Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 12, December, 2025

Performance of Sustainable Underwater Concrete Containing GGBS and Micro Silica with Anti-Washout

Moslih Amer Salih [1*], Shamil Kamil Ahmed [2], Ahmed Salih Mohammed [3]

[1] *Department of Surveying Techniques, Technical Institute of Babylon, Al-Furat Al-Awsat Technical University (ATU), Najaf 54003, Iraq.*

[2] *Segment General Manager, TECH REMIX LLC, Ajman P.O. Box 4778, United Arab Emirates.*

[3] *Department of Civil Engineering, College of Engineering, University of Sulaimani, Kurdistan 46001, Iraq.*

Received 09 August 2025; Revised 13 October 2025; Accepted 09 November 2025; Published 01 December 2025

Abstract

Anti-washout concrete (AWC) is engineered for underwater constructions, with resistance to dispersion achieved through the use of anti-washout admixtures (AWAs). This study experimentally investigated the design of sustainable anti-washout concrete mixtures containing a high content of by-product waste materials. The study aims to evaluate sustainable underwater concrete mixtures with high supplementary cementitious materials content, analyze the influence of AWA on compressive strength, and assess the compatibility of anti-washout admixture with both SCMs and superplasticizers. However, the interaction of AWA with a high content of ground granulated blast furnace slag (GGBS) and microsilica in underwater concrete has not been previously investigated. Two groups of concrete mixtures were developed: the first group consisted of two sustainable mixtures, with and without AWA, containing 52.15% ordinary Portland cement (OPC), 43.5% GGBS, and 4.35% micro silica. The second group consisted of two conventional mixtures: one with 100% OPC and the other with 100% OPC plus AWA. Fresh properties, such as slump flow, viscosity (measured by the V-funnel), and air content, were evaluated. Compressive strength was measured to assess mechanical performance. Durability was investigated using four tests: rapid chloride penetration tests (RCPT), water penetration, water absorption, and initial surface absorption tests (ISAT). An anti-washout test was conducted to determine the effectiveness of AWC in minimizing the washout of cement particles. The mixture design introduces an innovative approach to utilizing high levels of SCMs for producing high-strength, durable, and sustainable AWC. The durability results showed that the ISAT test was ineffective for evaluating concrete performance underwater. This research contributes to understanding the effects of AWAs and their compatibility with superplasticizers and SCMs. AWA forms a thixotropic gel that protects cement particles from washout and is highly compatible with superplasticizers.

Keywords: AWC, Antiwashout Concrete; Underwater Concrete; Thixtropy of Cement Paste Concrete; Anti-Washout Admixture; Durability; Sustainable Concrete.

1. Introduction

1.1. History of Underwater Concrete

Conventional concrete, made from ordinary Portland cement (OPC), aggregate, and water, remains the primary construction material worldwide. Moreover, it is considered the source material for new and innovative developments suggested to address advanced environmental problems in the construction sector. Significant challenges are regarded as motivations for scientists to investigate new types of concrete mixtures that can withstand the harsh environmental

* Corresponding author: moslih.a.salih@atu.edu.iq; moslih.a.saih@gmail.com

http://dx.doi.org/10.28991/CEJ-2025-011-12-018

conditions [1–3]. However, the worldwide cement market is facing a surge in cement demand, accompanied by high levels of CO_2 emissions in the cement industry, which is urged to incorporate waste materials into concrete production [4–7]. In this context, scientists have developed concrete for underwater applications. Underwater concrete is a specialized type of concrete characterized by high performance, specifically designed for foundations and structures submerged underwater, such as dams and bridges [3, 8]. Concrete is the essential building material for major structures planned for coastal areas, rivers, and harbors. Which are scientifically described as underwater engineering constructions [5, 9–14]. The technology of underwater concrete, also known as anti-washout concrete (AWC), is a type of non-dispersible underwater concrete [10, 11, 15, 16]. It was developed to solve problems and manage the challenges of placing, compacting, and repairing traditional concrete in underwater structures. Anti-washout concrete was applied to non-structural elements, such as cofferdams or caisson seals, as well as to structural components, including bridge piers, dry-dock walls, floors, water intakes, ports, and harbor installations. Additionally, it was used for bridge piers in rivers, metro systems, and deep shafts in unstable, waterlogged ground. Additionally, it has been utilized to sink precast tunnel sections, join tunnel sections, and repair erosion or cavitation damage to major hydraulic structures [5, 17, 18].

The history of Anti-washout concrete (AWC) dates back to 1970, when Germany had a requirement to enhance and improve concrete casting underwater. The invention of AWC was introduced practically in 1974 by adding concrete viscosity-modifying admixtures based on cellulose ether to traditional concrete used for underwater applications associated with low water velocity conditions. Japan successfully continued to meet this target by developing new anti-washout admixtures through various product innovations [11]. In the mid-1980s, the U.S. Army Corps of Engineers applied AWC to structures in the ocean [19]. To evaluate the washout ability of underwater concrete, the U.S. Army Corps of Engineers adopted the C61-89A and subsequently the CR D-C 661-06 as specifications for Anti-washout admixtures for concrete in 1989 [20, 21]. Non-dispersible underwater concrete refers to concrete containing anti-washout admixtures (AWAs), which are water-soluble polymers with long-chain structures and strong absorption capacity. When absorbed, these admixtures produce advanced viscous concrete [22, 23]. Higher fluidity was developed using a superplasticizer (SP) to reduce the water-to-binder ratio (w/b). Additionally, anti-washout admixture (AWA) is added to the concrete ingredients as the primary constituent to enhance viscosity and segregation resistance [24]. AWC can be used to solve problems, including the placement and repair of traditional concrete in underwater construction, which is a significant challenge. Due to its self-leveling, self-compacting, and minimal environmental impact, non-dispersible underwater concrete plays a vital role in underwater and underground construction. The main crucial improvement of the casting process of AWC is related to the enhancement of the reduction in mass loss underwater, which is described as the washout resistance ability. High fluidity and a decrease in the water-to-binder ratio (w/b) were achieved by incorporating ingredients that altered the yield value and viscosity of the mixture, thereby enhancing washout and segregation resistance. According to previous publications, AWAs are water-soluble polymers that improve the yield value and viscosity of concrete [23].

1.2. Literature Review

Nasr et al. [15] investigated the washout resistance of self-protected underwater concrete containing 533 kg/m^3 OPC by varying water features; however, traditional concrete mixtures were used without either AWAs or SCMs. The recommendations emphasized adjusting the mixtures and considering water flowability, referring to the increase in the water-to-cement ratio or SP, which results in a high slump and high workability associated with high mass loss. This is an expected result due to the lack of use of AWA. In another experimental work presented by Ali Sikandar et al. [10], different anti-washout admixtures, also referred to as viscosity modifiers, were applied to study their effect on the properties of non-dispersible AWC, which contained 450 kg/m^3 of OPC as the primary and only binder, along with 2.5 kg/m^3 of AWA. Although the high content of OPC resulted in the highest 28-day compressive strength of 44.4 MPa with different AWAs, the study concluded that biopolymers in AWAs may enhance the compressive strength. Ganesh Kumar et al. [25] produced AWC using 480 kg/m^3 OPC silica fume (SF) and fly ash (FA). At 28 days, the maximum compressive strength was 32.4 MPa, which is considered low strength compared to the extremely high content of OPC. The conclusions showed that incorporating FA and SF leads to better washout resistance and durability performance; however, a loss in workability and strength was registered due to some defects in the mixture design related to SF and FA content.

Moon & Shin [26] evaluated the resistance against corrosion and strength of AWC using three mixtures: 100% OPC, 20% FA as a partial replacement, and the third mixture contained 50% blast furnace slag as a partial replacement. At 28 days, the OPC reference mixture showed the highest strength; however, after 91 days, the mixture with 50% Slag showed only a 13.8% increment. Liquid-based cellulosic AWA and melamine-based high-range water reduction were used in the mixture design. The results showed that anti-washout underwater concrete exhibited better slump flow with increased SCMs content; moreover, SCMs increased the resistance against corrosion. Recently, underwater repair concrete was produced using 429 kg of Portland cement, supplemented with an anti-washout admixture and superplasticizer. The work aimed to study the adhesion of underwater repair concrete exposed to hydrostatic pressure. The highest compressive strength was recorded as 59.2 MPa; however, the results analysis revealed the complexity of the casting problem associated with this type of concrete mixture [27]. AWA was employed to produce underwater cement grout.

The result showed a decrease in strength at 28 days when compared with the OPC reference mixture [17]. Resisting washout is a vital characteristic that enhances the performance of concrete cast underwater; moreover, it secures quality repairs underwater with minimal water pollution from this type of casting. Mass loss (washout loss) and slump flow in concrete produced with 592 kg/m³ of OPC (non-sustainable concrete) were negatively affected by the water-cement ratio; meanwhile, silica fume and fly ash can enhance washout resistance. Thus, anti-washout admixtures have been developed by manufacturers to enhance and control the stability of fresh concrete systems based on cement and cementitious materials [28].

1.3. Problem Statement and Research Gap

The majority of the research was conducted to study UWC with a high content of OPC, which is the first problem addressed in this experimental research. This may be considered the main defect in mixture design, which is analyzed as a non-sustainable concrete with no compatibility and no matching for the new global climate enhancement demands. According to the United Nations website, under its climate actions, Carbon dioxide (CO_2) levels in 2023 were 151% of pre-industrial levels. Between 2014 and 2023, 48% of human-caused emissions remained in the atmosphere. The statistics showed that due to CO_2, heating impacts of long-lived greenhouse gases increased by 81% [29]. The second challenge in UWC is that the disintegration of concrete due to laying underwater may result in layered and heterogeneous concrete characteristics with low strength. This can be practically avoided by using a sustainable mixture design that contains AWAs, ensuring the fresh mixture, when cast, does not mix with water and wash away [30]. Flowability can be enhanced by using admixtures, as previously studied through experiments examining the influence of selected additives and admixtures on concrete designed for underwater use. Bleeding can also be controlled or adjusted by using a proper aggregate amount or admixture [10]. The main binder for AWC is still OPC; however, it is a sophisticated concrete that requires the addition of various admixtures, such as polycarboxylates, phosphonates, and other additives, to produce self-compacting characteristics that enable it to be poured underwater for self-leveling [31].

For example, stabilized polycarboxylates provide high flowability, a crucial characteristic for filling the formwork, whereas modified polycarboxylates and phosphonates promote low viscosity [32, 33]. In this context, the relationship between AWA and superplasticizer in underwater concrete remains undefined**,** as it was not clearly defined in previous research or has not been thoroughly investigated by researchers. Different findings from earlier studies also emphasized the vital role of SCMs in underwater concrete properties; however, most studies focused on a single test for durability. Supplementary cementitious materials have become crucial materials that enhance concrete performance and durability, while also reducing OPC content for sustainability and contributing to climate change mitigation. Reducing OPC content means reducing CO_2 emissions [34]. Durability is another characteristic of underwater concrete that has not been studied carefully. However, it is considered one of the primary properties affecting the longevity of underwater structures, although it has received little systematic attention. The durability of concrete in aggressive saline environments was enhanced by incorporating up to 20% silica fume, consistently meeting expectations for improved resistance to chloride and sulfate ions [5]. Pozzolanic materials, such as fly ash, may enable underwater concrete to be self-compacted with a low dosage of antiwashout admixture [34]. In 2020, it was suggested that GGBS content may range from 6% to 12%, while fly ash content may range from 6% to 9%. The study's objective focused on abrasion resistance and chloride ion penetration resistance; however, the results showed a low content of SCMs in concrete. Moreover, the research does not consider the fresh properties of other durability tests. It showed that GGBS with the same content provided better properties for OPC mortar, which was related to the enhancement in concrete structure compactness, resulting in a reduction in the diffusion of chloride ions [35].

Grzeszczyk et al. [32] studied the effect of nano-silica fume on the washout property of UWC. They concluded that there was no effect on physical properties and compressive strength, which is an infrequent finding. Moreover, UWC without nanoparticles achieved similar density, water absorption, and water penetration depth. Nevertheless, silica fume with a nano level showed efficiency in reducing the washout property. Ali Sikandar et al. [10] found that UWC achieved 33.5 MPa and 44.4 MPa using OPC as the main binder, which is a low strength with a high OPC content, indicating a critical mixture design that lacks sustainability; moreover, the bleeding capacity increased over time. The viscosity also increased when AWA was added to the mixture, and durability was not investigated. Replacing cement with GGBS and Fly ash was studied by Yuan et al. [35], who reported that up to 36% replacement was possible. However, the results were inconsistent, as they found that slag provides similar strength to the control, while fly ash reduces both strength and abrasion resistance, without considering other durability tests. GGBS with a range of 6% up to 12% showed an improvement in abrasion resistance and reduced chloride penetration with higher content. GGBS and Silica fume with 20% replacement for each material showed an increase in abrasion loss over time; however, durability was studied through a single test [36].

No study has yet examined the interaction of AWA with high GGBS-Micro silica mixes in real underwater projects. Most researchers have used high OPC content in mixture design for AWC, without addressing sustainability requirements. The main observed defects were low compressive strength, despite the high cement content. Additionally, the durability of underwater concrete has received less attention. Only scattered and limited tests are available, and they show unclear behavior regarding durability, both with and without SCMs. Moreover, the compatibility of anti-washout agents and superplasticizer, and their effect on UWC properties, needs further investigation as a crucial point of discussion. No previous work has addressed this critical issue.

2. Experimental Program

In this experimental work, sustainable mixtures were formulated using low ordinary Portland cement (OPC) content and high proportions of supplementary cementitious materials (SCMs) [31]. The laboratory program began by systematically identifying and selecting materials with properties required for the targeted application. Experiments were performed in a state-of-the-art laboratory using advanced equipment. The effects of anti-washout agents and superplasticizers on durability were evaluated with specialized testing methods to ensure accurate results. This methodology has been successfully applied to actual underwater projects in the UAE. Figure 1 outlines the process and methods used to achieve the research objectives. Figure 1 shows the methodology used to achieve the aim of this research.

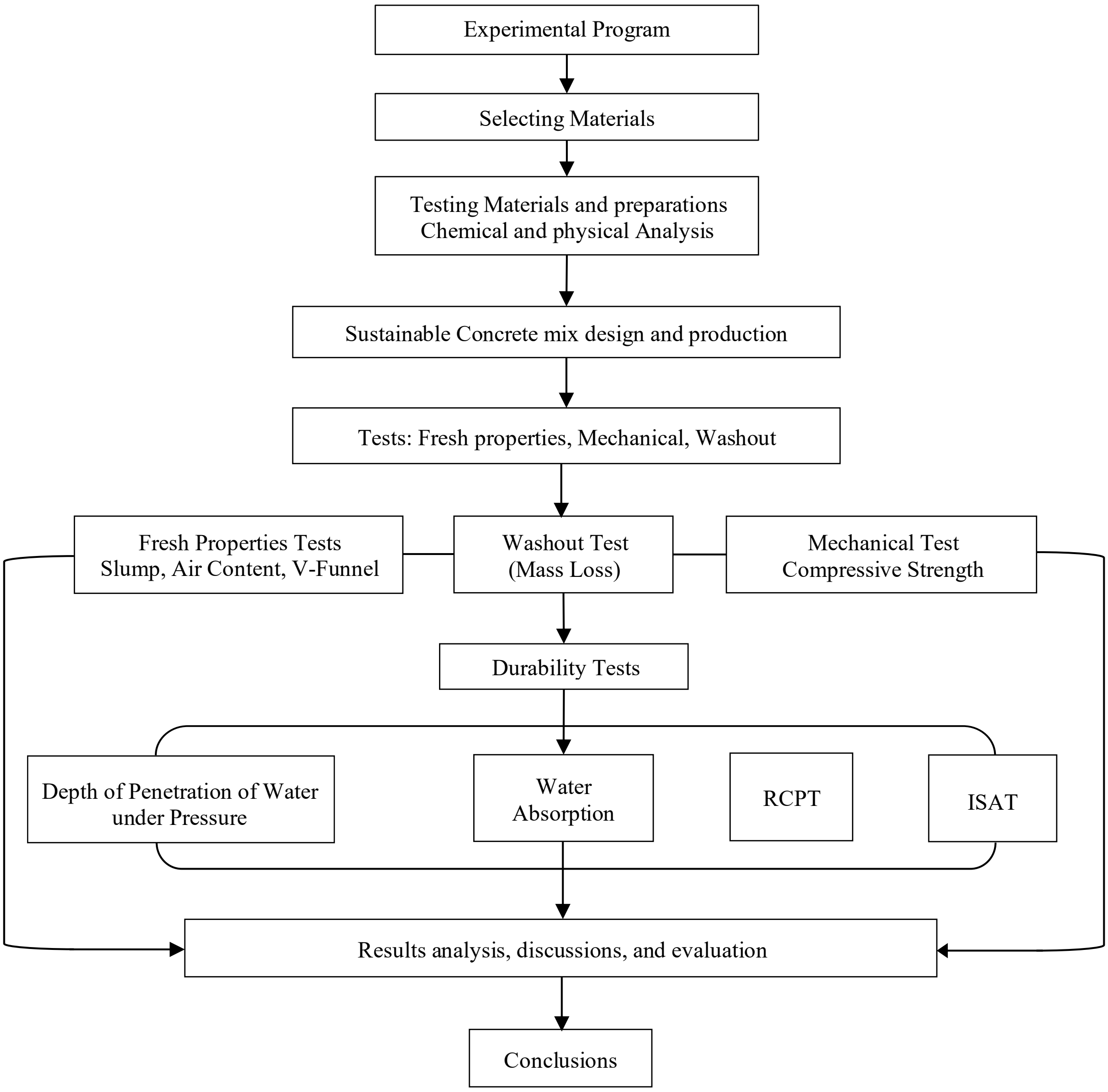

Figure 1. Research methodology flowchart

2.1. Materials

Ordinary Portland cement grade 42.5 N, compliant with CEN [37], was used. GGBS, complying with BS EN standards [38], was used as the primary supplementary cementitious material, while microsilica (MS) was added in a constant quantity. The chemical composition of OPC, GGBS, and MS is shown in Table 1. Table 2 illustrates the residue on a 45-micron sieve for OPC, GGBS, and MS. A polycarboxylated high-range superplasticizer was used to reduce mixing water and improve slump retention; it is a high-performance admixture based on a modified polycarboxylate ether [39, 40]. Coarse aggregate, with a maximum diameter of 20 mm, was used. Washed crushed sand and red dune sand were used as fine aggregates, and Figure 2 shows the combined gradation chart. To produce anti-washout concrete, an underwater stabilizer for concrete and mortar, which is a ready-to-use powder admixture that prevents cement from being washout was used. The AWA is recommended for all types of concrete placed underwater where anti-washout properties are required [18]. Table 3 shows the mixture details. A constant low water-to-cement ratio was used in all mixtures.

Table 1. Chemical composition for OPC and cementitious materials

Chemical composition %	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	C_3A	C_3S	C_2S	C_4AF	TiO_2	SO_3	Cl	Na_2O	L.O.I
OPC	19.7	5.53	3.23	61.8	1.88	9.20	53.51	16.24	9.48	-	2.21	0.01	-	2.50
GGBS	21.27	13.34	0.64	41.55	6.90	-	-	-	-	0.98	0.11	0.01	-	-
MS	92.38	-	-	-	-	-	-	-	-	-	-	-	0.46	5.01

Table 2. Residue on 45-micron sieve

Material	Quantity
GGBS	1.78%
MS	2%

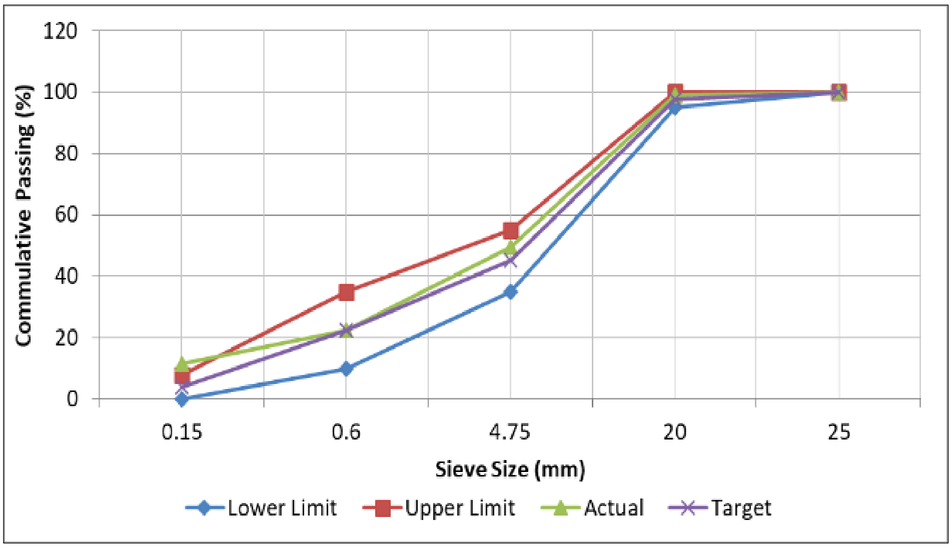

Figure 2. Combined aggregate gradation chart

Table 3. Anti-washout concrete (AWC) and normal concrete mixtures details

Mixtures	Mixture Type	Cementitious Content (kg/m³)			AWA (kg)	w/c	Coarse Aggregate (kg/m³)	Fine and Dune Sand (kg/m³)	Superplasticizer (kg/m³)
		OPC	GGBS	MS					
Mix 1	Normal	200	200	20	0	0.34	1000	880	7.00
Mix 2	AWAC	200	200	20	4	0.34	1000	880	8.00
Mix 3	Normal	460	0	0	0	0.34	1000	880	8.50
Mix 4	AWAC	460	0	0	4	0.34	1000	880	9.00

2.2. Testing Procedures

AWC fresh properties were measured by using the slump-flow test to determine concrete flowability according to (BSEN 12350-P8:2010) as presented in Figures 3 (a and b) [41]. Concrete fresh density was measured according to (BS EN 12350-6:2000) [42]. The air content was measured according to BS EN 12350-7:2000 [43], as presented in Figures 4 (a and b). V-Funnel Test was applied according to (BS EN 12350-9:2010) [44]. A compressive strength test was conducted at 3, 7, and 28 days, following the procedure outlined in BS EN 12390-3:2002 [45], as shown in Figures 5 (a and b). The washout test (mass loss) was measured according to US Corps CRD-C 661 [21, 46], as shown in Figures 6, which explain the steps of measuring mass loss. The test begins by measuring the empty basket, followed by the basket containing a sample of the concrete, and then immersing the sample inside a tube filled with seawater. Washout test (loss of mass) calculations of concrete samples were expressed as a percentage of the initial mass of the sample as follows [21]:

$$D = \frac{Mi - Mf}{Mi} \times 100 \quad (1)$$

where: D = washout %; Mi = mass of sample before initial test; Mf = mass of sample after each test.

(a) (b)

Figure 3. (a) Slump test preparation, (b) measuring the diameter

(a) (b)

Figure 4. (a) Air content preparation, (b) The apparatus

(a) (b)

Figure 5. (a) Cubes preparation for compressive strength test, (b) applying the test

Figure 6. The washout test steps according to the US Corps-C661 [21, 46]

In this research work, the durability performance was studied using four tests, which were implemented for the first time. The tests include: Depth of penetration of water under pressure according to BS 12390 Part 8 [47], water absorption test according to BS 1881:P122-2011 [48], Rapid Chloride Penetration test (RCPT) according to ASTM C1202-19 [49], and Initial Surface Absorption test (ISAT) according to BS 1881:P208-1996 [50].

3. Results and Discussions

3.1. Slump Test

The slump results are presented in Figure 7. The test was measured over three periods: directly after casting as an initial slump, after 30 minutes, and after 60 minutes [31]. The flow decreased when measured between 30 minutes and 60 minutes. Such behavior is logically related to the initial chemical reactions between the binder and the constituents of the concrete, as well as the bonding effect of the hydration of cement particles. Previously, it has been reported that the superplasticizer will affect the conjunction with the anti-washout admixture, AWC will show a decrease in fluidity and longer setting time [13, 22, 51]; however, in the current experimental work, the combined effect of the superplasticizer and the AWA admixture showed a minimal decrease in flow. In comparison with another study, a reduction in setting time and strength development was registered for OPC and Metakaolin concrete containing AWA and HRWR-Naphthalene-based [52]. This behavior suggests that AWA admixture has a minimal effect on the rheology of both sustainable and traditional concretes. A reduction in flow was observed due to the addition of AWA, which is attributed to the impact of AWA on retention water [53]. In this work, SCMs were used with a high content, which has not been previously studied in terms of their effect on AWA. The harsh environment for casting concrete underwater is still considered a significant challenge for meeting technical requirements during casting, such as the ability to self-level, self-consolidate, and spread freely into the framework section without the use of vibrating equipment [54]. Advanced rheology properties are necessary to ensure optimal mixing, handling, and concrete casting times for various applications. Slump flow for SCC between 660 and 750 mm is compatible with multiple concrete applications [55, 56].

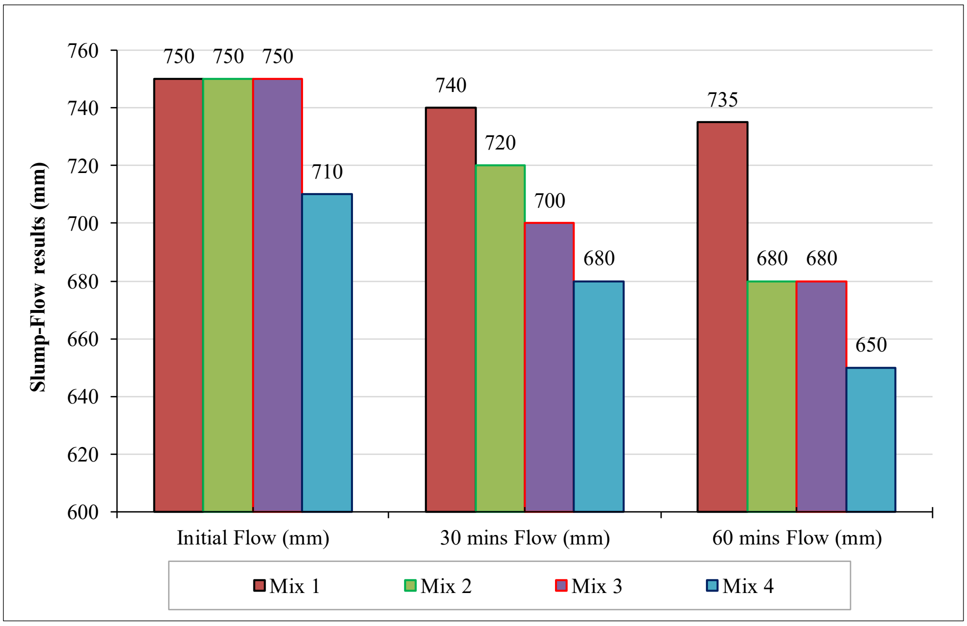

Figure 7. Slump flow results

3.2. Air Content

Figure 8 shows that the addition of AWA admixture caused a positive decrease in air content. This behaviour was measured in Mix 2 and Mix 4 when 4 Kg of AWA was added to produce AWC. Mixture 1 without AWA showed 1.9% air content, whereas mixture 2 showed 1.4% with a 26.31% reduction. Mixture 3 without AWA admixture showed 1.7% air content, whereas mixture 4 showed 1.3% air content with a 23.5% reduction. Previously, it has been reported that the addition of AWA admixture increases air content when the dosage increases up to 0.5% by weight of cement [57]. In contrast, in this investigation, the dosage of AWA was 0.02% by weight of cement, resulting in a lower air content. The reduction of air content due to AWA addition did not affect the AWC fresh density value, as presented in Table 4. According to the specification for anti-washout admixtures for concrete, Part 11 [21], the mixture design must result in an air content of 3.0% or less, which should be compatible with the binder blend of two or more cementitious materials. It was crucial to measure the air content to ensure that it would not negatively impact the mechanical properties and durability [11, 58]. Previously, a reduction in air content with the use of AWA was reported, using a higher w/c ratio [53]. In this current work, the cement ratio was 0.34 to reduce the effect of water on increasing compressive strength.

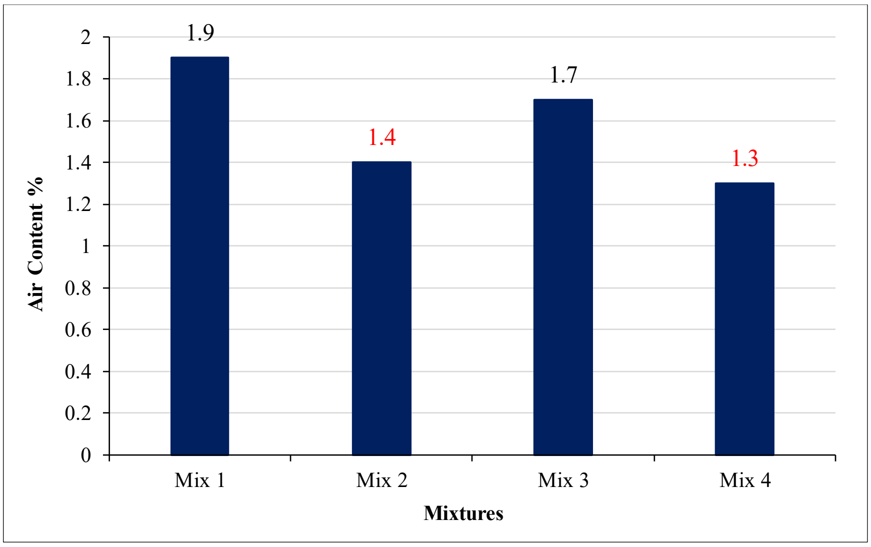

Figure 8. Air content results

Table 4. Fresh density in relation to air content reduction

Mix	Cementitious Content (kg/m^3)			w/c	Admixture (kg/m^3)	AWA (kg)	Air content (%)	Fresh density (kg/m^3)
	OPC	GGBS	MS					
Mix 1	200	200	20	0.34	7.0	0	1.9	2430
Mix 2	200	200	20	0.34	8.0	4	1.4	2470
Mix 3	460	0	0	0.34	8.5	0	1.7	2460
Mix 4	460	0	0	0.34	9.0	4	1.3	2465

3.3. V-Funnel Test

As shown in Figure 9, the V-funnel test results indicate that the addition of AWA has a significant effect on the flow rate. Mix 1 showed a 13-second slump flow. Mix 2, with a binder consisting of 200 kg of OPC, 200 kg of GGBS, 20 kg of MS, and 4 kg of the AWA admixture, showed an 18-second flow rate. The addition of AWA admixture resulted in a 38% increase in flow time. Incorporating SCMs may work as viscosity-enhancing agents [28]. The same behavior was observed for mixtures 3 and 4, which were produced with 460 Kg of OPC as the main binder. Mix 3 showed a flow rate of 12 seconds, whereas Mix 4, with the addition of 4 Kg of AWA admixture, showed a flow rate of 20 seconds. Mix 4 registered a 67% increase compared to Mix 3. Mixing AWA with concrete ingredients will modify the viscosity of the concrete, increasing its capacity to hold suspended particles and stabilize the concrete. Furthermore, it will enhance the plastic viscosity of UWC, which exhibits thixotropic properties [10]. It can be concluded that the increment in viscosity of the cement pore solution containing AWA will result in a more stable suspension [59]. Previously, it has been reported that the fluidity of the mixture may reflect the viscosity and washout resistance of the UWC; moreover, it can give a reflection of the workability of the concrete and fluidity loss as a reference [60].

The increase in the rate of flow indicates the viscosity of concrete by showing the time required to pass through the V-funnel. Previously, AWAs were added to the concrete to improve and enhance yield value, viscosity, and segregation resistance due to their structure as water-soluble polymers [24, 61, 62]. Incorporating AWA admixture affected the flow rate of the AWC by altering its rheology, making the material stickier. Concrete with high viscosity may flow continuously over an extended period; however, low viscosity will produce a quick initial flow followed by a stop [55]. Slump flow and flow rate results show adequate filling capability, indicating a potential for pouring into congested reinforcement sections. Additionally, the mixture's self-leveling ability can provide a smooth surface finish, a crucial parameter for underwater concrete applications. While self-leveling underwater is not necessary for the shape, it can improve overall performance. Previously, concrete with self-consolidating properties often suffered from bleeding and segregation; however, in this work, the handling mixtures showed no bleeding or segregation. Presented bleeding and segregation [55, 63]. UWC likely reflects an advanced mixture design and improved performance. Viscosity is a critical parameter that must be measured for AWC to ensure a good surface finish, especially when reinforcement is very dense, which is a positive factor for underwater pours. As observed, AWA introduces a new characteristic by increasing the flow rate, which may reduce casting time underwater. Additionally, it demonstrates compatibility with cementitious materials.

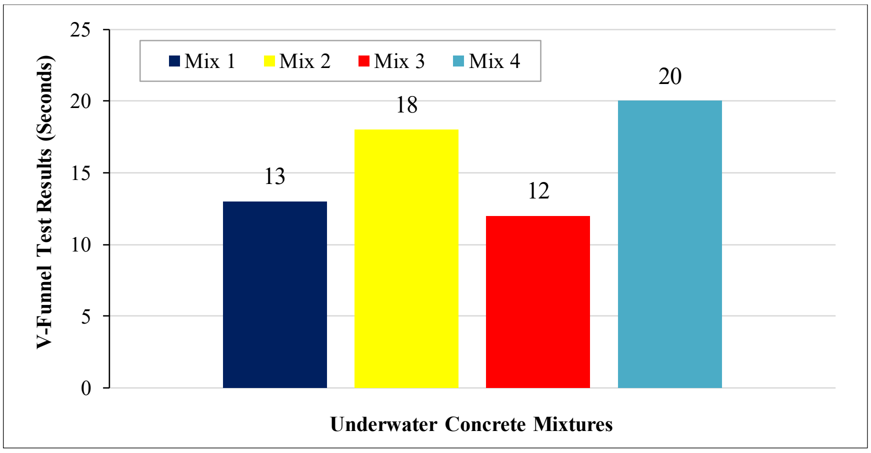

Figure 9. V-funnel results

3.4. Compressive Strength

Figure 10 shows the compressive strength results at ages 3, 7, and 28 days. As illustrated, all mixtures attained high compressive strength at all ages. Typically, the strength ranged from 45 to 60 MPa at 3 days, indicating a practical strength for enduring harsh underwater environments. It can be concluded that the addition of AWA for AWC in Mixes 2 and 4 did not negatively affect compressive strength and had a slight positive effect at early ages. The addition of AWA to concrete resulted in stable interpenetrating cross-linking in the microstructure, leading to improved concrete strength [64]. In another study, enhancements in compressive strength for viscosity-modifier admixtures in SCC were also reported [65]. However, compared to conventional reference concrete with the same mixture design, AWC tends to show a slight decrease in compressive strength. This behavior is attributed to AWA's effect on delaying the cement hydration process at early ages [58, 66–68]. In reference to concrete Mix 1, which contains 200 Kg of OPC, 200 Kg of GGBS, and 20 kg of MS without AWA, the compressive strength was 45.53 MPa at 3 days.

The same ingredients in Mix 2 with AWAs recorded a compressive strength of 47.53 MPa at 3 days. At 7 and 28 days, both Mixes 1 and 2 showed a slight decrease; however, the high-strength results for AWC containing 200 Kg GGBS and 20 kg MS with 4 Kg AWAs demonstrate an innovative approach to produce a sustainable mixture design that can replace more than 50% of OPC. Previously, UWC produced with 467 kg/m³ OPC attained a compressive strength of around 32 MPa at the age of 28 days with a w/c ratio of 0.45 [53], which is lower than the results in this current work. This may indicate the effect of SCMs and the compatibility of AWA with SCMs used in this investigation. For the traditional reference concrete, Mix 3, with a binder made of 100% OPC, recorded a compressive strength of 60.33 MPa at 3 days. As shown in the figure, the addition of AWA in Mix 4 slightly reduced the early compressive strength. In Mix 4, with a binder of 100% OPC and 4 kg of AWA, the compressive strength results at 3 days were 56.60 MPa. Similar behavior was observed at 7 and 28 days. Overall, adding AWA to different concrete mixtures did not increase compressive strength as some previous research suggested; instead, a slight and marginal decrease was observed. Prior literature indicates that UWC achieved compressive strength comparable to that of control samples (between 38.5 MPa and 44.4 MPa), with the addition of slag providing a similar level of strength [8, 10, 35]. This may indicate that AWA is compatible with OPC, SCMs, and superplasticizer. It is important to note that concrete cast underwater may have a compressive strength up to 20% lower than concrete prepared in air [27].

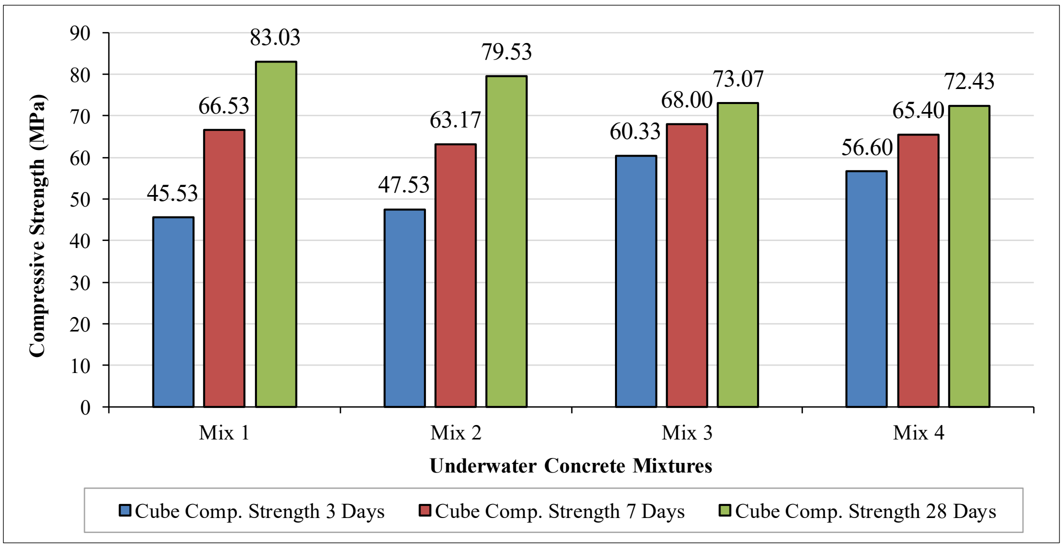

Figure 10. Compressive strength results

3.5. Washout Test (Loss of Mass)

Figure 11 shows the washout and weight loss for the control concrete and AWC from the plunge test. Concrete water resistance, or anti-washout capacity, is the primary characteristic of AWC for underwater applications. As can be seen, mass loss was measured three times in this experiment: initially, after 30 minutes, and after 60 minutes. For Mix 1 without AWA, the composite binder consisted of 200 kg of OPC, 200 kg of GGBS, and 20 kg of MS. The anti-washout capacities were 2.80%, 2.50%, and 2.40% during initial testing, after 30 minutes, and after 60 minutes, respectively. In Mix 2 AWC with 4 kg of AWA, washout percentages were 1.50%, 1.30%, and 0.9% at initial, 30, and 60 minutes, respectively. As shown, there is an apparent reduction in mass loss compared with Mix 1. AWC can preserve water by holding suspended particles in the matrix; this behavior may reduce dilution, bleeding, and segregation in concrete [30]. Previously, a superabsorbent polymer was used as AWA to produce anti-washout concrete containing 1320 kg/m^3 OPC; the washout resistance was evaluated using a self-designed method that visually assessed the mass loss without calculation. The analysis of optical images focused on the color of water and cement, which were stirred in the beaker. The darker color of the water indicates that more cement has been washed out, which is incompatible with the Corps of Engineers' method for calculating mass loss and cannot be used for comparison with current results [17].

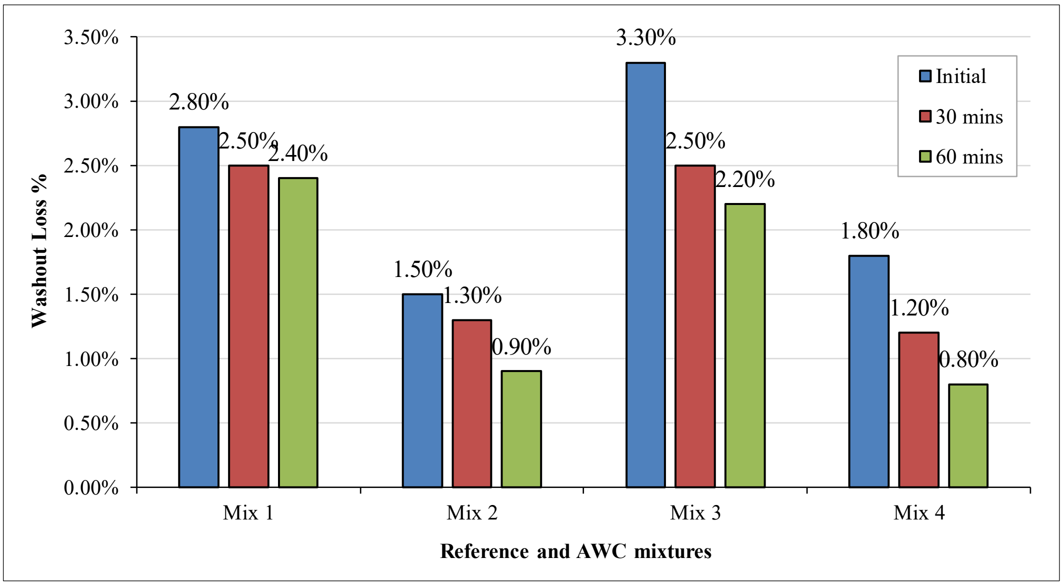

Figure 11. Washout loss results

In another study, underwater concrete was made with 533 kg/m³ OPC and a w/c ratio between 0.4 and 0.44. The results showed that washout resistance was significantly decreased by increasing the w/c ratio; nevertheless, a high content of OPC with high water content made the mixture loose, resulting in aggregate segregation. Moreover, the study reported a conflict between the superplasticizer agent and the AWA [15]. In contrast, the current work presents a sustainable mixture with a high content of SCMs and approximately 50% OPC, characterized by a 0.33 w/c ratio, which demonstrates performance comparable to the recommendations of the US Army Corps of Engineers [21]. AWAs are hydrophilic, water-soluble polymers; when mixed with concrete ingredients, they increase viscosity [69]. However, in this work, the anti-washout mechanism was designed to create a thixotropic gel surrounding the cement particles, protecting them from being washed out. This mechanism will increase the cohesion of concrete mixes, minimize washout during placement, and reduce pumping pressure [18].

The effect of thixotropy has been mentioned previously, but with less emphasis. Flocculation and structuration are two steps of thixotropy in cement paste; flocculation begins within minutes, while structuration, caused by cement hydrate nucleation, occurs over tens of minutes [59, 70]. The washout results for Mix 3, which consisted of 460 kg OPC as the main binder and without AWA, showed washout percentages of 3.30%, 2.50%, and 2.20% at initial, 30, and 60 minutes, respectively. For Mix 4, with 460 Kg of OPC and 4 kg of AWA, the washout percentages were 1.8%, 1.20%, and 0.8% at initial, 30 minutes, and 60 minutes, respectively. The same effect of AWA was observed in traditional concrete with 100% OPC. The results indicate that anti-washout admixtures are effective in reducing the mass loss of concrete underwater. Bleeding and segregation will be reduced due to the high molecular weight and synthetic copolymer in concrete; moreover, the anionic charges bind the cement particles, increasing the viscosity and cohesiveness, which may result in better washout resistance [11, 71, 72]. Experimental tests showed that the use of anti-washout admixture, along with superplasticizers, did not demonstrate any critical relationship. AWA may also help enhance the robustness of concrete particles [59]. It is crucial to note that no previous work has investigated the washout loss of underwater concrete over three distinct periods, characterized by a low cement content, a low water-to-cement (w/c) ratio, and a high content of SCMs.

3.6. Depth of Penetration of Water under Pressure

Figure 12 shows the water penetration depth. All samples were exposed to a water pressure of (500 ± 50) kPa on the surface of the hardened concrete for up to 72 ± 2 hours [47]. The first group of concrete, made from a binder consisting of 47.8% OPC, 43.5% GGBS, and 4.35% MS, showed a penetration depth of 8 mm for both Mix 1 and Mix 2. In contrast, the second group, made from 100% OPC, showed penetration depths of 18 mm and 20 mm for Mix 3 and Mix 4, respectively. Concrete containing OPC, GGBS, and MS with and without AWA (Mix 1 and Mix 2), exhibited lower penetration depths compared to concrete with OPC only (Mix 3 and Mix 4). The reduction in water penetration depth was 55.5%, with an overall decrease of 60%. Micro silica helps develop the cement through densification and grain refinement in the interfacial transition zone [73]. Micro silica particles are known to improve compaction and reduce bleeding in freshly mixed mortars and concrete, thereby decreasing permeability [20]. GGBS has also been shown to mitigate pore sizes in concrete effectively; higher replacement levels create a denser structure due to the pozzolanic binder, which enhances water resistance. GGBS reacts with water and calcium hydroxide to form new hydration products through a pozzolanic reaction, producing additional C-S-H gel. Consequently, concrete with a denser microstructure, or lower porosity, results from higher C-S-H content, leading to greater durability [74]. It has been previously reported that adding AWA may benefit the durability of AWC by lowering water permeability; however, no previous test has exposed samples to the pressure of water in AWC [75]. The high reduction in water penetration may partly be due to AWA polymers adhering to the boundaries of water molecules, thereby adsorbing and fixing some of the mixing water. Furthermore, AWA continues to accumulate and begins to expand as it absorbs water. The reduction in water penetration depth will enhance durability by slowing the iron oxidation process, especially at lower oxygen and chloride levels [11].

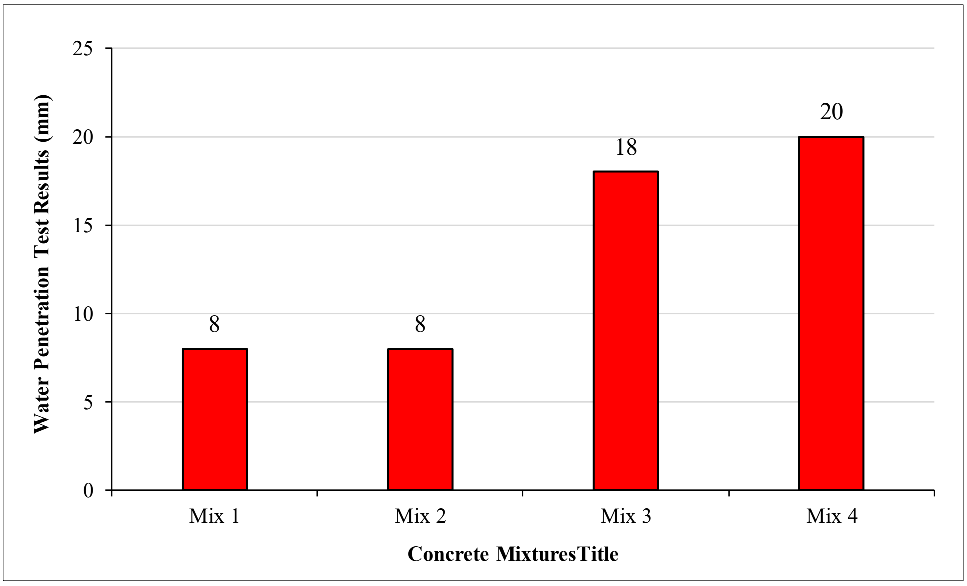

Figure 12. Water penetration results

3.7. Water Absorption

Figure 13 illustrates the water absorption results for AWC and traditional concrete at 28 days of age. Overall, the current mixture design demonstrated high resistance to water absorption. ASTM C642 provides a test method but does not specify limits. The < 5% value is derived from industry interpretation and practical engineering judgment [76]. BS EN 206 / BS 8500 standards indirectly suggest water absorption values by defining durability classes and maximum allowable water-cement ratios, generally resulting in less than 5% absorption for durable concrete [63, 77, 78]. Nonetheless, water absorption of less than 5% is regarded as good quality concrete; whereas, water absorption between 2% and 3% classifies concrete as high-performance concrete with advanced low permeability. Marine concrete durability is strongly related to permeability, with low absorption values (1–3%) being desirable, indicating advanced low water absorption [79]. FHWA publications on marine concrete durability recommend water absorption below 3% for structures exposed to chlorides and aggressive environments [80]. The most effective methods of producing low-permeability concrete involve the use of SCMs [31, 81]. As shown, Mix 1, with a binder containing OPC, GGBS, and MS, along with Mix 2 as the AWC, demonstrated lower water absorption compared to Mix 3 and Mix 4. Incorporating SCMs as a partial replacement for OPC in both composite binder concrete and AWC significantly enhances water resistance. Mix 2 showed 20% and 62% lower water absorption than Mix 1 and Mix 4, respectively.

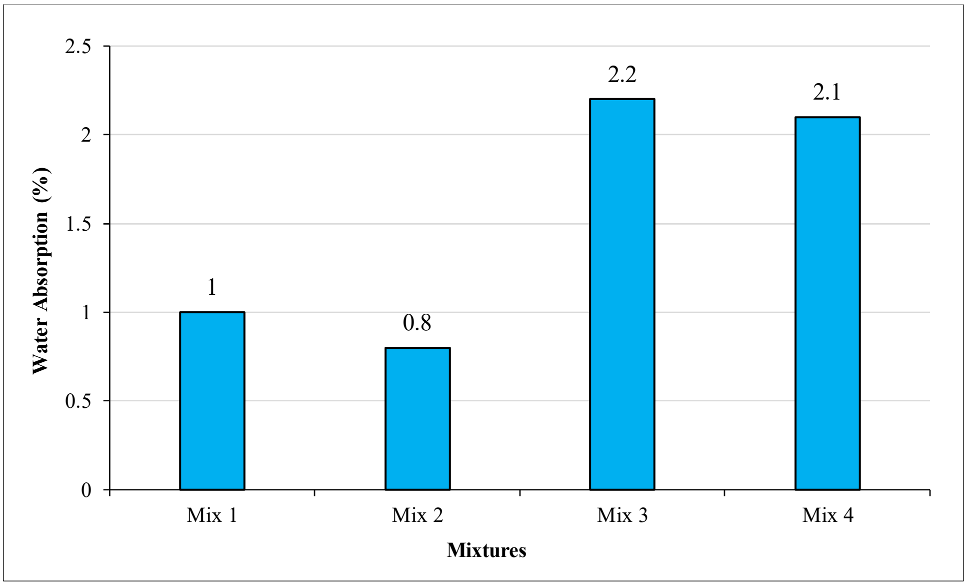

Figure 13. Water absorption results

3.8. Rapid Chloride Penetration Test (RCPT)

Figure 14 shows the RCPT results. The total charge passed through Mix 1 and Mix 2 is 244 and 278 Coulombs, respectively. Mix 2, containing AWA, GGBS, and Micro silica in addition to OPC, demonstrated an advanced mixture design by using ingredients suitable for the production of sustainable AWC that can be applied to underwater applications. According to ASTM standards [49, 82], Group 1 for concrete containing SCMs in Mix 1 and AWC Mix 2 is classified as concrete with very low chloride ion penetrability. This is because the chloride ion penetrability ranges between 100 and 1000 Coulombs. For concrete mixtures made of 100% OPC, as presented in Mix 3 and Mix 4, the total charge passed is 3,500 and 3,200 Coulombs, respectively. Group 2 for concrete with 100% OPC in Mix 3 and AWC Mix 4 is classified as concrete with moderate chloride ion penetrability. This is because the charge passed ranges between 2,000 and 4,000 Coulombs as presented in ASTM standards. In this study, concrete containing GGBS and MS showed an advanced ability to reduce chloride ion penetrability, even with the addition of AWA, as shown in Mix 2. Incorporating GGBS and Micro silica with high content was an effective method for producing sustainable anti-washout concrete [83]. The porosity of concrete was reduced and refined due to the effects of GGBS and SF [84]. As can be seen, the mixture design introduced a reliable method for enhancing the service life of structures used in marine environments. Previously, no study had shown RCPT results for sustainable underwater concrete containing a high quantity of supplementary cementitious materials; moreover, no previous data were available for the correlation between anti-washout admixtures, SCMs in AWC, and their effect on durability evaluation through rapid chloride ion penetration.

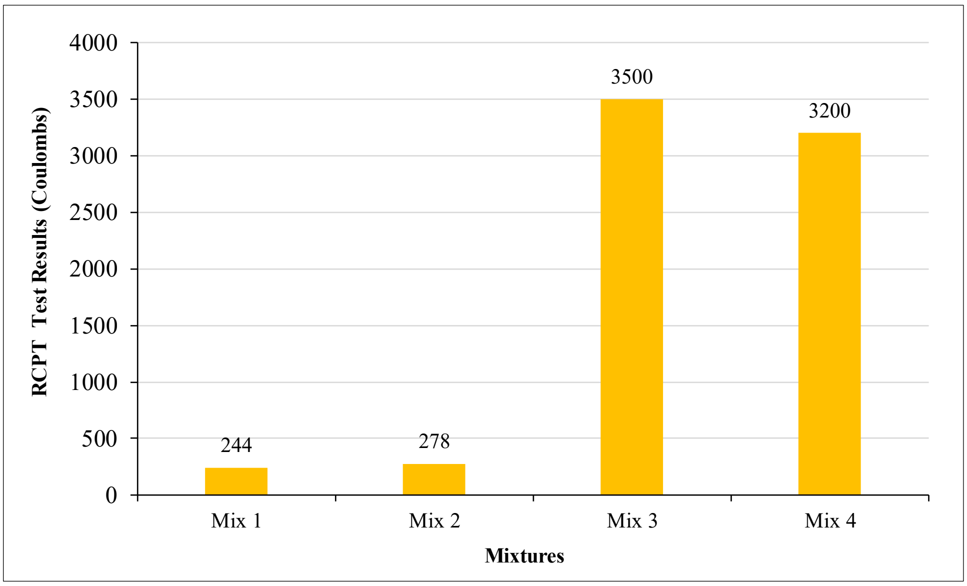

Figure 14. Rapid chloride penetration results

3.9. Initial surface absorption (ISAT)

Figure 15 shows the ISAT test results. Mix 1, without AWA, and Mix 2 with AWA demonstrated high-performance concrete with readings of 0.02 and 0.02, respectively. Mix 3 and Mix 4, with high content of OPC, demonstrated readings of 0.03 and 0.03, respectively. According to the ASTM, the concrete mixture design in this experimental work is classified as water-resistant, with excellent durability and very low permeability [85]. ISAT test was studied previously for normal concrete with high content of OPC to evaluate durability and service life prediction with 35% of fly ash as a partial replacement. The ISAT test was previously studied for normal concrete with a high content of OPC to evaluate durability and predict service life, using 35% fly ash as a partial replacement. The finding was that initial surface absorption had high sensitivity to w/c ratio and fly ash content; however, normal concrete with a 35% w/c ratio was able to achieve a 0.105 value with a 0.3 w/c ratio [86]. In this study, the ISAT test was used to evaluate the performance of AWC in a harsh environment and to investigate the effectiveness of the mixture design. Supplementary cementitious materials have the primary effect of lowering ISAT results; the composite becomes denser and more compact [87]. Moreover, the anti-washout admixture showed no contraction when combined with the superplasticizer and SCMs. The initial surface absorption test measures the flow rate into concrete per unit area at a specific time from the start of the test, under a constant applied head. This test method provides data for assessing the uniaxial water penetration characteristic of concrete surfaces, indicating their quality and durability. An applied pressure of 200 mm head of water exceeds the severity of most weather exposure conditions caused by driving rain [50]. ISAT results can be linked to the finish quality and surface durability under natural weathering conditions. Capillary and interior pores significantly influence ISAT, as they are related to pore size, diffusion, and the interconnectedness of pores within the material. The density of the cement paste, the continuation of the hydration process, and the reduction of shrinkage are all affected by pore size and the physical properties of supplementary cementitious materials, in addition to their function and grain size [86, 88].

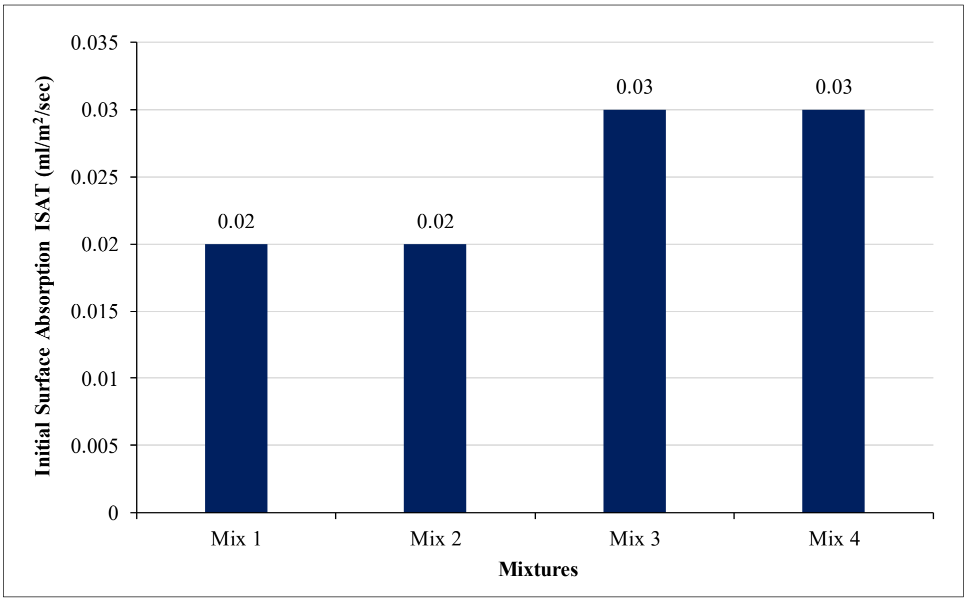

Figure 15. Initial surface absorption results

4. Conclusions

This experimental work was conducted due to the lack of information related to the performance and durability of anti-washout concrete. The main objective was to experiment with concrete mixture design with a sustainable approach. A concrete mixture containing high levels of supplementary cementitious materials was designed. The effect of AWA on concrete strength, compatibility with SCMs, and compatibility with superplasticizer was investigated. Durability was studied using various tests to determine the most effective method for evaluating performance under harsh environmental conditions. The results showed high-performance UWC, and the following conclusions can be drawn:

- AWC, compared to conventional reference concrete with the same mixture design, tends to show a slight decrease in compressive strength. This behavior was attributed to the effect of AWA on retarding the cement hydration process; however, the decrease can be evaluated as marginal.
- AWA demonstrated compatibility with SCMs and superplasticizer; moreover, they were effective in producing durable UWC. This may present a synergistic effect of SCMs with AWA. The results for water penetration under pressure, water absorption, the Rapid Chloride Penetration Test (RCPT), and Initial Surface Absorption (ISAT) indicated highly durable UWC.

- The AWA caused a decrease in air content, which consequently affected the final strength of concrete.
- Incorporating AWA admixture affected the flow rate of AWC by altering the rheology and making the mixture sticky. Concrete with high viscosity may continue to flow over an extended period; however, low viscosity results in a quick initial flow and then stops.
- The addition of an anti-washout admixture demonstrated the mechanism of generating a thixotropic gel. The main concept involves creating a thixotropic gel that surrounds cement particles, acting as a defense system to prevent washout. This mechanism will increase the cohesion of concrete mixes, minimize washout of cement paste during placement, and reduce pumping pressure.
- Experimental tests showed that the use of anti-washout admixture along with superplasticizer did not reveal any critical interactions.
- Durability tests for AWC showed that depth of penetration of water under pressure, water absorption, and rapid chloride penetration are the most effective tests in evaluating the performance of AWC. These tests showed clearer results that may help to make a decision in comparison to ISAT for the contraction of anti-washout admixture and its correlation with SCMs and superplasticizer.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A.S., S.K.A., and A.S.M.; methodology, S.K.A.; validation, M.A.S.; investigation, S.K.A.; data curation, S.K.A.; writing—original draft preparation, M.A.S.; writing—review and editing, A.S.M.; visualization, M.A.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Xiao, S., Zhang, M., Zou, D., Liu, T., Zhou, A., & Li, Y. (2023). Influence of seawater and sea sand on the performance of Anti-washout underwater concrete: The overlooked significance of Mg2+. Construction and Building Materials, 374, 130932. doi:10.1016/j.conbuildmat.2023.130932.

[2] Wang, J., Huang, K., Chu, H., & Li, J. (2025). Synthesis and Performance Evaluation of Anti-Washout Admixtures for Underwater Non-Dispersive Concrete Based on Nanosilica. Materials, 18(11), 2541. doi:10.3390/ma18112541.

[3] Sun, Z., Xu, B., Yang, Z., Sun, M., Xian, X., & Chen, B. (2025). Resolving rheological dilemma in non-dispersible underwater concrete: Conflict between fluidity and anti-washout. Construction and Building Materials, 493, 143258. doi:10.1016/j.conbuildmat.2025.143258.

[4] Poudyal, R., Paneru, B., Paneru, B., Giri, T., Paneru, B., Reynolds, T., Poudyal, K. N., & Dangi, M. B. (2025). Exploring cement Production's role in GDP using explainable AI and sustainability analysis in Nepal. Case Studies in Chemical and Environmental Engineering, 11, 101128. doi:10.1016/j.cscee.2025.101128.

[5] Alsaffar, D. M., Al-Shathr, B. S., & Abed, S. K. (2025). Durability of reactive powder underwater concrete exposed to saline environment: Shatt Al-Arab, Southern Iraq case study. Innovative Infrastructure Solutions, 10(3), 102. doi:10.1007/s41062-024-01857-z.

[6] Amran, M., Makul, N., Fediuk, R., Lee, Y. H., Vatin, N. I., Lee, Y. Y., & Mohammed, K. (2022). Global carbon recoverability experiences from the cement industry. Case Studies in Construction Materials, 17. doi:10.1016/j.cscm.2022.e01439.

[7] Dahanni, H., Ventura, A., Le Guen, L., Dauvergne, M., Orcesi, A., & Cremona, C. (2024). Life cycle assessment of cement: Are existing data and models relevant to assess the cement industry's climate change mitigation strategies? A literature review. Construction and Building Materials, 411, 134415. doi:10.1016/j.conbuildmat.2023.134415.

[8] Ahmad Zaidi, F. H., Ahmad, R., Al Bakri Abdullah, M. M., Abd Rahim, S. Z., Yahya, Z., Li, L. Y., & Ediati, R. (2021). Geopolymer as underwater concreting material: A review. Construction and Building Materials, 291, 123276. doi:10.1016/j.conbuildmat.2021.123276.

[9] Zhong, W. Q., Gang, M. S., & Ren, H. T. (2010). Compression performance of non-dispersible concrete columns. Large Structures and Infrastructures for Environmentally Constrained and Urbanised Areas, 255, 468–469. doi:10.2749/222137810796025393.

[10] Ali Sikandar, M., Wazir, N. R., Khan, M. A., Nasir, H., Ahmad, W., & Alam, M. (2020). Effect of various anti-washout admixtures on the properties of non-dispersible underwater concrete. Construction and Building Materials, 245, 118469. doi:10.1016/j.conbuildmat.2020.118469.

[11] HLu, H., Sun, X., & Ma, H. (2022). Anti-washout Concrete: An overview. Construction and Building Materials, 344, 128151. doi:10.1016/j.conbuildmat.2022.128151.

[12] Wei, M., Tang, Y., Chen, L., Zhang, B., Zhang, S., Zhao, K., & Wu, Z. (2022). Enhanced mechanical properties and anti-washout of calcium phosphate cement/montmorillonite composite bone-cement for bone-repair applications. Ceramics International, 48(23), 35185–35197. doi:10.1016/j.ceramint.2022.08.117.

[13] Liu, F., Wang, B., Wang, M., & Yuan, X. (2021). Analysis on pore structure of non-dispersible underwater concrete in saline soil area. Journal of Renewable Materials, 9(4), 723–742. doi:10.32604/jrm.2021.013664.

[14] Al-Tamimi, A. K. (2019). Design and evaluation of underwater concrete. Developments in the Formulation and Reinforcement of Concrete, Elsevier, Amsterdam, Netherlands. doi:10.1016/b978-0-08-102616-8.00014-9.

[15] Nasr, A. A., Chen, S., & Jin, F. (2021). Washout resistance of self-protected underwater concrete in freshwater and seawater. Construction and Building Materials, 289, 123186. doi:10.1016/j.conbuildmat.2021.123186.

[16] Lu, H., He, Y., Li, C., Wei, H., & Xiang, J. (2025). Anti-washout mechanism of underwater cement paste: a DEM-CFD coupling analysis method. Computational Particle Mechanics, 12(5), 3461–3477. doi:10.1007/s40571-025-01029-5.

[17] Guo, H., Tang, Z., Liu, Q., Xu, J., Wang, M., Liang, R., & Sun, G. (2021). Ultra-stable anti-washout cement grout achieved by super water absorbing villus-like nanocomposite hydrogel. Construction and Building Materials, 301, 124035. doi:10.1016/j.conbuildmat.2021.124035.

[18] CONMIX Ltd. (2015). Technical datasheet: Mega Add UW – Underwater stabilizer for concrete and mortar. CONMIX Ltd., Sharjah, United Arab Emirates.

[19] Yao, S. X., Berner, D. E., & Gerwick, B. C. (1999). Assessment of underwater concrete technologies for in-the-wet construction of navigation structures (Report No. USACE TR INP SL-1). U.S. Army Corps of Engineers, Washington, DC, United States.

[20] Assaad, J. J., Daou, Y., & Harb, J. (2011). Use of CEM Approach to Develop and Optimize High-Performance Underwater Concrete. Journal of Materials in Civil Engineering, 23(7), 1094–1102. doi:10.1061/(asce)mt.1943-5533.0000254.

[21] CRD-C 661-06. (2006). Test Method for Determining the Resistance of Freshly Mixed Concrete to Washing out in Water. US Army Experimentation System, Maryland, United States. Available online: https://mtc.erdc.dren.mil/pdfs/Standards/crd_c61.pdf?utm_source=copilot.com (accessed on November 2025).

[22] Khayat, K. H. (1995). Effects of antiwashout admixtures on fresh concrete properties. Materials Journal, 92(2), 164-171. doi:10.14359/9767.

[23] Kurniawandy, A., Ismeddiyanto, Haekal, M., & Zikri, R. (2025). Study of the Mechanical Properties of Underwater Concrete in Seawater Environments. Journal of Geoscience, Engineering, Environment, and Technology, 10(1), 51–58. doi:10.25299/jgeet.2025.10.1.20989.

[24] Mindess, S. (Ed.). (2019). Developments in the Formulation and Reinforcement of Concrete. Woodhead Publishing, Sawston, United Kingdom. doi:10.1016/C2017-0-03347-5.

[25] Ganesh Kumar, B., Muthu, M., Chajec, A., Sadowski, Ł., & Govindaraj, V. (2022). The effect of silica fume on the washout resistance of environmentally friendly underwater concrete with a high-volume of siliceous fly ash. Construction and Building Materials, 327, 127058. doi:10.1016/j.conbuildmat.2022.127058.

[26] Moon, H. Y., & Shin, K. J. (2006). Evaluation on steel bar corrosion embedded in antiwashout underwater concrete containing mineral admixtures. Cement and Concrete Research, 36(3), 521–529. doi:10.1016/j.cemconres.2005.09.014.

[27] Brzozowski, P., & Horszczaruk, E. (2021). Influence of surface preparation on adhesion of underwater repair concretes under hydrostatic pressure. Construction and Building Materials, 310, 125153. doi:10.1016/j.conbuildmat.2021.125153.

[28] Khayat, K. H., & Sonebi, M. (2001). Effect of mixture composition on washout resistance of highly flowable underwater concrete. ACI Materials Journal, 98(4), 289–295. doi:10.14359/10397.

[29] United Nations (2025). Climate Reports. United Nations, New York, United States. Available online: https://www.un.org/en/climatechange/reports (accessed on November 2025).

[30] Assaad, J. J., Gerges, N., Khayat, K. H., Lattouf, N., & Mansour, J. (2019). Assessment of bond strength of underwater polymer-modified concrete. ACI Materials Journal, 116(6), 169–178. doi:10.14359/51716982.

[31] Salih, M. A., Ahmed, S. K., Alsafi, S., Abullah, M. M. A. B., Jaya, R. P., Abd Rahim, S. Z., Aziz, I. H., & Thanaya, I. N. A. (2022). Strength and Durability of Sustainable Self-Consolidating Concrete with High Levels of Supplementary Cementitious Materials. Materials, 15(22), 7991. doi:10.3390/ma15227991.

[32] Grzeszczyk, S., Jurowski, K., Bosowska, K., & Grzymek, M. (2019). The role of nanoparticles in decreased washout of underwater concrete. Construction and Building Materials, 203, 670–678. doi:10.1016/j.conbuildmat.2019.01.118.

[33] Ge, X., Duran, L., Tao, M., DeGroot, D. J., Li, E., & Zhang, G. (2020). Characteristics of underwater cast and cured geopolymers. Cement and Concrete Composites, 114, 103783. doi:10.1016/j.cemconcomp.2020.103783.

[34] Horszczaruk, E., & Brzozowski, P. (2017). Properties of Underwater Concretes Containing Large Amount of Fly Ashes. Procedia Engineering, 196, 97–104. doi:10.1016/j.proeng.2017.07.178.

[35] Yuan, J., Wu, J., Liu, Z., & Zou, Z. (2020). Effects of Slag and Fly Ash on the Durability of Acrylic Emulsion Polymer–Modified Mortar. Journal of Materials in Civil Engineering, 32(7), 04020155. doi:10.1061/(asce)mt.1943-5533.0003223.

[36] Liu, Y. W., Lin, Y. Y., & Cho, S. W. (2020). Abrasion behavior of steel-fiber-reinforced concrete in hydraulic structures. Applied Sciences (Switzerland), 10(16), 5562. doi:10.3390/app10165562.

[37] BS EN 197-1. (2011). Cement Part 1: Composition, Specifications and Conformity Criteria for Common Cements. British Standard Institute (BSI), London, United Kingdom.

[38] BS EN 15167-1:2006. (2006). Ground granulated blast furnace slag for use in concrete, mortar and grout - Definitions, specifications and conformity criteria. British Standard Institute (BSI), London, United Kingdom.

[39] ASTM C494/C494M-19e1. (2024). Standard Specification for Chemical Admixtures for Concrete. ASTM International, Pennsylvania, United States. doi:10.1520/C0494_C0494M-19E01.

[40] BS EN 934-2:2001. (2001). Admixtures for concrete, mortar and grout - Concrete admixtures. Definitions, requirements, conformity, marking and labelling. British Standard Institute (BSI), London, United Kingdom.

[41] BS EN 12350-12:2010. (2010). Testing fresh concrete - Self-compacting concrete. J-ring test. British Standard Institute (BSI), London, United Kingdom.

[42] BS EN 12350-6:2000. (2009). Testing fresh concrete - Density. British Standard Institute (BSI), London, United Kingdom.

[43] BS EN 12350-7:2000. (2010). Testing fresh concrete - Air content. Pressure methods. British Standard Institute (BSI), London, United Kingdom.

[44] BS EN 12350-12:2010. (2010). - Testing fresh concrete - Self-compacting concrete. J-ring test. British Standard Institute (BSI), London, United Kingdom.

[45] BS EN 12390-3:2002. (2002). Testing hardened concrete - Compressive strength of test specimens. British Standard Institute (BSI), London, United Kingdom.

[46] CRD-C 661-06. (2006). Specification for Antiwashout Admixtures for Concrete. US Army Experimentation System, Maryland, United States.

[47] EN 12390-8. (2000) Testing Hardened Concrete. Depth of Penetration of Water under Pressure. British Standard Institution (BSI), London, United Kingdom.

[48] BS 1881-122:2011+A1:2020. (2020). Testing concrete - Method for determination of water absorption. British Standard Institution (BSI), London, United Kingdom.

[49] ASTM C1202-19. (2022). Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. ASTM International, Pennsylvania, United States. doi:10.1520/C1202-19.

[50] BS 1881-208:1996. (1998). Testing concrete - Recommendations for the determination of the initial surface absorption of concrete. British Standard Institution (BSI), London, United Kingdom.

[51] Tsunoda, S. (1992). Antiwashout underwater concrete. Suichu fubunrisei concrete. Semento Konkurito (Cement and Concrete); (Japan), 548.

[52] Hwalla, J., Saba, M., & Assaad, J. J. (2020). Suitability of metakaolin-based geopolymers for underwater applications. Materials and Structures/Materiaux et Constructions, 53(5), 119. doi:10.1617/s11527-020-01546-0.

[53] Song, X., Zheng, H., Xu, L., Xu, T., & Li, Q. (2024). Comparative Study of the Performance of Underwater Concrete between Anionic and Nonionic Anti-Washout Admixtures. Buildings, 14(3), 817. doi:10.3390/buildings14030817.

[54] Wang, Y., Chen, S. Gui, Qiu, L. chao, Nasr, A. A., & Liu, Y. (2023). Experimental study on the slump-flow underwater for anti-washout concrete. Construction and Building Materials, 365, 130026. doi:10.1016/j.conbuildmat.2022.130026.

[55] European Project Group. (2005). The European guidelines for self-compacting concrete: Specification, production and use. Available online: https://www.theconcreteinitiative.eu/images/ECP_Documents/EuropeanGuidelinesSelfCompactingConcrete.pdf (accessed on November 2025).

[56] EFNARC. (2005). The European Guidelines for Self-Compacting Concrete. European Federation of National Associations (EFNARC), Moosseedorf, Switzerland.

[57] Heniegal, A. M. (2017). Developing underwater concrete properties with and without anti-washout admixtures. International Journal of Scientific & Engineering Research, 7, 97-106.

[58] Khayat, K. H. (1996). Effects of antiwashout admixtures on properties of hardened concrete. ACI Materials Journal, 93(2), 134–146. doi:10.14359/1412.

[59] Bessaies-Bey, H., Khayat, K. H., Palacios, M., Schmidt, W., & Roussel, N. (2022). Viscosity modifying agents: Key components of advanced cement-based materials with adapted rheology. Cement and Concrete Research, 152, 106646. doi:10.1016/j.cemconres.2021.106646.

[60] Li, X., Li, G., Zhang, K., Pei, Z., Zhao, S., & Li, J. (2021). Cu-loaded Brushite bone cements with good antibacterial activity and operability. Journal of Biomedical Materials Research - Part B Applied Biomaterials, 109(6), 877–889. doi:10.1002/jbm.b.34752.

[61] EKoehler, E. P. (2007). Aggregates in self-consolidating concrete. Ph.D. Thesis, The University of Texas at Austin, Austin, United States.

[62] Koehler, E. P., Fowler, D. W., Foley, E. H., Rogers, G. J., Watanachet, S., & Jung, M. J. (2007). Self-consolidating concrete for precast structural applications: mixture proportions, workability, and early-age hardened properties. FHWA/TX-08/0-5134-1, Report No. 0-5134-1, Texas Department of Transportation, Austin, United States.

[63] BS EN 206:2013. (2013). Concrete - specification, performance, production and conformity (+A1:2016) (incorporating corrigendum May 2014). British Standard Institution (BSI), London, United Kingdom.

[64] Kim, D., Petrisor, I. G., & Yen, T. F. (2005). Evaluation of biopolymer-modified concrete systems for disposal of cathode ray tube glass. Journal of the Air and Waste Management Association, 55(7), 961–969. doi:10.1080/10473289.2005.10464682.

[65] Isik, I. E., & Ozkul, M. H. (2014). Utilization of polysaccharides as viscosity modifying agent in self-compacting concrete. Construction and Building Materials, 72, 239–247. doi:10.1016/j.conbuildmat.2014.09.017.

[66] Assaad, J. J., Daou, Y., & Salman, H. (2011). Correlating washout to strength loss of underwater concrete. Proceedings of Institution of Civil Engineers: Construction Materials, 164(3), 153–162. doi:10.1680/coma800035.

[67] Wang, J., Jiang, S., Cui, E., Yang, W., & Yang, Z. (2022). Strength gain monitoring and construction quality evaluation on non-dispersible underwater concrete using PZT sensors. Construction and Building Materials, 322, 126400. doi:10.1016/j.conbuildmat.2022.126400.

[68] Wu, S., Ge, Y., Jiang, S., Shen, S., & Zhang, H. (2021). Experimental study on the axial compression performance of an underwater concrete pier strengthened by self-stressed anti-washout concrete and segments. Materials, 14(21), 6567. doi:10.3390/ma14216567.

[69] Pacheco-Torgal, F., Ivanov, V., Karak, N., & Jonkers, H. (2016). Biopolymers and biotech admixtures for eco-efficient construction materials. Woodhead Publishing, Sawston, United Kingdom. doi:10.1016/C2014-0-02075-8.

[70] Roussel, N., Ovarlez, G., Garrault, S., & Brumaud, C. (2012). The origins of thixotropy of fresh cement pastes. Cement and Concrete Research, 42(1), 148–157. doi:10.1016/j.cemconres.2011.09.004.

[71] Sonebi, M. (2006). Rheological properties of grouts with viscosity modifying agents as diutan gum and welan gum incorporating pulverised fly ash. Cement and Concrete Research, 36(9), 1609–1618. doi:10.1016/j.cemconres.2006.05.016.

[72] Roussel, N. (2012). Understanding the rheology of concrete. Woodhead Publishing, Sawston, United Kingdom. doi:10.1533/9780857095282.

[73] PMehta, P. K., & Monteiro, P. J. (2006). Concrete microstructure, properties, and materials. McGraw-Hill, Columbus, United States.

[74] Loeb, A. F. A., & Ellis, R. S. (2008). First Light in the Universe. Springer, berlin, Germany. doi:10.1007/978-3-540-74163-3.

[75] Assaad, J. J., & Issa, C. A. (2013). Mechanisms of strength loss in underwater concrete. Materials and Structures/Materiaux et Constructions, 46(10), 1613–1629. doi:10.1617/s11527-012-0004-2.

[76] ASTM C642-21. (2022). Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. ASTM International, Pennsylvania, United States. doi:10.1520/C0642-21.

[77] Kale, S., & Arditi, D. (2003). Differentiation, conformity, and construction firm performance. Journal of Management in Engineering, 19(2), 52-59. doi:10.1061/(ASCE)0742-597X(2003)19:2(52).

[78] BS EN 206:2013+A1:2016. (2016). Concrete. Specification, performance, production and conformity. British Standard Institution (BSI), London, United Kingdom.

[79] Technical Report 54. (2000). Diagnosis of deterioration in concrete structures: identification of defects, evaluation and development of remedial action. Concrete Society, Sandhurst, United Kingdom.

[80] Cronin, B. (2024). Federal Highway Administration (FHWA) Update. IEEE Transactions on Intelligent Transportation Systems, 25(4), 54–70. doi:10.1109/tits.2024.3376187.

[81] Abolitz, A. L., Anderson, A. R., Birdy, J. N., Boaz, I., Boyd, A. D., Cichanski, W. J., ... & Hognestad, E. (1984). Guide for the Design and Construction of Fixed Offshore Concrete Structures. ACI 357R-84, 1-23.

[82] Andrade, C., Prieto, M., Tanner, P., Tavares, F., & d'Andrea, R. (2013). Testing and modelling chloride penetration into concrete. Construction and Building Materials, 39, 9-18. doi:10.1016/j.conbuildmat.2012.08.012.

[83] ACI 233R-03. (2003). Slag Cement in Concrete and Mortar. American Concrete Institute (ACI), Michigan, United States.

[84] Bremner, T., Hover, K., Poston, R., Broomfield, J., Joseph, T., Price, R., ... & Nmai, C. K. (2001). Protection of metals in concrete against corrosion. Technical Report for ACI Committee 222, American Concrete Institute (ACI), Michigan, United States.

[85] Report BR 254. (1994). Repair and maintenance of reinforced concrete. Building Research Establishment (BRE), Garston, United Kingdom.

[86] Fonseka, N. H. I. C., & Nanayakkara, S. M. A. (2023). Assessment of Concrete Durability by Surface Resistivity and Initial Surface Absorption. 12th International Conference on Structural Engineering and Construction Management, Lecture Notes in Civil Engineering, Springer, Singapore. doi:10.1007/978-981-19-2886-4_43.

[87] Singh, N., & Singh, J. (2025). Characterization of Concrete with Ferrock as a Potential Cement Substitute: Mechanical Strength, Durability and Microstructure analysis. Iranian Journal of Science and Technology - Transactions of Civil Engineering, 2025, 1–25. doi:10.1007/s40996-025-01885-4.

[88] Zeyad, A. M. (2024). Effect of harsh environment on cement mortar containing natural pozzolans. Case Studies in Construction Materials, 20. doi:10.1016/j.cscm.2023.e02808.