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Durability performances of ferronickel slag aggregate and seawater concrete

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Abstract: The rising demand for concrete in the building sector has resulted in the exhaustion of natural sand and freshwater supplies, leading to the pursuit of sustainable substitutes. Coastal areas have plentiful ferronickel slag (SL) and seawater (SW), which can be used to manufacture concrete. Nevertheless, the possibility of corrosion to steel reinforcement raises concerns that require further research. This investigation examines the mechanical and durability performance of concrete that incorporates SL as a partial replacement for fine aggregate and SW as a mixing component. The objective is to optimize SL content to improve compressive strength, resistance to chloride ions, and overall durability. Experimental results show that replacing 25% of the aggregate with SL yields the best combination of workability, strength, and durability, significantly enhancing compressive strength, decreasing porosity, and lessening chloride ion penetration, as evidenced by the Rapid Chloride Penetration Test (RCPT). Although seawater promotes early-age hydration and strength development, its extended use slightly diminishes compressive strength due to salt-induced micro-cracking. However, SL counters these effects, making SW–SL mixture a feasible and sustainable option for concrete production in coastal and resource-limited areas. A significant relationship between RCPT and compressive strength underscores the important role of SL in densifying the matrix and improving impermeability. The concrete mixture with 25% SL exhibits the lowest abrasion weight loss at 28 and 120 days, showing improved durability. This study highlights the potential of using SL and seawater to create eco-friendly and high-performance concrete for harsh environments.

Keywords: workability; permeability; pozzolanicity; no poverty; sustainable cities and communities

1. Introduction

The construction industry must critically assess its persistent reliance on freshwater resources, particularly in concrete production, in light of escalating environmental challenges and the increasing pace of urbanization. This reliance is becoming increasingly unsustainable due to the global water scarcity. The surge in infrastructure growth has considerably increased the need for concrete, which has further exacerbated the strain on already scarce freshwater sources. Consequently, the industry encounters significant obstacles in obtaining adequate water supplies to sustain its operations. Around 2.2 billion individuals across the world do not have access to safely managed drinking water services, while about 703 million people lack basic water services, creating substantial pressure on water-intensive industries such as construction [1], [2], [3], [4], [5]. The concrete industry represents about 9% of total global industrial water usage, worsening water

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shortages in arid and semi-arid areas [6]. Additionally, the production of a single ton of concrete can consume as much as 1,000 gallons of water, highlighting the substantial water impact of this sector. In response, exploring innovative strategies that utilize alternative water sources and industrial by-products such as seawater and ferronickel slag to lessen reliance on freshwater is needed, in line with global initiatives aimed at fostering sustainable urban development and enhancing the resilience of infrastructure over the long term [7], [8], [9], [10].

Seawater has attracted a growing interest as a feasible substitute for blending and curing concrete, especially in areas where freshwater is scarce. Its proximity to coastal construction locations offers logistical and financial advantages by minimizing the need for transporting freshwater. A concrete mixed with seawater sets faster and achieves greater early compressive strength compared to freshwater mixture [11], [12]. These improvements are mainly due to the presence of chloride ions, particularly calcium chloride ($CaCl_2$), which expedite cement hydration and enhance early strength development [12], [13]. Seawater not only accelerates the hydration process but also leads to greater compressive strength and elastic modulus after 28 days of curing [14]. Using seawater in conjunction with supplementary cementitious materials boosts early performance, microstructural density, and strength development, presenting a promising method for sustainable construction in coastal and resources-limited areas [15], [16].

The incorporation of seawater into concrete offers both environmental sustainability and logistical advantages, but it also presents durability challenges that require careful examination. Research has shown a potential reduction in compressive strength up to 10% when using seawater in comparison to concrete created with tap water, particularly after longer curing periods of 90 and 180 days [17], [18], [19], [20]. However, this reduction is inconsistent and is greatly affected by the binder composition, exposure conditions, and mix design. Additional investigations suggest that, despite the marginal loss of strength, seawater can accelerate early hydration reactions, resulting in denser microstructures and enhanced performance in the early stages [18], [21]. The presence of chloride and sulfate ions in seawater plays a major role in the possible deterioration of concrete characteristics, as they interfere with the hydration process of cement and increase the likelihood of corrosion in steel reinforcements. To address these issues, considerable research has focused on the application of supplementary cementitious materials (SCMs) and reinforcements that resist corrosion [20], [21], [22]. Materials such as fly ash, ground granulated blast-furnace slag, silica fume, and rice husk ash have demonstrated their ability to diminish permeability, refine pore structures, and improve resistance to the ingress of aggressive ions. For example, the inclusion of silica fume enhances chemical stability and long-term strength in chloride-rich environments by promoting the formation of additional C-S-H gel and lowering calcium hydroxide content [23], [24]. Furthermore, substituting steel reinforcement with fiber-reinforced polymers (FRP) has been shown to be highly effective in combating corrosion induced by chloride, significantly extending the life of structures in contact with seawater. These integrated strategies present a feasible approach to optimizing concrete mixed with seawater for marine and coastal applications, achieving a balance between mechanical performance and durability over time [25], [26].

Concrete manufacturing that makes use of resources supplied from the local area, in addition to the incorporation of waste materials from industrial processes, makes a substantial contribution to sustainability through industrial waste recycling. This method not only reduces the amount of trash produced, but also diminishes the impact of the concrete manufacture on the environment. Ferronickel slag (SL) is a by-product of electric arc furnace smelting laterite ores which extracts nickel and iron. About 14 tons of SL produce one ton of ferronickel [27], [28], [29]. The increasing production of ferronickel, particularly in regions such as South Sulawesi, Indonesia, where the annual output exceeds 6 million tons [30], highlights the requirement of developing effective recycling processes in order to solve the environmental concerns that are associated with the disposal of slag. SL as a concrete substitute solves waste management problems.

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It has been established through research that the incorporation of SL into concrete can result in improvements to the mechanical properties of materials. Studies, for instance, have demonstrated that concrete mixtures, including SL are capable of achieving compressive strengths that are comparable to those of conventional concrete. More specifically, some of the findings indicate that the strengths can range from 60 to 75 megapascals (MPa) when SL is largely replaced for fine aggregates [29], [31], [32], [33]. In addition, the integration of SL has been linked to increased durability, particularly in marine environments, where it contributes to an increase in resistance to ion diffusion and a decrease in permeability [30], [31], [34]. The incorporation of SL with additional supplementary materials, such as fly ash or blast furnace slag, might result in synergistic effects that improve the performance of the concrete [31], [34]. However, there are aspects of SL utilization that pose difficulties. One of the most significant problems is the possibility of alkali-silica reactions (ASR), which is caused by the reactive silica found in certain SL aggregates. These reactions can lead to concrete cracking and expansion. Several solutions have been offered as a means of addressing this problem. These strategies include the utilization of non-reactive aggregates or the addition of supplemental cementitious materials which potentially alleviates the impacts of ASR [35], [36].

This study uses seawater and SL in concrete; two unconventional materials that have not been extensively explored. Recent research has shown that the chemical composition of seawater can affect cement hydration and bonding time, thereby improving initial characteristics. Meanwhile, the use of ferronickel slag (SL) improves the microstructure and mechanical strength of concrete due to its physical characteristics and pozzolanic potential. While these materials have demonstrated individual benefits, their combined effects on concrete performance remain insufficiently understood. Most previous studies have focused on seawater or fine industrial by-products separately without considering the complexity of their interaction within the cementitious matrix. To address this gap, this study investigates the synergistic effects of seawater and SL on concrete performance, including fresh properties, compressive strength, abrasion resistance, porosity, and chloride ion penetration. This research also explores how SL may compensate for the long-term drawbacks of seawater use, such as microcracking or reduced strength over time. The objective is to evaluate the feasibility of seawater and SL for producing durable and sustainable concrete in coastal and resource-limited environments. The findings contribute to sustainable construction strategies by optimizing alternative material use and reducing dependence on natural sand and freshwater.

2. Material and methods

2.1 Material

The Indonesian standard of chemical properties for Portland composite cement (PCC) as a binder with a specific gravity of 3.16 is provided in Table 1. In this study, natural seawater (SW) sourced from South Sulawesi Island, Indonesia, was used instead of tap water (TP), with its properties described in Table 2.

Table 1. Chemical properties of PCC

Chemical properties (%)							
Ig. Loss	**SiO_2**	**Al_2O**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Free CaO**
4.08	19.52	5.51	3.40	62.88	0.81	1.79	0.96

Table 2. Properties of SW

pH	Chemical compounds (ppm)				
	Natrium	Calcium	Magnesium	Chloride	Sulfate
8.6	1985.23	365.34	1125.68	1916.82	129.6

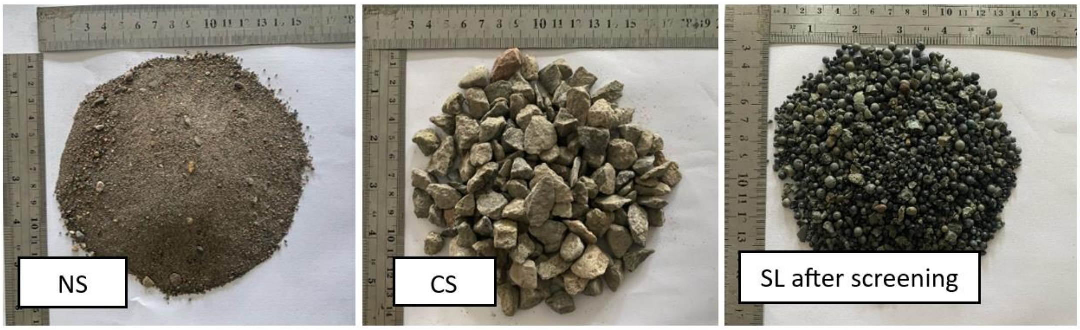

Figure 1. Aggregate used in concrete mixture

Ferronickel slag (SL) aggregate was used to partially replace river sand (RS) that was from the surroundings of the concrete production area. At a local smelter in South Sulawesi, Indonesia, SL was immediately cooled with seawater and screened in the laboratory to achieve a particle size of less than 4.75 millimeters and a mostly spherical particle morphology. This process involved the addition of seawater. The crushed stone (CS) that was up to 20 millimeters in size was the coarse aggregate in concrete. Figure 1 visually represents the aggregates used, while their physical properties are detailed in Table 3. The composition of SL is based on metals, which resulted in a greater specific gravity and a lower water absorption compared to RS. The fineness modulus of SL was more than the range of 2.2 to 3.1 for fine aggregates in concrete, referring to ASTM C33/C33M. As a result, its utilization was restricted to partial replacement. This implies that SL can only partially replace conventional fine aggregates. Furthermore, the SEM images shown in Figure 2 demonstrates that the SL particles predominantly have a spherical shape. This shape is beneficial for workability, as spherical particles usually decrease internal friction and improve the flowability of the fresh mixture. The smooth surface texture also aids in achieving better packing and compaction, highlighting the effectiveness of SL as a substitute for fine aggregates.

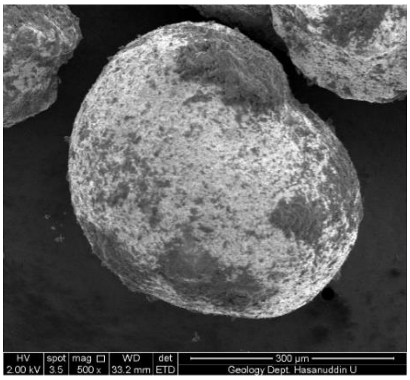

Figure 2. SEM images of SL used in concrete mixture [37]

Figure 3 depicts the grading curve derived from mixing natural sand (NS) with 25% and 50% ferronickel slag (SL) and crushed stone (CS). It has been observed that using 100% SL surpasses the limits established by ASTM C33 for fine aggregates because SL predominantly consists of larger particles. Therefore, relying solely on 100% SL does not meet the necessary gradation standards for fine aggregates in concrete, which can negatively impact the workability and overall

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performance of the mixture. However, combining SL with natural sand at replacement levels of 25% and 50% generates a grading curve that aligns with the ASTM C33/C33M guidelines, which specify acceptable fineness modulus values and particle distribution for fine aggregates used in concrete. The fineness modulus for the 25% and 50% SL replacement was found to be 2.73 and 3.09, respectively, thus fulfilling the gradient requirements for concrete use. Properly graded fine aggregates contribute to improved workability, strength, and durability of concrete, whereas the poorly ones can increase voids, require more water, and diminish overall strength.

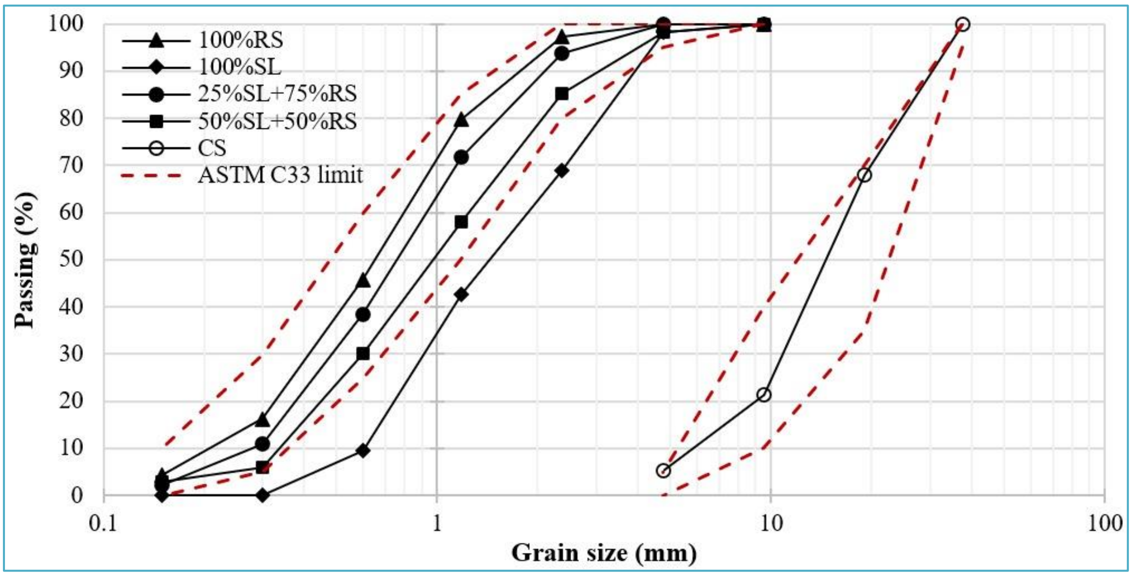

Figure 3. The grading curve of aggregates

Table 3. Physical properties of aggregate used in concrete mixture

Parameter	RS	SL	CS
Specific gravity	2.51	2.83	2.77
Water absorption, %	1.56	0.21	1.99
Fineness modulus	2.29	4.35	6.67
Particles size, mm	0 – 4.75	0.5 – 4.75	5 – 20

2.2 Mixture proportion and specimen manufacture

The concrete mixture had a 50% water-to-cement ratio. This study used tap water (TW) and seawater (SW) as mixing agents, and 25% and 50% ferronickel slag (SL) by volume to substitute natural sand (NS). Figure 4 shows the six mixture proportions and their constituents. All aggregates are moistened to surface dry before mixing to maintain uniformity. SNI 03-3976-1995 requirements were followed when mixing concrete in a 50-liter pan mixer [38]. Fresh concrete was poured into 100-mm-diameter, 200-mm-high cylindrical, and 100mm x 100mm x 400mm prism molds. After the pouring process, the specimens were allowed to dry under laboratory conditions for 24 hours before being removed from the mold. Following this, all concrete samples were submerged in tap water at a temperature of 23 ± 2°C and maintained at a relative humidity of 60% until they reached the designated testing age. The sequence of mixture identification starts with the type of mixing water (TW for tap water or SW for seawater) and is succeeded by the percentage of natural sand (NS) replaced by ferronickel slag (SL). For instance, TW-25SL indicates concrete that has been mixed with tap water and contains 25% ferronickel slag aggregate.

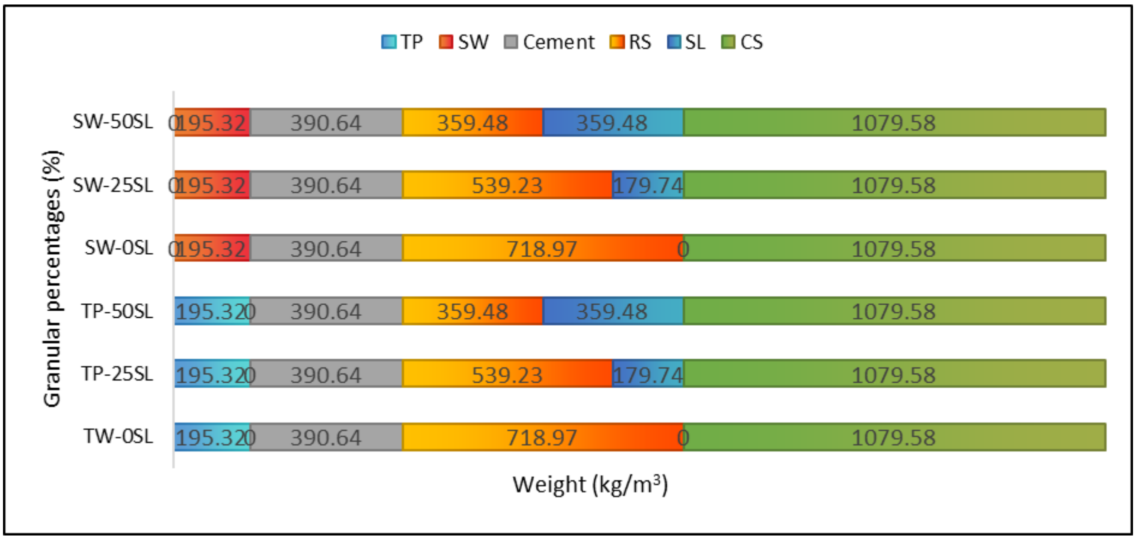

Figure 4. Concrete mixture composition with variation of ferronickel slag aggregate, tap water, and sea water

2.3 Testing methods

2.3.1 Fresh properties

The fresh properties of the concrete were evaluated using the slump test, while density measurements followed the procedures specified in ASTM C143 [39] and ASTM C138 [40], respectively.

2.3.2 Mechanical properties

The uniaxial compressive strength of the concrete was evaluated in accordance with ASTM C39 [41] at curing intervals of 7, 28, and 120 days. For the tests, cylindrical samples measuring 100 mm in diameter and 200 mm in height were utilized. A compression machine with a capacity of 2000 kN was employed to apply a loading rate of 0.25 MPa/s until failure occurred. The value of compressive strength (f'c) was determined using Eq. (1).

$$f_c' = \frac{P}{A} \quad (1)$$

where f'c is compressive strength (MPa), P is maximum load (N) and A is area of applied load (mm^2).

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Figure 5. Compressive strength test

2.3.3 Water absorption

28-day-old cylindrical specimens with dimensions Ø100 mm x 50 mm were tested for their water absorption (WA). The wet specimen weight was compared with that of the dry specimen. Based on ASTM C 642-17, the water absorption test can be calculated using the equation:

$$WA = \frac{(B - A)}{A} x100\% \quad (2)$$

where WA is water absorption (%), A is 105°C oven dry sample weight (gr), and B is wet sample weight (gr).

2.3.4 Rapid Chloride Permeability Test (RCPT)

The RCPT is an accelerated method utilized to assess the durability of mortar against chloride ion intrusion. This testing procedure adheres to ASTM C1202-19, in which a 3% NaCl solution was applied to the surface of mortar samples, measuring 100 mm in diameter and 50 mm in thickness, using a direct electric current of 60 volts, as shown in Figure 6. The outgoing electrical current was recorded at 30-minute intervals over a duration of six hours. The total outgoing current is subsequently calculated using this Eq. (3).

$$Q = 900\,(I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{330} + 2I_{360}) \quad (3)$$

where Q is the total charge passed (Coulombs), I_0 is the initial current at the start of the test (Amperes), and I_t is the current at time t during the test (Amperes).

Concretes were grouped according to Cl^- permeability based on electric charge. Then the electric charge was calculated to determine the classification of tested concretes.

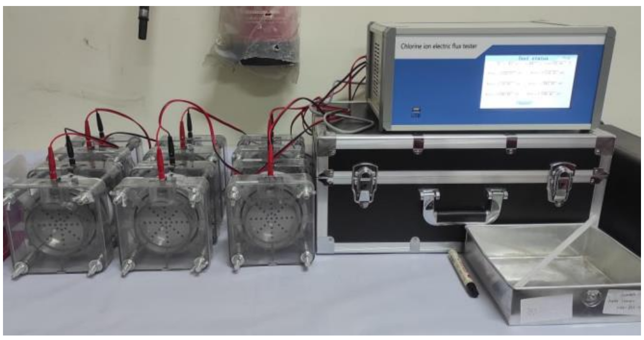

Figure 6. RCPT Method in laboratory

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2.3.5 The Abrasion Weight Loss Testing Method (ASTM C944)

The abrasion resistance test was conducted in accordance with ASTM C944, which measured the surface durability of concrete based on mass loss caused by a rotating-cutter device applied to the specimen surface. This approach rotated a steel cutter under a designated force across the surface of a concrete specimen for a predetermined period. Measuring the mass both before and after testing helps one to estimate the amount of material lost from abrasion. Especially appropriate for assessing durability in uses exposed to mechanical friction or erosion, the test offered a direct indicator of the surface wear resistance of concrete. Reduced abrasion weight loss values showed more resilience to surface deterioration and, thus, improved general durability. This approach is generally agreed upon for its dependability and applicability in evaluating concrete wear performance under controlled environments.

3. Results and discussion

3.1 Slump value and fresh density

The results of the concrete slump test are presented in Figure 7. The findings indicate that the slump value is affected by the proportions of SW and SL used in the mixtures. When the SL content was increased to 25%, the slump rose to nearly 9 cm for TP, compared to 8.5 cm for SW, indicating a reduction of 5.6% in the SW mixture. Conversely, at an SL content of 50%, the slump decreased to 8 cm for TW and 7 cm for SW, with the SW mixture experiencing a more significant decrease of 12.5%. These results indicate that SW consistently produces lower slump values in comparison to TP, regardless of the amount of SL. The lower slump value observed in the SW mixture can be related to the higher salt concentration found in seawater. More specifically, sodium chloride ($NaCl$) and magnesium chloride ($MgCl_2$) are the salts that speed up the process cement hydration [42]. As a consequence of this fast hydration, the mixture became more rigid faster, resulting in decreased fluidity and workability. On the other hand, the addition of SL aggregates resulted in an increase in the slump value until a certain threshold is achieved. The finer surface texture and lower water absorption properties of the SL aggregates contributed to an improvement in the workability of the mixture between 0% and 25% SL. This improvement occurred between these two percentages [43], [44].

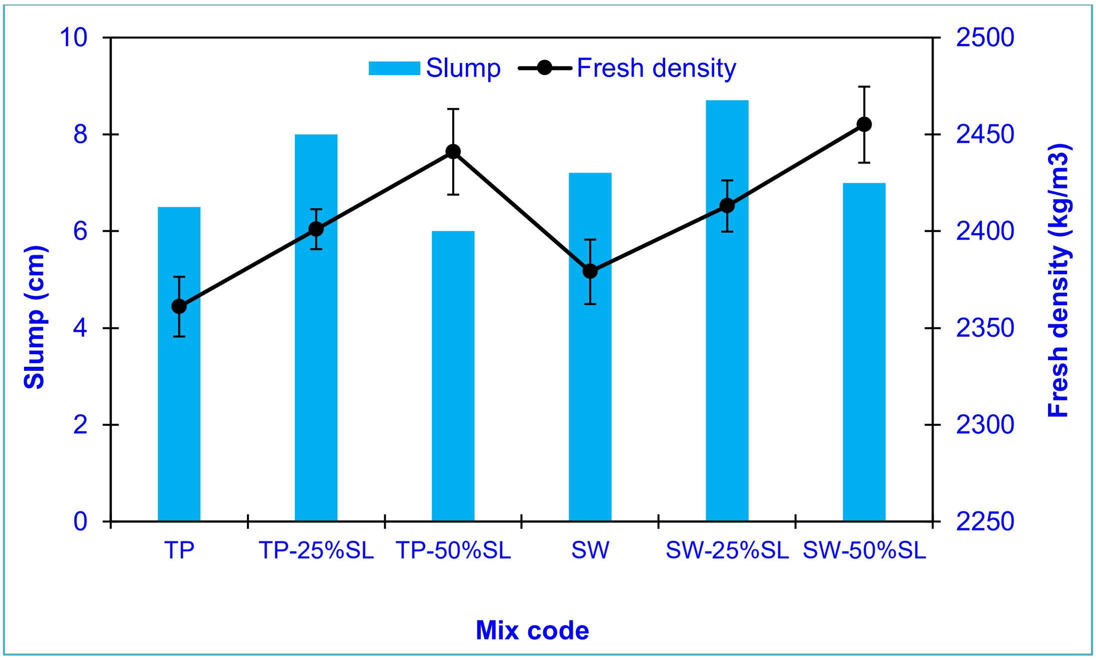

Figure 7. Slump value and fresh density of concrete

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The addition of SL aggregates, in contrast, has the effect of increasing the slump of concrete mixtures up to a specific degree of replacement. Between 0% and 25% SL, there was a discernible increase in workability, which might be attributed to the distinctive physical features of SL particles. This improvement could be noticed between 0% and 25% SL. In particular, the scanning electron microscopy (SEM) examination (shown in Figure 2) demonstrates that the particles of SL have a surface texture that is comparatively smooth and a shape that is mostly spherical in comparison to natural sand. In order to reduce the amount of friction occurred between the particles and to improve the flow of the new concrete mixture, these morphological characteristics played a significant role. SL particles have a spherical shape, which enables them to behave like "rolling bearings" within the mixture. This helped reduce the amount of internal shear resistance that occurred during mixing and placement process, respectively. This behavior resulted in an improvement in the flexibility and flowability of the concrete, which was reflected in the improved slump values at a replacement percentage of 25% for SL. Additionally, the smoother surface of SL minimized the water consumption that is generally associated with aggregates that are rougher and need more angular shapes. A higher degree of lubrication was maintained in the matrix, which further contributed to increased workability without affecting the water-to-cement ratio contained in the matrix.

When the SL content was increased to a greater level (for example, 50%), the slump tended to diminish significantly. This was mostly because the overall gradation was rougher, and the paste content was lower, compared to the aggregate surface area. This indicates that although the spherical form of SL is advantageous for fresh properties, an excessive amount may disturb the particle packing and balance of the mixture, hence balancing the workability improvements. This is because the spherical shape of SL is favorable for fresh properties [32], [33], [45], [46], [47]. Concrete incorporating 30% slag aggregate exhibited a 12% increase in slump; however, subsequent measurements indicated a linear reduction in slump values thereafter [46]. The incorporation of natural sand (NS) with ferronickel slag (SL) enhanced the workability of concrete mixtures containing 25% to 40% SL fine aggregate. The results indicate that the use of seawater (SW) led to a reduction in slump ranging from 5.6% to 12.5%, while the addition of fly ash (SL) resulted in a 25% increase in slump. These results corroborate earlier research regarding the influences of SL and SW on the characteristics of concrete [47], [48].

The impact of SL on the fresh density of TP and SW concrete mixtures is also shown in Figure 7. SW consistently increased fresh density by 0.35% to 0.45% over TP, regardless of SL content. This rise was presumably due to dissolved salts increasing mixture specific gravity. These data showed numerous key tendencies when compared to comparable research. The dissolved salts, such as sodium chloride in saltwater, resulted in a slight increase in fresh density without compromising the workability of concrete [49]. Additionally, an increase in fresh density of 0.4% to 0.6% was observed in concrete mixed with seawater compared to that with tap water, which aligns with the findings of this study [50]. Additionally, substituting NS with SL consistently enhanced fresh density, with improvements varying from 0.85% to 1.49%, depending on the level of replacement. This improvement is directly associated with the greater specific gravity of ferronickel slag in comparison to NS, as demonstrated in Table 3. The observed enhancements in fresh density are in agreement with prior studies, which reported a 1.5% increase when 50% of natural sand was substituted with ferronickel slag [42]. Similarly, an increase in fresh density between 1.4% and 1.6% was noted when ordinary sand was replaced by industrial by-products with a higher specific gravity [31]. Research has also indicated that the compact structure of ferronickel slag contributes to a similar range of density improvements [51]. Furthermore, a combination of seawater and industrial slag has been shown to increase density by 1.4% to 1.6% when denser materials partially replaced sand [52]. Another study reported a 1.3% to 1.6% increase in fresh density when ferronickel slag was used as a 50% replacement for sand, reinforcing these findings [53].

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3.2 Compressive strength

Figure 8 shows the compressive strength of concrete mixtures that include SL as a fine aggregate (with 0%, 25%, and 50% substitution) and use TP or SW during curing periods of 7, 28, and 120 days. In general, the findings demonstrate how the amount of SL and the use of SW influence the development of compressive strength over various curing times. The inclusion of SW improved the compressive strength at 7 days, due to the accelerating impact of chloride ions, promoting the early hydration of cement [49], [50], [54]. The use of SW increased the compressive strength about 9% for the 0% SL mixture compared to TP. For the 25% SL replacement, strength reached its peak, with SW showing a 16.7% improvement over the 0% SL level, attaining 28 MPa. Both TP and SW exhibited advantages from the optimized SL content, as SL contributed to mechanical properties through enhanced particle packing and densification, lowered porosity, and improved the density of the concrete matrix [30], [47]. The strength slightly decreased to 24 MPa for TP and 25 MPa for SW with 50% SL, indicating that excessive SL negatively affects workability and initial bonding. In the 28-days period, all mixtures showed significant strength improvements. SW provided a 7.4% advantage over TP for the 0% SL case. The compressive strength peaked once again at 25% SL, with TP and SW achieving 32 MPa and 34 MPa, respectively, signifying increases of 19% and 17.2% compared to the 0% SL mixture. SL improves mechanical characteristics through particle packing and densification, as demonstrated by these results [53], [55]. The strengths of 30 MPa and 32 MPa for TP and SW combinations, respectively, were down 5% - 6% from the 25% SL mixtures at 50% SL. Replacing 50% NS with SL lowered the compressive strength [46], [56]. SL particles were able to produce voids and a more porous microstructure due to their low water absorption, smooth glassy surface texture, and spherical shape.

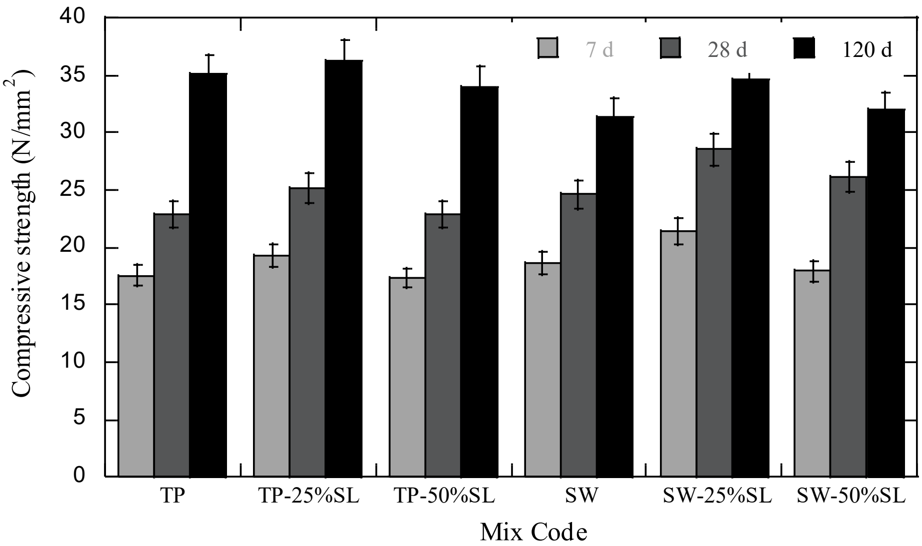

Figure 8. Compressive strength of concrete at 7-, 28-, and 120-days curing period

The reduction in compressive strength at 50% SL replacement is primarily linked to the distinct physical properties of SL, such as its low water absorption, smooth glassy texture, and predominantly spherical shape. While these traits are beneficial for improving workability at moderate replacement levels, they can adversely affect bonding efficiency and promote the formation of voids when used in excess. A high proportion of SL disrupts the gradation balance, leading to inadequate particle packing and insufficient cement paste coverage. This, in turn, contributes to a more porous matrix and diminished internal cohesion. Despite the higher specific gravity of SL, these negative microstructural effects outweigh its densifying potential, ultimately reducing the concrete's load-bearing capacity.

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The compressive strength of the SW mixture slightly surpassed that of the TP mixture at all SL replacement levels in the 120-days period. Concrete blended with TP reached a compressive strength of roughly 35.08 MPa at 0% SL content, while the SW mixture recorded a strength about 31.39 MPa, indicating a decrease of approximately 10.51%. A minor increase in compressive strength occurred when the SL content was raised to 25%, with values approaching 36.21 MPa for TP and 34.60 MPa for SW, preserving a difference of 4.46%. The compressive strength fell to 34.03 MPa for the TP concrete mixture and 31.96 MPa for the seawater mixture (SW) with a 50% SL content, indicating a consistent decrease of approximately 6.07% in the SW mixture. The formation of salt crystals from seawater within the pores of the concrete caused the observed decrease in compressive strength over time. Internal expansion was led by this accumulation of salts, which induced micro-cracking. The structural integrity of the material is adversely impacted by such micro-cracking, culminating in an overall reduction in compressive strength [12], [56].

In general, TP consistently produces higher compressive strength than SW, with SL replacement showing the best improvement at 25% before experiencing a slight decrease at 50%. This suggests that increased replacement percentages might result in a decrease of benefits. The compressive strength data also show that TP mixtures are superior to SW ones. On the other hand, the addition of SL enables SW mixtures to reach a strength level, greater than those that do not contain SL. This shows that SL can assist to reduce some of the harmful consequences by utilizing seawater.

3.3 Water absorption

Figure 9 presents the water absorption values for concrete mixtures in 28- and 120- days period, reflecting various levels of ferronickel slag replacement and the use of either freshwater or seawater in the mixing process. It is clear that as concrete ages, water absorption diminishes, which can be explained by the ongoing hydration process. This process leads to a reduction in the volume of capillary pores, contributing to a denser and more impermeable concrete structure.

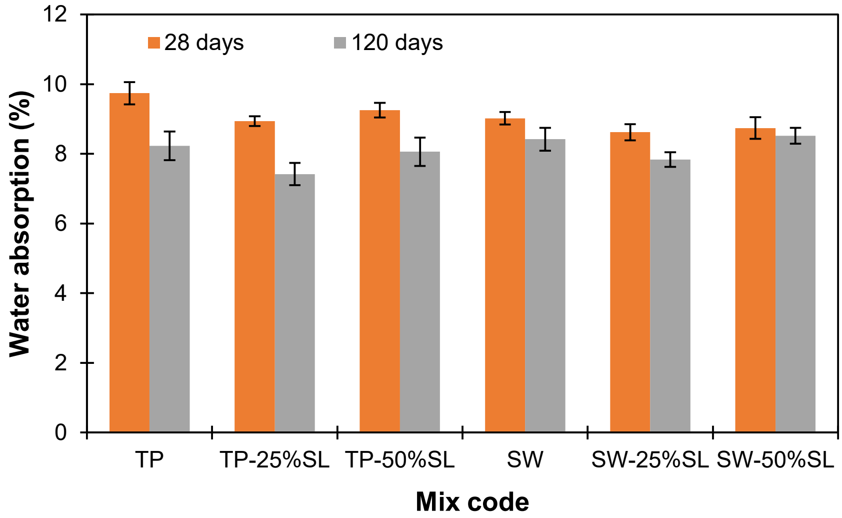

Figure 9. Water absorption in concrete in 28- and 120-days period

The findings indicate that concrete mixtures containing 25% and 50% ferronickel slag (TP-25%SL and TP-50%SL) show lower water absorption than the control mixtures (TP) at both time intervals, with reductions ranging from 8% to 16%. This emphasizes the compacting effect of ferronickel slag, which fosters a tighter microstructure due to its specific gravity and pozzolanic characteristics. In contrast, mixtures that utilize seawater in conjunction with ferronickel slag (SW-25%SL and SW-50%SL) demonstrate slightly higher water absorption compared to those made with

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freshwater. This can be attributed to the salts in seawater, which may influence hydration efficiency and introduce minor microstructural irregularities, however, these differences remain below 10%.

The results are consistent with those of the compressive strength in section 3.2 which the lower water absorption observed in ferronickel slag mixtures is associated with enhanced strength, as a denser matrix reduces voids. Although concrete made with seawater and ferronickel slag exhibits marginally higher absorption, it still achieves sufficient durability and mechanical performance due to the beneficial properties of ferronickel slag that help mitigate permeability. Previous studies have reported similar outcomes, demonstrating that the incorporation of ferronickel slag can improve both impermeability and compressive strength, thereby confirming its efficacy as a sustainable alternative for aggregate replacement [30], [31].

3.4 Porosity

Figure 10 illustrates the porosity levels of different concrete mixtures after 28 and 120 days, emphasizing the influence of using ferronickel slag (SL) as a partial replacement for natural sand at 25% and 50%, along with the effect of the kind of mixing water employed. The data indicates a reduction in porosity as the concrete ages, showcasing ongoing hydration and pore refinement processes. The data indicates a reduction in porosity as the concrete ages, indicating ongoing hydration and pore refinement processes. This reduction is largely attributed to the progressive formation of hydration products, such as calcium silicate hydrate (C–S–H), calcium hydroxide (CH), and ettringite. C–S–H is the primary gel-like compound responsible for binding and densifying the concrete matrix by filling capillary pores. CH contributed to the initial structural framework, while ettringite aided in initial stage pore filling. Moreover, the pozzolanic reaction between the silica in ferronickel slag and CH generated secondary C–S–H, which further enhanced microstructural densification and reduced porosity. The findings demonstrate that the mixtures containing ferronickel slag, especially TP-25%SL and TP-50%SL, have notably lower porosity than the control mix (TP) in both 28- and 120- days period. This reduction, ranging from 8% to 16%, highlights the capacity of ferronickel slag to enhance microstructural density owing to its tight grain configuration and pozzolanic properties, which facilitate the filling of voids through secondary hydration mechanisms. Conversely, mixtures utilizing seawater (such as SW-25%SL and SW-50%SL) presented greater porosity compared to those formulated with freshwater. This trend may be attributed to the salts in seawater, which can influence hydration kinetics and the formation of the pore network. However, the difference in porosity between the seawater and freshwater mixtures was within acceptable limits (below 10%), reflecting the positive effect of ferronickel slag.

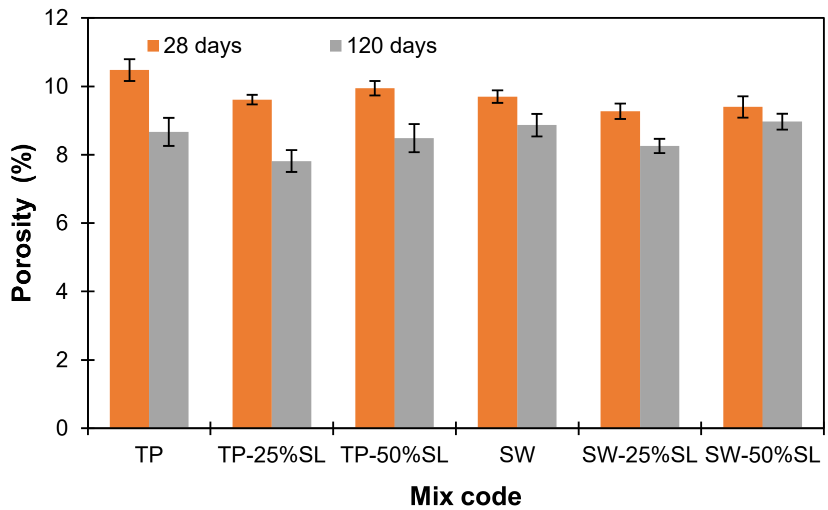

Figure 10. Porosity in concrete in 28- and 120- days period

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Porosity correlates directly with other durability metrics, including water absorption and compressive strength. The lower porosity in the ferronickel slag mixtures corresponds to diminished water absorption rates (as shown in Fig. 8), since a denser matrix reduced void connectivity and capillary movement. This improvement improved the concrete's resistance to water and strong chemicals, ensuring its endurance. As a denser microstructure resisted cracking and increased load-bearing capacity, decreasing porosity increased compressive strength. Furthermore, voids weakened matrix integrity resulted an increase on water absorption by seawater mixtures, and poorer compressive strength due to the higher porosity. Ferronickel slag increases concrete's impermeability and robustness, even in coastal situations [24], [34], [38]. Although there is a minor rise in porosity for seawater mixtures, their overall durability remained adequate due to the dense microstructure provided by ferronickel slag, which helped lower permeability. The improved resistance to chloride ion penetration, sulfate attack, and freeze-thaw cycles can be attributed to the reduction.

3.5 Rapid chloride penetration test (RCPT)

Figure 11 illustrates the resistance of concrete to chloride ion penetration, assessed using the Rapid Chloride Penetration Test (RCPT), in 28- and 120- days period. In the first period, the RCPT values for every concrete mixture were within the 1900–2300 Coulombs range, classifying the mixtures as having "moderate" resistance to chloride penetration. This relatively high RCPT measurement at this early stage indicates the existence of interconnected capillary pores, resulted from insufficient hydration. However, by 120 days, the RCPT values showed a notable reduction to between 850 and 1200 Coulombs, moving all mixtures into the "very low" resistance classification. This decrease highlights the ongoing hydration process, which improved the microstructure and reduced pore connectivity, thereby enhancing resistance to chloride ions.

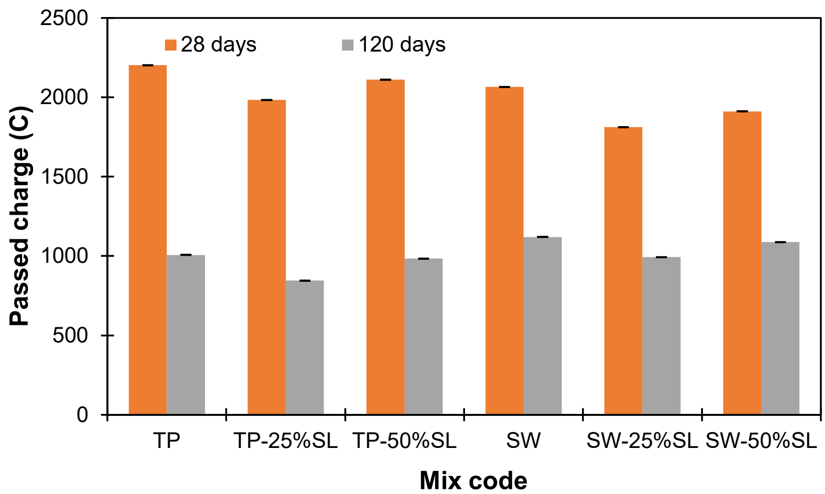

Figure 11. RCPT in concrete in 28- and 120- days period

Among the mixtures, the concrete containing 25% ferronickel slag (TP-25%SL) exhibited the highest resistance to chloride ions in 120-days period, as evidenced by its lowest RCPT measurement. This enhancement was due to the pozzolanic properties of ferronickel slag and its capacity to improve the pore structure, which increased impermeability. The hydration progress and microstructural densification could be inferred from the declining RCPT values over time. RCPT results showed that mixtures containing seawater and 25% ferronickel slag experienced a substantial reduction in charge passed in both 28- and 120-days period. This indicates ongoing hydration and the formation of C–S–H, aided by the pozzolanic reaction of slag with calcium hydroxide. The presence of chloride and magnesium ions in seawater might accelerate early hydration, but long-term densification was more strongly influenced by the reactive silica in slag

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forming additional C–S–H. This synergistic effect explains why the RCPT values for seawater mixtures, although initially higher, converge toward very low permeability over time, reflecting a refined pore structure and improved durability. Conversely, seawater mixtures (SW-25%SL and SW-50%SL) exhibited higher RCPT values than freshwater equivalents. This may be due to the salt contained in seawater, which can interfere with the hydration process and lead to increased porosity.

The patterns seen in the RCPT results are consistent with the compressive strength and porosity findings. The lower RCPT values in the ferronickel slag mixtures are associated with decreased porosity (as illustrated in Fig. 9) and enhanced compressive strength, indicating a denser and less permeable microstructure. The excellent chloride resistance of TP-25%SL makes it a promising option for marine settings, where corrosion from chlorides is a major issue. On the other hand, the higher RCPT values found in seawater mixtures suggest that their durability might be lower due to greater porosity. Fortunately, the use of ferronickel slag helps counter these drawbacks, ensuring that performance remains satisfactory. However, the presence of ferronickel slag helps mitigate these concerns, ensuring an adequate level of performance. To summarize, low RCPT values reflect a high resistance to corrosion caused by chloride ions, which is essential for prolonging the durability of reinforced concrete structures in challenging conditions. Previous research has shown that adding ferronickel slag improves impermeability and increases the long-term resistance to chloride ion infiltration, making it a beneficial material for marine applications, environments, and applications [30], [43], [46].

3.6 Abrasion weight loss

Figure 12 displays the abrasion resistance of different concrete mixtures in 28- and 120-days period based on the ASTM C944 test method. According to the results, the concrete mixture that substitutes ferronickel slag for 25% of the fine particles (TP-25%SL) showed the best abrasion resistance among all the combinations tested, underscoring its superior performance in wear-prone applications. As the curing duration increased, the abrasion resistance showed notable improvement, which correlates with the ongoing hydration process that led to a denser and stronger microstructure.

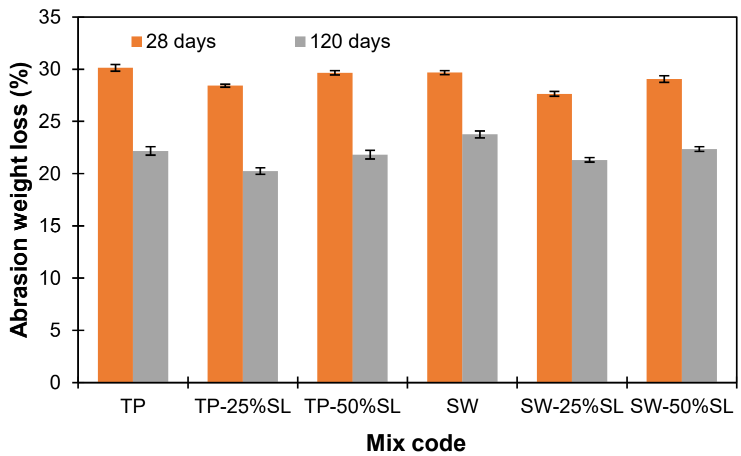

Figure 12. Abrasion weight loss in concrete in 28- and 120-days period

The high abrasion resistance of TP-25%SL is related to lower RCPT values, less water absorption, and reduced porosity. All of them indicate that the concrete matrix has higher density and lower permeability. The pozzolanic characteristics and greater specific gravity of ferronickel slag promoted particle organization and filled holes in the mixture. The pozzolanic process also produced calcium silicate hydrate (C-S-H), which densified concrete and improved its abrasion

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resistance and compressive strength. Resistance to abrasion is fundamentally related to compressive strength; materials with a denser and stronger structure are better able to resist surface wear. Due to their refined microstructure, ferronickel slag-containing concrete compositions, such as TP-25%SL, have higher compressive strength. Voids were reduced by the denser interfacial transition zone (ITZ) and enhanced pore system, increasing mechanical stress resistance. The observed abrasion resistance patterns match the RCPT results, which showed decreased chloride permeability, indicating a more compact structure that improves surface durability and wear resistance.

4. Conclusion

This research investigates the mechanical properties and leaching characteristics of concrete that incorporates SL as a substitute for sand, combined with either TP or SW. From the laboratory test results, the following conclusions can be made:

1. The incorporation of seawater (SW) and ferronickel slag (SL) in concrete mixtures significantly influences various characteristics. SW tends to reduce slump due to the rapid hydration initiated by dissolved salts, while SL aggregates enhance both slump and workability, particularly up to a 25% inclusion level.
2. An excessive amount of SL can disrupt the balance between the paste and aggregate, resulting in diminished workability. This combination also enhances the density of concrete by 1.8% to 3%, attributed to the salt content in SW as well as SL higher specific gravity compared to River Sand (RS). Additionally, SW contributes to increased early compressive strength due to accelerated hydration, with optimal results seen when substituting 25% of SL. SL enhances mechanical properties through densification, mitigating some of the adverse effects of SW in the long term, highlighting the necessity for a balanced use of SL.
3. RCPT and compressive strength are closely related, as a rise in compressive strength usually corresponds with a denser concrete composition that has lower porosity, which in turn improves resistance to chloride ion infiltration. In this study, the mixtures including a 25% replacement of SL exhibited the lowest RCPT results and the highest compressive strength for all curing periods, suggesting that an optimal level of SL substitution enhances both mechanical and durability properties. Conversely, a higher SL replacement of 50% resulted in an increase in RCPT value and a decrease in compressive strength, possibly due to greater porosity and weakened matrix cohesion.
4. The inclusion of SL significantly enhances resistance to chloride ion infiltration, as shown by the RCPT findings, emphasizing its potential to improve durability in coastal areas. A 25% SL substitution level strikes an ideal balance between strength and durability, minimizing porosity and water absorption while retaining workability and long-term mechanical effectiveness.
5. Although the use of seawater tends to slightly reduce long-term compressive strength due to microcracks caused by salt, the combination of seawater and SL can overcome this problem. This combination allows seawater-based mixtures with 25% SL to achieve performance levels equivalent to or better than freshwater-based mixtures without SL, thereby supporting their use in areas with limited resources or coastal areas.

Author's declaration

Author contribution

Nevy Sandra: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Muhammad Akbar Caronge:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Jati Sunaryati**: Formal analysis, Methodology, Writing – review & editing. **Keiyu Kawaai**: Conceptualization, Supervision, Validation. **Willick Nsama:** Formal analysis, Methodology, Writing – review & editing. **Yaumal Arbi:** Visualization, Validation, Writing – review & editing. **Ari Syaiful Rahman Arifin:** Project administration, Writing – review & editing.

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Data Availability

Data will be made available on request.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical clearance

This research does not involve humans or animals as subjects, so an ethical document is not required.

AI statement

The language use in this article has been validated and verified by an English language expert, and none of the AI-generated sentences is included in this article.

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