Effect of Partial Replacement of Cement with Micro Silica on The Mechanical Properties of Concrete Before and After Exposure to Seawater

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ABSTRACT

Concrete structures in marine environments are vulnerable to chloride and sulphate attack, leading to corrosion and reduced mechanical performance. This study examines the effect of partially replacing cement with microsilica at 5 w%, 10 w%, and 15 w% on the compressive and tensile strengths of concrete before and after 28 days of seawater exposure. Concrete mixes were designed with a ratio of 1:2:4 and a water/cement ratio of 0.4. The inclusion of microsilica significantly enhanced compressive strength before exposure, with the optimum performance observed at 10 w% replacement, showing a 26.1% increase after seawater exposure. Conversely, tensile strength declined across all mixes following exposure, with reductions between 18.45% and 27.19%, attributed to the ingress of chloride and sulphate ions that weakened the interfacial transition zone. Despite this, microsilica-modified concretes retained higher residual tensile strength than the control mix. The findings indicate that microsilica improves the strength and durability of concrete exposed to marine environments, making it an effective supplementary cementitious material for sustainable coastal and offshore applications.

Keywords: Microsilica, Seawater Exposure, Compressive Strength, Tensile Strength, Durability.

INTRODUCTION

Concrete used in marine and coastal environments is constantly subjected to aggressive chemical and physical conditions, which compromise its long-term performance (Li et al., 2023; Qu et al., 2020; Chen et al., 2017). The combined effects of chloride ingress, sulphate attack, and continuous wetting and drying cycles result in cracking, spalling, and corrosion of reinforcing steel (Zhang et al., 2022; Ting et al., 2020). These deterioration processes not only reduce structural capacity but also increase maintenance and repair costs, posing significant challenges for sustainable construction in such environments (Rincón et al., 2024; Kim et al., 2020; Diaferio & Varona, 2024). The need to improve the resistance of concrete to seawater attack has led to the incorporation of mineral admixtures known as supplementary cementitious materials (Miah et al., 2023; Park et al., 2021). These materials enhance the microstructure and chemical stability of concrete while partially substituting cement to reduce the environmental impact (Miah et al., 2023; Park et al., 2021). Among the various SCMs, microsilica (silica fume) has been recognised for its superior pozzolanic reactivity and ultra-fine particle size, which contribute to improved strength and durability characteristics (Kancharla et al., 2021; Kumar et al., 2020; Li et al., 2018)

Micro silica reacts with the calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H), which is responsible for strength development (Trebukhin et al., 2024; Kashyap et al., 2023; Bach, 2019). This reaction not only refines the pore structure but also decreases the permeability of concrete, making it less susceptible to the penetration of chloride and sulphate ions (Khan & Abbas, 2021;

Chaudhary & Sinha, 2020). As a result, concrete containing micro silica typically exhibits higher compressive and tensile strengths and better long-term durability than conventional mixes (Sharaky et al., 2019; Li et al., 2018). In marine-exposed environments, such improvements are critical because they directly influence the structural integrity and service life of reinforced concrete elements (Lee et al., 2024; Melchers, 2020; Miah et al., 2023). Evaluating the performance of microsilica–modified concrete before and after exposure to seawater provides a clear understanding of its mechanical response under aggressive conditions (Park et al., 2021; Qiao et al., 2022; Sadati et al., 2017). The information obtained from such investigations supports the development of durable and sustainable concrete suitable for coastal, offshore, and port-related infrastructure where seawater exposure is inevitable (Kim et al., 2025; Margapuram et al., 2024; Georges et al., 2020; Qu et al., 2020; Malaga et al., 2019).

OBJECTIVES

The objective of this study was to assess the effect of partial replacement of cement with microsilica on the compressive and tensile strengths of concrete before and after exposure to seawater for 28 days.

LITERATURE REVIEW

Concrete deterioration in marine environments has been widely documented due to the aggressive action of chloride, sulphate, and magnesium ions, which cause cracking, expansion, and reinforcement corrosion (Huang et al., 2024; Kobayashi et al., 2023; Li et al., 2023; Zhang et al., 2022; Esteban-Arranz et al., 2021; Qu et al., 2020). Chloride-induced corrosion is considered the most critical mechanism because it destroys the protective film on steel reinforcement (Mehta & Monteiro, 2014; Moffatt & Thomas, 2018). To enhance durability, supplementary cementitious materials, especially microsilica, are commonly incorporated into concrete (Mostofinejad et al., 2024a, 2024b; Garg et al., 2021). Due to the aggressive action of chloride, sulphate, and magnesium ions, which result in cracking, expansion, and reinforcement corrosion, concrete deterioration in marine environments has been extensively documented (Kobayashi et al., 2023; Li et al., 2023; Esteban-Arranz et al., 2021; Qu et al., 2020). Chloride-induced corrosion is considered the most critical mechanism because it destroys the protective film on steel reinforcement (Moffatt & Thomas, 2018; Mehta & Monteiro, 2014). To enhance durability, supplementary cementitious materials, especially microsilica, are commonly incorporated into concrete (Mostofinejad et al., 2024a, 2024b; Garg et al., 2021). Microsilica, composed mainly of amorphous SiO_2, refines pore structure by filling voids and producing a denser, less permeable matrix (Altawaiha et al., 2023; Luo et al., 2021; Li et al., 2018, 2020; Karim et al., 2019; Gerasimova & Berdysheva, 2018; Neville, 2012). Through pozzolanic reaction, microsilica forms additional C–S–H that strengthens the matrix and increases chemical resistance (Liu et al., 2023; Geng & Zhang, 2023; Duque-Redondo et al., 2022; Janča et al., 2019; Maddalena et al., 2018).

While excessive microsilica may decrease workability Suda and Rao (2020); Wu et al., (2019); Li et al. (2018), research indicates notable mechanical benefits at 5–15% replacement levels (Husain et al., 2021; Thomas & Siddique, 2011; Burhan et al., 2019). Studies on seawater exposure indicate that microsilica reduces chloride and sulphate ingress and improves long-term performance in saline environments (Dashti et al., 2025; Khan et al., 2023; Ali et al., 2022; Fu et al., 2020). Despite these advances, further comparative research assessing strength changes before and after seawater exposure is needed to guide the development of durable marine-grade concrete.

MATERIALS AND METHODS

MATERIALS

The following materials were used in this study: GHACEM (42.5N) Portland composite cement Type-II, river sand from the seaside, quarry dust from JUSTMOH Construction Limited, crushed granite aggregates from JUSTMOH Construction Limited, micro silica from MC-BAUCHEMIE GHANA LTD, Accra, potable tap water from Takoradi Technical University, and natural seawater from the Teshie-Nungua coastal area. All these materials were obtained from reliable suppliers and local sources.

Mix Proportion and Casting

Using a concrete mixer, the dry ingredients were combined first, and then water was gradually added to create concrete mixes. Standard cube moulds (150mm) were oiled, concrete layers were poured, and a tamping rod was used to compact each layer and remove any remaining air. The specimens were cured for 7 days in a temperature-controlled tank after being demoulded 24 hours after casting. Four concrete mixes were prepared with 0 w%, 5 w%, 10 w%, and 15 w% microsilica replacements using a concrete mixer. The mix ratio was 1: 2: 4 with a water-cement ratio of 0.4. The concrete mixes were designed to achieve a target strength grade (**C30**) using a standard method, such as the American Concrete Institute method ACI 211.1-91 standard guidelines.

Seawater Exposure

In the non-corrosive plastic tanks, the concrete specimens were submerged in a natural seawater solution. The specimens were continuously submerged to replicate submerged marine conditions, and the pH and ion concentration of the solution were routinely checked. The exposure duration was predetermined (28 days).

XRF For Seawater

Only oxides and ions known to affect concrete deterioration processes were mentioned. Magnesium and sulphate species appeared in significant quantities, indicating potential for magnesium-induced decalcification and sulphate attack. Alkali species (K^+), reactive silica, and iron were also present, contributing to ASR susceptibility and corrosion risk in reinforced concrete exposed to seawater.

Table 4.1 Seawater Chemical Constituents Relevant to Concrete Durability (XRF Results)

Chemical / Ion	Measured Form	Concentration	Significance to Concrete Durability
Mg^{2+}	MgO / Mg	MgO = 1.00 wt.% ; Mg = 5865–6953 ppm	Promotes magnesium attack by converting $Ca(OH)_2$ to brucite and decalcifying C–S–H.
SO_4^{2-} / SO_3	SO_4 / SO_3	SO_4 = 0.28 wt.% ; SO_3 = 0.24 wt.%	Causes sulphate attack, leading to gypsum/ettringite formation and expansion.
Ca^{2+}	CaO / Ca	CaO = 0.22 wt.% ; Ca = 1577–1630 ppm	Contributes to leaching and interacts with Mg^{2+} during deterioration.
K^+	K_2O / K	K_2O = 0.087 wt.% ; K = 715–726 ppm	Participates in alkali–silica reaction (ASR) mechanisms.
Si / Reactive Silica	SiO_2 / Si	$SiO_2 \approx 0.23$ wt.% ; Si = 1062–1112 ppm	Supports potential ASR in aggregates exposed to alkalis.
Fe	Fe	99–110 ppm	Accelerates reinforcement corrosion in chloride environments.
Trace Elements (Pb, Cd, Ag)	Pb, Cd, Ag	Pb = 2–4 ppm; Cd = 19–22 ppm; Ag = 32–35 ppm	Occur in low levels; reported for completeness but limited structural impact.

Testing

Compressive and tensile strength tests were used to assess the cube's strength. The cube specimens were loaded into a compression-testing machine after seawater curing until they failed as part of the compressive strength test. A cylindrical specimen was positioned horizontally and loaded along its length until there was a split to perform the tensile strength test.

RESULTS AND DISCUSSION

Compressive Strength Before and After Seawater Exposure (28 Days)

The compressive strength test was conducted on concrete specimens containing different levels of microsilica replacement at 28 days of curing, both before and after exposure to seawater. The comparative 28-day results are presented in **Table 5.1 and Figure 5.1**, which show the corresponding compressive strength for each mix before and after exposure.

Table 5.1 Compressive Strength before and after Seawater Exposure

Mix ID	Microsilica Replacement (%)	Failure load Before Exposure (kN)	Before Exposure (kN/m²)	Failure load After Exposure (kN)	After Exposure (kN/m²)	% Change
(OA)	Control (0%)	693.8	30.5	733.50	32.6	+6.9%
(A)	MS–5 w%	843.2	37.0	897.75	39.9	+7.8%
(B)	MS–10 w%	707.4	31.0	879.75	39.1	+26.1%
(C)	MS–15 w%	919.8	40.4	936.00	41.6	+3.0%

Figure 5.1 Variation of Compressive Strength before and after Seawater Exposure (28 Days)
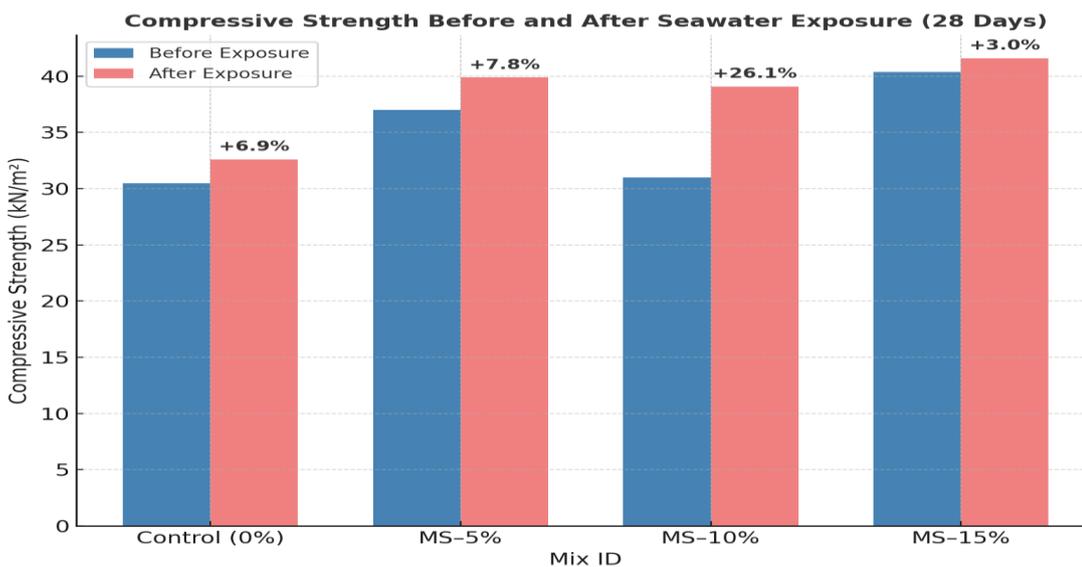
The difference in the compressive strength of concrete before and after 28 days of exposure to seawater with varying amounts of microsilica replacement is shown in Table 5.1 and Figure 5.1. The findings show that after exposure to seawater, the compressive strength of all mixes increased, although the amount of improvement varied depending on the microsilica content.

The seawater analysis revealed high levels of aggressive ions, particularly Mg^{2+}, SO_4^{2-}, and alkalis that are known to cause decalcification of cement paste Zhang et al. (2021), sulphate-induced expansion Huang et al. (2024); Li et al. (2023), and reinforcement corrosion (Kobayashi et al., 2023). These chemical conditions correspond with the modest strength increase observed in the control mix (**+6.9%**), confirming its limited resistance to marine deterioration (Purwantoro et al., 2024; Yao & Chen, 2022). In contrast, microsilica-modified concretes displayed markedly improved performance after exposure, with the 5w% MS and 15w% MS mixes gaining (**+7.8%**) and (**+3.0%**) respectively, while the 10% MS mix exhibited the highest increase at (**+26.1%**) (Khan et al., 2023; Gerasimova & Berdysheva, 2018).

This enhancement is attributed to the pozzolanic reaction of microsilica, which consumes Ca_2 and produces additional C–S–H (Miah et al., 2023; Malaiškiene & Jakubovskis, 2025). Resulting in a denser microstructure Hoque and Presuel-Moreno (2025); Vandhiyan et al. (2020) and reduced permeability that restricts the ingress of harmful ions (Hoque & Presuel-Moreno, 2025; Kumar et al., 2023). Overall, the combined effects of seawater chemistry and cementitious reactions highlight the vulnerability of ordinary concrete Miah et al. (2023); Qu et al. (2020); Yi et al. (2020) and the substantial durability gains provided by microsilica under marine exposure (García et al., 2020; Sikora et al., 2020; Ghanei et al., 2018).
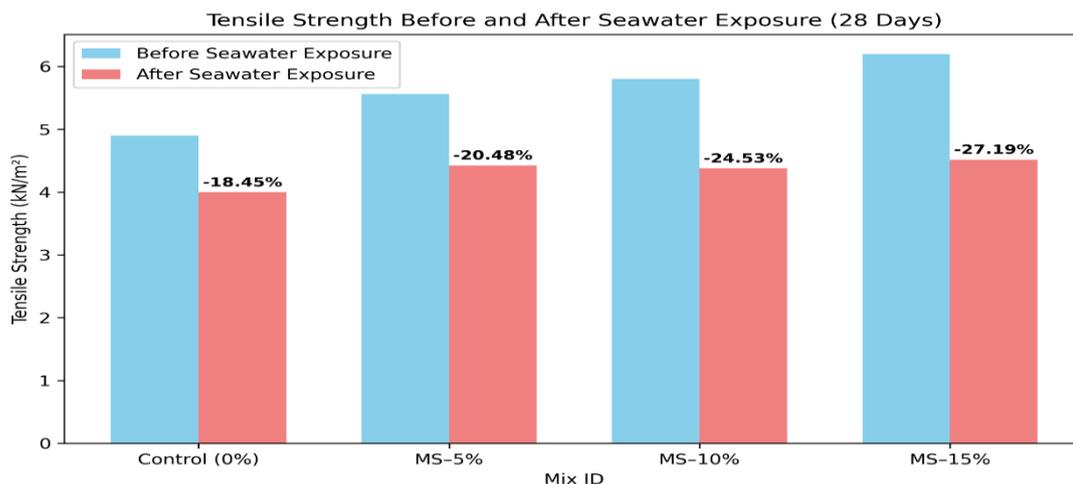
Tensile Strength Before and After Seawater Exposure

When evaluating concrete's ability to withstand tensile stresses, tensile strength is crucial. After microsilica replacement at 28 days of curing, both before and after exposure to seawater, this study examined the effects of seawater exposure on the tensile strength of concrete with varying microsilica levels. The results are shown in Table 5.2 and Figure 5.2 for comparison.

Table 5.2 Tensile Strength before and after Seawater Exposure

Mix ID	Microsilica Replacement (%)	Failure load Before Exposure (kN)	Before Exposure (kN/m²)	Failure load After Exposure (kN)	After Exposure (kN/m²)	% Change
(OA)	Control (0%)	110.15	4.90	89.91	3.996	−18.45 %
(A)	MS–5 w%	125.13	5.56	99.47	4.421	−20.48 %
(B)	MS–10 w%	130.52	5.80	98.48	4.377	−24.53 %
(C)	MS–15 w%	139.42	6.20	101.56	4.514	−27.19 %

Figure 5.2 Variation of Tensile Strength before and after Seawater Exposure (28 Days)

The study investigates the effects of microsilica replacement in cementitious matrices on tensile strength before and after seawater exposure. Results show that tensile strength increased significantly with up to 15% microsilica replacement, rising from 4.90 kN/m² in the control mix to 6.20 kN/m², attributed to additional C–S–H gel formation and reduced capillary porosity (Li et al., 2025; Miah et al., 2023; Kashyap et al., 2023; Burhan et al., 2019). However, after seawater exposure, all mixtures experienced a decline in tensile strength, with losses ranging from 18.45% in the control to 27.19% in the 15% microsilica mix (Alomayri et al., 2023; Qiao et al., 2022; Moffatt et al., 2020). Despite the microsilica mixes maintaining higher strength, the proportional loss increased with microsilica content, highlighting how environmental conditions affect deterioration (Qiao et al., 2022). XRF analysis indicated elevated levels of magnesium and sulphate ions, contributing to C–S–H destabilisation and the formation of weaker phases (Chakkor et al., 2020; Metalssi et al., 2023; Esteban-Arranz et al., 2021).

The sulphate concentration also exacerbates deterioration, as it fosters the formation of ettringite and gypsum, causing expansion and microcracking that notably impair tensile strength (Chen et al., 2020; Elahi et al., 2021; Guo et al., 2019). Additionally, the presence of Ca^{2+} in the seawater facilitates leaching Huang et al. (2024); Zhang et al. (2023), while alkali elements (K^+ and reactive silica) may trigger minor alkali-silica reactivity under cyclical wetting and drying conditions (Deschenes et al., 2018). Despite low levels of trace metals and iron, their presence aligns with the corrosive characteristics of the environment (Yu et al., 2025; Kim et al., 2018). Overall, the data reflect that while microsilica enhances the initial structural integrity of the mortar Altawaiha et al. (2023); Bansal et al. (2024), the aggressive magnesium- and sulphate-rich seawater leads to significant gradual degradation primarily driven by C–S–H destabilisation (Peng et al., 2024; Jia et al., 2023). Nevertheless, the mixes modified with microsilica exhibited better post-exposure strength, suggesting improved performance relative to conventional OPCC under marine exposure conditions (Georges et al., 2021; García et al., 2020).

CONCLUSION

This study examined the effects of microsilica as a partial cement replacement on the compressive and tensile strengths of concrete after 28 days in seawater. The results showed that microsilica enhanced the compressive strength, with a peak increase of 26.1% at a 10 w% replacement, which was attributed to improved pozzolanic activity and microstructure densification. Following seawater exposure, all concrete mixes gained additional compressive strength owing to the secondary calcium silicate hydrate formation. However, the tensile strength decreased owing to chloride and sulphate penetration, leading to microcracking, with losses ranging from 18.45% to 27.19%. However, concrete with 10-15 w% microsilica replacement exhibited higher residual tensile strengths than the control, indicating better resistance to chloride damage. Although further protective measures are recommended, the findings indicate that microsilica can enhance the strength and durability of concrete in marine environments, making it a viable supplementary cementitious material for sustainable coastal structures.

FUTURE RESEARCH

1. Evaluating other properties such as workability, shrinkage, and resistance to cyclic wetting and drying would enhance practical relevance.

2. Comparative studies with other supplementary cementitious materials (e.g., fly ash, slag) could contextualize microsilica's performance advantages.

3. Including environmental and economic assessments of partial cement replacement could support sustainable construction claims.

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