mohammad Isneini, Endro Prasetyo Wahono, Dyah Indriana Kusumastuti

Civil Engineering Department, Faculty of Technology, University of Lampung, Jl. Sumantri Brojonegoro No 1, Gedong Meneng Campus, 35141, Bandar Lampung, Lampung, Indonesia

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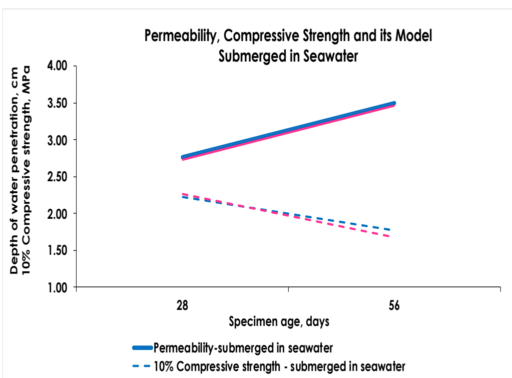
*Corresponding author
chatarinaniken@yahoo.com

Graphical abstract



Abstract

Indonesia, an archipelagic nation with numerous rivers and the longest coastline in the world, is home to many small and simple piers, most of which utilize normal concrete. This study examines the permeability of concrete with a compressive strength of 22.5 MPa (fc') and its degradation when immersed in seawater and brackish water at a small pier in Lampung, Indonesia. The immersion durations were 28 and 56 days. The permeability test samples and the immersed concrete samples for the compression test were cylinders with a diameter of 15 cm and a height of 30 cm, subjected to a split tensile test. Permeation depth was measured from the split samples. The standard permeability test resulted in a depth of 2.66 cm, meeting the material requirements for a strong, aggressive environment. The permeability of the samples immersed in seawater increased by 4.14% and 31.74%, while those immersed in brackish water increased by 6.65% and 24.21% at 28 and 56 days, respectively, compared to the standard permeability. A deeper permeation correlated with a reduction in compressive strength. The compressive strength of concrete submerged in seawater decreased by 1.3% and 29%, and by 7% and 18.5% when submerged in brackish water at 28 and 56 days, respectively, against the original f_c'. The 10% reduction in compressive strength (C_c) at 28 and 56 days is reflective of permeability and can be expressed by the equation: 10% C_c = (-tan αa) t + C_f, where the permeability slope and C_{sf} are constants.

Keywords: Brackish water, compressive strength, concrete, seawater, seepage-flow

1.0 INTRODUCTION

Concrete is a commonly chosen material for coastal structures due to its superior durability compared to steel and wood. However, improper concrete mix design can lead to a significantly reduced lifespan of coastal concrete structures, sometimes lasting less than 5 years (Figure 1). The construction of a pier involves substantial financial and labor resources, and low material durability can render these investments ineffective. Additionally, concerns about a potential clean water shortage by 2050 [1] have Å efforts to optimize the use of river water in estuaries and coastal areas. Several researchers have addressed this issue by studying concrete exposed to seawater and brackish water or incorporating materials sourced from the sea. However, the results of these studies vary, indicating that further research is necessary.

Figure 1 Degradation of concrete columns, beams, and plates at Way Ratai pier, Lampung, Indonesia.

The compressive strength of 28-day-old concrete cured in seawater is 8% higher than that cured in freshwater [2]. Concrete produced using seawater as a mixing medium exhibits better quality than that made with ordinary water [3]. The compressive strength of seawater concrete is generally higher than that of freshwater concrete [4,5]. However, studies by Adnan *et al*. (2020) and Hamdi & Imran (2019) reported lower compressive strength in seawater concrete [6,7]. Using seawater and sea sand in concrete production is promising due to accelerated cement hydration, improved pore structure, and enhanced durability, provided the material composition is properly adjusted to mitigate chemical corrosion from sea salts [8].

Research aimed at enhancing concrete performance using seawater has been conducted, including reducing the salinity of brackish water [9] and incorporating white cement. The compressive strength reduction in concrete without white cement is greater at 11.28%, whereas concrete with white cement shows an average reduction of only about 4% [10].

Concrete is inherently porous, with a surface area of pores around 500 m^2/cm^3 [11]. This porosity allows substances between 10-700 nm (0.00001 mm- 0.0007 mm) to penetrate the concrete. The size of a water molecule is approximately 3 Å in diameter (0.3 nm or $3x10^{-8}$ cm), enabling seawater to infiltrate concrete. The chemical parameters of seawater and brackish water impact concrete strength and the rate of chemical ingress can be determined through concrete penetration and permeability tests.

Rapid chloride penetration tests on cracked and uncracked samples have been performed to estimate the service life of concrete [12, 13]. Water content significantly influences concrete permeability, and the degradation of beams and plates can occur due to seawater vapor ingress [14]. The mechanism of water vapor entry into concrete is complex, depending on materials, mixture characteristics, curing conditions, and other factors [15]. Studies on concrete permeability and durability, from theoretical concepts to field applications, have been published [16]. As the water-cement (W/C) ratio increases, porosity increases; conversely, as the aggregate-cement (A/C) ratio increases, porosity decreases [17]. The optimal W/C ratio for water-permeable concrete performance is 0.28 [18]. Increased porosity reduces concrete compressive strength. Differences in porosity and permeability coefficients across various aggregate ratios and the presentation of a mix ratio that meets compressive strength requirements as per Korean specifications have been investigated [19]. The oven-drying system has been found to increase concrete permeability [20]. A strong correlation between water and gas permeability in concrete with varying water-binder (W/B) ratios has been studied [21]. A method combining the beetle antenna search algorithm and random forest to predict permeable concrete permeability has also been developed [22]. A correlation between permeability and porosity was proposed based on Darcy and Bernoulli's law [23]. Measuring water permeability and porosity accurately is challenging, and it becomes more difficult as concrete quality improves [24]. Assessing concrete cover quality is essential for the proper maintenance of concrete structures. Tests on laboratory-prepared concrete and concrete exposed to actual marine conditions have shown that air permeability, neutralization, and chloride ion diffusion coefficients are highly correlated [25]. Moisture has a detrimental impact, leading to unexpected results [26]. With Indonesia's average relative humidity at 72% [27], adverse effects on concrete can occur rapidly.

Indonesia has the longest coastline in the world, leading to the construction of many coastal structures such as small piers, fish markets, tourism spots, and even hotels, most of which use standard concrete. The country is also rich in rivers, all of which flow into the sea. Given the above context, research on concrete in contact with seawater and brackish water is crucial. Concrete permeability dictates the degradation rate of concrete in coastal and riverine environments. Ocean waves, which continuously ebb and flow, allow seawater to penetrate concrete through a unique mechanism. Standard penetration tests do not account for the fluctuating pressures of tidal movements. Understanding actual penetration is essential, particularly in high-humidity regions like Indonesia, yet this has not been extensively studied, especially in real locations within humid tropical areas.

2.0 METHODOLOGY

This research was conducted experimentally, using normal concrete with a target quality of 22.5 MPa.

The experimental procedures are described in the following paragraphs, and the research methodology is illustrated in the flow chart shown in Figure 2.

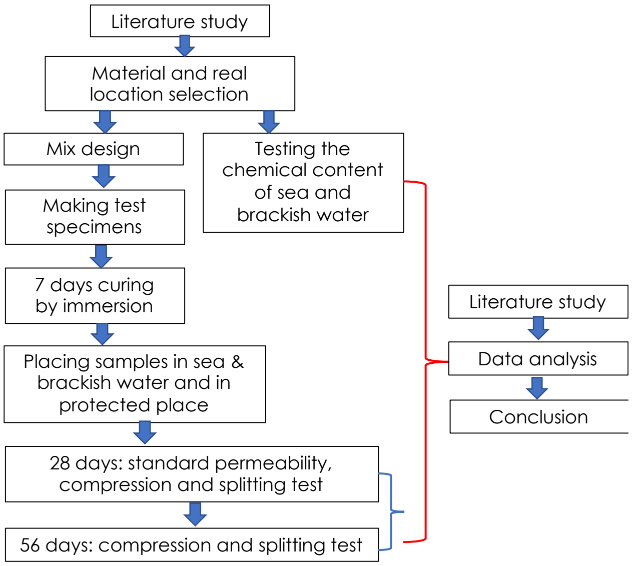


Figure 2 Research flow chart

2.1 Materials

The properties of the materials used in this research are presented in Table 1, and the mix design details are shown in Table 2.

Table 1 Materials properties

Properties	Normalconcrete
Mix design	SNI 03-2834-2000 [28]
Sand	Gunung Sugih Sumatra
-Specific gravity	2.514
-Absorption	1.03%
Coarse aggregate	Sumber Batu Berkah Ltd (size maximum 20mm)
-Specific gravity	2.663
-Absorption	2.22%
Cement	Portland Composite Cement- Tiga Roda Ltd

Table 2 Mix design

Materials	Normal concrete
Cement (kg/m³)	379.6
Fine aggregate (kg/m³)	741.6
Coarse aggregate (kg/m³)	1013.75
Water (kg/m³)	205
W/C	0.54

2.2 Methods

At the age of 1 day, all samples were cured by soaking in water for up to 7 days. After curing, samples for the standard permeability test and six cylindrical samples were placed in a protected environment. The six cylindrical samples were then transported to two different locations for immersion:

1. in the sea at Pondok Nelayan port, Teluk Betung, Lampung, Indonesia (Figure 3a)
2. in brackish water at the confluence of a river and the sea in Cuku Nyi Nyi Village, Pesawaran, Lampung, Indonesia (Figure 3b)

(a) (b)

Figure 3 Immersion of samples at the actual location: (a) Pondok Nelayan Port in Teluk Betung, Lampung, (b) Confluence of sea and river water in Cuku Nyi Nyi Village, Pesawaran, Lampung

The tests conducted included compressive strength tests, permeability tests, and chemical content analysis of seawater and brackish water.

2.2.1 *Compressive Strength*

Compressive strength was measured by testing cylindrical samples with a diameter of 15 cm and a height of 30 cm. The samples were tested under three different conditions: protected, submerged in seawater, and submerged in brackish water. Observations and tests were carried out at the ages of 28 and 56 days.

2.2.2 *Permeability Test*

Permeability was assessed using two methods: laboratory experiments for standard permeability and an approach based on actual conditions, known as the splitting test.

Permeability Test Using Standard Method

Samples were prepared in the form of blocks with dimensions of 20 cm × 20 cm × 150 cm, with three pieces tested under protected conditions at the age of 28 days. The reference standard used was Deutsches Institut für Normung (DIN) EN 12390-8:2009-07. Pressure was applied at 5.09 ± 0.5 kg/cm² for 72 ± 2 hours (Figure 4).

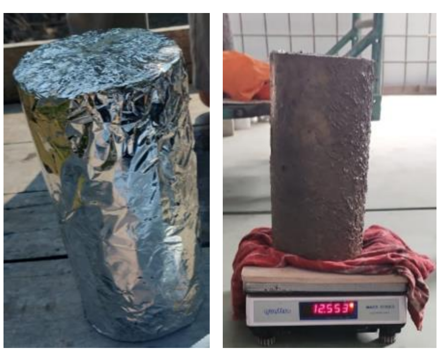
Figure 4 Permeability test according to DIN EN 12390-8:2009-07

After applying pressure, the samples were split, and the resulting cleavages were examined. The depth of water seepage was measured (Figure 5).

Figure 5 Splitting the sample by using water seepage

Permeability Test Using a Simple Method

The simple method (splitting test) was conducted on samples submerged in seawater and brackish water at the ages of 28 and 56 days. Cylindrical samples with a diameter of 15 cm and a height of 30 cm were soaked in seawater and brackish water. Three samples for each type of soaking water were tested at 28 days and three at 56 days. Immediately after removal from the sea and brackish water, the samples were wrapped in aluminum foil and transported to the laboratory (Figure 6a). Before conducting the split tensile test, the aluminum foil was removed (Figure 6b).



(a) (b)

Figure 6 (a) Samples wrapped in aluminum foil, (b) Samples unwrapped from aluminum foil

The condition of the samples after immersion can be seen in Figure 7 for 28 days, and Figure 8 for 56 days.

(a) (b)

Figure 7 (a) Submerged in seawater, (b) Submerged in brackish water for 28 days

(a) (b)

Figure 8 Samples submerged for 56 days: (a) Seawater, (b) Brackish water

In samples submerged in seawater, the surface appears to be covered in marine life, while the surface of samples submerged in brackish water appears smooth, with some shells beginning to adhere to the surface.

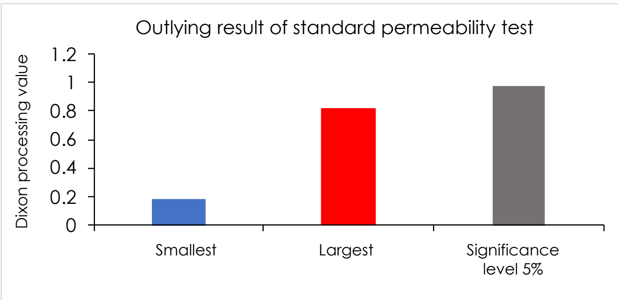
2.2.3 pH, Salinity, and Chemical Content

The pH of the seawater and brackish water was tested according to Indonesian Standard SNI 2588-2017 using a Martini Mil 80 pH meter. Salinity was tested using an in-house method with a refractometer. XRF testing was conducted using an Epsilon 1 instrument with an Ag radiation source. The XRF instrument manufacturer was Malvern Panalytical. Testing was carried out at the Integrated Laboratory of the University of Lampung, Indonesia.

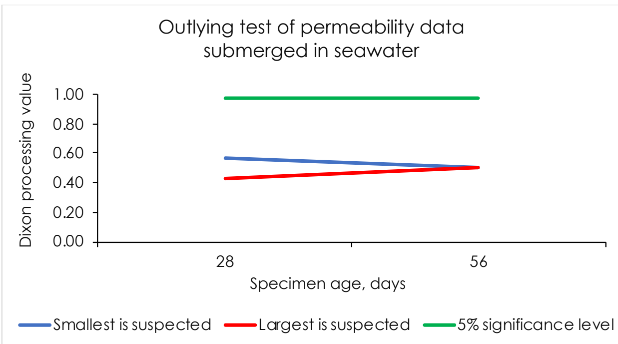
3.0 RESULTS AND DISCUSSION

3.1 Data Processing

All data were processed using the outlier detection method as per ASTM E178-02 [29], with a significance level of 5%. The results of processing the data from the three permeability, compressive, and splitting test samples are shown in Figure 9.



(a)



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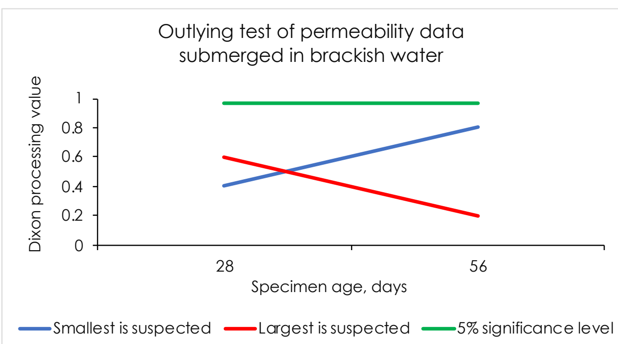

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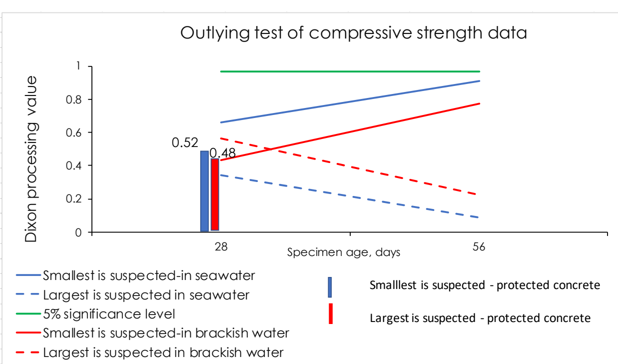

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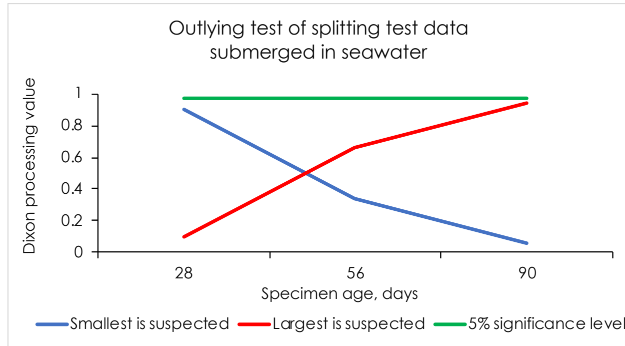

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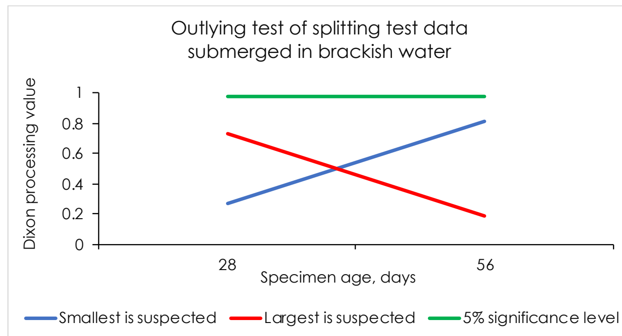


(f)

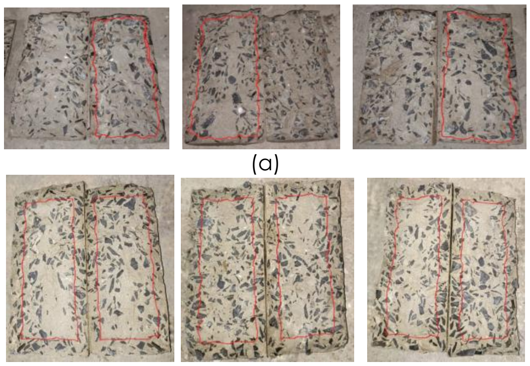
Figure 9 Outlier test results: (a) permeability standard, (b) permeability in seawater, (c) permeability in brackish water, (d) compressive strength in seawater, brackish water, and protected concrete, (e) splitting in seawater, (f) splitting in brackish water

From Figure 9, it can be observed that all outlier test results with Dixon's criteria are below the 5% significance level threshold, indicating that all data are accepted. The value for each type of test and observation is derived from the average of all data.

3.2 Result

3.2.1 *Permeability Test Results*

The permeability from the standard test is 26.39 mm, which is below the permeability limit value for concrete in moderately aggressive environments (50 mm) and strongly aggressive environments (30 mm) as per SNI 03-2914-1992 [30]. The results of permeability testing using the split tensile method are shown in Figure 10.



(b)
Figure 10 Results of permeability testing using the split tensile method: (a) Permeability of submerged in seawater, (b) Permeability of submerged in brackish water

The results of the permeability test, using both the split and standard methods, as well as the split tensile tests, are presented in Figure 11.

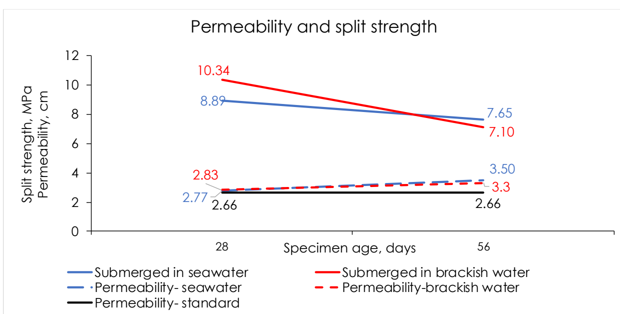


Figure 11 Permeability and split tensile strength results

3.2.2 *Compressive Strength*

The results of the compressive strength test are shown in Table 3.

Table 3 Compressive strength results

Sample	Compressive strength, MPa				
	Submerged in				
	28 days			56 days	
	Protected	Sea water	Brackish water	Sea water	Brackish water
1	23.6	22.3	21.8	17.4	16.8
2	22.6	21.8	20.3	17.9	18.9
3	21.5	22.6	20.9	12.7	19.5
Average	22.5	22.3	21	16	18.4

All data in Table 3 are acceptable based on the processing results stated in Figure 9d.

The relationship between permeability and compressive strength for concrete submerged in seawater and brackish water is shown in Figure 12.

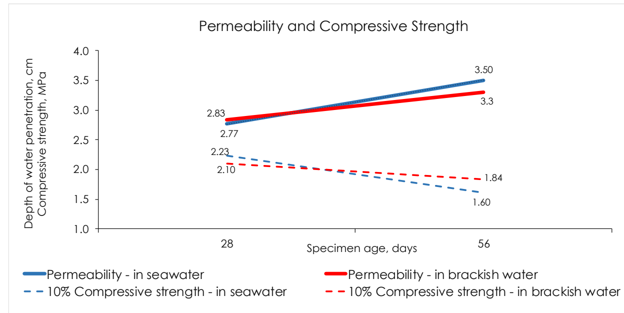


Figure 12 Permeability and compressive strength of concrete submerged in seawater and brackish water

From Figure 12, it can be observed that 10% of the compressive strength of concrete submerged in seawater and brackish water reflects its permeability.

3.3 Discussion

Observations and tests were carried out at 28 days because, up to this age, the growth of hydration products such as CSH, C-AF-H, and the decrease in the number of pores occur very rapidly, while the rapid growth of CH (Calcium Hydroxide) continues until 56 days [31]. Pozzolanic reactions occur when pozzolanic materials containing silica and aluminum interact with water and CH. CH is a hydration product of C_3S and C_4AF, so the pozzolanic reaction occurs after CH forms and ends when CH is depleted. The reaction rate of pozzolanic materials also depends on the content and fineness of vitreous silica [32]. Therefore, the optimum pozzolanic reaction is considered to occur at 56 days.

The decrease in splitting tensile strength in samples submerged in brackish water was faster than in those submerged in seawater. This decrease in strength was accompanied by an increase in permeability but at different rates (Figure 10).

The relationship between permeability and 10% compressive strength which is a reflection of one another, can be modeled as linear equations:

$$P_s = (\tan \alpha) + C_{sp} \quad (1a)$$
$$10\%C_{cs} = (-\tan \alpha)t + C_{sf} \quad (1b)$$

$$P_b = (\tan \beta)\, t + C_{bp} \quad (2a)$$
$$10\%C_{cb} = (-\tan \beta)\, t + C_{bf} \quad (2b)$$

Where:
P_s : permeability of concrete in seawater;
P_b : permeability of concrete in brackish water

C_{sp} : constant number permeability in seawater =2
C_{bp} : constant number permeability in brackish water = 2.35

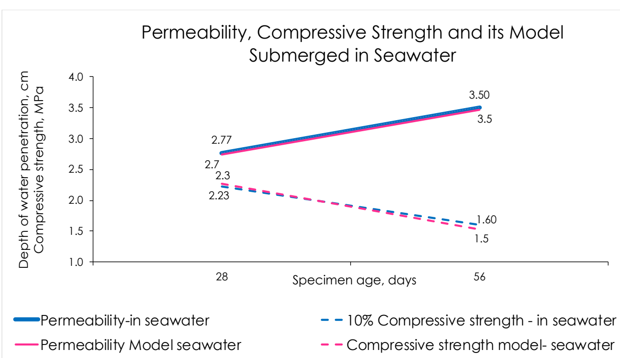
C_{cs} : compressive strength in seawater;
C_{cb} : compressive strength in brackish water

C_{sf} : constant number compressive strength in seawater = 3
C_{bf} : constant number in brackish water for compressive strength = 2.67
t : time, days

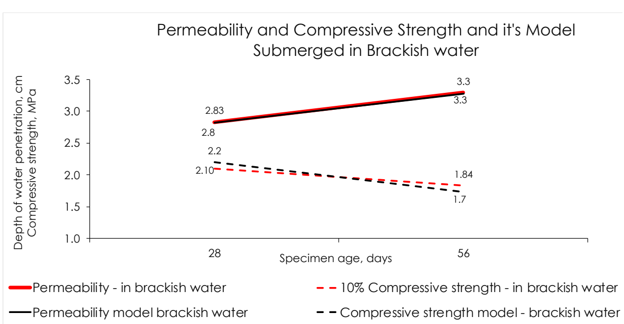
The permeability growth rate is as follows:
α : sample submerged in seawater, tan α: 0.026
β : sample submerged in brackish water, tan β : 0.017

From the equations above (Eq. 1a, 1b, 2a, 2b), it can be stated that there is a linear relationship between the depth of infiltration and the compressive strength. A linear relationship also occurs between the decrease in air permeability and the increase in the compressive strength of dry concrete for qualities greater than 40 MPa, f_c' less than 40 MPa, the relationship is curved [14]. The samples in this study were submerged in seawater and brackish water after the freshwater curing phase ended. This condition causes some of the pores to be filled with water, so the number of empty pores approaches the compressive strength of dry concrete with f_c' 40 and above, resulting in a linear relationship between permeability during immersion in seawater and brackish water. This value is obtained from the permeability rate observed from 28 to 56 days.

Using the constant and slope values mentioned above, the mathematical model and experiment are compared in Figures 13a and 13b.



(a)



(b)

Figure 13 Permeability and compressive strength modeling, (a) submerged in seawater, (b) submerged in brackish water

Ten percent (10%) of the compressive strength of concrete submerged in seawater and brackish water is expressed in Equations 1b and 2b or Figures 13a and 13b. The reflection of Equations 1b and 2b coincides with the permeability of concrete, whether submerged in seawater or brackish water (Figures 13a and 13b).

Permeability is related to open pores. The number and size of pores decrease at a very slow rate starting from the age of 28 days. Additionally, pore size decreases at a slower rate because the growth of hydration products that cover part of the pore space also slows down. Even though the same materials and quality are used, the permeability of concrete submerged in seawater is different from that submerged in brackish water. The slope value (tan angle) for samples submerged in brackish water is lower than for concrete submerged in seawater. Due to the one-way flow, the pore water pressure in concrete submerged in brackish water is more consistent than in concrete submerged in seawater, even though flash floods occasionally occur. Thus, the hydration process from 7 to 28 days occurs under this pressure, causing expansion, which opposes water seepage and results in a lower permeability rate.

The permeability rate for samples submerged in seawater from 28 to 56 days is higher than that for samples submerged in brackish water. The pores around the surface are filled with seawater. When the waves come, the water penetrates deeper, but when the waves recede, the water is drawn back, causing the penetration to stop. The strength of the incoming waves is greater than that of the outgoing waves, and this process occurs continuously, making the permeability of concrete submerged in seawater approximately 1.25 times greater than that submerged in brackish water. The permeability rate for concrete submerged in seawater from 28 to 56 days is 0.26 mm/day, while in brackish water it is 0.16 mm/day.

Seawater and brackish water will permeate through the concrete, causing the concrete pore water to be continuously renewed, leading to rapid leaching. Leaching is a process where the concrete pore solution balances with the surrounding pH. The pH of the water around the concrete, i.e., seawater and brackish water, is presented in Table 4.

Table 4 pH of seawater and brackish water

No	Sample	Salinity gr/kg	Specific gravity	pH
1	Seawater	32	1.024	8.51
2	Brackish water	31	1.023	8.28

The chemical components in the water will react with the concrete surface as it enters it. The chemical components in seawater and brackish water are shown in Table 5.

Table 5 Chemical components of seawater and brackish water

Chemical, mg/l	Seawater (1)	Brackish water (2)	Difference: (1)-(2)
Cl	377.19	371.53	5.66
Ca	285.08	288.59	-3.51
Fe	0.46	0.41	0.05
Mg	941.74	999.92	-58.18
Cr	0.083	0.085	-0.002
Al	0.11	0.11	0
P_2O_5	0.362	0.251	0.111

pH is an important parameter in monitoring concrete health. Cement-based materials, such as paste, mortar, and concrete, are highly alkaline with a high initial pH due to the presence of the Portlandite oxide mineral and alkali metal content in Portland cement. The pH of fresh concrete is around 13.1 and increases gradually to 13.8 over time [33]. By soaking, the concrete pH decreases from around 13 to approximately 8, making it more acidic. This washing can be considered an acid attack on the paste.

Due to aging and other defect-causing factors, such as chloride entry, alkali leaching, carbonation, corrosion, acid attack, humidity, and biodegradation processes, the pH of concrete becomes unstable [34]. If water comes into contact with concrete, the pH will rise at the surface, which can cause precipitation. A well-known phenomenon is the precipitation of carbonate, which can form calcite ($CaCO_3$). Precipitation occurs because carbonate elements exit through the pores, and those contained in seawater settle on the surface.

The surface of the concrete submerged in seawater appears rough, indicating that deposition occurred at 28 days, and it is also overgrown with marine biota (Figure 6a). The surface will change, and these changes will develop [35]. This change is visible in concrete submerged in seawater. The deposition seems to disappear at 56 days, and the concrete surface becomes covered in marine life (Figures 7a and 8a). The pH on the surface decreases, as does the deposition of calcite. Meanwhile, in concrete submerged in brackish water, the surface appears smoother, as if no sedimentation occurs, but with a darker color than in protected conditions. The color is an indicator of H_2S when the concrete is submerged in water and substrate [36].

Concrete submerged in brackish water in this study predominantly receives one-way currents from land. This continuous compressive action within the pores of the concrete causes calcite to be blocked from leaving the pores, thereby preventing sedimentation and resulting in a smoother surface compared to concrete submerged in seawater. This smoother surface is more attractive to shellfish, which prefer concrete submerged in brackish water over that submerged in seawater (Figures 6b and 7b). However, despite this preference, pier columns submerged in seawater are often covered with shells.

No visible difference in the surface texture of concrete submerged in brackish water was observed between the 28-day and 56-day aging periods (Figures 6b and 7b). Mussels, in particular, are known to thrive in environments with a pH of approximately 7.3, temperatures of 28-30°C, current speeds of 0.35-0.44 m/s, salinity levels of 23-26, and water brightness of 30-34 [37]. Given that the pH and salinity of brackish water are lower than those of seawater (as shown in Table 3), concrete in brackish water is more rapidly attacked by shellfish compared to concrete in seawater.

At high pH levels (around 13), calcite exhibits low solubility, leading to its precipitation on concrete surfaces, particularly during the initial stages of submersion when the pH at the surface begins to equilibrate with the pH of the immersion water [36]. As the pH of the concrete surface decreases and approaches the pH of the surrounding water, calcite dissolves more easily, leading to a reduction in the concrete's strength.

By the 28-day mark, the compressive strength of concrete submerged in seawater had decreased by 1.03%, while concrete submerged in brackish water showed a more significant decrease of 7%. At 56 days, these reductions in compressive strength were 29% for seawater-submerged concrete and 18.5% for brackish water-submerged concrete, relative to the control compressive strength (fc'). The rate of decrease in compressive strength for samples submerged in seawater was 0.22 MPa/day, compared to 0.09 MPa/day for those submerged in brackish water. This decline in compressive strength is likely due to the evolving internal structure of the concrete as a result of the ingress of chemical elements from the seawater and brackish water, as well as the mechanical actions of wave forces and river currents. The differences in pressure and pH between the two water types, along with the varying chemical compositions of seawater and brackish water, play significant roles in the degradation of the concrete's compressive strength.

Notably, three chemical elements—magnesium (Mg), chlorine (Cl), and calcium (Ca)—exhibit substantial differences in concentration between seawater and brackish water (Table 4). When Mg enters the concrete, it can replace dissolved Ca, leading to an increase in porosity. Since the magnesium content in seawater is lower than in brackish water, the rate of pore formation is faster in seawater, which results in a greater reduction in compressive strength for concrete submerged in seawater compared to that submerged in brackish water at 56 days.

The high chlorine content in seawater accelerates the dissolution of bonds within the concrete matrix. A 1 ml/l increase in chlorine concentration results in a rate of compressive strength reduction of 0.0006 MPa for samples submerged in seawater and 0.00024 MPa for those in brackish water. This is attributed to the additional pore formation caused by the dissolution of more Ca in the cement paste or portlandite in seawater-submerged concrete compared to brackish water-submerged concrete. Once the calcium hydroxide (CH) in the concrete is depleted, pore volume can increase by 12-15%.

Chloride penetration into concrete from seawater leads to the formation of Friedel's salt ($3CaO.Al_2O_3.CaCl_2.10H_2O$), which occupies a larger volume after crystallization within the concrete pores, thereby filling the pores and binding free chloride in the concrete. This binding process reduces the amount of free chloride in the concrete, as long as CH is still present to continue binding the chlorides [38]. Given that the Cl concentration in seawater is higher than in brackish water (Table 4), bond dissolution occurs more rapidly in seawater-submerged concrete. This accelerated bond dissolution contributes to the lower compressive strength of concrete submerged in seawater at 56 days compared to concrete submerged in brackish water.

4.0 CONCLUSION

The sample used in this research exhibited a permeability value of 26.39 mm, meeting the criteria for strong aggressive environments according to Indonesian Standards, which set the limit at 30 mm. However, the penetration rate of water exceeded the standard. This increased penetration is attributed to the dynamic pressure conditions experienced by the concrete submerged in seawater at the study location. The wave action causes water to penetrate deeper into the concrete when the wave approaches and then appears to be drawn out as the wave recedes. In contrast, the water in concrete submerged in brackish water primarily experiences pressure in one direction, dominated by river currents. As a result, water penetration in concrete submerged in seawater is deeper than in that submerged in brackish water.

The deeper water penetration into the concrete leads to a reduction in its compressive strength. At 28 days, the compressive strength of concrete submerged in seawater and brackish water decreased by 1.3% and 7%, respectively. By 56 days, these reductions had increased to 29% and 18.5% relative to the control compressive strength (fc').

A linear correlation was observed between compressive strength loss and penetration depth, suggesting that a 10% reduction in compressive strength (in MPa) is indicative of deeper water penetration.

At 28 days, sedimentation was visible on the surface of the concrete submerged in seawater, whereas the concrete submerged in brackish water appeared smooth. The high pH of early-age concrete contributes to calcite deposition upon contact with seawater. In contrast, concrete submerged in brackish water, which lacks tensile forces, undergoes the hydration process under the pressure of river currents. This pressure prevents sedimentation, as particles are continuously pushed away, resulting in a smoother surface.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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