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Research Article

Investigation of Strength Development of Underwater Concretes in Seawater and Freshwater Environment

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Keywords

Underwater concrete,
Compressive strength,
Curing conditions,
Durability,
Washout resistance,
Workability.

Abstract

The effective use of concrete in underwater engineering applications requires optimization, especially in terms of washout resistance, workability and mechanical strength. This study analyzed the compressive strength development of underwater concrete in marine and freshwater environments to determine the effect of environmental factors on concrete strength. In this context, the same underwater concrete was poured on the Black Sea coast and in the İyidere Stream and underwater concretes on the shore exposed to air. Core samples were extracted from concretes cured in seawater, river water, outdoor air, and laboratory environments at 7 and 28 days. Their compressive strengths were then measured and compared. As a result of this study, it was determined that the compressive strength of underwater concretes exposed to Black Sea water and river water was higher than that of concretes cured in air. Despite the wave motion in the Black Sea and the river flow, the underwater concretes exhibited similar strength development, comparable to concretes cured in laboratory conditions.

1. Introduction

For decades, various engineering applications, such as bridge abutments, harbor structures, sea and river defense systems, and more recently the construction of offshore oil fields have necessitated the placement of concrete underwater. This process presents an engineering challenge that requires technical precision due to the harsh environmental conditions to which concrete is exposed. The successful application of concrete underwater is directly dependent on optimizing the mix design and selecting appropriate production techniques. In particular, washout resistance, workability, and mechanical strength are among the most important engineering parameters encountered during underwater placement. In this context, effective management of factors such as the type of cement used, superplasticizers and anti-washout additives plays a decisive role in ensuring that the concrete meets the desired performance criteria. Therefore, with appropriate material selection and method optimization, it is possible to obtain high-strength and long-lasting concrete under water [1,2].

Underwater concrete structures are considered as a critical building material in civil, hydroelectric and marine engineering disciplines and are widely used in large-scale infrastructure projects such as dams, underwater tunnels, piers, shore protection systems, underwater bridges and docks. Such structures are exposed to harsh environmental and mechanical conditions such as erosion due to water flow, corrosion caused by seawater and environmental factors, chemical attacks, fatigue effects caused by dynamic loads and freeze-thaw cycles. In particular, high salt content in the marine environment, corrosive effects caused by fluid movements and sulfate attacks lead to crack formation on concrete surfaces, loosening of aggregates and reduction in the service life of concrete. This situation causes deterioration in the physical and mechanical properties of concrete, threatening its structural integrity and reducing its durability. In order for underwater concrete structures to be long-lasting and durable, it is of great importance to develop engineering solutions to improve material performance [3-5]. In this context, the underwater concreting process involves various engineering challenges from design to application and control phases, and quality and integrity uncertainties may arise during placement due to limited accessibility and visibility and low visibility of underwater work areas. In addition, concrete placed underwater is susceptible to adverse conditions such as segregation, grouting, cement washout, void formation, cold joints and water entrapment. Therefore, innovative techniques such as grouting aggregates are used to increase the strength of concrete and these methods are integrated with key production strategies such as offshore production, onshore production and marine transportation [6,7].

In the literature, it has been reported that various additives are used in underwater concrete production and that these additives offer both advantages and disadvantages. Indeed, polysaccharide gums have been found to increase flow resistance in underwater concrete pours, shotcrete applications and pumping-assisted concrete types, but have a limited effect on hardness. It was also reported that polysaccharide gums and highly spaced water-reducing admixtures increased flow resistance over time, but this effect was based on a physical, not chemical, mechanism [8]. Seawater and sea sand were found to improve the washout resistance of anti-washout underwater concretes, but negatively affect the compressive strength. It was emphasized that magnesium ions in seawater chemically interact with cement to improve the washout performance, but form a film that leads to structural defects [9]. It was revealed that anionic anti-washout admixtures improved the workability and strength of underwater concrete more effectively than non-ionic admixtures, and the concrete produced with these admixtures showed a significant increase in 28-day compressive strength and exhibited a more stable structure [10]. In addition, anti-washout admixtures were found to improve mechanical properties by preventing dispersion in underwater three-dimensional concrete printing. The combination of micro silica, nano silica and hydroxypropyl methyl cellulose was reported to provide significant improvements in flexural and bond strengths while increasing pumpability under water [11].

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The use of alternative materials to improve the durability and mechanical properties of underwater concrete is a widely researched topic. In the literature, there are many studies in which performance improvements are achieved by adding different materials to concrete mixtures for this purpose. For example, Wang et al. showed that nano-silicon dioxide and nanometakaolin significantly increased the compressive strength of non-dispersible underwater concrete and it was found that these materials increased the density of concrete by filling the pores [12]. Sonebi and Khayat found that anti-washout admixtures and silica fume-substituted cements increased the relative residual strength of underwater concrete, while Heniegal et al. found that increasing the dosage of anti-washout admixtures increased the resistance of concrete to water erosion [13,14]. Grzeszczyk et al. reported that silicon dioxide nanoparticles reduce washout by promoting polymer lattice formation, while Nasr et al. highlighted a new approach that improves washout resistance and increases compressive strength with the concept of self-protecting underwater concrete [15,16]. Sikandar et al. showed that admixtures such as gum arabic and super absorbent polymers improve the mechanical properties of concrete, while Assaad and Issa demonstrated the strong relationship between water permeability and washout loss [17,18]. Falkner and Henke emphasized that the use of steel fiber concrete increases safety in deep underwater structures, while Zaidi et al. studied the effect of alkali activator ratios on the engineering properties of underwater geopolymer concretes [19,20]. Alsaffar et al. optimized the performance of reactive powder underwater concretes containing anti-flushing admixture and micro steel fibers, while Jeon et al. showed that the addition of nano-silica and MgO provided positive effects on durability and microstructure [21,22]. Horszczaruk and Brzozowski tested the abrasion resistance and mechanical properties of underwater concretes cured under hydrostatic pressure and found that hydrostatic pressure can have positive effects under certain conditions [23]. In addition, Ustabaş et al. revealed that mineral admixed mortars showed higher strength and exhibited a more resistant structure against sulphate effects in concretes exposed to intense sulphate-containing conditions such as marine environment compared to various cement-based mortars [24].

The compressive strength development of underwater concretes used in marine environments and rivers is a critical parameter for the longevity of reinforced concrete structures. In the literature, studies on the strength properties of underwater concretes have generally focused on the adverse effects of salt water, while the effect of freshwater environments has been relatively less studied. In this study, the effects of abrasive effects due to the continuous motion of sea waves and the flow of river water on the compressive strength of underwater concretes through washing and abrasion on the surface of underwater concretes were investigated in detail. Within the scope of the research, underwater concretes were cast on the Black Sea coast and in the İyidere Stream, and reference concretes that were not exposed to water were produced in the same region. In the experimental study, four different curing environments were determined and classified as seawater, stream water, outdoor environment and laboratory environment. Compressive strength measurements were performed by taking core samples at 7 and 28 day periods from concrete samples cured in different environments. In line with the data obtained, the effect of environmental conditions on the compressive strength development of underwater concretes was evaluated comparatively.

The main objective of the study is to determine the compressive strength changes of underwater concretes exposed to seawater and freshwater and to compare the strength performance of the same concretes in the environmental conditions of Rize province and in the laboratory environment and to reveal the effect of field conditions on concrete strength. The results obtained are expected to contribute to the development of design criteria for optimizing the strength performance of underwater concretes.

2. Material and Methods

2.1. Cement

CEM I 42.5R SR 5 sulfate-resistant cement was selected for underwater concrete in this study. This cement is produced by Aşkale Cement Factory and is classified with the SR symbol indicating sulfate resistance in accordance with the TS EN 197-1 standard [25]. SR 5, a cement type with a C3A content below 5%, is recommended for seawater and sulfate environments, as cements with lower C3A content react less with sulfates, increasing the concrete's resistance to sulfate attack [26,27]. The chemical composition, chemical, and physical properties of the cement are shown in Table 1.

Table 1. Properties of CEM I 42.5 R SR 5 cement

Chemical Composition (%)		Physical and chemical properties		
CaO	62,13	Remaining in 32 μ sieve (%)	7,5	
Si_2O	18,44	Remaining in 90 μ sieve (%)	0	
Al_2O_3	4,22	Specific surface cm2/g (Blaine)	3973	
Fe_2O_3	4,42	Specific gravity	3,08	
MgO	1,44	Setting time (minutes)	Start	190
			Finish	255
SO_3	2,98	Standard consistency water requirement (%)	26,9	
Na_2O	0,21	Volume	1	
		constancy Le Chatelier (mm)		
K_2O	0,97	Clinker C_3A (%)	3,69	
Cl^-	0,0120	Insoluble residue	0,49	
		Loss of ignition (%)	4,60	

2.2. Aggregate

Basalt rock obtained from Cevizlik Quarry in İkizdere district of Rize province was preferred as aggregate in concrete design since it is a widely available material in the region with high hardness, strength and abrasion resistance properties and high specific gravity values. The sieve passing rates, percentages added to the mixture, and water absorption percentages of the four aggregate groups in the concrete mixture are presented in Table 2. The specific gravity values of the concrete components were 3.08 for cement, 2.682 for (0/5) mm aggregate, 2.667 for (5/12) mm aggregate, 2.691 for (12/25) mm aggregate and 2.704 for (22.4/38) mm aggregate, respectively [28]. In addition, the granulometric distribution curve showing the conformity of the aggregate mixture to the TS 802 (2016) standard is given in Figure 1 [29].

The sieve analysis curves of the three different aggregate mixes (Series 2, Series 3 and Mix Gradation) presented in Figure 1 reveal that all mixes have similar gradation and show a uniform distribution. The curves show a balanced transition between fine and coarse aggregates, with gradually increasing percentages of passing material across a range of sieve sizes from 0.063 mm to 31.5 mm.

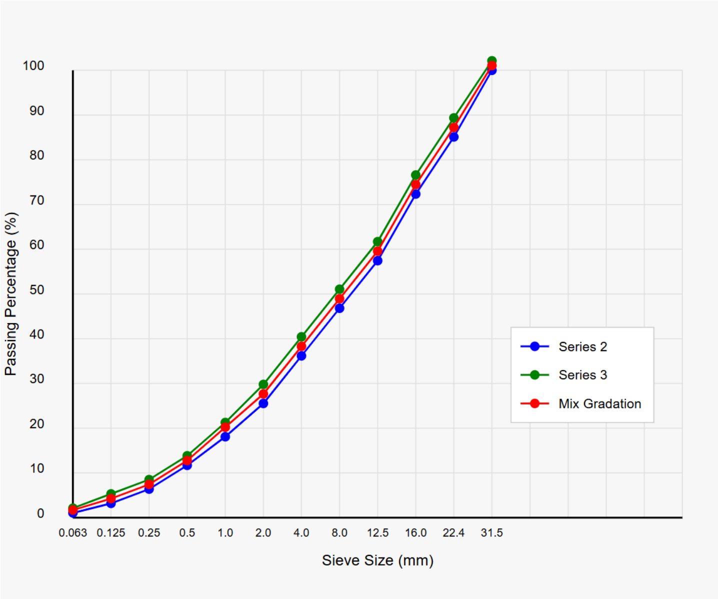

Figure 1. Granulometry curve of underwater concrete

Table 2. Aggregates used in concrete and percentage and water absorption in the concrete mixture

Aggregate type	0/5 mm crushed sand	5/12 mm crushed stone	12/22.4 mm crushed stone	22.4/37.5 mm crushed stone
Sieve size (mm)	% passing			
37,5				100
31,5			100	92,3
22,4			86,5	54,3
16		100	47,5	6,1
11,2		97,6	6,3	
8	100	71,3	1,1	
4	96,4	8,7		
2	71,3	1,3		
1	48,6			
0,5	32,7			
0,250	23,6			
0,125	14,3			
0,063	7,6			

Mix proportions (%)	49	18	20	13
Water absorption (%)	1,98	1,05	1,03	0,86

2.3. Chemical Additive

In the concrete design, CHRYSO DELTA new generation poly carboxylate based plasticizer chemical admixture was used, the optimum usage rate of the admixture was calculated as 0.8% of the cement mass and the concrete design was carried out with this rate. This chemical admixture is preferred in underwater concretes due to its high water reduction and early strength gain properties; technical data regarding these properties are presented in Table 3.

Table 3. Technical specifications of Chryso delta plasticizer chemical additive

Product Feature	Value
Product Structure	Liquid
Color (COL)	Brown
Lifespan	12 months
Chloride Ions	<0,100 %
Density	1,075 ± 0,020
pH	4,50 ± 1,00

2.4. Water Chemistry

In this study, samples taken from the Black Sea coast and İyidere Stream were cured for 7 and 28 days. During the curing period, the effects of both water sources on the concrete were analysed. The ion concentrations of the Black Sea coast and İyidere Stream are presented in Table 4 [5,30]. For İyidere Stream, the concentrations of SO_4^{2-}, Cl-, and Na^+ are not presented in the table, as these parameters were not measured.

Table 4. Ion concentrations of the Black Sea coast and İyidere stream

Water	Total Salinity (%)	pH	Mg^{2+} (mg/l)	SO_4^{2-} (mg/l)	Cl^- (mg/l)	Na^+ (mg/l)	Ca^{2+} (mg/l)
Black Sea	1.76	8,2	301	2708	400	5260	250
İyidere Stream	0.0275	7,4	5.81	-	-	-	10.81

2.5. Methodology

The underwater concretes produced in this study were poured in four different areas to be tested under different curing conditions. The concrete pours were carried out at the logistics center construction site at the junction of the İyidere River with the sea in the İyidere district of Rize province on the Black Sea coast. The casting process was carried out in August 2024 using the tremie pipe method and the details of this process are presented in Figure 2. The curing conditions applied to the concrete were carried out in the curing pool prepared in the laboratory environment, on the seashore, on land and in the natural environmental conditions determined in the stream. Within the scope of the study, a total of 12 concrete specimens were poured, two specimens each in land, sea and river environments and six specimens in the laboratory environment. The concretes in the sea and river were removed after a certain period of time in underwater conditions, core samples were taken and placed back into the water. Core samples taken on the 7th and 28th days were prepared with a length/diameter ratio of 1/1 for strength measurements according to TS EN 12390-4 standard [31]. The compressive strengths of core samples taken from underwater concretes in the sea, underwater concretes in the river and concretes cured outside were measured. The concrete specimens cured on land were watered for the first two days after casting and the compressive strengths obtained from these specimens on the 3rd, 7th and 28th days were determined using 150x150x150 mm cube specimens. The tap water used in these studies was selected in accordance with TS EN 1008 standard [32].

The material quantities (kg) for 1 m³ concrete mix examined in the study are detailed in Table 5. The specimens were designed to meet C30/37 concrete class requirements, with a water/cement ratio of 0.45 and a slump of 210 mm, and concrete production was carried out according to TS 802 (2016) standard [27]. In the concrete mix, 0/5 mm crushed sand, 5/12 mm crushed stone, 12/22.4 mm crushed stone and 22.4/37.5 mm crushed stone were added at the rates of 49%, 18%, 20% and 13%, respectively. The control specimens were cured in lime-saturated water for 28 days at a temperature of 20 ± 2 degrees Celsius. The results of all mechanical tests were based on the average values of the specimens cured for 3, 7 and 28 days [33-36].

Table 5. Materials and quantities used for 1m³ underwater concrete mix

Materials	Mass (kg)	Specific gravity	Volume (dm³)
Cement	340	3,08	110,4
Water	153	1	153
Air			15
Chemical additive	2,72	1,1	2,5
0/5 (mm) aggregate	940	2,682	352,4
5/12 (mm) aggregate	348	2,667	129,4

12/25 (mm) aggregate	388	2,691	143,8
22,4/38 (mm) aggregate	253	2,704	93,5
Total	2424,4		1000

Figure 2. (a) Tremie placement method, (b) core extraction, (c) core samples

2.6. One-way analysis of variance (Anova)

In this study, statistical differences between the groups were analyzed using the one-way ANOVA test by calculating the mean compressive strength values of the samples belonging to each environment. As a result of the analyses, it was found that there were statistically significant differences between the 7 and 28 day groups of specimens. (7 days: $F = 87.90$, $p = 1.83 \times 10^{-6}$; 28 days: $F = 16.47$, $p = 8.74 \times 10^{-4}$) The data set analyzed in the study is presented in Table 6.

Table 6. Compressive strength dataset of concrete samples

Sample Type	Sample No/Name	7-day strength (MPa)	28-day strength (MPa)
Underwater Concrete Samples	Sea 1	31.20	37.80
	Sea 2	32.42	43.49
	Sea Average	31.81	40.645
	River 1	31.92	40.53
	River 2	32.71	40.55
	River Average	32.315	40.54
	Land 1	28.98	38.34
	Land 2	29.83	38.15
	Land Average	29.405	38.245
Laboratory Samples	1	37.12	45.26
	2	37.00	44.62
	3	39.06	45.95
	4	38.01	45.44
	5	37.50	45.79
	6	37.82	46.01
	Average	37.75	45.68

2.7. Tukey HSD (Honestly Significant Difference Test)

After the variance analysis (ANOVA) performed on the compressive strength data, Tukey HSD test was applied to determine the differences between the groups. According to the results obtained, it was determined that the compressive strengths of the samples cured in the laboratory environment on the 7th and 28th days were significantly higher than the samples cured in land, river and sea environments. No statistically significant difference was detected between the river and sea groups at both ages ($p>0.05$). Table 7 shows the Tukey HSD results for both 7-Day and 28-Day strength.

Table 7. Tukey HSD Results for 7-Day and 28-Day Strength

Comparison	Group 1	Group 2	Mean Difference	p-value	Significant
7-Day	Land	Laboratory	~8.3 MPa	< 0.001	Yes
7-Day	River	Laboratory	~5.4 MPa	< 0.01	Yes
7-Day	Sea	Laboratory	~5.9 MPa	< 0.01	Yes
7-Day	Land	River	~2.9 MPa	0.07	No
7-Day	Land	Sea	~2.4 MPa	0.09	No
7-Day	River	Sea	~0.5 MPa	> 0.05	No
28-Day	Land	Laboratory	~7.4 MPa	< 0.001	Yes
28-Day	Sea	Laboratory	~5.0 MPa	< 0.01	Yes
28-Day	River	Laboratory	~5.1 MPa	< 0.01	Yes
28-Day	Land	River	~2.3 MPa	0.06	No
28-Day	Land	Sea	~2.4 MPa	0.09	No
28-Day	River	Sea	~0.1 MPa	> 0.05	No

3. Results and Discussion

3.1. Examination of compressive strength features

This study aimed to determine the effects on the strength development of concretes poured in marine and river environments. In particular, in coastal areas where wave action is effective and in areas exposed to river flow, the strength changes of concretes directly in contact with water without the use of molds were examined. In this context, it was investigated whether the movements of salt and fresh water in the natural environment cause a lower strength level than the designed concrete class. The study was conducted within a scientific framework to evaluate the effects of marine and river environments on the mechanical properties of concrete.

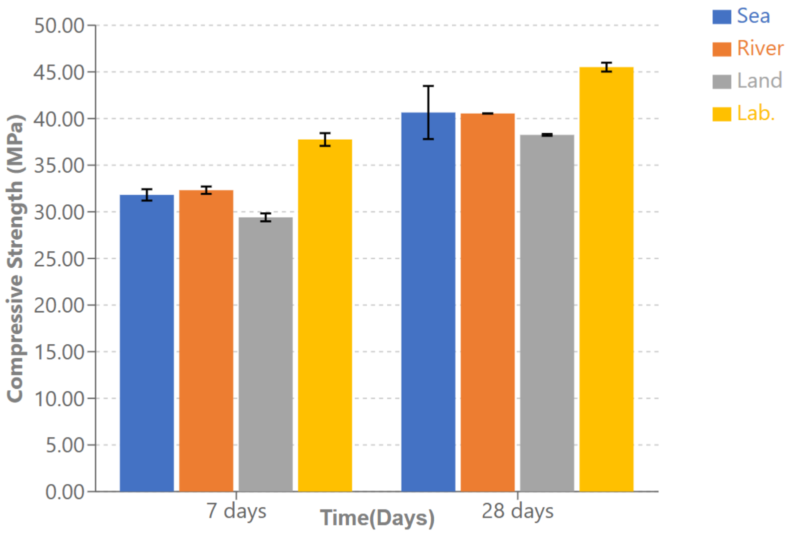

Figure 3. Compressive strengths of specimens cured in the sea, river, land and laboratory conditions

Figure 3 shows the compressive strengths of core samples obtained from concrete specimens named as sea, river, and land with a length/diameter ratio of 100/100 mm. The compressive strengths of core samples from specimens cured in the sea and river are higher than those of specimens cured on land in an air environment and watered for three days in the morning and evening. While the compressive strengths of the concretes cured in the sea and in the stream are very close to each other, the 28-day compressive strengths of the concretes cured on land are 6.27% lower than those cured in the sea and 5.99% lower than those cured in the stream. Similarly, the 7-day compressive strengths reveal that the average strength values of the sea (31.81 MPa) and river (32.315 MPa) samples are comparable, whereas the land-cured specimens exhibit a lower strength of 29.405 MPa. This indicates that underwater curing environments are more effective in early-age strength development. Additionally, Black Sea water and İyidere river water were equally effective in enhancing the compressive strength of underwater concretes, with 7-day and 28-day strength values being very close to each other. According to TS EN 13791, it is stated that a strength difference of 0.85 occurs between the concretes cured in the curing pool and the field concretes [37]. In Figure 3, the compressive strength obtained from 150mm cube concrete specimens in the curing pool for 7 days is 37.75x0.85 = 32.08 MPa, aligning closely with the sea (31.81 MPa) and river (32.32 MPa) samples, while the concrete cured on land shows lower strength compared to the curing pool. In the 28-day samples, 45.68x0.85= 38.828 value was obtained, which is very close to the core strength of the samples cured in the air and lower than the core strengths of the samples cured in the sea and stream. This shows that the compressive strength development of concretes cured in the sea and stream is better than that of concretes cured on land with intermittent watering. The performance of underwater concretes is presented in Table 8 under the headings of environmental conditions, additives/cement type and strength outcomes.

Considering the recent studies on the effects of seawater on concrete, it is seen that comprehensive and comparative data have accumulated in this field. Kumar found that the compressive strength of concretes exposed to seawater decreases over time and strength losses increase, and emphasized that especially Type I cements modified with pozzolan admixtures give successful results in marine environments. This coincides with the high performance of CEM I 42.5R SR 5 type sulfate resistant cement used in our study in marine environment [38]. On the other hand, in the study conducted by Cui et al. no adverse effect was observed at macro and micro levels on the 7 and 28-day strengths of concretes produced using seawater and brine despite increased salinity [39]. This result is consistent with our findings that there was no significant difference in the strength of concretes produced with fresh and salt water in our study.

However, there are some literature findings that seawater increases the development of strength in concrete at early ages, but the effect might have limitations in the long term. For instance, Mohammed et al. indicated that concretes produced using seawater exhibited increased strength at early age, but at the end of long-term immersion, there was no difference in compressive strength from concretes produced using tap water [40]. In similar studies, Wegian also determined that early-age compressive and tensile strengths in concretes mixed and cured with seawater were greater than concretes made using fresh water [41]. As noted above, the findings are in line with increases in our study for 7-day compressive strength. However, there are various opinions in the literature about the sustainability of the increase at long term. Thus, although there are benefits at early age, it might be better to prefer cements with additives to marine structures from the view of long-term behavior.

Li et al. reported that curing processes applied in environments with high ion content adversely affect the mechanical performance of concrete and irregularities in the hydration process impair the integrity of the cement matrix and weaken its binding properties [42]. In this context, it was reported that the strength development of concrete in aggressive environmental conditions where magnesium and sulfate ions are concentrated varies depending on the environmental ion level. Binici et al. revealed that cements developed with special admixtures exhibited higher sulfate resistance compared to conventional cements under environmental conditions containing sodium and magnesium sulfate [43].

These results show that cements enriched with additives significantly reduce strength loss and become more resistant to harsh environmental conditions, as found in our study.

Table 8. Overview of underwater concrete behavior in various environments

Study	Environment	Admixtures / Cement Type	Strength Outcomes
Kumar [38]	Seawater exposure	Type I, Type II, and Type V cements with pozzolanic admixtures	Strength loss over time; pozzolan-modified cements performed well in marine settings.
Cui et al. [39]	Seawater & brine (7- and 28-day)	Ordinary Portland Cement (OPC) type P.O 42.5	No macro/micro adverse effect; strength similar to freshwater mixes.
Mohammed et al. [40]	Seawater (short- and long-term)	Ordinary portland cement(OPC), slag cement, and fly ash cements	Increased early strength; long-term strength similar to tap water mixes.
Wegian [41]	Seawater for mixing and curing	Ordinary Portland cement (OPC) and sulphate-resisting cement (SRC)	Higher early compressive and tensile strengths than freshwater concretes.
Li et al. [42]	High ion (Mg^{2+}, SO_4^{2-}) environments	Type I 52.5 Ordinary Portland Cement (OPC), fly ash (FA) and silica fume (SF)	High ions impair hydration and matrix integrity, reducing long-term strength.
Binici et al. [43]	Sodium & magnesium sulfate environments	Basaltic pumice, ground granulated blast furnace slag (GGBS) and clinker	Improved sulfate resistance; better long-term strength than conventional cements.
Nasr et al. [16]	Fresh and seawater curing	Portland cement 42.5 and protective (anti-washout) admixture	Positive effects on 7 and 28-day compressive strength.
Beik et al. [44]	Laboratory	Type II cement and biopolymer admixtures	Improved abrasion resistance and strength; reduced shrinkage.
Present Study	Marine, laboratory, land	Sulfate-resistant CEM I 42.5R SR 5 cement + anti-washout admixture	No significant strength difference with seawater; early strength gains preserved.

Compressive strength of submarine concrete is considered as a critical parameter in terms of hydraulic and structural integrity of structures. In the literature, it has been reported that the increase in washout rate adversely affects the strength properties of concrete over time. As a solution to this problem, the use of anti-washout admixtures is recommended. Nasr et al. reported that the protective admixture used in 7 and 28-day samples cured in fresh and seawater provided positive effects on compressive strength [16]. Beik et al. reported that using biopolymer admixtures not only improved the abrasion resistance, but also some types of these admixtures improved the compressive, tensile and flexural strengths and all types of admixtures reduced the shrinkage of concrete [44]. In this study, it was observed that the specially selected anti-washout admixture prevents possible strength losses due to washout and provides positive effects in maintaining concrete strength.

In conclusion, this study not only evaluates the strength performance of concretes used in marine environments but also reveals the effectiveness of admixtures and cement types. Although many findings were consistent with the literature, it was evaluated that seawater, which shows positive effects at an early age, may limit the strength when used with cements without admixtures in the long term. In this respect, the study emphasizes the importance of preferring cements containing admixtures and anti-washout admixtures in concretes to be used in marine environment and provides concrete engineering recommendations for practitioners.

4. Conclusions

In this study, the effects of sea wave and river current on the compressive strength development of underwater concretes were investigated. The mechanical performance of concretes cast underwater on the Black Sea coast and in the Iyidere River was evaluated in comparison with concretes produced on land and under laboratory conditions. The important results observed in the study are presented below.

- It was found that the compressive strengths of the concretes cured in sea and river environments were very close to each other.
- The 28-day compressive strengths of concrete specimens cured on land were found to be 6.27% lower than those cured in the sea and 5.99% lower than those cured in the stream. This shows that the compressive strength of underwater concretes varies depending on the natural environment conditions.
- When compared with samples cured in the laboratory curing pool, the compressive strengths of concretes cured in the sea and stream environments were approximately 15% lower than the TS EN 13791 standard.
- The compressive strength development of underwater concretes designed with CEM I 42.5R SR 5 sulphate-resistant cement showed positive results under both seawater and freshwater conditions.
- The tremie pipe method used for casting underwater concretes provided homogeneous concrete placement in underwater environments, prevented segregation and contributed to early strength gain.
- It has been shown that the strength of concrete that is not molded and exposed to direct water flow can be reduced.
- The one-way ANOVA analysis revealed that varying environmental conditions exerted statistically significant effects on the compressive strength of concrete specimens at both 7 and 28 days; notably, the influence was more substantial during the early curing phase (7 days), indicating heightened sensitivity of mechanical performance to environmental exposure in the initial hydration period.

- According to the results of Tukey HSD test, it was determined that environmental factors (such as land, river or sea) affect the compressive strength of concrete, both 7-day and 28-day compressive strength values of samples cured in laboratory environment were statistically significantly higher compared to samples in open environment conditions.

4.1. Recommendations for future Works

- Laboratory tests on underwater concretes produced with different compositions and admixtures can help predict the short and long-term performance of concrete, while more extensive testing can provide more reliable and detailed findings on the durability of underwater concrete.

- Increasing the long-term compressive strength of underwater concretes is possible by improving the adaptation of concrete to underwater environmental conditions, and in order to develop such concretes and expand their usage areas, it is important to better understand the effects of physical and chemical interactions in the underwater environment on concrete, in this context, new types of cement, aggregate and waste materials can be used in underwater concrete production in order to adapt concrete to underwater conditions more effectively.

- In order to increase the durability of underwater concretes, the use of sulfate-resistant cements in different ratios can be optimized, especially in aggressive environments such as seawater, chemical reactions, microstructures and mechanical properties of these cements can be studied, new formulations can be developed to extend the life of concretes in marine structures, and the effect of combinations with different additives on durability in the marine environment can be investigated, and strategies for more reliable and sustainable use of underwater concretes can be created.

Nomenclature

X : The length of the specimen in horizontal direction
Y : The length of the specimen in vertical direction

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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