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EVALUATION OF ENGINEERED CEMENTITIOUS COMPOSITE FOR UNDERWATER APPLICATIONS: WASHOUT RESISTANCE AND FLOWABILITY

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Abstract

This study investigates the fresh properties and washout resistance of Engineered Cementitious Composite Underwater Concrete (ECCUWC) incorporating varying dosages of Anti-Washout Admixtures (AWAs) and Polyvinyl Alcohol (PVA) fibres. The aim is to optimize mix design to achieve sufficient flowability while minimizing material loss under submerged conditions. Twenty ECCUWC mixtures were prepared with a constant fly ash (FA) content of 25% by mass of cement and a fixed water-to-binder ratio of 0.40, while systematically varying AWA (0.5% to 1.1%) and PVA fibre content (1.0% to 1.75%). Fresh properties and washout resistance were evaluated through slump flow, V-funnel (at air and underwater), turbidity, and pH stability tests. The results showed that increasing AWA content significantly improved cohesion, resulting in reduced slump flow and turbidity values. The mixture containing 1.1% AWA and 1.75% PVA exhibited the best overall performance, achieving a slump flow of 240 mm, minimal washout loss of 2.1%, and turbidity as low as 58 NTU. Mixtures with 0.7% and 0.9% AWA also performed well, maintaining high flowability and reduced turbidity. The optimized range of 0.7–1.1% AWA and 1.5–1.75% PVA was found to provide the best balance between workability and stability. These findings contribute to the development of sustainable, non-dispersive ECCUWC mixes that meet the stringent requirements of underwater construction, particularly in marine and hydraulic environments where conventional concrete typically underperforms due to washout and poor cohesiveness.

Keywords:

Underwater Concrete (UWC); Engineered Cementitious; Composite (ECC); Anti-Washout Admixtures (AWA); Polyvinyl Alcohol Fibers (PVA); Washout Resistance.

1 Introduction

Underwater Concrete (UWC) Technology in marine and hydraulic structures requires precise placement with adequate flowability, segregation resistance, mechanical integrity, and washout resistance. Engineered Cementitious Composites (ECC), particularly those reinforced with Polyvinyl Alcohol (PVA) fibres, have been recognized as superior alternatives to conventional concrete in such applications due to their enhanced flexibility and crack control capabilities. The tensile strength and ductility of ECC are significantly improved by incorporating PVA fibres in the range of 1–2% by volume, enabling the formation of multiple microcracks and allowing the material to sustain large deformations before failure [1,2]. Optimizing the dosage of PVA fibres in cement mortar composites has been shown to significantly enhance flexural strength, thereby supporting the rationale for examining various PVA levels in ECCUWC mixtures [3].

ECC is characterized by a fine, aggregate-free matrix combined with high-performance polymeric fibers, forming a ductile, bendable material with superior crack control and strain-hardening capabilities. According to [4], ECC incorporating PVA fibers exhibited enhanced mechanical behavior and structural uniformity, which makes it an excellent choice for complex construction environments such as underwater concrete placement. These characteristics contribute directly to improving flow stability, minimizing segregation, and supporting resistance against material washout in submerged conditions.

Achieving uniform dispersion of PVA fibres within the ECC matrix is critical for optimizing both fresh and mechanical properties. Poor fibre distribution can lead to clumping, adversely affecting flowability and compromising the homogeneity of the hardened composite. Monofilament PVA fibres, when properly dispersed, form a multi-directional network that enhances workability and mechanical performance. Conversely, improper dispersion can reduce the workability of cementitious composites [5]. The workability of ECC, often assessed through slump flow and V-funnel tests, governs its ease of placement and compaction. High slump flow values indicate lower viscosity and higher fluidity, which are desirable for underwater placement to minimize material loss and structural defects [6].

Beyond fibre optimization, incorporating fly ash (FA), a byproduct of coal combustion, offers substantial benefits for the fresh and hardened properties of ECC. The spherical shape and smooth texture of fly ash particles provide a "ball-bearing effect" that reduces inter-particle friction, enhancing the flowability of fresh mixtures without increasing water demand [7]. Fly ash improves particle packing density, leading to a more lubricated matrix with enhanced rheological behavior [8,9]. It also contributes to reduced yield stress and plastic viscosity, facilitating better workability [6]. Furthermore, the slower hydration kinetics of fly ash extend the working time, while its pozzolanic activity refines the pore structure, improving long-term durability and mechanical performance [10,11]. High-volume fly ash ECCs have demonstrated superior tensile ductility and strain-hardening behavior while reducing environmental impact by lowering cement consumption [12].

One of the major challenges in underwater concrete applications is the washout of cementitious materials upon placement. To mitigate this, Anti-Washout Admixtures (AWAs) are incorporated to increase the viscosity of the mix, reducing segregation and material dispersion under water. Typical AWA dosages range from 0.5% to 1.5% by weight of cementitious materials, with performance being dosage-dependent [13]. Proper optimization of AWA content is essential to balance flowability and washout resistance. While higher AWA dosages improve cohesion and reduce washout, they may also increase viscosity to the extent that workability is compromised. Therefore, achieving an optimal balance between AWA and PVA fibre content is crucial for producing high-performance, non-dispersive ECCUWC mixes.

Although previous studies have addressed the use of PVA fibers and anti-washout admixtures individually in concrete systems, limited research has explored their combined effect within ECC mixtures under fully submerged conditions. Moreover, most existing studies have evaluated flowability or washout resistance separately, without optimizing the balance between both properties. This study addresses these gaps by systematically investigating the synergistic impact of PVA fiber content and AWA dosage on the fresh behavior and washout stability of ECCUWC mixtures.

This study aims to optimize the mix design of ECC for underwater applications by ensuring adequate flowability and minimizing material dispersion under submerged conditions. The optimization process involves the combined use of PVA fibres (1–1.75% by volume), anti-washout admixtures (0.5–1.3% by weight of cementitious materials), and a constant fly ash content (25% by mass of cement). The ultimate goal is to develop high-performance, durable, and environmentally compatible underwater concrete mixtures.

2 Experimental setup

ECCUWC samples investigated within the present paper have been organized with Ordinary Portland cement (CEM I 42.5) and Class F fly ash were used as the cementitious materials in all mixtures. Fly ash was incorporated at a fixed dosage of 25% by mass of cement. This constant addition was maintained across all ECCUWC mixtures to enhance workability and durability.

Five different dosages of anti-washout admixture (AWA) were used in the mix design: 0.5%, 0.7%, 0.9%, 1.1%, and 1.3%, expressed as percentages by weight of the total cementitious materials [14,15]. Natural welan gum in powdered form was used for the ECCUWC. Tables 1 and 2 summarise the chemical and physical properties of the cement and fly ash, respectively. PVA fiber was used in this research in four percentages: (1%, 1.25%, 1.5% and 1.75%), with an aspect ratio of 200. PVA properties are shown in Table 3. Figure 1 illustrates powdered materials were used to produce ECCUWC. A constant w/b of 0.4 was used for all ECCUWC mixtures. The sand used was Zone II natural river sand with a specific gravity of 2.65 and sulfur content of 0.19%.

Moreover, in the production of ECCUWC, a polycarboxylate ether-based high-range water-reducing admixture was utilized. This admixture contains a unique carboxylic ether polymer that conforms to ASTM C494/C494M Type F [16].

The dosage of the superplasticiser (SP) was not constant across all mixtures; instead, it was adjusted to meet the workability requirements of high-flowable concrete, targeting a slump flow in the range of 220–240 mm [17].

The required SP dosage was influenced by both the AWA and the PVA fiber content. Specifically, higher AWA dosages increased the viscosity of the mix, necessitating greater amounts of SP to maintain adequate flow. Similarly, the inclusion of PVA fibers—especially at higher volumes—reduced the available free water due to their hydrophilic nature and surface area, further affecting flowability. Therefore, SP dosages were optimized for each ECCUWC mix to balance cohesion and fluidity, ensuring that all mixtures satisfied the required fresh performance criteria under submerged conditions. ECCUWC mixing composition in (kg/m³) details are presented in Table 4.

Table 1: Chemical and Physical Properties of Ordinary Portland Cement.

Oxides	OPC	Specification according to Iraqi standard N.5 \ 2019 [18]
SiO_2	18,64	-
Al_2O_3	7.71	-
Fe_2O_3	1,98	-
CaO	63.01	-
MgO	4.32	≤5.0%
SO_3	2.36	≤2.8%
Cl	0.007	≤0.1%
L.O.I	0.96	≤4.0%
Blaine fineness, cm^2/gm	4325	-

Table 2: The Chemical Composition of Fly Ash Compering With ASTM C618*.

Oxides	Contents, %	(ASTM C618) Requirement [19]
Fe_2O_3	5.34	The sum of values more than 70%
Al_2O_3	17.58	
SiO_2	65.67	
SO_3	0.85	Max. 5%
MgO	0.84	--
CaO	0.97	--
L.O. I	2.85	Max. 6%
K_2O	2.34	--
Na_2O	1.33	--

*According to Manufacture.

Table 3: Polyvinyl Alcohol Fiber (PVA) Properties*.

Item	Content	Unit	Standard
1	Tensile strength	MPa	1788
2	Modulus of Elasticity	GPa	58
3	Ultimate elongation	%	<31
4	Length	mm	8
5	Diameter equivalent	μm	40
6	Alkali resistance	%	≤96
7	Elongation at break	%	7
8	Hot water resistance	°C	≥98
9	Density	g/cm³	1.28

*According To Manufacture

2.1 Eccuwc mixture preparation

For the best performance, adding the AWA admixture as a thick slurry is preferred by mixing the powdered AWA with one-quarter of the mixing water, followed by 15 minutes of rest. To accelerate the hydration of AWA in the dry phase, it was mixed with warm water at 75-95 degrees Celsius [20]. All concrete mixes were mixed using an electrical laboratory mixer. First, all dry powders were mixed at low speed for approximately 3 minutes until a uniform mixture was obtained. Subsequently, with the mixer still in operation, a liquid mix consisting of the remaining three-quarters of mixing water and SP was added gradually within approximately 6 minutes at high speed. Afterward, with the equipment still in operation and the mixture reaching better consistency, the hydrated AWA in the aqueous phase was added and mixed for another five minutes then the PVA fiber was added gradually for two minutes; the total mixing time ranging from 15-18 minutes.

3 Test Method

The research study employed various experimental test methods to evaluate the rheological properties and washout resistance of Engineered Cementitious Composite Underwater Concrete (ECCUWC). The assessment encompassed both direct and indirect tests. Direct tests included slump flow [21] and V-funnel tests conducted on air (conventional (CO)) and underwater conditions [22] as illustrated in Figures 2 and 3. Indirect tests comprised turbidity, stream, and pH stability assessments. These evaluations were carried out under standard guidelines to assess the performance of ECCUWC comprehensively.

3.1 Slump flow and V-funnel tests

The integration of anti-washout admixtures and Polyvinyl Alcohol (PVA) fibers in Engineered Cementitious Composites (ECC) for underwater applications significantly influences the fresh properties of the concrete. This study examines the effects of varying anti-washout admixture dosages (0.5%, 0.7%, 0.9%, 1.1%, 1.3%) and PVA fiber contents (1%, 1.25%, 1.5%, 1.75%) on slump flow, V-funnel (CO), and V-funnel (UW) tests' to measure the flowability and viscosity. The V-funnel test is an essential test that assesses the time it takes for the mortar to flow through a funnel with a specified opening, indicating the mortar's resistance to flow under its weight. The flow time must be between 6 and 12 seconds for a typical high-flowable mortar. Times greater than 12 seconds indicate higher viscosity or potential blockages, while times shorter than 6 seconds might suggest a mixture that is too fluid and has low viscosity. The flows of all mixtures were determined according to requirements [21]. The flow test was completed 1 min after the completion of mixing.

3.2 Fundamental Principles of the Method for the Modified Stream Test

It is a simple test that visually assesses the degree of washout resistance. The test can be used in a laboratory and on-site. The test procedure uses a 100-150 mm diameter guttering channel 2 m long set at a slope of 15-20° to the horizontal [23]. As shown in fig. 4, A 1,000 g sample (W1) of test concrete is placed 400 mm from the raised end of the channel. A constant volume (1 letter) of water is then poured down the pipe and over the concrete sample to simulate washout conditions. After the washout procedure, the remaining material was carefully extracted and weighed (W2)
to assess the washout resistance (%).

3.3 Fundamental Principles of the Method for the Modified Turbidity and pH stability tests.

The pH stability and turbidity tests are commonly used to investigate the washout resistance of underwater concrete. PH test for underwater concrete measures the surrounding water's PH level to evaluate the concrete's chemical impact on the environment and ensure that the mix has not undergone harmful reactions when submerged. The pH levels of the water samples are measured using pH indicator strips, as shown in Fig. 5. Fresh concrete has a high pH due to its alkaline nature. A 100-ml sample of ECCUWC was placed in a beaker containing 500 ml of tap water [24]. The reading was taken instantaneously. The concrete's interaction with water can raise the pH due to the leaching of calcium hydroxide from cement. A significant rise in pH can indicate large leaching of materials, which may affect the concrete's long-term durability and the environment. Ideally, the pH should not rise excessively, which would signify an appropriate underwater concrete mix with low leachability. Excessive leaching can weaken the concrete's structural integrity. In this study, the pH measurement was conducted immediately at the moment of casting to evaluate the initial washout resistance of the concrete. No subsequent readings were taken after a certain period, as the concrete tends to settle after placement, making pH measurement at later stages inaccurate and unreliable for providing a valid indication of washout resistance.

Also, the Turbidity test for underwater concrete is used to assess the washout resistance of freshly placed concrete. The test measures the turbidity (or cloudiness) of water in which the concrete has been submerged, indicating the amount of fine particles washed out from the concrete mix [25]. A Hach 2100N turbidimeter was used to measure the turbidity of ECCUWC, as shown in Fig 6. The water's turbidity is measured using a turbidity meter. The turbidity reading in Nephelometric Turbidity Units (NTU) reflects the number of fine particles released into the water. Higher turbidity values suggest a greater loss of fines, indicating poor washout resistance. In contrast, low NTU values indicate good washout resistance, meaning the concrete maintains its cohesiveness and doesn't release fine particles into the water.

Table 4: ECCUWC mixing composition in (kg/m³).

Croup no.	OPC[1]	FA[2]	Sand	SP[3]	AWA	W/CM	PVA
G1-1[4]	1202	301	564	6	7.5	605	12.8
	1202	301	564	7.5	10.5	605	12.8
	1202	301	564	9	13.5	605	12.8
	1202	301	564	10.5	16.5	605	12.8
	1202	301	564	12	19.5	605	12.8
G2-1.25	1202	301	564	7.5	7.5	605	16
	1202	301	564	9	10.5	605	16
	1202	301	564	10.5	13.5	605	16
	1202	301	564	13.5	16.5	605	16
	1202	301	564	15	19.5	605	16
G3-1.5	1202	301	564	16.5	7.5	605	19.2
	1202	301	564	18	10.5	605	19.2
	1202	301	564	19.5	13.5	605	19.2
	1202	301	564	21	16.5	605	19.2
	1202	301	564	22.5	19.5	605	19.2
G4-1.75	1202	301	564	18	7.5	605	22.4
	1202	301	564	19.5	10.5	605	22.4
	1202	301	564	21	13.5	605	22.4
	1202	301	564	22.5	16.5	605	22.4
	1202	301	564	22.5	19.5	605	22.4

1 ordinary Portland cement, 2 fly ash, 3 superplasticisers, 4 PVA fiber%

(a) (b) (c) (d) (f)

Fig.1: Powdered materials were used for ECCUWC: (a) OPC Ordinary Portland Cement, (b) Fly ash type F, (c) Sand, (d) anti-wash admixture, and (f) PVA fibres.

Fig. 2: Slump flow test.

Fig. 3: V-funnel test (conventional and underwater).

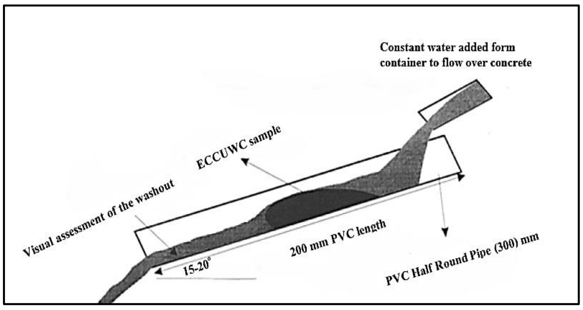

Fig. 4: Stream test .

Fig. 5: PH indicator strips.

Fig. 6: Turbidimeter instrument.

4 Results and discussion

This study focused exclusively on the evaluation of fresh properties and washout resistance of ECCUWC mixtures. The following sections present the outcomes of slump flow, V-funnel, turbidity, stream, and PH tests under submerged conditions.

4.1 Flowability of ECCUWC

Table 5 and Figs. 7 to 11 present the slump flow, washout loss, the relation between slump flow and washout loss, V-funnel at air (CO) and V-funnel (UW) results, respectively, for a different amount of AWA made with (1,1.25,1.5 and 1.75) % PVA fiber.

The fresh properties and washout resistance test results of ECCUWC, including slump flow test, V-funnel test, washout loss, and turbidity test, are summarised in Table 5. The slump flow test, which evaluates the horizontal spread of concrete and thus its filling ability, showed a clear decline in flowability with increasing AWA dosage. As the dosage of anti-washout admixture increased, the cohesion of the mix improved significantly, which in turn reduced the spread diameter. Specifically, with a constant PVA content of 1.75%, increasing AWA from 0.5% to 1.3% (M0.5–1.75 to M1.3–1.75) led to a 21.57% reduction in slump flow, indicating a strong thickening effect of AWA. Likewise, increasing the PVA content while keeping AWA constant at 0.9% resulted in a 4.33% reduction in slump flow (M0.9–1.0 to M0.9–1.75), attributed to the internal fibre network restricting matrix movement. Interestingly, when AWA was held constant at 1.1%, the slump flow reduction between 1.0% and 1.75% PVA (M1.1–1.0 to M1.1–1.75) was only 0.41%, suggesting saturation of flow resistance at higher fibre dosages.

This pattern is reflected in Fig. 7, where the slump flow consistently decreased with increasing AWA and PVA contents, confirming the influence of viscosity on flowability. These trends align with previous findings, where higher AWA content improved internal cohesion, thereby limiting dispersion and flow [26,27]. The presence of PVA fibres, while beneficial for crack control, forms a dense network that restricts free movement of the mix, especially at higher volumes [28] Additionally, previous studies have demonstrated that ECC reinforced with PVA fibres exhibits superior flexural strength and fracture resistance under bending loads, further confirming the mechanical advantages of fibre incorporation in ECC systems,confirming the mechanical advantages of fibre-rich ECCUWC mixtures [29,30]. For underwater concrete, using vibrators is impractical and can disturb the surrounding water, leading to potential washout of cement particles. A denser and more durable concrete structure is essential in underwater environments, where maintaining mix homogeneity is particularly challenging due to continuous water movement. The combined use of AWAs and PVA fibers presents a challenge: the significant rise in viscosity can impede flowability, making it difficult to achieve High Flowable Mortar properties essential for effective underwater casting.

Fig. 8 shows that higher AWA content strengthens the internal cohesion of the mix, reducing the tendency of cementitious materials to disperse in water. However, the simultaneous increase in PVA fibres further reinforces the matrix but also raises the overall viscosity, making the mix more resistant to flow while increasing the material's resistance to washout; these findings align with [31] who reported that AWA enhances anti-dispersion properties by binding water molecules and improving matrix viscosity. This dual effect highlights the need to carefully balance AWA and fiber content to achieve a mixture that combines high workability, bendability, and washout resistance. The results in Fig. 9 clearly demonstrate the balance between flowability and washout resistance in Engineered Cementitious Composite Underwater Concrete (ECCUWC). These illustrate the effect of varying AWA dosages (0.5%–1.3%) and PVA fiber content (1%, 1.25%, 1.5%, and 1.75%) on washout loss and slump flow. The addition of fly ash contributes to better washout loss performance of the ECCUWC mix. Due to its special spherical particles contributes to an increase in packing density and a decrease in permeability, and its pozzolanic reaction is beneficial to the enhancement of the matrix [32].

The V-funnel test results, illustrated in Figs. 10 and 11, provide further insight into the influence of AWA and PVA fibre content on the viscosity and underwater stability of ECCUWC mixtures. A consistent trend was observed in both conventional (CO) and underwater (UW) conditions, where increasing AWA and PVA contents led to prolonged flow times, indicating increased viscosity and cohesiveness.

When AWA dosage was increased from 0.5% to 1.3% with constant PVA content at 1.75%, the CO V-funnel flow time increased by 100%, while the UW flow time increased by 76.47%. These notable increases highlight the thickening effect of AWA, which enhances resistance to segregation and washout, particularly under submerged conditions where water interaction adds significant drag and destabilizing effects [33].

Similarly, increasing PVA fibre content from 1.0% to 1.75% at constant AWA dosage of 0.9% resulted in a 29.17% increase in flow time in CO conditions and a 29.41% increase in UW conditions. This is attributed to the development of a stronger internal fibre network that enhances cohesion and slows down the flow rate by reducing internal mobility, especially under underwater placement scenarios [34]

These results confirm that both AWA and PVA fibres contribute to enhanced rheological resistance and underwater stability. However, the increases in flow time emphasize the importance of optimizing these components to maintain a balance between workability and stability for ECCUWC mixes. The greater rise in (UW) flow times compared to (CO) further underscores the complexity of submerged placement, which necessitates a careful mix design approach. Table 6 presents the main comparison between V-funnel conventional and underwater.

Table 5: The results of fresh properties.

MIX NO.	Slump Flow [mm]	CO. V-funnel test [sec]	UW. V-funnel test [sec]	Weight loss [%]	Turbidity [NTU]
M0.5a-1b	280	7	9	31.2	1150
M0.7-1	277	7.5	10.5	28.1	810
M0.9-1	260	8.5	12	20.3	618
M1.1-1	256	9	14	15.1	450
M1.3-1	235	11	17	13.3	311
M0.5-1.25	270	9	12	29.4	950
M0.7-1.25	265	10.5	15	24.5	715
M0.9-1.25	254	12	17	19.1	511
M1.1-1.25	245	15	21	14.3	305
M1.3-1.25	230	18	23	12.2	280
M0.5-1.5	260	11	15	22.2	615
M0.7-1.5	253	13	18	18.1	405
M0.9-1.5	246	14	21	14.4	215
M1.1-1.5	241	17	25	10.5	182
M1.3-1.5	220	22	29	7.1	108
M0.5-1.75	255	12	17	10.2	300
M0.7-1.75	250	14	20	9.5	215
M0.9-1.75	243	15.5	22	7.1	105
M1.1-1.75	240	17	26	2.1	58
M1.3-1.75	200	24	30	1	15

a-AWA[%] by weight of cementitious materials b-PVA[%]

Table 6: Comparison between V-funnel (CO) and V-funnel (UW).

Parameter	V-Funnel CO	V-Funnel UW
Flow Time	Shorter	Longer
Impact of AWA	Visible	More pronounced due to underwater cohesion requirements
Impact of PVA Fibers	Significant	More significant in resisting washout
Environment	Air-based	Submerged in water (adds resistance and washout challenges)

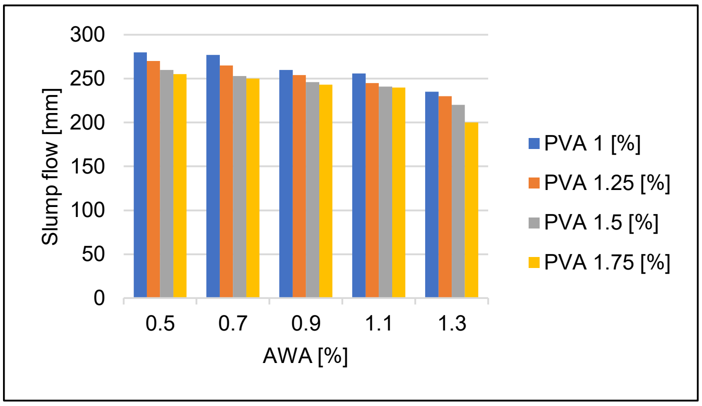

Fig. 7: Effect of AWA[%] and PVA[%] on slump flow.

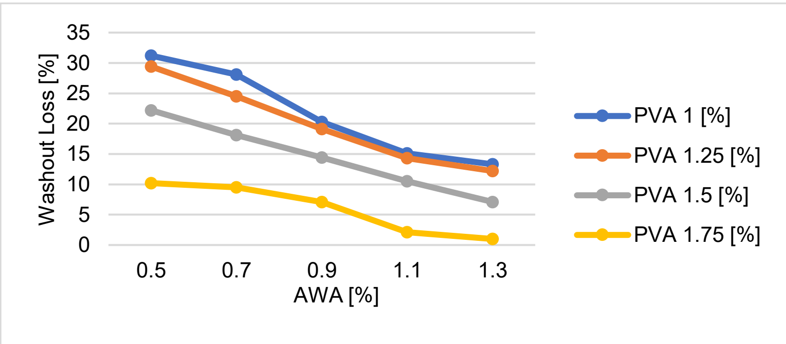

Fig. 8: Effect of AWA[%] and PVA[%] on washout loss.

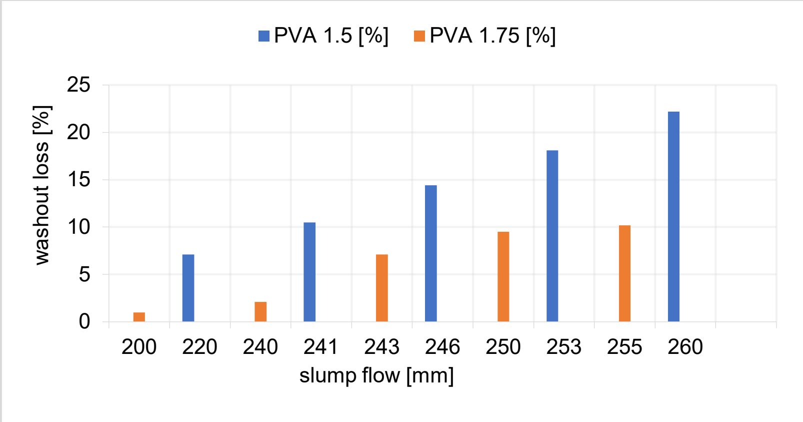

Fig. 9: Relationship between Slump flow and Washout loss.

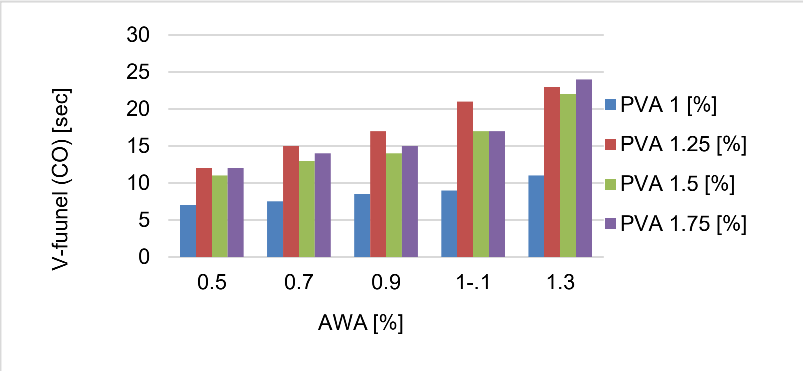

Fig. 10: Effect of AWA[%] and PVA[%] on V-funnel (CO).

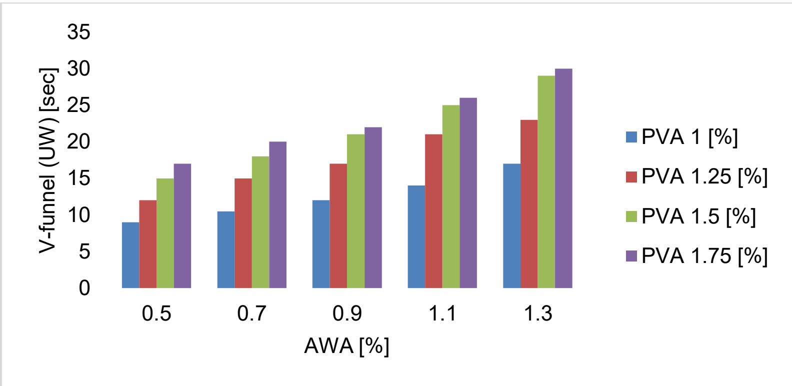

Fig. 11: Effect of AWA[%] and PVA[%] on V-funnel (UW).

4.2 PH factor and turbidity tests of ECCUWC

The pH stability and turbidity tests reveal critical insights into the behavior of ECCUWC under submerged conditions. The observed trends in pH reduction and turbidity control with increasing AWA dosages (0.5%–1.3%) and PVA fiber contents (1%, 1.25%, 1.5%, and 1.75%) highlight the impact of mix design in controlling particle dispersion in water and enhancing underwater performance. The gradual drop in pH from 11.5 when using 0.5% AWA to 7.5 in the presence of 1.3% AWA demonstrates the efficiency of AWA in reducing the dispersion of cementitious components that could leach into the surrounding water. This behavior agrees with the cohesive gel matrix formed by AWA, which can bind fine cement particles and restrict their exposure to water. This trend is supported quantitatively by a 34.78% reduction in pH when AWA was increased from 0.5% to 1.3% at a constant 1.75% PVA fiber content. Similarly, when the PVA dosage increased from 1.0% to 1.75% at a fixed AWA content of 0.9%, the pH value declined by 17.14%, indicating enhanced matrix stability due to fiber reinforcement.

The turbidity levels exhibit an analogous pattern by dramatically decreasing with increasing AWA dosages and PVA fiber. Due to inferior binding at a constant 1.75% PVA fiber content, increasing AWA from 0.5% to 1.3% led to a 94.12% reduction in turbidity. Likewise, increasing the PVA fiber content from 1.0% to 1.75% at a constant 0.9% AWA led to a 79.37% decrease in turbidity. This enhancement is due to increased viscosity due to AWA, which helps avoid washout. At the same time, PVA fibres improve mechanical properties, forming a network of interconnected strands that limit the movement of the mix, further enhancing stability. The synergistic effect of AWA and PVA fibres ensures an effective interfacial area for the pullout, enhancing the overall tensile strength of the composite system and making it resistant to material dispersion.

The reduction in turbidity and pH values emphasizes the enhanced synergistic effect. This strategy is for sustainability and minimization of the ECCUWC's environmental footprint. By optimizing the ECCUWC, improved AWA dosage and fiber content are achieved. These results are further supported by the optimized ECCUWC mixtures summarized in Table 7, which present the most effective combinations of AWA and PVA contents (specifically 0.7%, 0.9%, and 1.1% AWA with 1.5%–1.75% PVA) that achieved high flowability and minimized dispersion, confirming their suitability for underwater applications. Previous experimental findings confirmed that increasing the dosage of anti-washout admixture (AWA) contributes to minimizing turbidity levels and maintaining stable pH values during underwater placement, thereby indicating reduced leaching of fines and improved environmental compatibility of the mix [35].

Based on the optimized fresh and washout resistance properties achieved in this study, the proposed ECCUWC mixture is designed for underwater structural applications such as submerged bridge components, tunnel linings, hydraulic structures, and dam repairs, particularly in environments subjected to high dynamic forces. Engineered Cementitious Composites (ECC) exhibit superior mechanical properties including high compressive strength, enhanced tensile capacity, and notable flexural performance. In addition, ECC is characterized by its ability to form multiple closely spaced microcracks with controlled crack widths typically below 100 µm, which significantly improves durability by limiting permeability and enhancing the material's resistance to aggressive environmental conditions. These unique strain-hardening and crack-dispersing behaviors make ECCUWC an ideal solution for demanding underwater infrastructure [36].

Table 7: Optimal ECCUWC Mixes.

Mix ID	AWA[%]	PVA[%]	Slump flow [mm]	Washout loss[%]	Turbidity [NTU]
M0.7-1.75	0.7	1.75	250	9.5	215
M0.9-1.75	0.9	1.75	243	7.1	105
M1.1-1.5	1.1	1.5	241	10.5	182
M1.1-1.75	1.1	1.75	240	2.1	58

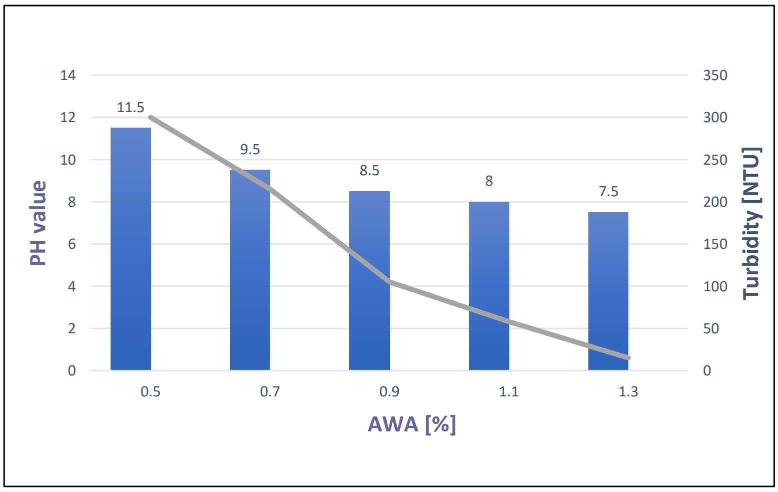

Fig. 11: Relationship between Turbidity and PH value.

5 Conclusion

Multiple ECCUWC mixes demonstrated optimal performance in terms of achieving high flowability, minimal washout loss, and low turbidity, all while maintaining environmental stability. The following mixes were identified as optimal:

1) 0.7% AWA with 1.75% PVA fibres, which achieved a slump flow of 250 mm, washout loss of 9.5%, and turbidity of 215 NTU, indicating high fluidity and acceptable dispersion resistance in underwater conditions.

2) 0.9% AWA with 1.75% PVA fibres, with a slump flow of 243 mm, washout loss of 7.1%, and turbidity of 105 NTU, demonstrating a favourable balance between workability and matrix cohesion.

3) 1.1% AWA with 1.5% PVA fibres resulted in a slump flow of 241 mm, washout loss of 10.5%, and turbidity of 182 NTU, reflecting efficient performance in terms of viscosity and fibre dispersion stability.

4) 1.1% AWA with 1.75% PVA fibres yielded a slump flow of 240 mm, the lowest washout loss of 2.1%, and turbidity of 58 NTU, highlighting the most cohesive and environmentally stable mix with superior washout resistance.

These mixes confirm that using AWA within the range of 0.7% to 1.1%, combined with PVA contents of 1.5% to 1.75%, leads to ECCUWC compositions that are both highly flowable and resistant to material dispersion, making them highly suitable for underwater concrete applications.

Increasing the AWA dosage beyond the optimal range of 1.1% is not recommended due to its potential to increase air content and extend the setting time, which could negatively impact both the strength and construction timeline. Similarly, increasing the PVA fiber content beyond 1.75% adversely affects the mix's workability, reducing its self-compacting capability. Therefore, carefully optimising AWA and PVA content is necessary to balance workability, washout resistance, and mechanical performance.

The results obtained from these studies confirm the optimised ECCUWC mix's desirable workability, durability, and environmental sustainability for underwater construction. Future work should investigate other viscosity-modifying additives, more optimal mix designs, and their long-term performance in making marine structures durable and sustainable.

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