



Washout Resistance Enhancement Of Concrete Casting Underwater Using Different Additives

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Abstract: Underwater concrete (UWC) is widely used in marine and hydraulic structures; however, its performance is often compromised by cement washout, loss of cohesion, and significant strength reduction during underwater placement. This study evaluates the fresh and hardened properties of selected underwater concrete mixtures incorporating silica fume and a hybrid combination of silica fume and fly ash, in comparison with a conventional control mix. The experimental program focused on assessing workability, washout resistance, air content, and compressive strength under both air and underwater casting conditions. The results demonstrate that the control mix suffered severe washout and substantial strength loss, confirming its unsuitability for underwater applications. The inclusion of silica fume significantly improved washout resistance and strength retention due to enhanced matrix densification and refined pore structure; however, it led to increased viscosity and reduced flowability. In contrast, the hybrid silica fume–fly ash mixture provided a more balanced performance, achieving improved workability, reduced air content, and satisfactory strength retention, particularly at later ages. The findings confirm that optimized combinations of supplementary cementitious materials can effectively enhance the stability and durability of underwater concrete. The hybrid silica fume and fly ash system is shown to be a promising solution for achieving improved overall performance in underwater construction while maintaining acceptable workability.

Index Terms – Underwater Concrete, Silica Fume, Washout Resistance

I. INTRODUCTION

Underwater concrete (UWC) has become an essential construction material for marine and hydraulic structures such as bridge foundations, offshore platforms, quay walls, and underwater repairs. Unlike conventional concrete, UWC is directly exposed to water during placement, which significantly affects its fresh and hardened properties. One of the major challenges associated with underwater casting is the loss of cementitious materials due to washout, leading to reduced strength, increased porosity, and poor durability [1,4].

Traditional underwater placement techniques, including cofferdams and tremie methods, were developed to minimize direct contact between fresh concrete and surrounding water. Although these techniques improved placement efficiency, they did not fully eliminate cement washout and segregation, particularly under turbulent water conditions [14,38]. Consequently, the need for specially designed concrete mixtures capable of maintaining stability and cohesion during underwater placement became evident.

The introduction of anti-washout admixtures (AWAs) represented a major advancement in underwater concrete technology. AWAs increase the viscosity of the cement paste and form gel-like networks that enhance particle cohesion, thereby reducing material dispersion during placement [5–7]. In parallel, the use of high-range water-reducing admixtures (HRWRs) enabled the production of highly flowable UWC mixes without increasing water content, improving both workability and placement quality [11,33].

In addition to chemical admixtures, supplementary cementitious materials (SCMs) such as silica fume and fly ash have been widely investigated for underwater applications. Silica fume contributes to microstructural densification and enhanced interfacial transition zone properties, while fly ash improves workability and long-term strength development [2,9,20]. However, the combined effects of AWAs and SCMs on washout resistance and compressive strength retention under underwater casting conditions are still not fully optimized and remain an active area of research.

Despite extensive previous studies, most available research focuses either on fresh properties or hardened performance independently. Limited attention has been given to the systematic comparison between air-cast and underwater-cast concrete using the same mixture proportions, particularly in terms of strength loss quantification. Therefore, this study aims to develop optimized underwater concrete mixtures with minimized strength loss by investigating the influence of varying AWA dosages and SCM combinations under both air and underwater casting conditions.

II. LITERATURE REVIEW

2.1. Underwater Concrete : Definition and Challenges

Underwater concrete (UWC) refers to concrete that is placed directly in water without the use of dewatering systems. It is commonly used in marine and hydraulic structures such as bridge piers, offshore foundations, underwater tunnels, and harbor facilities. Unlike conventional concrete, UWC must maintain its cohesion, workability, and mechanical performance while being exposed to water during placement, which presents significant technical challenges [1,4].

One of the primary difficulties associated with underwater concrete is cement washout, which occurs when fine particles disperse into the surrounding water during casting. This phenomenon leads to a reduction in cement content, increased porosity, and deterioration of mechanical properties, particularly compressive strength [5,6]. Additionally, segregation of aggregates and excessive bleeding further compromise the uniformity and durability of UWC mixtures.

Another critical issue is the loss of compressive strength when concrete is cast underwater compared to air-cast conditions. Several studies have reported strength losses ranging from 20% to more than 50%, depending on mixture composition, placement method, and water turbulence [7,14]. This strength reduction is mainly attributed to washout, increased entrapped air, and disturbance of the cement hydration process during early stages.

Therefore, the design of underwater concrete requires a careful balance between flowability and stability. The mixture must be sufficiently workable to allow proper placement while maintaining adequate viscosity to resist washout and segregation. These challenges have driven extensive research into the use of chemical admixtures and supplementary cementitious materials to enhance the performance of UWC under submerged conditions [9,11].

2.2. Historical Development of Underwater Concrete

The development of underwater concrete has evolved in response to the increasing demand for durable marine and hydraulic structures. Early construction practices faced significant limitations due to the inability of conventional concrete to maintain cohesion when placed in water. As a result, early underwater structures often suffered from poor mechanical performance, high permeability, and premature deterioration [14,38].

2.2.1. Early Underwater Construction Practices

Historical records indicate that the earliest underwater construction relied on rudimentary techniques such as manual placement, cofferdams, and temporary enclosures to isolate water from fresh concrete. Despite these measures, significant cement washout and aggregate segregation were frequently observed, particularly in tidal and flowing water environments. These shortcomings resulted in highly porous concrete with limited structural capacity and durability [49].

The introduction of the tremie method marked a major milestone in underwater concrete placement. This technique involves delivering concrete through a vertical pipe, allowing it to flow from the bottom upward while remaining continuously submerged. By minimizing direct contact between fresh concrete and surrounding water, the tremie method significantly reduced washout and segregation compared to earlier practices. The effectiveness of this technique was extensively documented by the U.S. Army Corps of Engineers, particularly in navigation and marine infrastructure projects [14,38].

However, despite the improvements offered by the tremie method, early underwater concretes still exhibited limited workability and poor resistance to washout. The lack of suitable admixtures meant that concrete mixtures relied heavily on low water-to-cement ratios and stiff consistencies, which often hindered

proper placement and compaction. Consequently, strength variability and construction defects remained common in early underwater applications [49].

2.2.2. Emergence of Anti-Washout Admixtures (AWAs) and High-Range Water Reducers (HRWRs)

The introduction of anti-washout admixtures (AWAs) in the late twentieth century represented a transformative advancement in underwater concrete technology. These admixtures, typically based on water-soluble polymers, significantly increased the cohesion and viscosity of fresh concrete, enabling it to resist cement washout even under turbulent underwater conditions [5,18,19].

AWAs function by forming gel-like networks within the cement paste, which stabilize fine particles and reduce their dispersion during placement. This development allowed for the production of highly flowable yet stable underwater concrete, eliminating the need for extremely stiff mixes that were common in earlier practices. As a result, placement quality, structural homogeneity, and strength retention were substantially improved [6,7].

In parallel with AWAs, the advancement of high-range water-reducing admixtures (HRWRs), particularly polycarboxylate-based superplasticizers, further enhanced the performance of underwater concrete. HRWRs enabled significant reductions in water content while maintaining high workability, which is essential for effective underwater placement. When used in combination with AWAs, these admixtures provided an optimal balance between flowability and stability, significantly improving resistance to segregation and washout [11,33,47].

Several studies have emphasized the synergistic interaction between AWAs and HRWRs, noting that improper dosage or incompatibility between the two can negatively affect rheological behavior and stability. Consequently, careful mix design and compatibility assessment have become essential components in modern underwater concrete technology [57].

2.2.3. Integration of Supplementary Cementitious Materials and Advanced Additives

Over the past two decades, research has increasingly focused on the incorporation of supplementary cementitious materials (SCMs) to enhance the durability and sustainability of underwater concrete. Materials such as silica fume, fly ash, and bentonite have been widely investigated for their ability to refine pore structure, reduce permeability, and improve long-term mechanical performance [2,4,9,20].

Silica fume, due to its ultrafine particle size and high pozzolanic activity, has been shown to significantly improve cohesion and resistance to washout when used in appropriate proportions. Fly ash, particularly Class F, contributes to improved workability and reduced heat of hydration, while also enhancing long-term strength and durability. However, excessive replacement levels may adversely affect early strength and washout resistance if not carefully optimized [9,20,21].

More recently, advanced SCM systems, including ternary and quaternary binder combinations as well as nano-scale additives, have been introduced to further improve the performance of underwater concrete. Studies on nano-silica and hybrid binder systems have demonstrated enhanced microstructural densification and improved strength retention under submerged conditions [15,22,23]. These developments reflect a broader global trend toward sustainable and high-performance concrete systems suitable for aggressive marine environments.

III. EXPERIMENTAL PROGRAM

3.1. Overview of Experimental Work

This experimental program was conducted to evaluate the performance of underwater concrete (UWC) incorporating supplementary cementitious materials, specifically silica fume and fly ash, to reduce strength loss during underwater placement. The study focused on comparing the behavior of concrete cast in air and underwater conditions using a limited number of representative mixtures suitable for journal publication.

Only **three concrete mixtures** were investigated in this study:

- One control mixture made with ordinary Portland cement (OPC)
- Two modified mixtures incorporating combinations of silica fume and fly ash

This simplified experimental approach allows a clear assessment of the influence of SCMs on fresh and hardened properties of underwater concrete.

3.2. Material

The materials used in this study included Ordinary Portland Cement (CEM I 42.5N) conforming to Egyptian Standard 4756/1-2007 [31], fly ash (FA), silica fume (SF), anti-washout admixture (AWA), and high-range water-reducing admixture (HRWR). Locally sourced natural siliceous sand and crushed dolomite were used as fine and coarse aggregates, respectively.

The physical properties of the supplementary cementitious materials, including bulk density, specific gravity, and average particle size, are summarized in **Table 1**. As shown in the table, silica fume exhibits a lower bulk density and finer particle size compared to fly ash, which is known to enhance particle packing and contribute to improved cohesion in underwater concrete mixtures.

The chemical compositions of cement, fly ash, and silica fume were determined using X-ray fluorescence (XRF) analysis, and the corresponding oxide contents are presented in **Table 2**. It can be observed that silica (SiO_2) is the dominant oxide in both supplementary materials, particularly silica fume, indicating their strong pozzolanic potential and their contribution to microstructural refinement of the hardened cement matrix.

The physical properties of the aggregates, including specific gravity, fineness modulus, and bulk density, were determined in accordance with ASTM C128 and ASTM C136 standards. The fine aggregate had a fineness modulus of 2.36, a specific gravity of 2.63, and a bulk density of 1.78 t/m^3 , while the coarse aggregate had a nominal maximum size of 12.5 mm and a specific gravity of 2.65. The particle size distribution of both fine and coarse aggregates is illustrated in Fig. 1, confirming the well-graded nature of the aggregates and their suitability for producing stable underwater concrete mixes.

The anti-washout admixture used was a cellulose ether-based product (MasterMatrix UW 404), which enhances cohesion and minimizes segregation during underwater placement [32]. In addition, a polycarboxylate-based high-range water-reducing admixture (Sika Viscocrete-3425) was used to improve flowability and achieve the required workability without increasing water content [33].

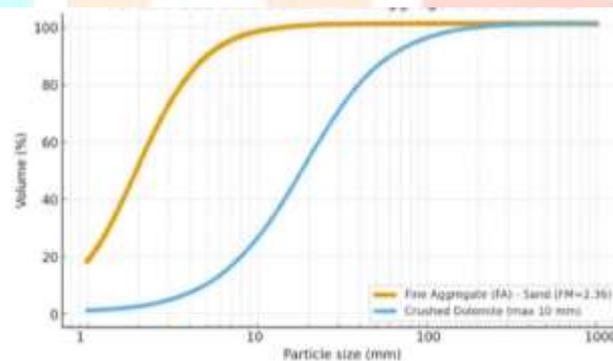


Fig. 1. Particle size distribution curves of fine aggregate (sand) and crushed dolomite.

Table 1. Physical properties of Silica fume and Fly ash.

	Physical properties	
	Silica fume	Fly ash
Bulk Density (kg/m^3)	345	-
Specific Gravity (SG)	2.15	2.22
Average Particle size (μm)	7.00	-

Table 2. Chemical composition of Cement, Fly ash, and Silica fume.

Compound	Content, Mass%		
	Cement	Fly ash	Silica fume
Si O ₂	21.07	39.06	94.31
Al ₂ O ₃	5.11	21.01	0.76
Ca O	63.77	10.74	0.11
SO ₃	3.2	6.83	0.36
Fe ₂ O ₃	4.12	5.55	0.25
K ₂ O	0.37	1.98	0.98
MgO	0.58	1.87	0.51
Na ₂ O	0.05	0.54	0.25
Cl	0.07	0.12	-
Ti O ₂	-	0.80	-
P ₂ O ₄	-	0.64	-
Mn ₃ O ₄	-	0.04	-
Loss of ignition	1.66	10.47	2.34

3.3. Mix Proportioning

Three concrete mixtures were prepared in this study. The control mixture consisted of OPC without any SCM replacement, while the other two mixtures incorporated different proportions of silica fume and fly ash as partial cement replacements. The mix proportions were designed to maintain comparable workability while allowing evaluation of the effect of SCM incorporation on underwater concrete performance. All mixtures were prepared using the same aggregate grading and water-to-binder ratio. Details of mix proportions are presented in **Table 3**.

3.4. Mixing and Casting Procedure

Concrete mixing was carried out using a laboratory pan mixer. Dry materials were first mixed to ensure uniform distribution, followed by the addition of water and chemical admixture. Mixing was continued until a homogeneous and workable concrete mixture was obtained.

Specimens were cast under two different conditions:

- Air casting
- Underwater casting was carried out using the tremie pipe method to ensure continuous placement below the water surface and reduce cement washout, as illustrated in **Fig. 2**.

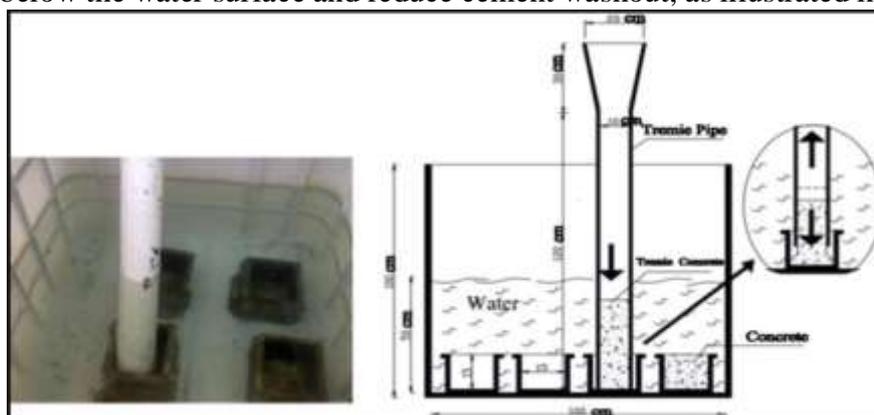


Fig. 2. Laboratory setup and schematic illustration of underwater concrete placement using the tremie pipe method (adapted from [55]).

3.5. Test Specimens and Curing

Concrete cube specimens with dimensions of $150 \times 150 \times 150$ mm were prepared for compressive strength testing. Specimens were tested at **7 and 28 days**. All specimens were cured under submerged conditions to simulate the actual service environment of underwater concrete.

3.6. Mixing Procedure

All concrete batches were prepared using a controlled and consistent mixing procedure in an open pan mixer to ensure uniformity among the investigated mixtures. Initially, the wet coarse and fine aggregates were introduced into the mixer and blended for approximately 30 seconds. Cement was then added gradually and mixed until a visibly homogeneous dry mixture was achieved. Subsequently, the pre-measured mixing water was added, and mixing was continued to ensure proper wetting of all constituents.

Afterward, the high-range water-reducing admixture (HRWR) was incorporated into the mixture, and mixing was continued for an additional 1 minute to enhance dispersion and flowability. Finally, the anti-washout admixture (AWA), previously prepared as an aqueous solution, was uniformly added to the mix. The concrete was then subjected to a final mixing stage lasting 3 minutes to ensure complete homogeneity and adequate development of cohesion.

This mixing procedure was consistently applied to all mixtures in the main experimental program. However, for the part of the study investigating the influence of mixing time, the duration of the final mixing stage was intentionally varied (1, 2, and 3 minutes) to evaluate its effect on workability, washout resistance, and compressive strength [28].

After casting, the concrete cubes were covered and left undisturbed for approximately 24 hours to allow initial setting. The specimens were then demolded and cured by immersion in a water tank maintained at a constant temperature of 20 ± 3 °C until the designated testing ages.

The fresh concrete properties were evaluated immediately after mixing. Consistency and workability were assessed using the standard slump test in accordance with ASTM C143/C143M-20 [36]. In addition, viscosity and flowability were evaluated using the slump flow test following ASTM C1611/C1611M-21 [37], where the spread diameter was recorded. Air content measurements were conducted using a calibrated Type A pressure meter in accordance with ASTM C231/C231M-22 [38].

Table 3. UWC mix proportions.

Materials	Mix ID	OPC	SF	F A	Water	AWA	HRW R	W/B	F/C	Fine agg.	Coarse agg.
		(kg/m ³)		(% of Binder Content)				(kg/m ³)			
OPC	UWC-CTRL	450	-	-	157.5	-	1.5%	0.35	0.6	601.5	1221.3
88%OPC+10%FA+2%SF	UWC-S1	396	9	45	157.5	1.0%	1.5%	0.35	0.6	582.9	1183.5
70%OPC+20%FA+10%SF	UWC-S2	315	45	90	157.5	1.0%	1.5%	0.35	0.6	573.5	1164.5

SF: Silica Fume, FA: Fly Ash, AWA: Anti-Washout Admixture, W/B: Water / Binder Ratio, F/C: Fine / Coarse Agg. Ratio

3.7. Testing Methods

3.7.1. Plunge (Washout Resistance) Test:

The washout resistance of the UWC mixtures was assessed in accordance with the guidelines of the United States Army Corps of Engineers CRD-C61-89A [39]. The experimental setup is illustrated in **Fig. 3**. The test employed an acrylic tube, 200 mm in diameter and 2000 mm in height, which was filled with potable water up to 1700 mm.

Approximately 2 kg of freshly mixed UWC was first pre-wetted with a damp cloth and placed into a perforated stainless-steel container. The container and its contents were weighed to determine the initial mass (M_1). Next, the container was lowered into the water column using a rope, ensuring a smooth descent until it reached the bottom. It was left to rest for 15 seconds, after which it was carefully withdrawn within 5 seconds to minimize disturbance. During lifting, excess water drained through the perforations of the container back into the tube.

The Container, now holding the residual concrete, was reweighed to obtain the final mass (M_2). The washout loss was calculated as the difference between the initial and final masses ($M_1 - M_2$). For each mixture, three specimens were tested, and the average washout loss was reported to ensure reliable and reproducible results.

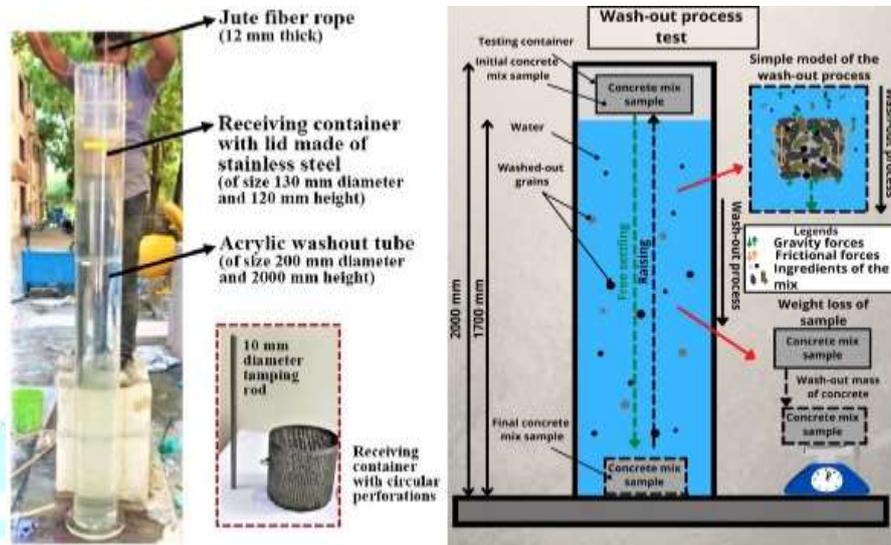


Fig. 3. Experimental setup of the plunge (washout resistance) test for underwater concrete, showing the acrylic washout tube, perforated stainless-steel container, and rope system (adapted from CRD-C61-89A).

3.7.2. Compressive Strength Testing

Compressive strength tests were performed on cube specimens at both 7 and 28 days in accordance with the procedures specified in ASTM C109/C109M-21 [40]. Standard cube samples of 150 mm × 150 mm × 150 mm were prepared, with parallel batches cast underwater and in air for comparison. After curing, the specimens were tested using a calibrated compression testing machine, and the maximum load at failure was recorded.

This comparative approach between underwater-cast and air-cast specimens was essential to evaluate the influence of placement conditions on strength development. The results provided valuable insights into the performance of the proposed UWC mixtures and their effectiveness under submerged construction environments.

3.7.3. Air Content Test

The air content of freshly mixed concrete was determined using the pressure method in accordance with ASTM C231/C231M-22 [38] and ASTM C138/C138M-17a [42]. In this procedure, a concrete sample of known volume is placed in the pressure chamber, and water is added to a calibrated level above the specimen. A predetermined air pressure is then applied, and the corresponding volume change is observed, which provides the percentage of entrapped air in the fresh concrete as shown in Fig. 4. In parallel, the density of the mixtures was evaluated in line with ASTM C138/C138M-17a [42]. The method involves filling a container of known volume with freshly mixed concrete, striking off the surface, and measuring its mass. The fresh density is then calculated as the ratio of mass to volume.



Fig. 4. The air entrainment meter measuring apparatus for determining air content percentage in fresh concrete.

IV. TEST RESULTS AND DISCUSSION

This section presents and discusses the experimental results obtained for the different underwater concrete (UWC) mixtures. The analysis focuses on both fresh and hardened concrete properties, highlighting the influence of SCM incorporation on workability, washout resistance, air content, and compressive strength under air and underwater casting conditions. The observed trends are interpreted in relation to underwater performance requirements and supported by relevant findings from the literature. **Table 4** summarizes the hardened compressive strength results for all UWC mixtures at 7 and 28 days under air (NC) and underwater (UW) curing conditions.

Table 4. Hardened Properties of UWC mixes.

MIix ID	7-day compressive strength				28-day compressive strength			
	F NC N/mm ²	F UW N/mm ²	FUW/FNC %	LOSS %	F NC N/mm ²	F UW N/mm ²	FUW/FNC %	LOSS %
UWC-CTRL	37	6	16.2	83.8	43.5	15	34.4	65.6
UWC-S1	42.5	33	77.64	22.36	56	40	71.42	28.58
UWC-S2	42	28	66.66	33.34	47	35	74.46	25.54

Fig. 5. Typical slump flow diameter and consistency for the UWC mixes.

Fig. 6. Slump flow diameter for the UWC mixes.

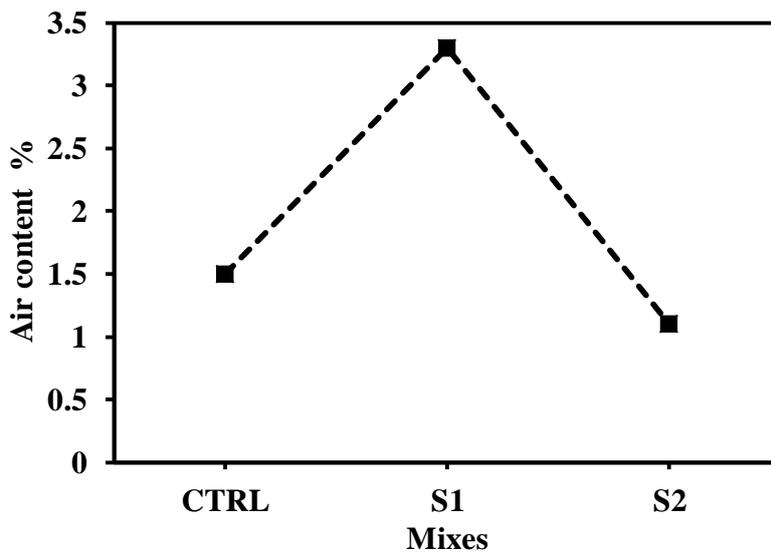
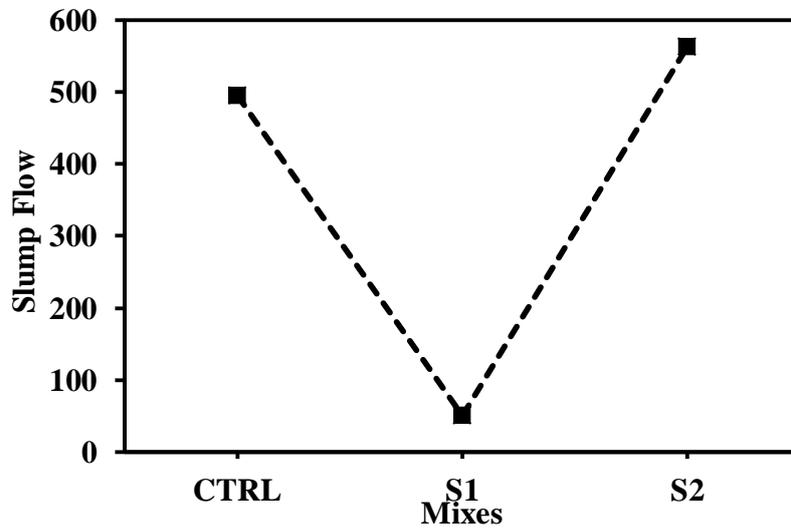
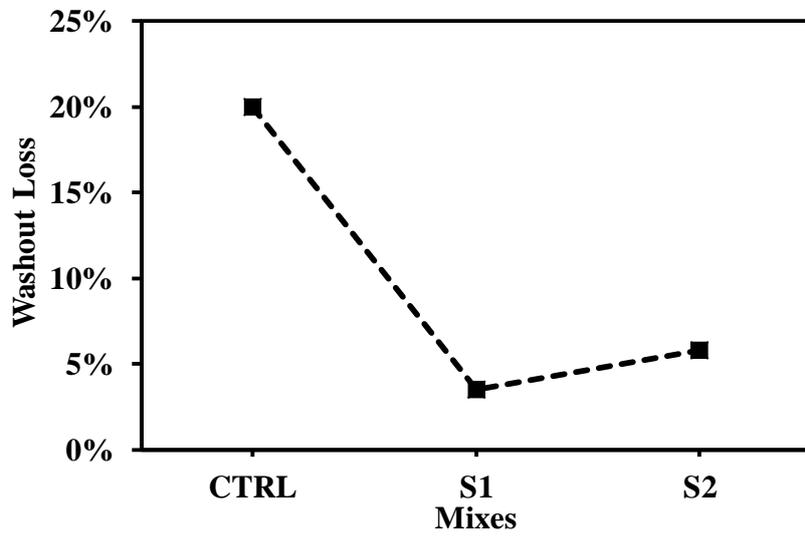


Fig. 7. Washout UWC mixes.

Fig. 8. Typical Air content (%) for the UWC mixes.

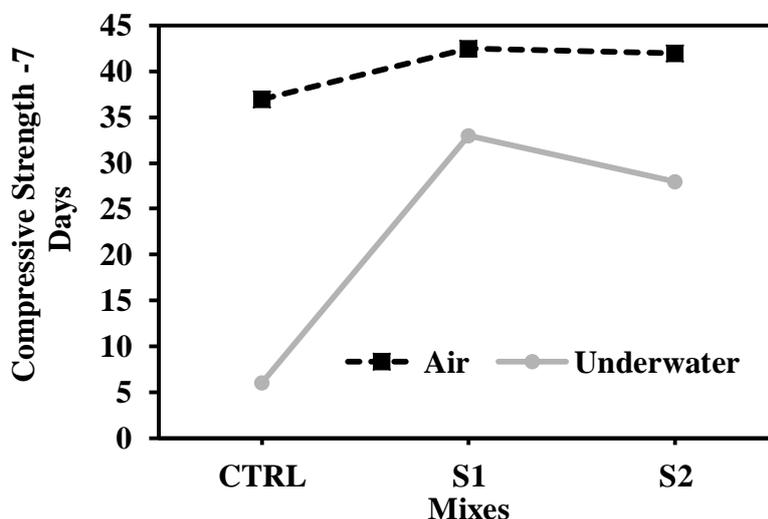


Fig. 9. 7-day Compressive Strength: Air vs. Underwater Casting.

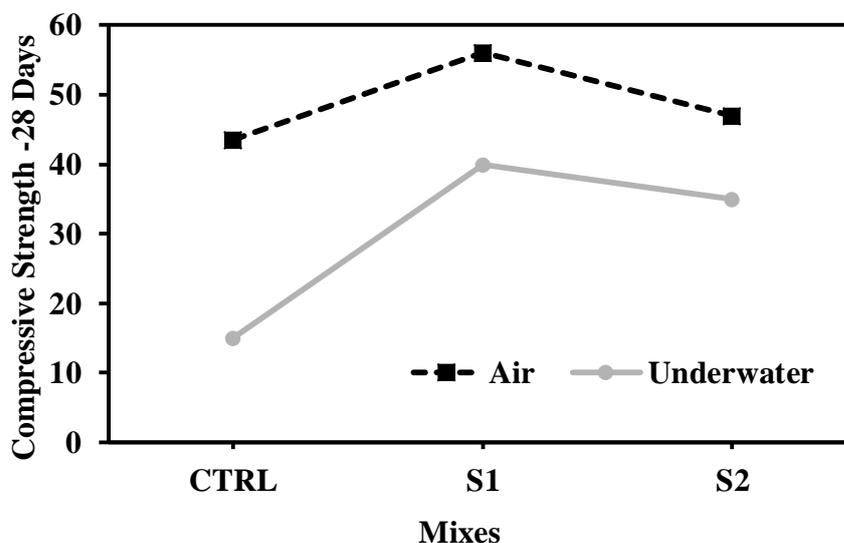


Fig. 10. 28-day Compressive Strength: Air vs. Underwater Casting.

4.1. Slump Flow

The slump flow results, illustrated in Fig. 6, revealed noticeable variations in workability among the investigated mixtures. The control mix (UWC-CTRL) exhibited relatively high flowability due to the absence of cohesion-enhancing constituents. Regarding SCM incorporation, contrasting behaviors were observed between UWC-S1 and UWC-S2. The UWC-S1 mixture experienced a significant reduction in slump flow, which can be attributed to the higher silica fume content and its associated increase in surface area and water demand. In contrast, UWC-S2 showed a recovery in flowability despite containing silica fume, owing to the higher fly ash content, which improved particle packing and acted as a lubricant within the fresh mix.

These observations are consistent with previous studies [5, 10, 12, 21], which reported that optimized combinations of SCMs—particularly silica fume and fly ash—can enhance flowability while maintaining adequate cohesion when properly proportioned.

4.2. Washout Resistance

Washout resistance is a critical parameter for evaluating the suitability of concrete for underwater placement, as it reflects the ability of the mix to retain cementitious materials when exposed to water turbulence. As shown in Fig. 7, the control mix (UWC-CTRL) exhibited the highest washout loss, confirming that plain concrete lacks sufficient cohesion for underwater applications.

The SCM-based mixtures (UWC-S1 and UWC-S2) demonstrated improved washout resistance compared to the control mix; however, their performance remained sensitive to the level and type of cement replacement. While silica fume and fly ash are well known for improving durability and reducing permeability, excessive replacement levels may adversely affect short-term stability during underwater placement. Similar trends were reported in previous studies, where high-volume SCM incorporation increased water demand and led to higher washout losses [21, 23]. These findings emphasize that SCM usage in UWC

must be carefully optimized to balance long-term durability benefits with adequate resistance to washout during placement.

4.3. Air content %

Air content significantly influences both durability and compressive strength of concrete. As illustrated in **Fig. 8.** the SCM-modified mixtures exhibited distinct air content behaviors. UWC-S1 showed a noticeable increase in entrapped air, which can be attributed to the high silica fume content. Due to its ultrafine particle size and large specific surface area, silica fume tends to increase air entrapment within the fresh concrete matrix [60].

Conversely, UWC-S2 demonstrated a lower air content, indicating that the presence of fly ash mitigated excessive air entrainment by improving particle packing and reducing internal voids. This behavior aligns with earlier findings that reported fly ash contributes to pore refinement and reduction of entrapped air in cementitious systems [16].

4.4. Loss in Compressive Strength

Compressive strength loss due to underwater placement is a key indicator of the structural performance of UWC. As presented in **Table 4** and illustrated in **Fig. 9.** and **Fig. 10.** the control mix (UWC-CTRL) exhibited the highest strength loss at both 7 and 28 days. This clearly indicates that conventional concrete, when cast underwater without stabilization measures, suffers severe degradation and is unsuitable for underwater construction.

In contrast, both SCM-modified mixtures (UWC-S1 and UWC-S2) showed substantially lower strength losses under underwater curing conditions. This improvement can be attributed to the combined effect of silica fume and fly ash, which enhanced particle packing, reduced permeability, and limited cement washout during placement. The synergistic action of these SCMs resulted in a denser microstructure and improved retention of cementitious materials, leading to superior underwater performance, as also reported in previous studies on SCM-modified underwater concrete [5, 21, 54]. These results confirm that properly optimized SCM combinations can significantly reduce strength loss and improve the structural reliability of underwater concrete.

V. CONCLUSIONS

Based on the experimental results obtained in this study, the following conclusions can be drawn:

1. Plain concrete (UWC-CTRL) exhibited the highest washout loss and compressive strength reduction when cast under water, confirming that conventional concrete lacks the cohesion and stability required for underwater applications.
2. The incorporation of supplementary cementitious materials significantly improved the performance of underwater concrete. Mixes containing silica fume and fly ash (UWC-S1 and UWC-S2) demonstrated enhanced stability, reduced washout loss, and improved strength retention compared to the control mixture.
3. Slump flow results indicated that the combined use of silica fume and fly ash influenced workability differently. The mixture with higher silica fume content (UWC-S1) showed reduced flowability due to increased viscosity, while the mix incorporating fly ash (UWC-S2) exhibited improved flowability as a result of better particle packing and the spherical morphology of fly ash particles.
4. Washout resistance was strongly dependent on binder composition. Although SCMs improved durability-related properties, excessive replacement levels adversely affected short-term stability during underwater placement, highlighting the need for optimized SCM proportions.
5. Air content measurements revealed that silica fume increased entrapped air due to its ultrafine particles and high surface area, whereas fly ash contributed to lowering air content by refining pore structure and improving particle distribution.
6. Compressive strength results at both 7 and 28 days confirmed that SCM-modified mixes achieved lower strength loss under underwater casting conditions compared to the control mix. This improvement is attributed to microstructural densification, reduced permeability, and enhanced interfacial transition zones.

Overall, the results demonstrate that properly proportioned silica fume and fly ash can effectively enhance the fresh and hardened properties of underwater concrete, leading to reduced material loss and improved structural performance when cast in submerged environments.

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