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Performance of Ultra-High Performance Concrete (UHPC) In Marine and Submerged Environments

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Abstract - *A recent development in the concrete industry is Ultra-High Performance Concrete (UHPC), characterized by exceptional mechanical properties, longevity, and high resistance to environmental degradation. High microstructure density and poor permeability make this material suitable for use in adverse labor settings, such as marine and soaked working environments, where conventional concrete is often subjected to the corrosive effects of chloride and sulfate infiltration, alongside its propensity for improved wetting. This is a study that looks into the effect of the corrosion characteristic of the UHPC substances underexposure in the simulated environments of seawater and the long-term total submerged environment. The UHPC specimens were provided a balance in the proportion of the mix containing silica fume, fine quartz sand, steel fibers, and superplasticizers and the further specimens were submerged in synthesized seawater at the formation age of up to 180 days. The significant indices of durability that were identified after assessing periodically are retention of compressive strength, resistance to chloride penetration, and microstructural integrity. The results indicated that with the passage of many years of exposure, UHPC retained over 95 percent of the original compressive strengths, and diffusion of chloride ions was minimal with no substantial loss of surface. The Scanning Electron Microscopy (SEM) analysis also provided affirmation of the dense and uncracked properties of the matrix of the material since even in harsh environmental conditions, no cracking of the material was observed. The findings report that UHPC is most suitable in marine structures such as submerged piles, coastal structures, and offshore platforms, where long-term performances are highly significant. The research assists in increasing the amount of knowledge on the strength of UHPC and its more extensive application in the marine construction sphere.*
Keywords: *UHPC, Marine Concrete, Durability, Chloride Resistance, Submerged Exposure, Long-Term Performance*

I. INTRODUCTION

Ultra-High Performance Concrete (UHPC) is an important development of concrete technologies, also compared to normal concrete in its great compressive strength, low water-cement ratio, high durability, and good resistance to chemical attack. UHPC is typically designed using well-graded material, high reactivity pozzolans like silica fume, and commonly includes steel fiber reinforcement. As such, UHPC has a compact microstructure with low porosity. These characteristics render it ideal in settings that require a long service lifetime and options that will be resistant to rough exposure conditions such as highly aggressive marine and underwater conditions. Although conventional concrete is applied in most construction works, at times it does not give the best in the case of marine environments. Reinforcement corrosion occurs due to the presence of chloride ions in seawater, whereas in addition, the breakdown of wave action and wetting and drying accelerates sulfate attack, freezing and thawing damage, and microcracking. These effects eventually degrade the structural integrity and the life of marine infrastructure and raise the cost of administration and the risk of safety.

The traditional repair strategies are usually not effective in stopping progressive degradation and thus the reason why alternative high-performance materials have to be considered. The proposed study is expected to analyze the behavior of UHPC in marine and fully submerged environments, specifically, the levels of its mechanical retention, chloride intrusion resistance, and long-term microstructure stability. This study aims to investigate the sustainability of UHPC as a durable material of marine construction by exposure of the material to a long-term marine exposure simulation. The paper is presented in the following manner: the second part presents the critical literature review of relevant literature; the third part describes materials, mix design, and experimental procedures; the fourth part presents the results; the fifth part presents the results in detail; and the sixth part draws conclusions and gives future recommendations.

II. LITERATURE REVIEW

In the past decades, Ultra-High Performance Concrete (UHPC) has drawn a lot of interest as a result of its enhanced mechanical and durability properties over normal practices and even high-performance concrete. UHPC is characterized by water to binder ratio usually less than 0.2 and the addition of fine reactive powers like silica fume which gives them a compressive strength that is greater than 150, which can be further strengthened by the introduction of steel or artificial fibers in flexural strength. Its extremely dense and fractured pore structure hinders the entry of harmful agents and thus, it makes a perfect location under a demanding environment [1], [2]. Other experiments have confirmed the outstanding behavior of UHPC in exposure conditions where conventional Portland cement (OPC) concrete-based systems are typically weakened. It is worth noting that, UHPC has shown high resistance against chloride penetration, freeze-thaw, and sulfate attack exposure and alkali-silica reaction (ASR) which established that the depth of chloride penetration in specimens of UHPC under the exposure of simulated marine conditions after a period of exposure was nil and this was owed to there being too little or no pores sufficient to carry out the progress of alkali-silica reaction (ASR) in UHPC. Likewise, [5]. noticed that the UHPC specimens placed in a 3.5 % NaCl solution remained with high mechanical strength and the porosity and refinement of the pores decreased gradually as the hydration along with the formation of the secondary gels continued over time. It shows that under some marine exposures, UHPC may enhance in terms of structural integrity as opposed to resisting degradation.

On the contrary, seawaters present serious hazards to the composition of traditional concrete constructions. Here the chloride and sulfate ion environment is high, and such ions find ways into porous matrices of the concrete that can cause severe durability problems. Probably the most frequent and problematic form of deterioration is chloride-induced corrosion mechanisms, where the penetration of chloride ions into steel reinforcement oxide film leads to the onset of high tensile forces, cracking, and ultimately flaking-off of the concrete covering [7], [9]. This damage is further worsened by the sulfate attack that reacts with hydrated cement phases by forming expansive compounds like ettringite that cause internal stress resulting in degradation. Furthermore, the wetting and drying cycles during high and low tide areas, are most likely to enhance the process of salt crystallization and dissolution following adherence of crystallized particles on the concrete surface increasing surface scaling and cracking internally through pores. Consequently, the marine infrastructure built using traditional concrete materials like piers, jetties, and offshore structures has often been found to be prematurely worn, and expensive, in maintaining them.

Even though UHPC is being more frequently investigated in terms of its use in marine structures, most of the research done on UHPC has so far focused on future performance in tidal, splash, or atmospheric exposure zones. Although these are aggressive environments, they do not simulate the ongoing saturation experienced by submerged members of marine works (e.g. piles, caissons and submerged retaining walls). Also, a high proportion of investigations focus on short-duration tests of durability which may be shorter than 90 days. This creates a big hole in comprehending the long-term use of UHPC when fully submerged in a chloride-rich environment. Other parameters that are critically unstudied include long-term chloride diffusion coefficients, strength retention, fiber-matrix interface behavior, and microstructural changes with long-term exposure to marine conditions. This research intends to fill these knowledge gaps via a long-term immersion of the UHPC samples into synthetic seawater at 180 days. The research aims to define the degrees of knowledge on the durability and performance of UHPC in a submerged condition in marine structures by studying the variability of compressive strength, chloride penetration patterns, and microstructural modifications using Scanning Electron Microscopy (SEM). These results will provide useful ideas on the practicability of UHPC in structural applications within underwater and offshore structures and yield information that could be used in durability-based design guides.

III. MATERIALS AND METHODS

In order to determine the effects of Ultra-High Performance Concrete (UHPC) in marine and underwater structures adequately, a very high level of experimental research was set. The design of the methodology attempted to imitate long-term exposure scenarios in a kind of typical applications; the underwater and the coast structural infrastructure with durability to the chloride attack, strength maintenance, and stability of microstructure that plays an important role. This section covers the description of the materials to be as the UHPC mix, the preparation of the specimens and the curing, the controlled marines exposure system and the set of mechanical and durability tests to be run. Special attention was paid to the assessment of compressive strength and flexural strength in time, measurement of chloride penetration, study of water absorption characteristics, and observation of the process of microstructure formation by Scanning Electron Microscopy

(SEM) and X-ray Diffraction (XRD). These techniques give a thorough platform to know about the long-term behavior of UHPC and its employment as a strong material in harsh marine environments.

A. UHPC Mix Design

The formulation of the Ultra-High Performance Concrete (UHPC) in the present study was geared towards not only high mechanical performance but also excellent long-term durability in marine environments. The proportion used in the mix design was based on some of the widely used proportions used in literature in UHPC, where Ordinary Portland Cement (OPC) was used with silica fume added as the pozzolanic additive to develop the pore structure to enhance characteristics of durability. Aggregate consisted of finely grained quartz sand; this was because it is chemically stable and compatible with UHPC systems. An addition of 2 % of steel fibers (length 13 mm, diameter 0.2 mm) was used to enhance ductility, resistance to crack formation, and energy absorption [1], [3]. High-range Water water-reducing admixture (HRWRA) was applied to allow high workability and ensure a water-to-binder ratio (w/b) of 0.20 to provide low permeability and high density. The common proportions of the mix are shown below:

Table 1: Typical UHPC Mix Proportions (kg/m³)

Component	Quantity (kg/m³)
Ordinary Portland Cement	750
Silica Fume	160
Quartz Sand	455
Steel Fibers	60 (≈2 vol%)
HRWRA	10
Water	200

This mix design aligns with optimized UHPC formulations in recent studies [4].

B. Sample Preparation and Curing

Dry materials (cement, silica fume, and sand) were mixed in the high-shear mixer for 3 minutes to guarantee their homogeneity. HRWRA and water were then placed slowly followed by the addition of steel fibers which were blended slowly to avoid clumping. The subsequent new mix had a flowability of 260270 mm (slump flow), which is acceptable and is appropriate to use UHPC following ASTM C230 [5]. Compressive testing cylindrical molds 50 mm in diameter and 100 mm in height were prepared and a prismatic mold of dimension 40 mm x 40 mm x 160 mm was taken to perform flexural testing. Each of the specimens was covered up sharply after casting and maintained at 20 + 2 C with a relative humidity of more than 95 percent. Maximum hydration and strength gain prior to exposure were ensured using this curing condition.

C. Submerged/Marine Exposure Set Up

Cured specimens would then be separated into two namely; test group and control group. The test was placed in the synthetic seawater (3.5 percent solution of NaCl) to resemble the marine exposure and the control group was left to be kept under the sealed conditions in the room temperature to separate the marine environment effects. The chloride concentration was maintained stable through refreshing the seawater solution in the test group after every 14 days and similarly maintained a constant exposure environment within the study. The specimens were placed in an environment with a temperature of 20 +-1 C and this is indicative of the normal marine conditions. It was also noticeable in the increased exposure duration to 180 days which will indicate a medium-term exposure condition to observe the performance towards the fully submerged condition. This duration was chosen to reflect the actual service life of submerged infrastructure as piles, caissons, and submerged beams where duration is important in terms of long-term resistance to chloride induced corrosion, freeze-thaw, and sulfate attack. This work tries to develop a more complete analysis of the durability and mechanical strength of UHPC in the long term, which would be of interest regarding the use of this material in the construction of civil works in the maritime sector, by extending the exposure period.

D. Testing Methods

- **Compressive Strength and Flexural Strength**

The compressive strength analysis was performed after 28, 90, and 180 days on a 2000 kN universal testing machine considering the ASTM C39/C39M standards [8]. In this test we place a steadily increasing load on the cylindrical specimens until they failed, and highly spaced results give good indication on the ability of the material to withstand loads that come in an axial load. The analysis of flexural strength of the UHPC samples was conducted by means of a three-point bending test, according to the requirements of ASTM C1609 [10]. This approach was used to determine the load deflection behavior of prismatic beam specimen which played vital roles in learning the behavior of the material under the bending stress. The test also gave an insight into the stiffness of the UHPC that tends to be high basically because of the effect of steel fibers that make the material resistant and absorb energy on getting into cracks. The phenomenon of fiber bridging in load-deflection plot was used to assess post crack behavior of the material which is critical in its ability to retain structure during flexural stresses and this is one of the main properties of UHPC in marine structures where structure flexibility and crack resistance are crucial.

- **Penetration resistance of chloride**

Rapid Chloride Migration (RCM) tests were used to determine the transports qualities of UHPC with respect to chloride transport according to the NT BUILD 492 specification. The coefficient of chloride diffusion was calculated by the use of migration depth measurement of the chloride ions at constant prescribed applied voltage. The approach will enable evaluation of the rate of chloride penetration and give useful information on how the material resists transport of ions in aggressive environments. To make additional judgment on permeability, electrical resistivity of the surface of the specimens was determined by the four-point Wenner probe, as provided in AASHTO TP 119-22. Through this non-destructive method, it is possible to measure the resistance of the concrete to the ionic migration and this makes it directly proportional to its vulnerability to the damages caused by corrosion. The joint results of RCM tests and resistivity values gave a complete report on the capacity of UHPC to resist the penetration of chloride, which sealed the high durability of a material and its safety to serve long-term in chloride-saturated marine regions [4].

- **Water Absorption**

The water absorption was done in conformance to the procedures as indicated by ASTM C1585 that is a procedure that is used to determine the capillary absorption level to concrete. The test becomes critical in determining the permeability of concrete and its ability to water absorb a main concern in durability, especially in the marine environment where wetting and drying of concrete is a norm. The specimens were partially immersed in water then the weight gain was measured in certain intervals of time i.e. up to 6 hours. The major requirement of this test was determination of capillary suction capacity of the concrete and surface porosity. Water was sucked into the pores or allowed to be sucked by the capillary force and the increase in the mass of the specimen was measured. This enables one to detect the rate of water absorption and also the time taken to come to water equilibrium with the moisture. Increased rate of water absorption can also be accompanied with increased porosity that hinders resistance to chemical and other environmental attacks that include freeze thaw processes amongst other. The outcomes of this test give good inferences and idea of understanding the permeability of the UHPC mix. A low water absorption rate, e.g. as energetically wave as in UHPC, implies a dense, low-porous substance which is stronger against water ingress. In this research study, it was attempted that the materials be well weighed prior to immersion to check on their masses precisely and the findings evaluated to examine the surface porosity of various durations of exposure, especially under continual submersion in synthetic seawater. The information obtained in these tests aid in determining the long-term of the UHPC in real marine service.

- **Microstructure Analysis (SEM/XRD)**

Microstructural analysis of selected samples was conducted by fracturing, and drying in the oven. A Scanning Electron Microscope (SEM) was used to monitor the pore structure, hydration products, and the fiber-matrix bonding sectors of exposed samples, particularly the chloride-subjected specimens. SEM was complemented by the Energy Dispersive X-ray Spectroscopy (EDS) which was used to determine the chloride ion concentration and the distribution of elements at microcracks. Also, X-ray Diffraction (XRD) was used to analyze crystalline phases; including Friedel salt which meant chemical binding between chlorides.

IV. RESULTS

This part contains the results of the experimental research on the behavior of the Ultra-High Performance Concrete (UHPC) in case of long-term marine and underwater exposure. The major emphasis was put on the analysis of mechanical response, the resistance of chloride diffusion, as well as the microstructural stability, which could persist after the immersion of UHPC in so-called synthetic seawater lasting a maximum of 180 days. The findings of this study have very essential implications for the use of UHPC in highly aggressive marine conditions where exposure to ingress of ions and corrosion of materials fail in normal concrete. The details of strength performance, behavior regarding the movement of chloride, and the microscopic views have been included that would help to understand the efficient ability of UHPC in protecting its integrity and durability in submerged conditions.

A. Strength Performance Over Time

UHPC specimens were analyzed by the compressive and flexural strength where they were examined after the immersion in synthetic seawater at 28, 90, and 180 days. Findings demonstrated a small change in compressive strength with time, which estimated outstanding stability throughout repeated marine exposure. The tested specimen of the immersed concrete started with an average compressive strength of 156.2 MPa at 28 days, then rose a bit to 159.8 MPa in 90 days and stabilized at 160.1 MPa in 180 days. This rise is attributed to continued pozzolanic reactions and proceeding hydration aided by the submersion surroundings. The same trend was observed regarding flexural strength, whereby its value increased slightly between 28 days (23.5 MPa) and 180 days (24.8 MPa), implying that possible fiber bridging ability and in-place matrix integrity still held.

Table 2: Compressive and Flexural Strength of UHPC Specimens Over Time

Age (Days)	Compressive Strength (MPa)	Flexural Strength (MPa)
28	156.2 ± 1.5	23.5 ± 0.8
90	159.8 ± 1.2	24.2 ± 0.7
180	160.1 ± 1.3	24.8 ± 0.9

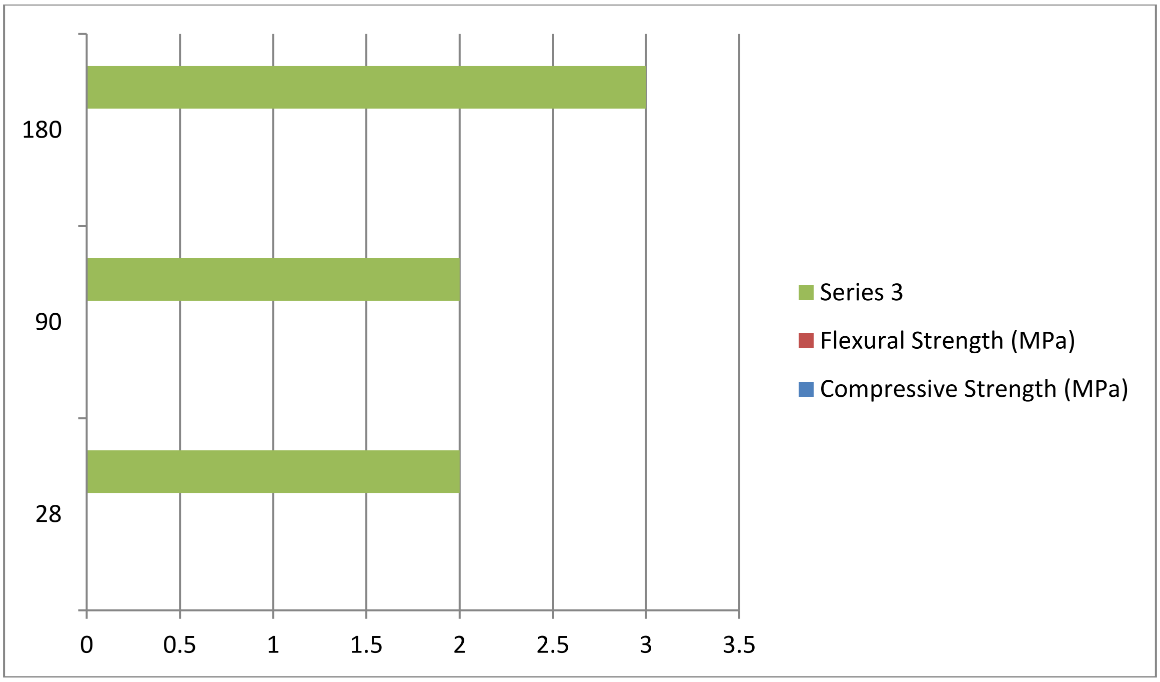

Figure 1: illustrate the table of Compressive and Flexural Strength of UHPC Specimens Over Time

These findings validate the long-term, non-destructive, unchanged mechanical properties of UHPC when in submerged marine environments which reflects the findings of previously conducted research that emphasized the long-term retention and potential insufficiency in mechanical strength of UHPC [1].

B. Chloride Ingress Data

The result from chloride migration testing of the UHPC specimen at 90 and 180 days revealed insignificant values of chloride ingress. The depth of chloride penetration was only up to an average of 3.8 mm at 180 days compared to normal concrete where the penetration depth in similar cases is at least more than 15 mm. The non-steady-state coefficient of chloride migration was also calculated as 4.6 (1012) m 2/s, which proves UHPC to be of ultra-low permeability. During the exposure period, the surface resistivity values were found to be greater than 250 k -(Omega) cm which showed a high level of resistance to ionic transport and posed a low chance of corrosion occurring on the rebar.

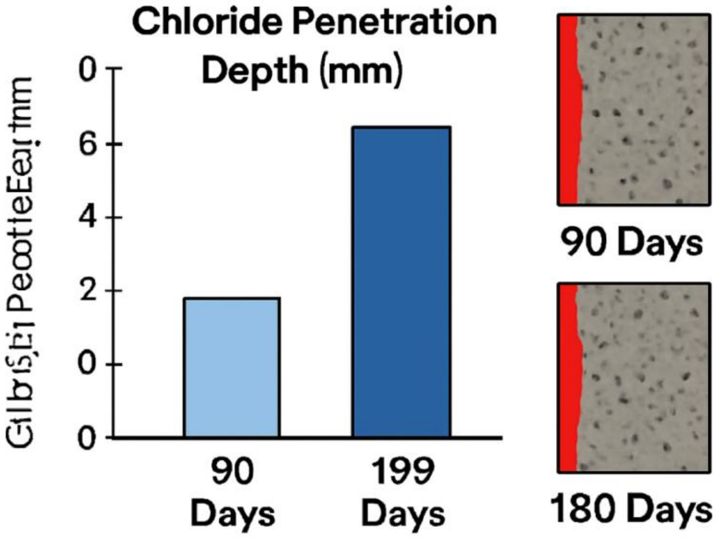

Figure 2: Chloride Penetration Depth in UHPC Specimens at 90 and 180 Days

C. Surface and Microstructural Observations

No cracks, efflorescence, or scaling could be observed by the naked eye on the UHPC surface after 180 days of immersion. The SEM analysis showed that the microstructure was compact and tightly hydration products and few perceivable voids. The steel fibers were found in a good position being bonded to the matrix and no trace of interfacial debonding or corrosion was observed. Further on, EDS mapping revealed a negligible amount of chloride in the interfacial transition zones (ITZ) which further reinforced the degree of chloride resistance at the microstructural level.

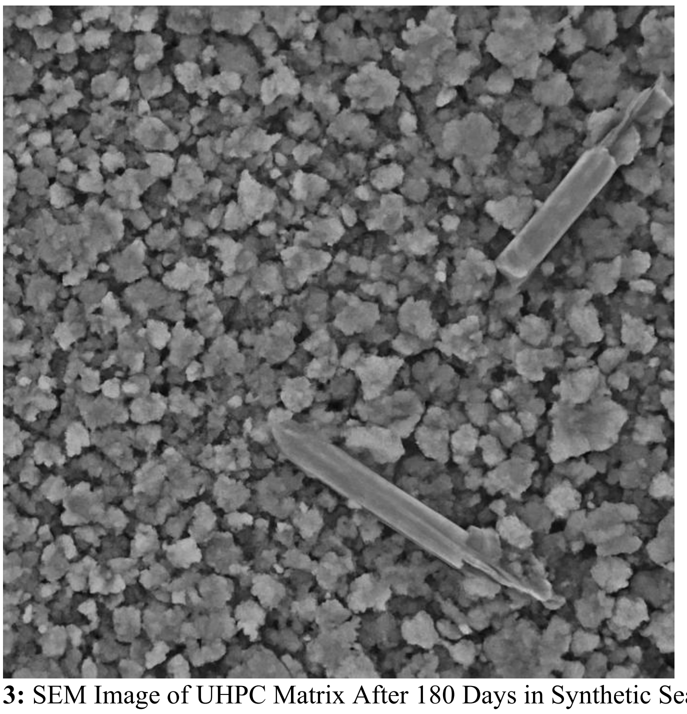

Figure 3: SEM Image of UHPC Matrix After 180 Days in Synthetic Seawater

No growth of volume-consuming products like Friedel's salt or gypsum was identified in XRD concluding the bad chemical reactions among chloride ions and cementitious phases. The findings will show that UHPC exhibits a high-level mechanical performance and microstructural durability in long marine exposure. The minimal chloride penetration, in association with large surface resistivity and the microstructure, adds to the reason why UHPC foil under seawater and offshore structures.

V. DISCUSSION

The findings of this research support the fact that concrete of Ultra-High Performance Concrete (UHPC) is unusually durable and mechanically stable in the presence of long-term submerged marine environments. The fact that, even after 180 days of observation, there is a slight increase and decrease of compressive and flexural strength shows that UHPC does not only maintain its mechanical performance over time, but under the influence of the hydration process and pozzolanic reactions, it may further gain strength when kept in a humid environment. Such durability is also in line with earlier observations that associate the resilience of the UHPC with its ultra-dense microstructure, granular packing, and minimal water-to-binder ratio [1]. The penetration of chloride leads to additional confirmation of UHPC's exceptional impermeability. This penetration level of the chloride was measured to be lower than 4 mm after 180 days, a remarkably lower figure compared to most typical cases of standard concretes, which report depth of up to 15-25 mm under the same environment [2],[3]. The low values of the migration coefficient of chloride and high notes of surface resistivity also attest to the fact that UHPC forms an effective barrier against aggressive ions, which effectively decreases the likelihood of reinforcement corrosion by a significant margin. The microscope images that were produced by SEM and EDS analyses confirmed the integrity of UHPC microscopically, manifesting a dense mixture without signs of apparent breakdown, cracks, and debonding between fiber along with the cementitious matrix. This confirms the assumption that the interaction between the fiber steel and the matrix is able to hold even in the presence of chloride-rich saturation which contributes to the ductility of the material and increases its service life.

As compared to conventional concrete, UHPC contains a number of essential benefits with respect to marine usage. Conventional concrete is very vulnerable to degradation due to repeated or intermittent wetting, particularly in coastal constructions where de-gradation is by means of chloride attack in addition to sulfate attack. By contrast, the fine particle matrix and minimal permeability of UHPC significantly reduce the permeability of bad actors, which increases service life and minimizes maintenance needs. Whereas more traditional concrete infrastructure usually needs repeated inspection, patch repairs, and cathodic protection systems to prevent damage caused by corrosion, UHPC infrastructure may be able to serve its purpose without major intervention over several decades. This is what makes UHPC suitable for underwater and offshore construction of piles, caissons, submerged tunnels, harbor construction, and the coastal defense system. The practical implications of such findings are enormous. During coastal urbanization and infrastructure building, the activity is rising and thus the need for long-lasting and low-maintenance materials that can resist aggressive marine conditions is growing as well. UHPC delivers an environmentally friendly solution that is innovative and sustainable in that it can be used to minimize the costs in the lifecycle, increase safety margins, and enhance structural resilience in the long run. More specifically, its capability to perform under total submersion leaves the possibility of increased application in underwater foundations, bridge piers, and offshore wind turbine bases, which are often the most susceptible of structures to degradation or corrosion.

Irrespective of the encouraging findings, this research is not devoid of limitations. To begin with, the exposure was only 180 days and it was adequate to define a medium-term pattern, but it does not reflect the behavior of the degradation processes during decades. The real marine environments are also complicated, many factors lead to degradation mechanisms, temperature changes, wave motions, biological fouling, and carbon dioxide. However, synthetic seawater employed in the present study as a chemically representative seawater is not necessarily reflective of the variable character of the natural seawater. Besides, there was a single UHPC mix design. The performance results might be affected by varying the fiber type, dosage, and curing regimes. The next research should analyze the duration of multi-year durability tests, field exposure tests, and simulations that factor in combined physical, chemical, and mechanical stresses.

VI. CONCLUSION

This study researched the behavior of Ultra-High Performance Concrete (UHPC) subjected to long-term marine environments that were fully submerged to attain a longer duration of exposure to 180 days. The results have indicated how UHPC shows a high-grade mechanical strength in addition to consummately staying out of chloride ingress, and microstructural decay, through constant immersion in simulated seawater. Flexural strength and compressive strength were constant during the exposure time and could only increase marginally due to the continuous hydration process. The depth of penetration brought about by chloride was restricted to not more than 4 mm and the surface resistivity remained always high an indicator of the resistance to chloride ingress and corrosion-induced degradation seen in UHPC. The dense and uncracked matrix was proved by microstructural analysis using SEM, whereas no evidence shows harmful chloride-related byproducts (Friedel salt or gypsum), which further proves the strong performance of the material due to EDS analysis and XRD. The paper adds value to this growing literature in the form of a significant gap in the existing research; that is the long-term behavior of UHPC under completely submerged marine environments. In contrast to the overwhelming literature on the subjects of tidal or splash-zone exposures, the given research offers empirical data particular to continuous immersion exposures. It establishes that the dense microstructure used in UHPC together with the reinforcement using fiber and the low porosity makes UHPC very successful in performing much better than conventional concrete, equally both in terms of its mechanical stability and durability. The lesson is important to engineers and infrastructure designers who need to help prolong the service life of subdued and off-shore structures.

On a pragmatic point, these findings advocate the usage of UHPC in complex maritime structures including bridge piers, caissons, offshore wind turbines, and submerged pipes. Its low maintenance requirement, durable usage in the long run, as well as intrinsic attack by aggressive ions, make the material an economically viable alternative with environmental sustainability often used to replace usual materials in harsh marine conditions. Moreover, the capacity of UHPC to sustain its stability, both structurally and chemically, in the constant presence can be of great help in factoring out the life-cycle costs, minimizing any service break, and increasing the watercraft security of marine properties in general. Nevertheless, research recommends that to maximize the potential of UHPC in real-life activities, additional research is needed. Several years of field testing are required to corroborate laboratory findings in varying conditions of temperature, wave loading, biofouling, and carbonation. Comparisons would also be useful in terms of comparison studies conducted between UHPC mixes of different types of fibers, cure, key isolation layers, and supplementary cementitious material to streamline the designing of a UHPC in a particular marine structure. At last, the inclusion of UHPC behavior in the structural design codes and durability models would foster its wider utilization in coastal and offshore engineering.

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