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Review

Anti-washout Concrete: An overview

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ABSTRACT

Anti-washout concrete (AWC) is a special cement-based material that can be directly employed in underwater environments without dispersion. It was developed around 50 years ago, and more than 150 journal articles and technical reports have been published. This paper provides a holistic review about the basic fresh-state and hardened-state properties of the AWC, such as water (washout) resistance, consistency, bleeding and segregation resistance, mechanical properties, and durability, as well as relevant testing methods. The discrepancies between AWC's characteristics and those of conventional concrete are clearly presented. The mixture compositions, supplementary cementitious materials (SCMs), and other conditions that affect AWC's performance are also elaborated. Finally, the paper discusses the specific performance requirements of AWC and corresponding construction strategies for its different applications, including normal construction, marine engineering, bulk filling, and repair practices. Future research needs to stimulate the development of AWC are also discussed.

1. Introduction

Concrete is widely-used for underwater and water-related constructions [1]. However, due to its poor scour resistance, conventional concrete cannot be cast directly into water. Measures must be taken to separate it from water at or before concrete casting to ensure project quality. According to reference [2], the commonly used separating methods can be divided into two categories: the cofferdam methods and special equipment methods. The cofferdam methods are usually used in concrete dam constructions, such as the Three Gorge Dam [3]. Cofferdam followed with weir drainage could realize a construction process of underwater projects in a similar way to that of land-based construction. However, the disadvantages of the cofferdam methods in terms of engineering volume, cost, and construction period are prominent. The second category of methods use special equipment to separate concrete from surrounding water and straightforwardly send the concrete into the construction site, such as tremie method, pre-filled aggregate method, membrane bags method, and container bottom-opening method [2]. Although these methods can reduce the contact between concrete and water, the contact cannot be completely avoided. Washout-induced quality degradation in real-world engineering practice occurs all the time. Therefore, researchers considered to innovate the mixture design of concrete to enable anti-washout capacity and solve the problems associated with underwater construction practices.

The origin of anti-washout concrete (AWC) can be traced back to the 1970 s [2], when the Federal Republic of Germany tried to find a way to improve the quality of underwater concrete. In 1974, the Sibo Group successfully invented AWC by adding cellulose ether viscosity modifying (or anti-washout) admixture to traditional concrete and accomplished the first application under a low water velocity condition. After introducing this patented technology in 1978, Japan successfully developed a variety of anti-washout admixtures (AWAs) based on its indigenous conditions. AWC was widely used in Japan for projects such as breakwater reinforcement, nuclear power plant foundation, and bridge foundation. More than 800,000 m^3 of AWC was used for the Kansai International Airport Access Bridge and the Akashi Kaikyo Bridge projects [2]. In the mid-1980 s, the U.S. Army Corps of Engineers prepared and applied AWC to ocean structures [4]. The concrete mixtures for use in underwater repairs was evaluated subsequently. A propylene-based AWA, called UWB-I type, was developed in 1987 by the Chinese Petroleum Science and Technology Research Institute after four-years cooperation with the Sibo Group [2,5]. Since then, non-dispersible underwater AWC has developed a wide range of applications all over the world.

AWC is also called underwater concrete or non-dispersible underwater concrete. By combining conventional concrete with AWAs, the

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internal structure of concrete and its rheological parameters are changed to achieve water-resisting capacities. With the continuous application of AWC and the rapid development of modern industrial technologies, different types of commercial AWAs have been invented and used [6]. Ramachandran [7] categorized the AWAs into five classes according to their physicochemical actions in concrete. Class A refers to water-soluble synthetic or natural organic polymers (e.g., cellulose-ether and polyethylene oxides) that could increase the viscosity of mixing water; Class B refers to organic water-soluble flocculants including styrene copolymers with carboxyl group, synthetic polyelectrolytes, and natural gums that could adsorb onto the cement grains and increase the viscosity due to enhanced inter particle attraction between cement grains; Class C refers to emulsion of various organic materials, including acrylic emulsions and aqueous clay dispersions that could enhance the inter particle attraction and supply additional superfine particles in the cement paste; Class D refers to high-surface area water-swellable inorganic materials, including bentonites, silica fume and milled asbestos that could intensify the water-retaining capacity of the paste; and Class E refers to inorganic materials of high-surface area, including fly ash, hydrated lime, and diatomaceous earth that could increase the content of fine particles in cement paste. According to AWAs production procedures, Kawai [8] classified the water-soluble polymers into nature, semisynthetic, and synthetic polymers. Nature polymers include starch, natural gums, and plant protein; semisynthetic polymers include starch derivatives, cellulose-ether derivatives, and electrolytes; and synthetic polymers include polymers based on ethylene and vinyl. According to references [9,10], three main categories of AWAs have been used the most commonly in underwater concrete structures: cellulose derivatives [11–14], polysaccharides [15–19], and acrylic-based polymers [2,5,20–22].

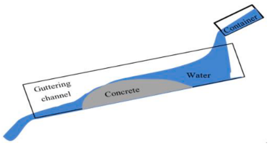
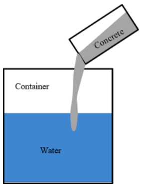
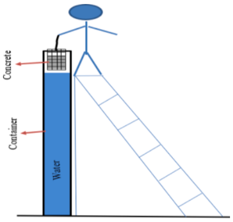
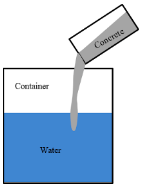
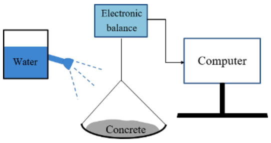
Although AWC was developed decades ago and various AWAs have been applied in different engineering fields, there is a scarcity of comprehensive reviews detailing the relevant research and development. This paper intends to conduct a holistic overview of AWC. For this, the basic properties of fresh and hardened-state AWC, such as water resistance, consistency, bleeding, segregation resistance, mechanical properties and durability are reviewed to provide an initial understanding of AWC. The discrepancies between AWC and conventional concrete are then presented emphatically. This review also elaborates on the common influential factors of the properties of AWC, including different mixture proportioning parameters, supplementary cementitious materials (SCMs, type and dosage), and other conditions that could help prepare suitable AWCs for specific engineering applications. Finally, the specific requirements and construction strategies of AWC designated in specific applications, such as normal construction, marine infrastructure, bulk filling, and repair, are summarized and discussed. Research needs that may be needed in the near future to spur further development of AWC are also discussed.

2. Basic properties of AWC

2.1. Fresh-state properties

Among all fresh-state properties, water resistance (i.e., anti-washout capacity) is the primary consideration in AWC for its underwater applications [23]. To express this performance accurately, various testing methods have been proposed. Schematic diagrams and corresponding parameters of these test methods are displayed in Table 1.

Table 1
Testing methods for anti-washout property.

Methods	Place	Year	Schematic diagram	Parameters
Stream test [25,26]	Belgium	1986		Gutter channel:15-20° slope; 2 m long; Concrete: 300 mm from the channel raised end
Drop test [25,27]	–	–		Concrete: 300–500 g
Plunge test [28–30]	U.S.	1989		Washout tube: 1700 ± 5 mm; Concrete: over 2000 g
pH test; suspended solid content [31]	Japan	1991		Washout cylinder: 1000 ml beaker with 800 ml water; Concrete: 500 g
Spray test [32]	Canada	1996		Concrete: 1 kg; Water spray for 4 min

In the stream test and drop test, the anti-washout capacity of concrete is evaluated through the turbidity of washed water. Although intended to characterize the water resistance of AWC, the tests only provide cursory results per the tester's subjective evaluations, which could lead to deviations among different testers. For the plunge test, pH test, and suspension solid content test, exact parameters such as the sample mass loss ratio, pH value, or solid content of washed water are selected and measured to represent the AWC's water resistance. In addition, the latter three methods have common advantages of simple testing procedures, minimal equipment requirements, and precise testing results. Therefore, they have been generally accepted and documented in civil engineering specifications, as shown in Table 2. Normally used judgement criteria for sufficient water resistance could be: a cement mass loss ratio less than 1.5%, a pH value less than 12, and the suspension solid content less than 150 mg/L [24]. With the development of measurement technology, the spray test was invented by connecting an electric balance with a computer which makes it possible to detect the real-time variations of sample mass. This method could improve the accuracy of measurement, but the scouring mode in this method is inconsistent with the actual situation, and, thus, the testing results need to be further verified or calibrated.

AWAs are normally viscosity modifying admixtures. Due to the effect of the admixtures, along with the higher water resistance, lower fluidity, better bleeding and segregation resistance, longer setting time, and more air content can also be found in AWC [9,33,34]. The changes in fluidity, bleeding, and segregation can be directly attributed to the variations of concrete viscosities. According to reference [9], there can be a chemical connection between the AWA's functional groups and the metal cations in concrete, causing hydration retardation; and this could explain the longer setting time. Higher air content could be attributed to the increased entrapped air during the concrete mixing process due to the improved viscosity.

According to references [9,35], common technical requirements for AWC should include: great resistance to water corrosion, self-leveling ability to flow into the construction site freely without vibration, sufficient bleeding and segregation resistance to guarantee the concrete homogeneity, and adjustable setting time to ensure the transportation and casting of concrete. Therefore, flowability and setting time of AWC requires further adjustment to meet construction demands. The addition of appropriate water-reducers or superplasticizers [9] and accelerators [36] can solve these problems, as shown in Table 3. Certainly, designers of AWC need to take care of the compatibilities of different chemical admixtures.

Nonetheless, these performance parameters are not completely independent [27,37,38]. Changing one performance often causes the variation of other ones. The analysis of the rheological characteristics of concrete plays an important role in clarifying the relationship between its fresh mixing characteristics [39]. In reference [40], the correlations between the rheological parameters and the washout resistance of AWC were established based on the Bingham model. Nevertheless, the AWAs added to concrete cause shear thinning behavior or shear thickening behavior [41]. This model was not adequate to describe the correlations accurately and precisely and predict anti-washout capacity based on rheological parameters; thus, an improved model needs to be developed via further research.

Table 2
AWC specifications in different countries.

Title	Year	Code	Country	Department published
[29]	1989	CRD-C61	United States	US Army Corps of Engineers
[28]	2006	CRD-C661	United States	US Army Corps of Engineers
[31]	1991	–	Japan	Japan Society of Civil Engineers
[42]	1992	–	Republic of Korea	Korean Society of civil Engineers
[43]	2000	DL/T 5117–2000	China	Former Ministry of Electric Power Industry
[24]	2003	Q/CNPC92-2003	China	China National Petroleum Corporation

Note: – means unclear.

Table 3
Characteristics of fresh-state AWC and the resultant influence on hardened-state properties.

	Properties	Tendency	Solutions	Main effects on hardened-state properties
Advantages	Water resistance	↑ (positive)	–	Mechanical properties; Bonding strength; durability
	Bleeding	↓ (positive)	–	–
	Segregation	↓ (positive)	–	–
Disadvantages	Fluidity	↓ (negative)	High range water reducing admixture [9]	–
	Air contention	↑ (negative)	Deforming admixture [9,44]	Mechanical properties and durability
	Setting time	↑ (negative)	Accelerators [36]	Mechanical properties

Note: ↑ means increase and ↓ means decrease versus conventional concrete.

2.2. Hardened-state properties

In this section, the hardened state properties (i.e., mechanical properties, bonding capacity, and durability; see Table 3) of AWC are summarized. Effects of the characteristics of AWC on these properties are summarized as follows.

2.2.1. Mechanical properties

The AWAs retard cement hydration, and may have long-term adverse effect on the cement hydration and microstructure formation processes (implying higher capillary porosity). Moreover, the higher viscosity of AWC normally leads to higher content of entrapped air. Due to these adverse effects, AWC tends to have lower compressive strength and flexural strength compared with its conventional concrete counterpart [44–48], as shown in Fig. 1. Herein a relative compressive strength is defined as the ratio of the compressive strength of AWC to that of AWA-free conventional concrete counterparts; and a relative flexural strength is defined similarly. For all the tested concrete mixtures (water-to-cement ratios, or w/c, equal 0.3 or 0.45, and different curing ages of 7d, 28d, 56d, and 84d), the relative compressive and flexural strengths are less than 100%. In China [24], specifications require that the 28-day compressive strength and flexural strength of AWC are no less than 70% and 60% of the strengths of the conventional concrete counterpart, respectively. In South Korea [46], the relative compressive strength of AWC (ratio to that of the conventional concrete counterpart) must be more than 80%. In the literature [1,49], it has been found that the addition of AWAs have little impact on the stress–strain relations and failure modes of concrete.

2.2.2. Bonding capacity

One of the most critical applications for AWC is underwater repair of deteriorated structures, which usually requires superior bonding capacity. Assaad and coworkers conducted many studies in this area [50–52]. In all AWC mixture properties, the mass loss ratio appeared to have a major influence on the ultimate cohesiveness and bonding strength. The mass loss ratio of 3.3% to 11.83% could result in a reduction of bonding strength by 9.17% to 24.66% [52], as shown in Fig. 2. As shown in the figure, with the increase of mass loss ratio, the

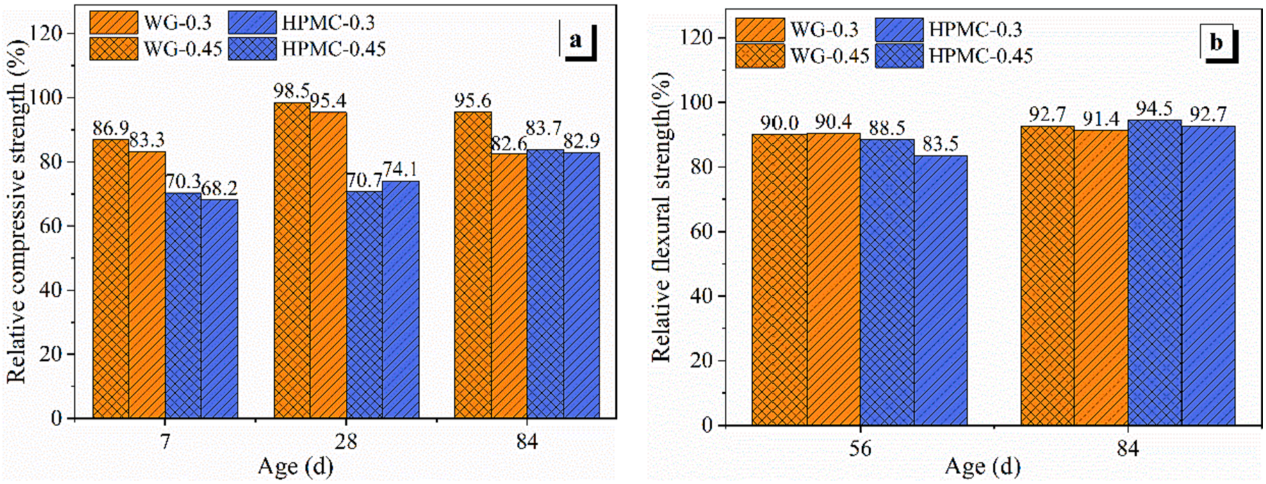


Fig. 1. Relative compressive (a) and flexural (b) strength results for welan gum (WG) or hydroxypropyl methyl cellulose (HPMC) added AWC mixtures [44].

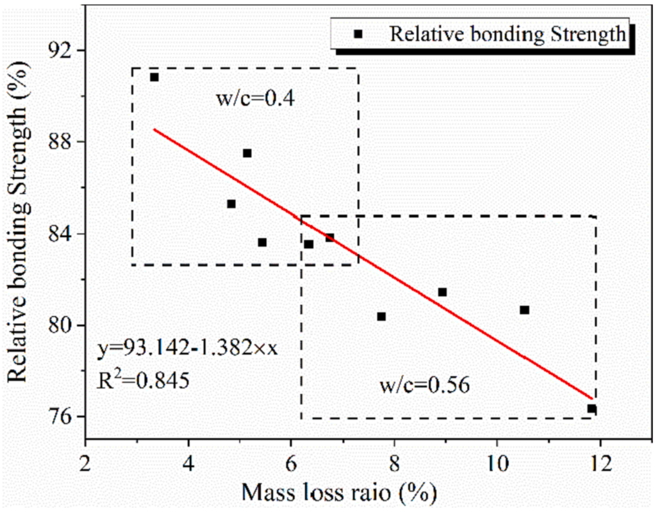


Fig. 2. Relative bonding strength of UWC versus mass loss ratio [52].

relative bond strength decreases monotonically. A simple linear relationship ($R^2 = 0.845$) diagram is also shown in the figure. Such empirical correlations can be used to predict bonding strength based on measured mass loss ratio, or set a target mass loss ratio toward a desired bonding strength. Adding styrene butadiene rubber [53] and light-curing resin [54] could further mitigate the mass loss ratio of AWC and, thus, increase its underwater bonding strength. This is because these admixtures could further increase the concrete viscosity, which improves the washout resistance (or decreases the mass loss ratio) and, thus, increases the bond strength to the substrate. So far, the majority of bonding studies have focused on the bonding characteristics of AWC to steel substrate, more research on the bonding capacity of AWC on old concrete or reinforced concrete substrate is needed in future studies.

2.2.3. Durability

While modifying the fresh-state properties and microstructure, AWAs added to concrete could be beneficial to concrete durability. According to the literature, lower chloride ion permeability [44] and lower water permeability [55] have been manifested in AWC, as compared to the conventional concrete counterparts. However, AWAs tend to decline the resistance of concrete to freezing-and-thawing cycles [56–58], likely due to increased volume of entrapped air and reduced amount of beneficial small air bubbles. Mass of scaling residue for 50 freezing-and-thawing cycles, rapid chloride permeability values at 33 days, and water permeability from several published papers are summarized in Fig. 3. When cured in seawater or mixed using seawater, the AWC can have higher early-age strength and lower rebar corrosion probability [59–63], which are both beneficial to the durability of structure. The decreased corrosion probability should be tied to the decelerated iron oxidation process at lower oxygen/chloride contents (due to reduced permeability).

3. Factors influencing performance of AWC

Many factors could impact the performance of AWC. A clear understanding of such factors is very important for guiding the design of AWC for different applications. In this section, the main factors are divided into the three categories: mixture proportion, SCMs, and other factors (i.e., water pressure and velocity); and their influences on AWC are reviewed.

3.1. Mixture compositions

3.1.1. AWAs

Conventional concrete can be considered as a suspension, and the cohesion within the suspension is normally poor. For the agglomeration

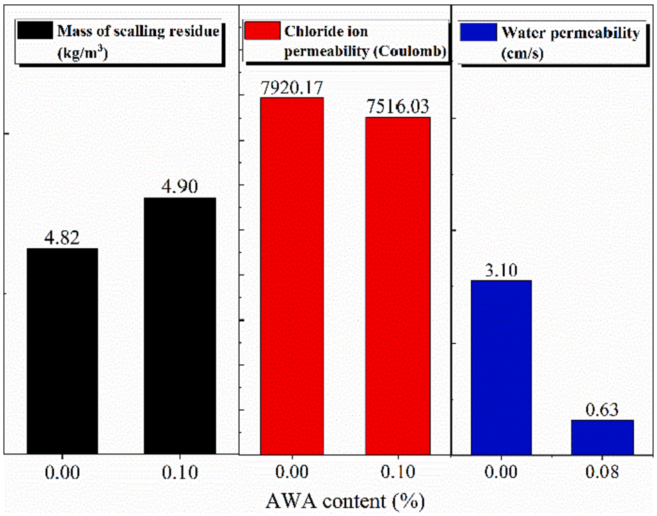


Fig. 3. Mass of scaling residue for 50 freezing-and-thawing cycles [58], chloride ion permeability [44], and water permeability [55] versus AWA content for UWC.

of cement paste and aggregate, the feature is more prominent due to the interface between these two distinct phases. Thus, once the concrete is in contact with water, cement paste immediately peels from aggregate and then disperses in water. AWAs can resolve this problem. AWAs are usually polymers with a long-chain structure to adsorb concrete components and entangle the whole system as a three-dimensional network structure. The formed three-dimensional AWC network has a higher viscosity than conventional concrete, that can resist water penetration or erosion, thus resulting in improved anti-washout performance. The schematic illustration of this mechanism is displayed in Fig. 4.

As shown in Table 4, different types of AWAs have been used in underwater constructions. For all the polymers, the AWAs added to concrete cause a decrease in slump flow and segregation, as well as an increase in water resistance, setting time, and air content. These effects can be more prominent given higher dosages of AWAs [11,12,15,16]. Fig. 5 displays the tendencies of these performances following the increase of AWA content in UWC. With increasing AWA from 0.0% to 0.5%, the slump flow, segregation, and mass loss ratio decrease by 60.84%, 82.97%, and 80.49%, while the air content increases 54.27%. According to [13,18], comprehensively, balanced performance of AWC can be obtained at an AWA dosage of 1%-1.5% (by weight of cement).

The molecular weights, side chains and electrical properties of AWAs have essential impacts on the performance of AWC. Normally, polymers with higher molecular weights or more side chains could attach more particles and form denser entangled network structures, thereby resulting in better water resistance [66,67]. Compared with cationic and nonionic types, anionic AWAs may connect more easily with the metal cations in cement particles, thus resulting in higher water resistance and lower fluidity [68]. By contrast, AWCs modified with nonionic AWAs appear to have better fluidity, despite its relatively poor water erosion resistance [69].

3.1.2. Water-reducers

The water-reducing admixtures (including superplasticizers) added to AWC could mitigate the decrease in slump (or fluidity) due to the incorporation of AWAs. Actually, water-reducing admixtures and AWAs could have totally opposite effects: while the addition of water-reducing admixtures leads to an increase in fluidity and a decrease in water (washout) resistance, the addition of AWAs results in a decrease in fluidity and increase in washout resistance. However, the coupling effects of water-reducing admixtures and AWAs cannot be estimated based on simple superposition; instead, the potential interactions between water-reducers and AWAs must be considered when multiple chemical admixtures are simultaneously used in AWC [41]. In reference [66], it was observed that the water-reducing admixtures added to AWC may diminish the AWAs' effect on water resistance. The polycarboxylate superplasticizers show better compatibility with AWAs compared with the naphthalene-based superplasticizers [93]. Suitable combination of two polycarboxylate superplasticizers could have a better impact on solving the contradiction between fluidity and water resistance [94,95]. When AWA content is more than 3.0%, the network of AWA molecules seems to break down in the existence of polycarboxylate superplasticizers and the mass loss ratio increases severely [18]. Although the mechanism was not clear, the optimal AWA dosage can be drawn from this phenomenon and relevant tests.

Table 4
AWAs used in AWC.

Categories	Designations
Cellulose derivatives	Hydroxy propyl methyl cellulose [9,70]; Methylbenzyl cellulose [71]; others [11,13,14,72]
Polysaccharides	Welan gum [11,15]; Chitosan [17,73–76]; Arabic gum [77]; Xanthan gum [77,78]; Starch [77]; Veegum [77]; Ludox [79]; Latex [80]; Gelatin [81]; Locust Bean Gum [82]; Konjac glucomannan [83]; Guar gum [83]; others [19]
Acrylic-based polymers	Polyacrylamide [2,5,10,84–86]; Sodium polyacrylate [20]; others [14]
Others	Polyvinyl alcohol [77];Geopolymer[87;88;89;90;91;92]

3.1.3. Water-to-binder ratio (w/b)

When AWA content is kept constant, a smaller *w/b* in AWC system tends to decrease the particle-to-particle distances and increase the interparticle force, leading to greater water (washout) resistance [11,12,96]. With the increase of *w/b* ratio, the AWC's relative compressive strength (ratio to the strength of the conventional concrete counterpart) tends to decrease, and it is recommended that the *w/b* ratio of AWC should not exceed 0.4 [18,24] to ensure that the relative compressive strength is not less than 70%. However, when the value of *w/b* is less than 0.3, there may be insufficient water for cement hydration [44], and the incorporation of welan gum will tend to further weaken the relative compressive strength of AWC.

3.1.4. Aggregate and Sand/Aggregate ratio

Compared with other mixture proportioning parameters, sand/aggregate ratio has less influence on AWC's washout resistance. Increasing sand/aggregate ratio (with other parameters fixed) could enhance the viscosity, which tends to improve the washout resistance slightly. However, the higher the sand/aggregate ratio is, the larger the total aggregate surface area in the AWC will be, which leads to decreased density (and, thus, effectiveness) of the AWA's network structure. In a test of the effect of sand/total aggregate ratio ranging from 0.38 to 0.66

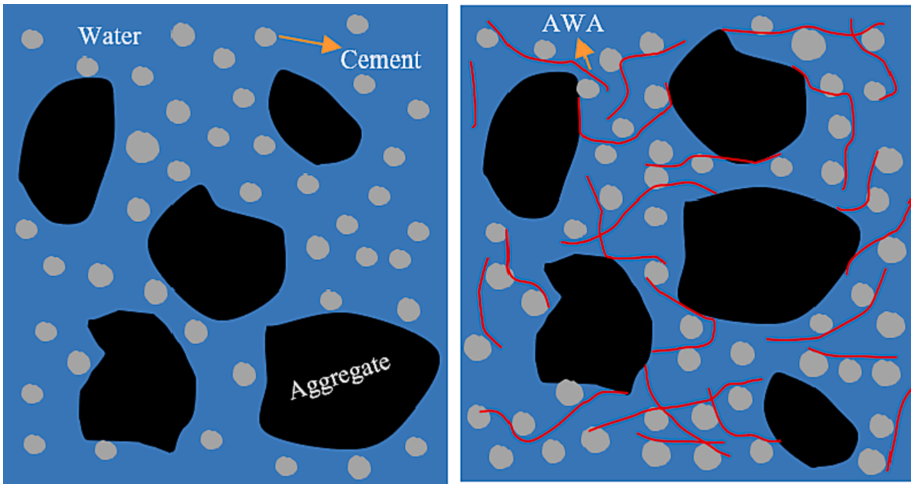


Fig. 4. Schematic illustration of AWAs mechanism in CC (derived from [64 65]).

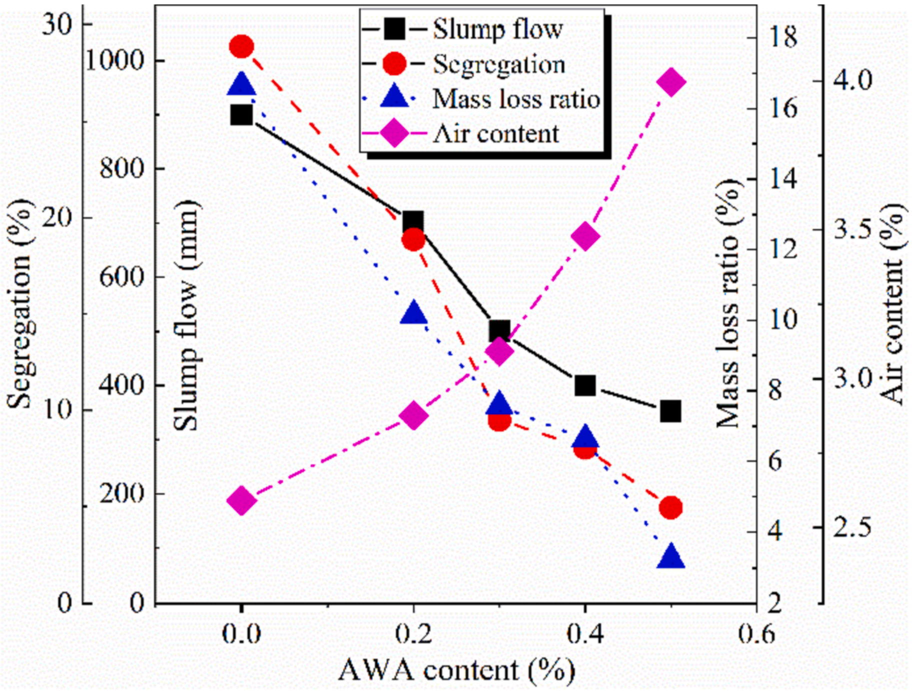


Fig. 5. Slump flow [15], segregation [15], Mass loss ratio [16], and Air content [16] versus AWA content for UWC.

[18], it was found that, following increasing sand/ total aggregate ratios, the AWC's washout-resistance and compressive strength increased and then decreased. An optimum sand/aggregate ratio appeared to be 0.4 for 1% AWA dosage mixtures. Different types of aggregates, due to their differences in composition, particle shape, angularity, and surface characteristics, may also lead to changes in AWC performance. Some commonly used aggregates and their effects on the performance of AWC are summarized in Table 5.

3.1.5. *Mixture proportion design methods*

To meet different technical requirements in applications and obtain the specific properties, design and optimization of the mixture proportions of AWC are needed [80,104]. Many methods have been developed and used for these purposes, as summarized in Table 6. In general, in these methods, *w/c* (or *w/b*) and types and contents of cementitious materials (i.e., cement and SCMs), aggregates, AWAs, and water reducers can be considered as independent variables, and slump flow, water resistance, setting time, and compressive strength can be chosen as dependent variables (as the targets of mixture proportion optimization) [105,106]. As shown in the table, mathematical statistics models are the most frequently used methods for mixture proportion optimization of AWC.

3.2. *SCMs*

Ordinary portland cement is normally utilized as the major binder for AWC. Nonetheless, for improvement of both eco-efficiency and performance of concrete, the usage of SCMs in AWC to partially substitute cement is more and more popular [113–115]. In this section, utilizations of the four major SCMs in AWC are discussed. They are: fly

Table 5
Aggregates used in AWC.

Title	Aggregates	Performances
[97]	River sand; Sea sand; Crushed sand	River sand results in better workability and compressive strength
[15,98]	Steel slag	Lower flowability; higher compressive strength
[98]	Crushed dolomite	Higher flowability; higher compressive strength
[99–103]	Mineral trioxide aggregate	Shorter setting time; higher water resistance; lower flowability; lower compressive strength

Table 6
Methods for AWC mixture proportion design.

References	Methods (models)	Independent variables	Dependent variables	Note
[107–109]	Factor model and Mathematical statistics model	Cementitious materials; AWA; water reducer; *w/c*; sand aggregate ratio	slump consistency; washout mass loss; compressive strength	–
[110]	Artificial neural network	Cement; Water; Fly ash; Slag; Silica fume; Sand; Gravel; AWA	slump-flow; washout resistance; compressive strength	4.6, 10.6, and 4.4% of absolute error, respectively
[111]	CEM (concrete-equivalent-mortar)	Cement; *w/c*; silica fume	Washout characteristics; threshold water head	–
[35]	Multiway ANOVA	Cement; AWA; Accelerating agent	Rheology parameters; setting time; flowability; compressive strength	1% CPAM, 2% HEC, 1% AA-1 or 7.5% Betonite, 5% UWB-II, 6% AA-2
[112]	Orthogonal test design and range analysis	AWA; aggregate; Expansion agent; water-reducer; fly ash	compressive strength; expansion; self-stress	C30: 0.43 *w/c*, 2.5% AWA agent, 10% expansion agent, 41% sand rate, 1% water-reducer

ash (FA), ground granulated blast slag (GGBS), silica fume (SF), and metakaolin (MK). The effects of these SCMs on the performance of AWC and their optimal contents are summarized in Table 7.

3.2.1. FA

Compared with ordinary portland cement, FA particles have better sphericity [116]; and the resultant ball-bearing effect could improve the flowability of AWC [117,118]. Since FA is normally a weak pozzolan, the addition of FA to AWC tends to retard hydration reaction and lead to longer condensation time and lower compressive strength in the early ages [119]. With the extension of curing time, the secondary hydration reactions between FA and calcium hydroxide occur, and the decrement in compressive strength could be effectively compensated [120,121]. According to references [117,122,123], the water resistance of AWC could decrease due to the substitution of cement by FA. The lower yield stress and viscosity induced by FA can explain this influence [124]. A comprehensive balancing of the workability, anti-washout property, and compressive strength yield 30% FA as the optimal content in AWC [117,125–127]. It has also been reported that substitution of 20% cement by FA can effective improve the steel bar corrosion protectiveness of AWC in corrosive service environment [128]; and the can be attributed to the densified microstructure (due to the secondary, pozzolanic reactions of FA) and improved rebar/AWC interfacial adhesion.

3.2.2. GGBS

The role of GGBS in AWC is similar to that of FA. Hence, a higher substitution ratio of GGBS tends to yield higher slump (or flowability) and a lower early-age compressive strength, but an increased long-term compressive strength [121]. Higher steel bar corrosion resistance [128–130] and chloride penetration resistance [131], as benefits of incorporating GGBS in AWC, should also be attributed to the pozzolanic reactions. The substitution of cement by 30% of GGBS (coupled with FA) was found to be an optimum dosage towards better anti-washout ability, flowability, and compressive strength compared with other reference groups [132]. When the content of GGBS added to AWC is too high, the AWC may suffer from insufficient washout resistance and adiabatic temperature rise (or early-age compressive strength) [133].

3.2.3. SF

Compared with FA and GGBS, the size of SF particles is much smaller [134,135]. The extremely high specific surface area induced by SF tends to improve the viscosity and cohesiveness of AWC and change its rheological parameters [124,136–138]. As a result, decreased slump and flowability, as well as improved water resistance, can normally be found when SF is incorporated into AWC [12,139]. In addition, the small SF particles facilitate formation of a denser microstructure of concrete. Along with the progress of pozzolanic reactions, higher compressive strength values (at both early and late ages) are normally seen in AWC with SF incorporation [140]. Substitution of cement with 10% SF or 6% SF (coupled with 20% FA) have been suggested as the optimum dosages of SF in AWC [11].

Table 7
SCMs effect on AWC performance.

Properties	FA	GGBS	SF	MK
Water resistance	↓	↓	↑	↑
Slump flow	↑	↑	↓	↓
Setting time	↑	↑	↑	↓
Compressive strength	=	=	↑	↑
steel bar corrosion resistance	↑	↑	–	–
Others	–	chloride diffusion resistance (↑)	–	–
Appropriate content	30% FA	30% GGBS + FA	10% SF or 6% SF + 20% FA	–

Note: ↑ means increase; ↓ means decrease; = means without clear increase or decrease.

3.2.4. MK

MK added to concrete mainly impacts the early-stage hydration rate, especially when highly reactive metakaolin is used. Additionally, metakaolin added to concrete could also improve the rheological performance, similar to the SF, thus improving the water resistance of AWC [141]. In addition, decreased slump and flowability and increased compressive strength of AWC are also associated with the utilization of MK.

3.3. Water pressure and water velocity

In addition to the internal factors of AWC that can affect its properties, various external water conditions (e.g., pressure and velocity) could also have influences. Commonly used water pressure and velocity testing apparatus are shown in Fig. 6 [142,143].

With increasing water head (pressure), the AWC tends to have greater mass loss ratio [144]. Therefore, when AWC is cast below a certain water depth, it is more vulnerable to washout erosion. Based on this, a threshold water depth at approximately 80 m to 95 m was suggested [145]. Nevertheless, water pressure has a favorable effect on the compressive strength (higher) and air content (lower) of AWC, and the effects are more prominent for the upper section of a concrete member [146]. As for bonding strength, the effect of hydrostatic pressure may have different influences depending the orientation of substrate [147]. In the case of horizontal substrates (see Fig. 7**a**), water pressure tends to improve the bond strength of the fresh AWC to the substrate. However, in the case of vertical substrates (see Fig. 7**b**), the hydrostatic pressure tends to decrease the interfacial bonding strength.

4. Applications

Compared with conventional concrete, AWC can solve many technical problems encountered in underwater construction due to the enhanced anti-washout and anti-segregation performance, as well as the maintained fluidity. In addition, the utilization of AWC is highly adaptive to water depth, substrate surface, topography, tide fluctuations, and concrete construction volume, which can simplify the construction process, shorten the construction period, ensure the project quality and reduce the associated cost. All of these characteristics and advantages yield a wide application range of AWC in underwater construction and repair [2,148–151].

In this section, the applications of AWC are described in four major areas: normal construction, ocean construction, filling applications, and repair. For each of the applications, both material requirements and construction strategies are discussed.

4.1. Normal underwater construction

As for normal underwater constructions, including plain concrete and reinforced concrete, the corresponding water resistance, fluidity, anti-segregation, and compressive strength are the main requirements for AWC, as illustrated in **Section 2**. Choosing the proper materials and composition could help obtain adequate underwater performance for AWC [152].

In addition to the properties of the material itself, certain construction techniques must be adopted to ensure the quality of construction. Conventional AWC placing methods include the following [153]: tremie, hydrovalve, skips, pumps, toggle bags, bagwork, concrete packaged under water, and aggregate grouting. From which, tremie is the most crucial construction methods for AWC, and its working mechanism is exhibited in Fig. 8. Based on different terrains, vertical or incline tremies can be designed for casting [154]. Nonetheless, different pouring conditions, such as unidirectional pouring or free pouring, may

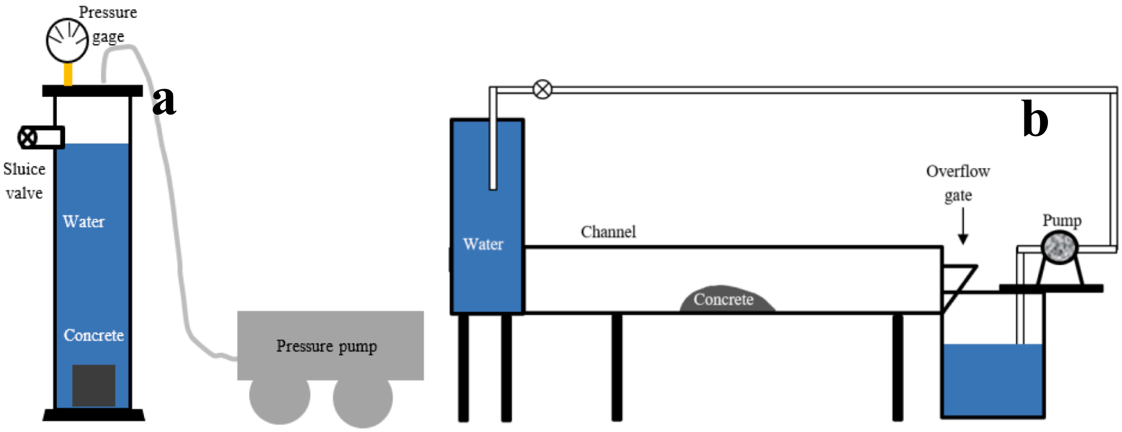


Fig. 6. AWC testing apparatus for different water conditions: **a**) water pressure testing apparatus; and **b**) water velocity testing apparatus.

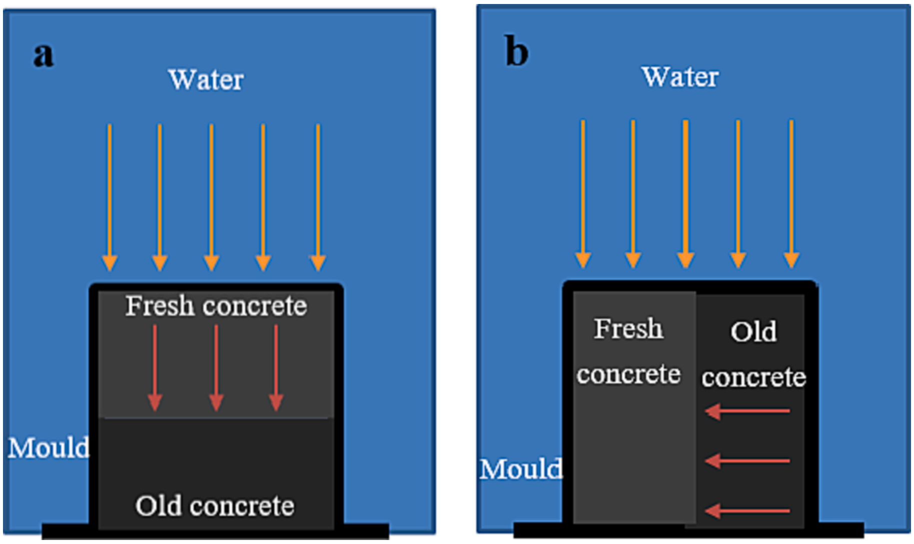


Fig. 7. Water pressure directions on concrete bonding strength (a-horizontal substrate, b-vertical substrate; orange arrows-water pressure, red arrows-bonding stress).

yield obvious influences on hardened concrete performance, like compressive strength and tensile strength [155,156]. In large scale constructions, there could be confluence points (or joints) where the strength is lower than the bulk AWC [157]. Mitigation of this issue will require better control of the placing pipes/tremies and special treatment of the horizontal joint face.

4.2. *Marine construction*

In marine engineering, which includes the coastal and offshore projects, the non-dispersible AWC has been applied widely [158,159]. Besides the basic performance requirements, the AWC must have sufficient impermeability to resist penetration of water, chloride and other harmful ions, so that the steel reinforcement can be well protected against corrosion.

The most common concrete placement methods in marine engineering [4,160] are tremie and pump methods, especially for underwater drilled shaft constructions. Construction problems encountered in the tremie method are normally less than those in the pump method. That is because when pumping concrete down directly to its deposit location, the pump pressure plus the self-weight of AWC can be greater than the hydrostatic balance head outside the pump line. The rapid descent rate of AWC can result in a vacuum in the pipeline and disturbance to the deposited concrete. Though the tremie method can be controlled more easily, some defects may also be created during the pouring process, such as: high void content of concrete due to loss of concrete workability during placement (e.g., becoming too viscous and blocked by steel cage); significant washout of concrete due to unbalanced concrete surface or failure of tremie pipe seal; and defects induced by debris due to inadequate bottom cleaning before casting [160].

4.3. *Filling and grouting applications*

AWC is generally required to be self-leveling, so it can be used for bulk filling and grouting, such as rock filling engineering [151,161] and geological defect reinforcement engineering [162]. For the concrete material itself, sufficient fluidity, appropriate setting time, and low shrinkage characteristics are needed to ensure adequate filling density and compactness. According to reference [163], their recommended values are: fluidity (according to Chinese Standard GB 8077–2000) ranging from 120 mm to 170 mm, initial setting time more than 30 min, and a retention rate of more than 75% with a flow velocity of approximately 0.2 m/s.

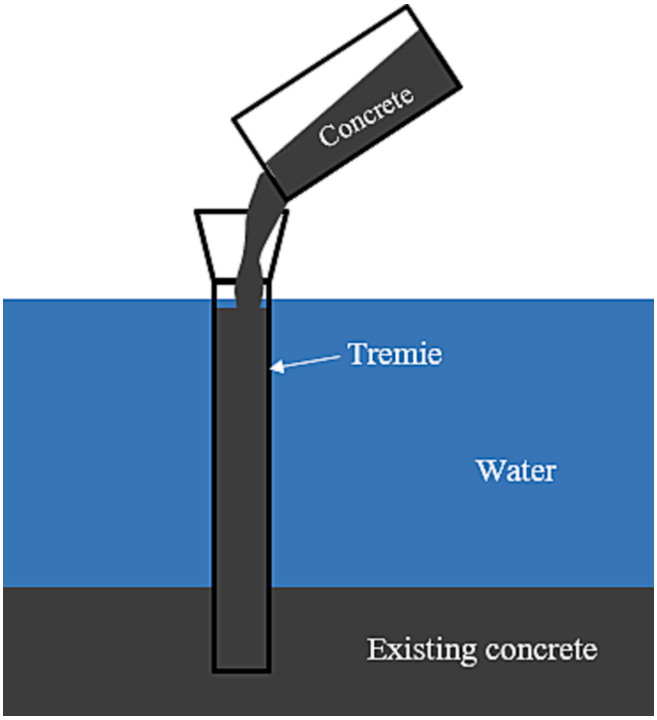


Fig. 8. Schematic diagram of Tremie method.

4.4. Repair

Regarding underwater repair applications, the invention of AWC greatly reduced the difficulties in field implementation. As for the repair AWC, the high fluidity and excellent bonding strength are required to ensure bonding intensity between the fresh repair material and the old concrete substrate [164–167].

Before underwater repair, the deterioration state of the old concrete structure has to be properly assessed [168]. As for submerged concrete piles that have undergone considerable losses in cross section, the repair process often involves jacketing the piles and filling the annular spacings between the jackets and the piles with AWC [169,170]. For this, underwater injection with vertical tremie operation is normally used [171], and it is suggested that the end of the placement device should be embedded approximately 0.9 m beneath the fresh concrete to decrease segregation and water erosion [154,172]. In small and shallow damaged areas, the inclined tremie methods are suitable to ensure the construction quality [154]. In practice, proper non-destructive testing or monitoring techniques, such as sonic tomography, can be employed to better evaluate the extent of deterioration or the effectiveness of repair [151].

5. Discussion

Water-related construction and repair projects are essential for the development and maintenance of infrastructure, and AWC plays an important role in ensuring the quality of these projects. In recent years, following the increase of ocean engineering projects (such as cross-sea bridges, undersea tunnels, and off-shore platforms), the engineering community has paid increasing attention to AWC. However, the initial development and modification for better application of AWC are still the main focus of research. This is because, to ensure the anti-scouring capacity and constructability, at least two chemical admixtures need to be used in AWC; which are AWAs and water reducing admixture (potentially aided by other admixtures). Taking water-reducing admixture as an example: the fluidity of AWC is significantly improved after the addition of water-reducing admixture, but the anti-scouring capacity of AWC is adversely affected due to the effect of competitive adsorption between water reducer and AWAs. Therefore, it is necessary to dissect the exact acting and compatibility mechanism of multi-chemical admixtures in a concrete system, so as to provide reference for the development of AWC mix design under different working conditions. The rheological and thixotropic properties of concrete with multiple chemical additives, especially with the addition of a variety of polymers, have not been fully clarified, and the corresponding rheological models needs to be further improved. Such models will help connecting AWC's rheological properties, anti-washout and anti-segregation performance, and even mechanical properties (e.g., compressive strength and bonding strength); and they may also facilitate development of new AWC formula for underwater 3D printing (or underwater digital construction/repair [173]).

It is well known that the surface of concrete is different from the internal structure, especially for AWC. With the long-term physical effect of water or solid particle carried by water, the surface of underwater non-dispersed concrete could change more or less. The hydration products, pore structure, and interface bonding of AWC surface layer under long-term service conditions need to be further clarified. And the durability problems such as water penetration, sea water erosion, or steel corrosion of underwater non-dispersed concrete engineering structures need more systematic and in-depth discussion. Research in these aspects is essential for ensuring the safety, effectiveness and stability of AWC structures.

As introduced in the Introduction section of this article, AWC specifications in the United States, China, the European Union, Japan, and Korea were mostly promulgated in the late 20th century and early 21st century. The specifications mainly present the erosion resistance and basic mechanical properties of AWC. With the increasing use of non-dispersible concrete underwater, it is clear that these specifications cannot meet the requirements of emerging engineering applications. Therefore, it is necessary to issue systematic specifications with the theme of AWC specialty concrete, which integrates mixture proportion design, fresh performance requirements, hardening mechanical properties, durability characteristics, etc.

With the modernization process and the gradual deepening of the concept of environmental protection, AWC is also facing new challenges. As a relevant note to sustainability, few studies have addressed the potential impact of AWC on water environments [174]. The application of AWC may cause changes in the chemical composition of the surrounding water. The potential adverse effects of these chemicals on aquatic organisms and water ecology must be studied; and if adverse effects are confirmed, special construction processes that allow for avoiding or mitigating these effects will need to be explored. Besides, the underwater structures and construction processes often need to be monitored or inspired. Appropriate underwater non-destructive testing and monitor technologies are vital in pre-construction inspection, and the discovery of construction problems during the construction process and the post-construction/repair defects (and other quality issues). Technologies and corresponding apparatus in this aspect need to be further developed and promoted.

6. Summary and conclusion

An overview of AWC is presented in this article. Fresh- and hardened-state performance and basic material requirements for AWC are discussed; Influences of mixture proportion, SCMs, and water conditions (pressure and velocity) on AWC are presented; and the materials properties requirements for various applications and their corresponding construction technologies are elucidated. Based on the information presented in this paper, the following conclusions can be drawn:

(1) To comprehend the AWC, the first step must involve understanding water (washout) resistance and its testing methods. In all the tests, plunging, pH measurement, and suspended solid content methods are commonly accepted to express the anti-

washout capacity. Generally, reduced fluidity, improved anti-bleeding and anti-segregation properties, prolonged setting time and increased air content are associated with AWC. These effects can be attributed to the improved viscosity of concrete due to the incorporation of AWAs.

(2) The use of AWAs tends to interfere hydration of cement and entrap more air in concrete, compromising compressive strength while improving many durability metrics (e.g., freezing-and-thawing resistance and impermeability). AWC is normally manifested by superior bonding strength to substrates, and, in some scenarios, superior rebar protectiveness (against corrosion) as compared with conventional concrete.

(3) Material composition, mixture proportioning parameters, SCMs, and water conditions could all affect the performance of AWC. For compositions, the structural properties of AWA and its compatibility with water reducers must be considered as those impact the core performance, say, anti-washout capacity. In mixture proportion parameters, w/b is the dominant one; and to successfully formulate AWC, a w/b higher than 0.4 should not be suggested. SCMs may have different effects on AWC. Generally, coarse and weak pozzolans (e.g., fly ash and GGBS) tend to compromise anti-washout capacity and early-age compressive strength; and fine and strong (highly reactive) pozzolans (e.g., silica fume and metakaolin) tend to improve the anti-washout capacity and strength at all ages. High water pressure and velocity both have detrimental impacts on AWC's washout resistance, and special considerations are needed in practice to manipulate these impacts.

(4) Designing AWC and the corresponding construction strategies are both essential for the applications of AWC. Washout resistance, fluidity, anti-segregation capacity, and compressive strength are the basic requirements for most AWC applications. Special applications may have specific technical requirements, such as sufficient impermeability to resist chloride in marine engineering, sufficient setting time and low shrinkage for bulk filling/grouting, and high bonding strength for underwater structural repair. Regarding construction technology, tremie is still the most commonly used, and likely the most suitable, method for various underwater applications of AWC.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration

The authors declare that the article has not been published before; that it is not under consideration for publication anywhere else; that its publication has been approved by all co-authors; and that they have not known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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