Chapter 6
Characterization Framework for Underwater Printable Concrete: Modified Testing Methods with Environmental Simulation

Masoud Pasbani, Sabit Timilsina, Yen-Fang Su, Ayman Okeil, Yaxin An, and Hyungu Jeong

Abstract The advancement of underwater concrete additive manufacturing (UCAM) is currently hindered by the lack of specialized characterization techniques that accurately reflect the challenges of submerged marine environments, such as material washout and temperature-induced rheological changes. This study introduces a comprehensive experimental framework for evaluating and optimizing ultra-high-performance concrete (UHPC) mortar designed for underwater applications. A printable UHPC mortar was first developed by incorporation of high-range water-reducing (HRWR), slump retaining agent (SRA) and anti-washout admixtures (AWA) to achieve target consistency and cohesion. To simulate realistic field conditions, all fresh-state tests were conducted in 35 ppt seawater at controlled temperatures of 10, 15, and $20°C$ using a chiller-assisted setup. The framework includes three modified testing protocols: a submerged flow table test, an adapted rheometer sample preparation for viscosity and yield stress assessment, and an underwater Vicat setting time test. The experimental results demonstrated that environmental conditions significantly alter the behavior of the material. The reduction in seawater temperature from $20°C$ to $10°C$ reduced the flowability from approximately 114 mm to 103 mm. Although submersion in $20°C$ seawater initially accelerated the setting time to 170 minutes compared to 200 minutes in air, the thermal effect dominated at lower temperatures, extending the initial set to 220 minutes at $10°C$. The rheological profiles confirmed that viscosity and shear stress increase as temperatures drop, emphasizing the need for temperature-adjusted pumping parameters. This investigation establishes a robust and realistic approach for the characterization of underwater-printable UHPC, providing the necessary data to improve the structural integrity and efficiency of autonomous marine construction and repair.

Keywords Underwater concrete additive manufacturing (UCAM) · Modified testing methods · Ultra-high performance concrete (UHPC) · Rheological properties · Setting time

Introduction

Additive manufacturing (AM), commonly known as 3D printing, has emerged as a promising technology in various sectors, including aerospace [1], automotive [2, 3], medical application [4, 5], biomaterials [6] and construction [7], where the application ranges from rapid prototyping and fabrication of architectural models to the production of full-scale structural components. In the construction sector, concrete additive manufacturing has gained substantial attention over the past decade due to its potential to revolutionize traditional construction practices through enhanced design flexibility, construction automation, reduced material waste, improved construction speed, reduced labor requirements and the ability to create

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complex geometries that would be economically prohibitive or technically challenging using conventional formwork-based methods [8, 9].

In recent years, the concept of underwater concrete additive manufacturing (UCAM) has emerged as a promising extension of conventional concrete additive manufacturing, especially for marine construction, offshore infrastructure, and underwater rehabilitation applications. Traditional underwater construction relies heavily on divers, complex formwork systems, and traditional underwater placement techniques, which are labor-intensive, time-consuming, and often lead to material loss and quality fluctuation [10]. By contrast, UCAM offers the potential for automated formwork-free fabrication directly in submerged environments, reducing operational risk, reducing project costs, and allowing greater geometric flexibility [11]. In addition, the buoyancy effect of the surrounding water partially compensates for the self-weight of the freshly deposited layers, which can be beneficial for shape retention and buildability [12]. However, printing in submerged conditions presents a unique set of challenges that are not experienced in conventional concrete additive manufacturing. The constant interaction between the fresh cementitious material and the surrounding water can cause cement washout and shape distortion, ultimately leading to poor mechanical properties [13]. Moreover, the reduced and variable temperatures present in marine environments significantly alter the hydration kinetics and the progress of the rheological properties over time [14], while the constant presence of water at the layer interfaces can affect inter-layer bonding [15].

The effectiveness of concrete additive manufacturing is primarily affected by fresh-state properties of the materials, which must meet the contradictory requirements of pumpability, extrudability, and buildability [16]. Pumpability is the ability of the cementitious material to be pumped through a pumping system to a printing head using pressure while maintaining its initial properties [17]. The extrudability of the printing materials is the ability to flow constantly through a nozzle without segregation or blocking, forming a continuous filament without voids or discontinuities [18]. Buildability is the ability of the extruded materials to retain its shape and withstand its own weight and the weight of subsequent layers without significant deformation or collapse [19]. Pumpability and extrudability are mostly determined by yield stress and plastic viscosity, where lower yield stress and plastic viscosity facilitate flow through pipes and nozzles. However, buildability of the materials requires a higher static yield stress or structural build-up after deposition, allowing the printed layers to resist deformation and maintain geometric stability [18].

The key flow properties are typically assessed using conventional characterization techniques developed for cementitious materials in air. Flow table tests, conducted in accordance with ASTM C1437-20 [20] guidelines, quantify the workability by measuring the spread diameter under controlled drop conditions. This test serves as an indicator of extrudability and pumpability [11]. Rotational rheometers are frequently used to characterize dynamic yield stress, plastic viscosity, and thixotropy of the cementitious material under controlled strain rate [21, 22, 23]. These properties of the material are commonly used to assess deformation resistance, flow behavior, and extrusion capacity [22]. Setting time tests, generally conducted with the Vicat apparatus following ASTM C191 [29], measure the initial and final setting times, which are essential for understanding the open time for printing operations and strength development rate [24].

Although these testing procedures provide reliable and consistent results for traditional concrete additive manufacturing applications, their direct applicability to UCAM is questionable. Most of these tests are conducted in an open-air environment at regulated temperatures, where the samples are protected from external extreme environments. However, in submerged conditions, the extruded cementitious materials are in continuous contact with water, which results in washout of materials, dilution of the material-water interface, and change in hydration behavior [25]. The presence of surrounding water can significantly affect flow characteristics, accelerate or retard setting time based on temperature and ion exchange, and modify the development of shear strength over time [26]. Despite these fundamental differences, most of the existing studies on UCAM rely on traditional rheological testing methodology developed for air-based additive manufacturing [21, 22, 23, 27, 28]. Therefore, this study addresses these gaps by providing a framework for the characterization of underwater printable concrete, including modified flow table, rheometer, and setting time tests. These adapted methods are specifically developed for cementitious material to provide more reliable and realistic fresh-state characterization for underwater construction.

Experimental procedure

Methodology

This study develops modified testing methods for evaluating the fresh properties of the underwater printable concrete, with particular emphasis on its performance at different water temperatures. The material development process began with formulating a printable UHPC mortar showing enough printability and buildability by careful adjustment of the liquid content. Furthermore, this mixture was optimized to have adequate open time and strong resistance to washout for UCAM.

To replicate real underwater construction, all the rheological tests were performed either underwater or after exposing the material to seawater at three controlled seawater temperatures of 20, 15, and 10 °C. A commercially available sea salt was employed at a concentration of 35 ppt, dissolved in tap water. Temperature control was achieved using a water chiller system. The chiller was operated prior to testing to cool and circulate the water until the desired temperature was reached. To offset the slight temperature increase that occurred during testing, the initial temperature was set 1 °C below the intended target. Continuous temperature monitoring was carried out using a digital thermometer, with the goal of maintaining fluctuations within ±2 °C of each setpoint. It should be noted that active chilling was necessary only for the 15 °C and 10 °C conditions. For the 20 °C case, ambient seawater temperature was sufficient.

Three modified test methods were designed and implemented to evaluate flowability, rheological properties, and initial setting time. The mix notations and detailed mixture descriptions are summarized in Table 1. Samples tested in air conditions are labeled Air, while underwater (UW) specimens tested at 20, 15, and 10 °C are identified as UW-20, UW-15, and UW-10, respectively.

Table 1 UHPC mortar mixture proportions designed for UCAM

Mix notation	Testing environment	Testing temperature
Air	Air	Ambient- 23 ± 2 °C
UW-20	Underwater	20 ± 2 °C
UW-15	Underwater	15 ± 2 °C
UW-10	Underwater	10 ± 2 °C

Printing process

A Delta WASP 40100 printer was used in this study to extrude material in different environmental conditions. The collected material upon extrusion was used for conducting the rheological tests in a rheometer. A manual feeding system was incorporated in the printer, extruding material using a screw-based augur through a circular nozzle with 8 mm diameter. For air-printed samples, material was extruded in ambient conditions into a beaker placed in air, while for underwater 3D printed samples, the head of the nozzle was inserted into the container containing water with pre-adjusted water temperature to fill the beaker underwater. The printing system used in this study is shown in Figure 1.

Material and mixing ratios

Due to its exceptional mechanical properties and enhanced durability, UHPC mortar can be a promising material for construction in unstable and extreme environments, such as underwater. Therefore, in this study, a printable mix design for



Fig. 1 Printing system used in this study for material extrusion

UHPC mortar was developed and used for the rheological tests. Portland limestone cement (PLC) was used as the primary binder, and silica fume (SF) and ground granulated blast furnace slag (GGBFS) were added to form the binder. Fine aggregate used in the mixture was silica sand with 40-60 mesh size. The particle size distribution of these materials is shown in Figure 2.

Furthermore, to have adequate flowability, a polycarboxylated high-range water reducer (HRWR) was incorporated to keep the water-to-binder ratio of the UHPC mortar as low as possible at 0.18. Tap water was used as the mixing water. To avoid particle dispersion during UCAM, an anti-washout agent (AWA) is usually added to the mix. In this study, a liquid cellulose-based AWA was used to maintain material consistency with the underwater concrete additive mixture for the modified rheological tests. Moreover, in order to increase the open time to have uniform extrusion, a slump retaining agent (SRA) was added to the mix. The dosage of the liquid components was determined based on the need to achieve an extrudable material with sufficient buildability, adequate open time, and minimal washout. This balance was achieved through several trial and error iteration to optimize the proportions. The final developed mix design for underwater additive manufacturing of the UHPC mortar is presented in Table 2.

Table 2 UHPC mortar mixture proportions designed for UCAM

Mix	PLC	SF	GGBFS	Silica Sand	Water	HRWR*	SRA*	AWA*
Reference	1	0.1	0.2	1	0.235	1.5%	0.5%	0.6%

**% by binder weight*

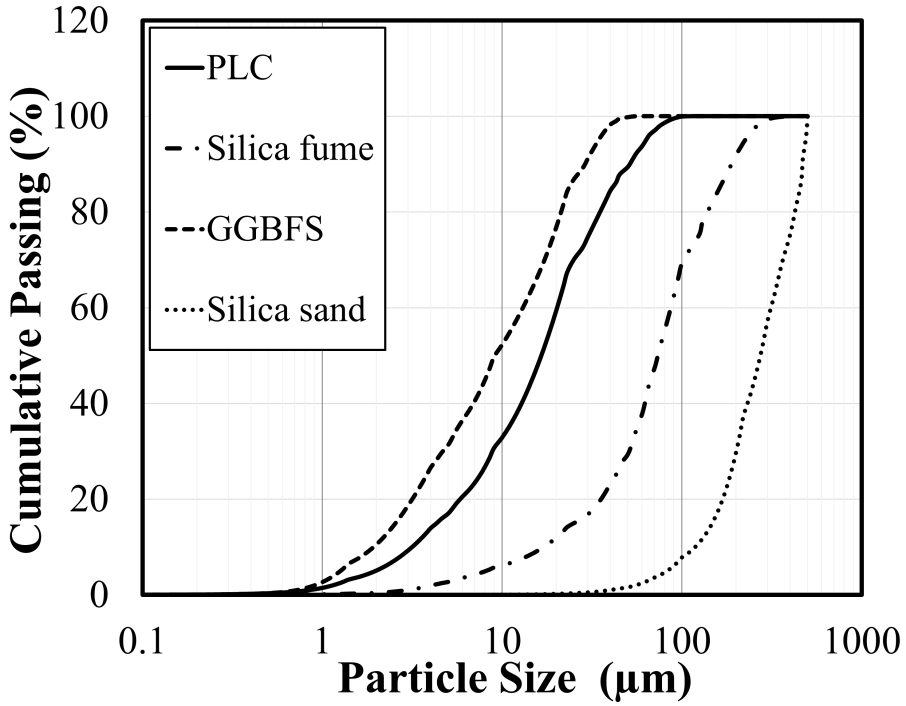

Fig. 2 Particle size distribution of the dry material

Mixing procedure

A small-scale planetary mixer was used in this study to mix the UHPC mortar. In the first step, all dry materials, including PLC, silica fume, slag, and silica sand, were mixed for 5 minutes and after that, half of the water, HRWR, and SRA were slowly added into the mix. Mixing continued for 5 minutes at this stage. Then, the second half of the liquids was added and mixed for 2 minutes. After this stage, the mixing speed was increased from low speed to medium speed and continued for 3 ± 2 minutes. When the mixture was enough flowable, AWA was added and mixing continued for another 3 minutes. The

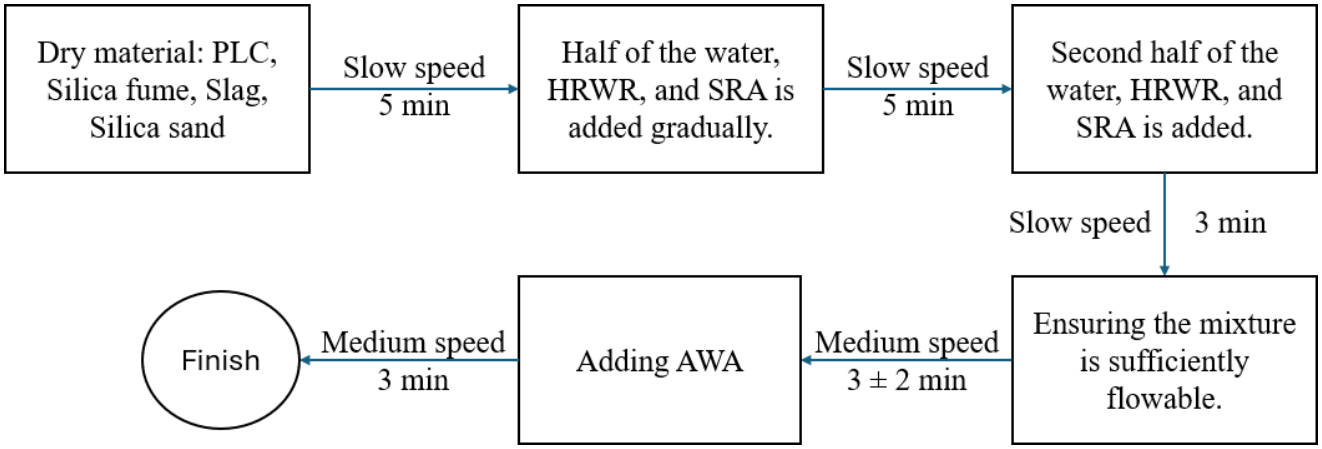

Fig. 3 Mixing procedure used in this study for 3D printable UHPC mortar

same mixing procedure was used for all of the mixes regardless of its testing application. A schematic mixing procedure is shown in Figure 3.

Modified fresh property testing methods

This study focuses on material development for UCAM under different temperature conditions. However, standard test methods do not accurately represent their fresh behavior because they fail to simulate real underwater environments. Therefore, modified testing approaches are necessary to obtain reliable and practical results. To better evaluate their fresh properties under submerged conditions, the flow table test, rheological measurements (viscosity and yield stress), and the Vicat setting time test were adapted accordingly.

Modified flow table test

For the assessment of the flowability of the UHPC mortar designed for UCAM applications, the testing method presented in ASTM C230 [30] was used and modified. To do so, a circular mold with the same diameter size to the flow table was designed and put on the top of the flow table to act as a container for the main flow table mold. Water with adjusted temperature was poured into this container to cover the entire flow table mold after filling it with the mixed material. This can simulate the underwater environment and allow the flow table test to be performed under such conditions, considering all other parameters that can affect the material's flowability, such as water temperature and water pressure. An illustration of the designed container and testing setup is presented in Figure 4. After lifting the flow table mold, three flow diameters were recorded, and the average value was reported.

Modified rheometer test

For the modified rheological tests, viscosity and shear stress of the mix were determined using a Brookfield RSX rheometer. The testing protocol applied in the rheometer included a 2-minute pre-shear of 50 s^{-1} followed by a 2-minute rest at 0 s^{-1}. After that, the shear rate was increased to 50 s^{-1} over 1 minute and then decreased to 0 s^{-1} over another 1 minute to generate the up-curve and down-curve. To prepare material for testing, a beaker was used and filled with the extruded material by collecting it upon extrusion. The same method was used for the samples printed underwater, with the difference that the beaker was placed underwater inside a container that was full of water at the adjusted temperature. This allowed the collection of the material required for the rheometer test after exposure to water at different temperatures. After filling the beaker, it was shaken to remove entrapped water, and then using a syringe, the excess water in the beaker was removed. Subsequently, the beaker was placed in the rheometer, and the test was started immediately. The rheometer used in this study is shown in Figure 5. This testing procedure was developed to evaluate the effect of underwater temperature on the rheological properties of fresh printable material and to establish a more realistic method for underwater applications.



Fig. 4 Modified flow table test setup, developed in this study



Fig. 5 Modified rheometer test setup, used in this study

Modified Vicat setting time test

For underwater UHPC mixes, the Vicat mold was submerged in a custom seawater container, with the water level kept 1 cm above the specimen and temperature controlled within ±2 °C by regularly replacing it with pre-cooled water. Initial setting time was measured with an automatic Vicat apparatus following ASTM C191 [29], recording needle penetration every 7 minutes until it reached 25 ± 0.5 mm. Air-printed mixes were tested under standard lab conditions (23 ± 2 °C, 50 ± 5% RH). All the tests, regardless of their testing environment, were conducted right after finishing the mixing procedure by filling the Vicat mold with the mixture and placing it in the Vicat machine as presented in the Figure 6. This setup was developed to make sure that both air and underwater tests accurately capture the material's initial setting time under their respective conditions.



Fig. 6 Modified Vicat setting time test using Vicat machine

Results and discussion

Flowability

The flowability of the UHPC mortar was evaluated using a modified flow table test designed to simulate submerged conditions at varying temperatures. The results, illustrated in Figure 7, indicate that environmental conditions and water temperature significantly influence the workability of the printing material. The reference sample tested in air exhibited a flowability of approximately 112 mm. For the underwater specimens, the highest flowability was observed in the UW-20 condition, reaching approximately 114 mm. As the seawater temperature decreased, a clear downward trend in flowability was recorded. The flow diameter reduced to approximately 110 mm at UW-15 and reached its minimum of approximately 103 mm at UW-10. The slight increase in flowability for the UW-20 specimen compared to the air-tested sample may be attributed to the initial interaction with the surrounding water and the buoyancy effects within the modified testing container. However, the substantial reduction in flow at lower temperatures ($15°C$ and $10°C$) highlights the sensitivity of the UHPC

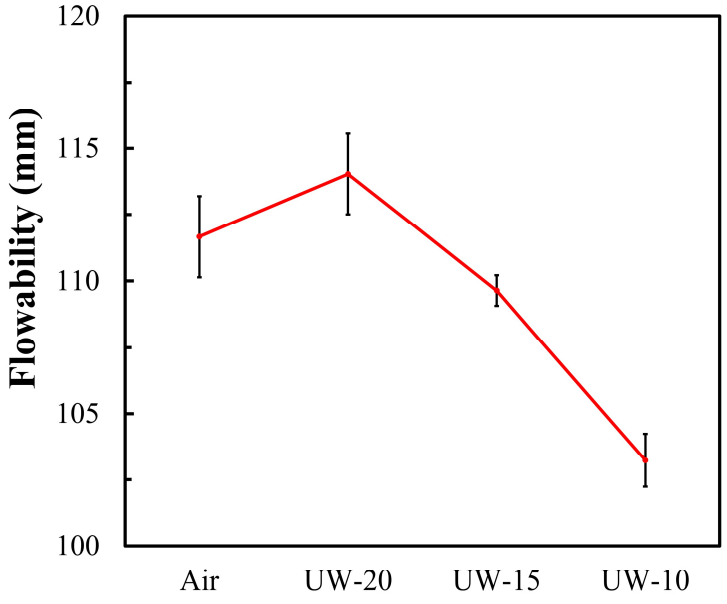

Fig. 7 Flow table test results for the mixtures exposed to different environmental conditions

mortar's rheological behavior to thermal conditions. Lower temperatures likely increase the internal resistance to flow, which is a critical consideration for maintaining consistent extrudability and pumpability in diverse marine environments.

Viscosity and shear stress

The rheological performance of the UHPC mortar was further characterized through viscosity and shear stress measurements using a modified rheometer setup. These tests provide essential data on the material's resistance to flow and its structural behavior under various shear rates, which directly impact extrudability and pumpability. The idealized results are presented in Figure 8 and Figure 9. All mixtures, regardless of the testing environment or temperature, exhibited a clear shear-thinning behavior, where viscosity significantly decreased as the shear rate increased.

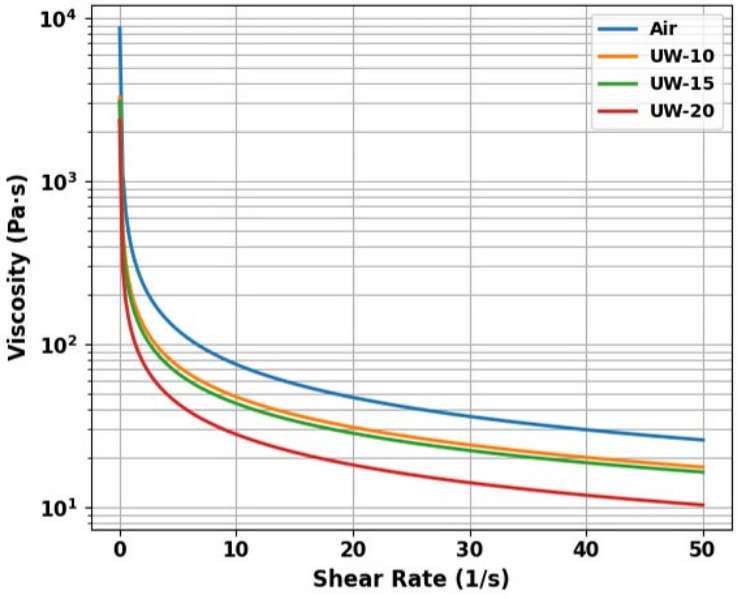

Fig. 8 Rheometer test results showing the viscosity of the mixtures exposed to different environmental conditions

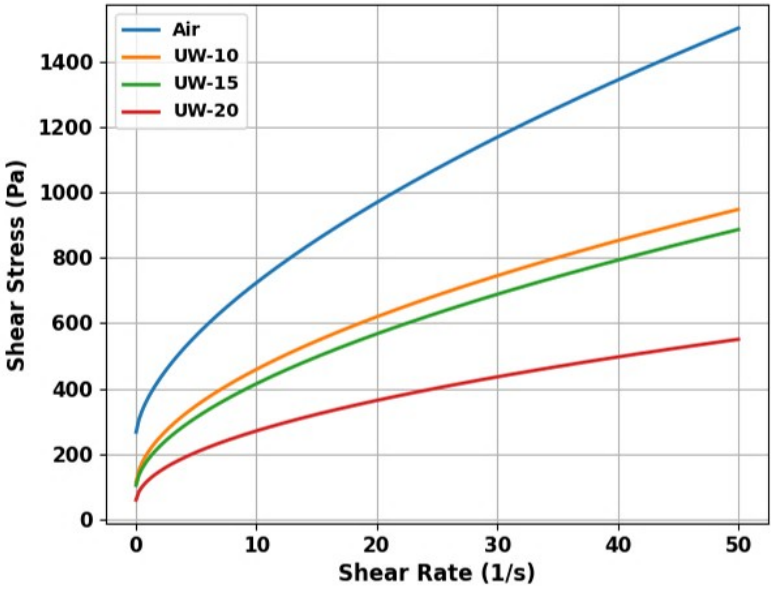

Fig. 9 Rheometer test results showing the shear stress of the mixtures exposed to different environmental conditions

The reference sample tested in air displayed the highest viscosity profile across all shear rates. Upon submersion, a notable reduction in viscosity was observed. Among the underwater specimens, the UW-20 case showed the lowest viscosity. As the seawater temperature decreased from $20°C$ to $10°C$, the viscosity of the underwater specimens increased. This trend suggests that lower temperatures enhance the internal friction and structural resistance of the fresh mortar. Correspondingly, the shear stress required to initiate and maintain flow was highest for the air-tested specimens, reaching approximately 1500 Pa at a shear rate of $50\ s^{-1}$.

Submerged specimens required lower shear stress compared to the air-printed reference. For the underwater conditions, the UW-10 specimen exhibited higher shear stress (reaching nearly 1000 Pa at $50\ s^{-1}$) compared to the UW-20 specimen, which required only about 600 Pa at the same shear rate. The reduction in viscosity and shear stress for submerged specimens compared to the air reference can be attributed to the interaction with the surrounding fluid and the buoyancy effect, which may temporarily lubricate or reduce the effective weight of the material during measurement. However, the consistent increase in both viscosity and shear stress at lower temperatures ($15°C$ and $10°C$) underscores the dominant role of thermal kinetics on the fresh properties of UHPC. These results confirm that while underwater environments generally facilitate easier extrusion due to lower resistance, operating in colder waters will require higher pumping pressures to maintain the same printing speed and consistency.

Initial setting time

The initial setting time of the UHPC mortar was evaluated using a modified Vicat apparatus to compare the behavior of specimens in air versus those submerged in seawater at various temperatures. Understanding these setting times is crucial for defining the ”open time” available for printing operations and predicting the rate of strength development in marine environments. The results of these tests are presented in Figure 10. The reference air-printed specimen exhibited an initial setting time of 200 minutes. In contrast, the UW-20 specimen showed a shorter initial setting time of 170 minutes. This acceleration in the submerged environment at ambient temperature likely results from the high ion concentration in seawater, which can accelerate cement hydration kinetics compared to freshwater or air curing.

A strong correlation was observed between seawater temperature and setting delay. As the temperature decreased from $20°C$ to $10°C$, the initial setting time increased significantly. At UW-15, the setting time increased to 190 minutes. At UW-10, the setting time reached its maximum at 220 minutes. These findings indicate that while the chemical composition of seawater initially accelerates the setting process at $20°C$, the thermal effect becomes dominant at lower temperatures, slowing down the hydration reaction. For UCAM, this implies that colder marine environments will require longer intervals before the material gains sufficient structural integrity to support additional layers, whereas warmer conditions may restrict the available window for extrusion and pumping.

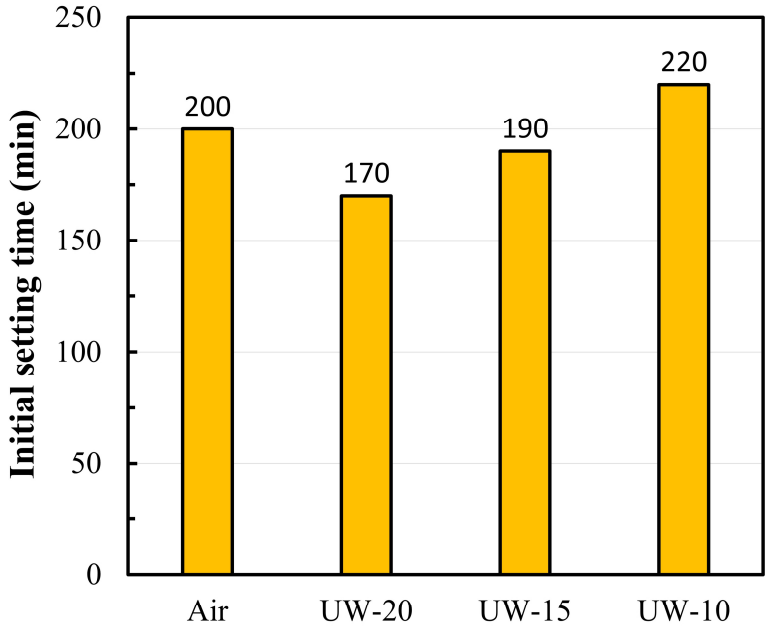

Fig. 10 Initial setting time for the mixtures exposed to different environmental conditions

Conclusion and Future Work

This study successfully established a comprehensive characterization framework for UCAM by developing modified testing methods that simulate actual marine environments. This study moves beyond traditional air-based standards to provide a high-fidelity assessment of cementitious material in submerged conditions. The following conclusions are drawn from the experimental results:

- The research shows that conventional ASTM testing in air is insufficient for predicting underwater behavior. The developed framework, including submerged flowability tests, temperature-controlled underwater Vicat setting time, and adapted rheometer protocols, effectively captures the interactive effects of hydrostatic environment and temperature on cementitious materials.
- Environmental simulation exhibited that while the chemical composition of seawater at $20°C$ initially accelerates the hydration process (reducing setting time from 200 to 170 minutes), the thermal effect of cold marine environments ($10°C$) becomes the dominant factor and significantly retards the set and reduces flowability.
- The framework identified a reduction in viscosity and shear stress in submerged environments compared to air-printed references. However, the simulation of lower temperatures demonstrated a direct increase in these parameters, providing a quantitative basis for adjusting pumping and extrusion pressures in variable marine climates.
- The use of the framework confirmed that the synergy of HRWR, SRA, and AWA admixtures is essential for maintaining printable consistency and anti-washout cohesion, validating the material design portion of the framework for autonomous marine construction.

Future research will focus on a comparative analysis to quantify the specific difference between measurements obtained via conventional ASTM standards and the modified testing framework developed in this study. Additionally, efforts will be directed toward standardizing the introduced methodologies by establishing robust reliability parameters and validation statistics. This will ensure the framework provides a consistent, universally applicable protocol for the characterization of underwater printable cementitious materials.

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