Underwater Concrete Pours and Non-Segregating Concrete

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16. Abstract

Underwater concrete placement in bridge substructures often raises concerns regarding concrete quality, primarily due to the potential for aggregate segregation, especially in deep drilled shafts. Recognizing these challenges, the goal of this research project was to critically evaluate and recommend enhancements to existing Wisconsin Department of Transportation (WisDOT) policies, standards, and specifications regarding underwater concrete placement for bridge substructures and the prevention of aggregate segregation in deep drilled shafts. Relevant research studies and the practices of other departments of transportation (DOTs) and the construction industry, especially agencies and companies operating in marine settings, were explored. Additionally, a nationwide survey was distributed to key personnel in 50 state DOTs to better understand current practices, trends, and common difficulties. This research synthesis report collates and presents a detailed assessment of concrete placement techniques, challenges in the construction of pile-encased piers, strategies to achieve non-segregating concrete in foundations, and the influence of materials and construction-related variables. Based on the insights obtained, the report sets forth refinements to available guidelines, particularly those regarding the construction of concrete piers and abutments in aquatic environments.

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EXECUTIVE SUMMARY

Underwater concrete placement in bridge substructures often raises concerns regarding concrete quality, primarily due to the potential for aggregate segregation, especially in deep drilled shafts. Such issues are not only difficult to identify but also entail substantial repair costs. The Wisconsin Department of Transportation (WisDOT) has recognized these challenges and, in Section 13.09 of its Bridge Manual, recently introduced constraints on underwater concrete pours for pile-encased piers. These constraints aim to mitigate the risks of poor concrete quality and expensive repairs.

The overarching goal of this project was to critically evaluate and recommend enhancements to existing WisDOT policies, standards, and specifications regarding underwater concrete placement or repair for bridge substructures and the prevention of aggregate segregation during concrete placement in deep drilled shafts.

A key component of this goal involved building upon established practices and crafting specifications that pave the way to properly benefit from underwater concrete. This approach minimizes the environmental impact while ensuring the concrete's quality and structural integrity. Items to assess included the materials, mix designs, and placement techniques that can prevent segregation. By thoroughly evaluating current practices, the recommendations formulated in this research can be both progressive and applicable.

Specific objectives were as follows:

1. Examine best practices for the placement of concrete underwater and in deep drilled shafts.
2. Evaluate current guidance and specifications for improvements based on best practices.
3. Prepare recommendations for changes to existing manuals, standards, specifications, and policies to promote higher quality concrete substructures.

Relevant research studies and the practices of other departments of transportation (DOTs) and the construction industry, especially agencies and companies operating in marine settings, were explored. The research team examined numerous materials and construction-related factors involved in pouring concrete underwater or in deep drilled shafts, including parameters such as concrete mix designs and placement techniques. Additionally, a nationwide survey was distributed to key personnel in 50 state DOTs to better understand current practices and trends, the difficulties faced by various DOTs, solutions to these challenges, and potential directions for the future.

This research synthesis report collates and presents a critical assessment of concrete placement techniques, challenges in the construction of pile-encased piers, and strategies to achieve non-segregating concrete in foundations. Information on other vital topics is also presented, including the influence of environmental and construction variables on underwater concrete. Based on the insights obtained, the report sets forth refinements to available guidelines, particularly those regarding the construction of concrete piers and abutments in aquatic environments; and offers supporting recommendations for applications such as pile-encased piers and abutments.

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ACRONYMS

AWC: Anti-washout concrete
C2S: Dicalcium silicate
C3S: Tricalcium silicate
CSA: Calcium sulfoaluminate
CSH: Calcium silicate hydrate
CSL: Crosshole sonic logging
DOT: Department of Transportation
G-G: Gamma-Gamma
GGBFS: Ground granulated blast furnace slag
HPMC: Hydroxypropyl methyl cellulose
HRWRA: High-range water-reducing admixture
LOI: Loss-on-ignition
NDT: Nondestructive testing
OPC: Ordinary portland cement
PIT: Pile integrity test
PPC: Portland pozzolan cement
PSC: Portland slag cement
QA: Quality assurance
QC: Quality control
SCC: Self-consolidating concrete
SCM: Supplementary cementitious material
TIP: Thermal integrity profiling
UPV: ultrasonic pulse velocity
UWC: Underwater concrete
VMA: Viscosity modifying agent/admixture
w/b: water-to-binder ratio
w/c: water-to-cement ratio
WG: Welan gum

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1. INTRODUCTION

1.1 Background and Problem Statement

Underwater concrete placement in bridge substructures often raises concerns regarding concrete quality, primarily due to the potential for aggregate segregation, especially in deep drilled shafts. Such issues are not only challenging to identify but also entail substantial repair costs. Recognizing these challenges, the Wisconsin Department of Transportation (WisDOT) has recently introduced constraints on underwater concrete pours for pile-encased piers, aiming to mitigate the risks of poor concrete quality and ensuing expensive repairs. WisDOT's Bridge Manual Section 13.09 elaborates on these restrictions, offering insights into various scenarios for underwater concrete pours for pile-encased pier applications.

This research synthesis report was motivated a desire to delve deeper into the complexities of underwater concrete placements for bridge substructures and the associated aggregate segregation. The report collates and critically assesses concrete placement techniques, challenges related to pile-encased piers, and strategies to achieve non-segregating concrete for foundations. Information on other vital topics, such as the influence of environmental and construction variables on concrete pouring and the behavior of underwater concrete mixes (including high-slump variants with non-segregating additives) during placements and within deep drilled shafts, are also presented. Ultimately, the report evaluates the directives set forth by Section 13.09, offering recommendations for applications like pile-encased piers and abutments.

While conducting this research, it was imperative to account for numerous materials and construction-related factors involved in pouring concrete underwater or in deep drilled shafts. For example, parameters like water velocity and depth, concrete confinement and placement techniques, and concrete mix design can adversely affect the long-term performance and strength of the concrete. The research also examined the nature and frequency of inspections necessary to maintain quality standards, including the use of post-installation diving inspections or remote inspection technologies.

The ultimate goal of this research was to critically evaluate and subsequently enhance the existing policies, standards, and specifications regarding underwater concrete placements. Inspiration was drawn from the practices of other DOTs and the broader construction industry, especially those agencies and companies operating in marine settings. The insights garnered were used to inform suggested refinements to the guidelines on underwater concrete placements and scenarios susceptible to aggregate segregation, especially the standards and specifications relevant to the construction of concrete piers and abutments in aquatic environments.

1.2 Objectives

The overall goal of this project was to develop recommendations and guidelines related to underwater concrete placement or repair for bridge substructures and the prevention of aggregate segregation during concrete placement in deep drilled shafts.

Specific objectives were as follows:

1. Examine best practices for the placement of concrete underwater and in deep drilled shafts.
2. Evaluate current guidance and specifications for improvements based on best practices.
3. Provide recommendations for potential changes to WisDOT manuals, standards, specifications, and policies to promote higher quality concrete substructures.

2. SYNTHESIS OF THE STATE OF THE PRACTICE

2.1 Introduction: Underwater Concrete Definitions and Background

When it comes to bridge substructures with submerged foundations or piers, attention is always focused on underwater concrete (UWC), which has been used in many applications and will likely see increasing use as cities develop and expand their infrastructure systems.

UWC is a specialized type of concrete designed and formulated to be used in submerged conditions, such as in marine structures, offshore oil platforms or wharves, or any other underwater infrastructure projects. Concrete used as UWC must excel in at least three essential characteristics: strength, workability, and service life. Based on this definition, it can be considered a type of "high-performance concrete." UWC needs to have distinct properties to withstand the unique conditions of underwater environments, such as water pressure or water flow, saltwater corrosion, and exposure to marine organisms. In addition to the threats that the underwater environment poses to concrete, the anti-washout concrete (AWC) used for underwater applications can prevent the spread of cement and other ingredients underwater, which protects the environment of aquatic animals. Careful attention must be paid to the concrete's setting time, workability, and strength development to ensure proper placement and curing in the underwater environment. To this end, UWC requires careful and specific oversight during every construction phase, including well-defined factors for choosing the best components and mix designs and specialized equipment for quality control and placement. Various approaches requiring specialized equipment are used to separate the concrete from the surrounding water to ensure the concrete's quality during the pouring operation. Various commercial admixtures have been developed and employed due to the ongoing use of AWC and the rapid development of contemporary placement technologies. Overall, the development of underwater concrete requires a deep understanding of concrete technology and a thorough knowledge of the equipment-related challenges posed by underwater construction [1-5].

Anti-washout or non-segregable concrete is another name for concrete that is specifically designed to prevent the separation of constituent materials during placement and transportation through the water. The segregation of materials, particularly the separation of cement paste from the aggregates, is a common problem in the construction of structures where the concrete is placed underwater or in other fluid environments. Anti-washout or non-segregable concrete addresses this problem by using specific admixtures that enhance the cohesiveness and consistency of the concrete mixture, preventing the separation of materials. In the past, the focus of underwater construction was on isolating concrete from water exposure, and engineers were looking for techniques to deliver concrete to underwater forms by drying the exposed environment. However, with recent advances in chemical admixture technologies, the emphasis has shifted to developing concrete that can maintain its stability without segregation by itself because the second method is one-fifth the cost of the first method [6-9].

The admixtures used in anti-washout or non-segregable concrete are named anti-washout admixtures (AWAs), which are chemical compounds added to concrete mixtures to improve the workability of concrete underwater. The main function of these admixtures is to prevent the segregation and bleeding of cementitious materials during the mixing and placing of concrete in the presence of water. Anti-washout admixtures function similarly to viscosity modifying agents/admixtures (VMAs) by enhancing the viscosity of the concrete mixture. This increase in viscosity is crucial for maintaining the mix's integrity and preventing the loss of cement particles due to water's scouring action. To achieve a balance between cohesiveness and flow, it is essential to use these admixtures in conjunction with superplasticizers. While superplasticizers assist in improving the flowability of the concrete, the role of anti-washout admixtures is not solely to increase flowability but to ensure the stability and consistency of the mix in underwater conditions. These admixtures are also known as non-segregating admixtures or underwater concrete admixtures. In other words, anti-washout admixtures must simultaneously maintain high flowability and slump-retention in concrete mixes, such as self-consolidating concrete and pumped concrete, without losing its cohesiveness or consistency. Additionally, anti-washout admixtures can be used to reduce the water-to-cement ratio (w/c) and increase the durability and mechanical properties of concrete. Anti-washout admixtures can be categorized based on their chemical composition and mode of action. The most common types of anti-washout admixtures are polymer-based admixtures, mineral-based admixtures, or a combination of these admixtures [10-13].

Some of the common names of anti-washout admixtures include VMAs, hydrophobic admixtures, viscosity-enhancing agents, and stabilizing agents. The chemical structure of hydrophobic admixtures is a little different from that of anti-washout admixtures. Hydrophobic admixtures work by forming a waterproof barrier on the surface of the concrete, which in turn prevents the concrete from water contact or being washed away by water after casting. The selection of the appropriate type and dosage of an anti-washout admixture depends on the specific project requirements and environmental conditions.

The German company Sibo Group was the first to develop AWC officially by mixing cellulose ether viscosity-modifying admixture with conventional concrete. After that, with advancements in admixture chemistry in Japan, various AWAs based on local circumstances for construction projects such as breakwaters and bridges were introduced [14]. The U.S. Army Corps of Engineers (USACE) created AWC for construction in water in the mid-1980s and released a test method for determining the resistance of freshly mixed concrete to washing out in water. In 2013, Assaad and Camille [15] determined that paste washout has a greater influence on reducing the strength of UWC compared to the impact of water infiltration. Furthermore, steel slag demonstrated a higher potential for enhancing the compressive strength of UWC in comparison to coarse aggregate and crushed dolomite [16]. Bentonite and limestone powders have positively improved flowability while limiting the loss of fine particles and can be applied as anti-washout powder additives [17]. Additionally, Sonebi and Khayat [10] established optimal mixing proportions that resulted in a relative compressive strength of up to 85% compared to mixtures cast in air. In their research, they found that increasing the amount of silica fume up to 10% and reducing the w/c ratio to near 0.4 can result in acceptable slump flow between 450 and 550 mm (18 and 22 in) and mass losses limited to between 4% and 6%.

The inclusion of air-entraining agents/admixtures (AEAs) significantly influences concrete rheology in that they increase flowability resistance and plastic viscosity and decrease water dilution. However, increased water velocity could decrease strength due to increased mass loss [18]. It has been verified that the use of sand-cement mortars without the inclusion of coarse aggregate, an increase in the w/c ratio and an elevated dosage of superplasticizer without a corresponding reduction in water content, can lead to diminished mechanical strength and heightened susceptibility to washout in UWC [19-21].

UWC has been used for various engineering applications, including repair and maintenance purposes. In 2020, Lu [22] evaluated the strength of specimens submerged in fresh water for one year (extracted from concrete structures damaged in water) and discovered no significant decrease in strength. Additionally, Huang et al. [23] proposed that the combined application of superplasticizers and VMAs can effectively decrease the washout rate and enhance the flowability of the grout used for repairing underwater concrete piles. The underwater abrasion of steel fiber-reinforced self-consolidating concrete (SCC) was also investigated, which showed that increasing strength directly enhanced the corrosion resistance of underwater concrete containing 1% steel fiber [24]. In other similar studies, mortar reinforced with steel or polypropylene fibers exhibited high resistance to abrasion, with micro polypropylene fiber displaying significant abrasion resistance [25]. Meanwhile, the bond strength between UWC and concrete substrates was assessed using various pull-off techniques following the European standard EN 1542 [26]. In repair cases, it was reported that the contact between UWC and steel relies on a combination of factors, including water level and head, concrete (mortar) segregation, and interfacial concrete-water velocity [27].

Based on an evaluation of previous studies, this research will highlight the best practices for selecting the appropriate materials, mixing proportions, and underwater concrete placement techniques for constructing new elements or repairing submerged bridge substructures.

2.2 Materials Selection

Designing a mix for underwater concrete is a complex task that requires careful material selection and proportioning to achieve optimal workability, flowability, compressive strength, and durability. Traditionally expensive methods like cofferdams are increasingly being replaced by direct underwater concrete deposition, which necessitates mix designs that prevent segregation and mass loss. This approach often involves increasing the margin between actual and target strengths. References suggest aiming for 80% of the compressive strength of ground-cast mixtures by taking into consideration washout effects. Effective material selection hinges on a fine balance of factors including particle size distribution, w/c ratio, use of supplementary cementitious materials (SCMs), density, and the chemical composition of admixtures, all aimed at ensuring the mixture remains cohesive and well-mixed during underwater placement. In this section, the main factors influencing UWC mix design and quality are reviewed.

2.2.1 *Binders*

2.2.1.1 Cement

The selection of cement for UWC is influenced by factors such as water depth and temperature, construction method, and performance requirements. Preference is generally given to cements with lower heat of hydration, higher early strength gain, and enhanced resistance to sulfate attack. Portland pozzolan cement (PPC) and portland slag cement (PSC) are commonly used in UWC due to their workability, reduced heat generation, and chemical attack resistance. PPC and PSC containing fly ash and ground granulated blast furnace slag (GGBFS), forms additional C-

S-H compounds, enhancing strength and sulfate attack resistance [28-30]. Recent studies emphasize the importance of cement parameters in UWC. Jeon et al. [31] found that the C3A content of cement impacts setting time and early-age strength, and that adding nano silica and MgO improves concrete's mechanical properties and durability. Sun et al. [32] showed that Type 1-525 Portland cement with a high specific surface area enhances washout resistance, due to its reactivity and strong interaction with additives like polyacrylamide.

The behavior of underwater concrete is influenced by cement's particle size, mineralogy, and Blaine fineness. These factors affect cement hydration and water demand, which is essential for optimizing UWC's performance and durability. UWC typically requires high cementitious material content ranging from 400 to 700 kg/m^3 (650 to 1200 lb/yd^3) to ensure cohesion, flowability, reduced laitance, and segregation prevention. High-performance UWC may require even more cementitious material for special performance requirements. In large-scale underwater projects, workability and heat of hydration are key concerns [33-38].

The properties of different cements can be summarized as follows:

- Type I Portland cement, characterized by moderate setting time and workability, can result in concrete with good compressive strength. A low water-to-cement ratio can reduce the risk of washout.
- Type II Portland cement, containing a moderate amount of tricalcium aluminate, can result in concrete with moderate early strength gain and reduced susceptibility to sulfate attack. However, it can lead to decreased workability compared to Type I cement. Nonetheless, it can still serve as a viable option for UWC applications.
- Type III Portland cement, containing a higher amount of tricalcium silicate, can result in concrete with faster strength gain and shorter setting times. Its production, however, is limited, and it can increase the heat of hydration and decrease workability, making it suitable for UWC applications only when construction progress is of critical importance.
- Type V Portland cement, which contains more tricalcium aluminate, is highly resistant to sulfate attack, resulting in concrete with reduced susceptibility to such attacks. However, it can also lead to decreased workability and increased water demand, increasing the washout risk. Nevertheless, it can still serve as an appropriate option for UWC applications where chemical attacks are a critical concern.
- Calcium sulfoaluminate (CSA) cement, a hydraulic cement made from a combination of limestone, bauxite, and gypsum and with a higher percentage of calcium aluminate than portland cement, is another option for UWC applications. CSA cement can be used alone or in conjunction with portland cement to improve setting time, strength gain, and durability. Its utilization can result in higher early strength gain, reduced shrinkage, and improved resistance to sulfate attack. Despite its higher cost and rapid setting time, CSA cement is widely used in specialized applications, including precast concrete, repair and restoration, and shotcrete. The high early strength gain of CSA cement can be particularly advantageous for UWC applications because it can help reduce the time required for formwork and decrease the risk of washout. Research has shown that CSA cement-based concrete exhibits better durability against chloride penetration and sulfate attack than portland cement-based concrete. It has also been found that CSA cement-based concrete has higher compressive strength and lower permeability than other cement-based concrete, with good durability against corrosion and erosion [37-38].

Recently, blended cement has gained prominence in construction projects. Blended cement refers to a mix of ordinary portland cement (OPC) with supplements, such as fly ash, silica fume, and slag cement, which help improve the cement properties, while making the cement production process environment friendly. A relatively new trend has also been initiated among cement plants, moving towards portland limestone (Type IL) cement. This type of blended cement incorporates limestone as a significant component, reducing the clinkers required for the cement. This shift results in a lower carbon footprint, further to enhancing the workability and durability characteristics of the concrete, mainly because the increased limestone content acts as a filler, improving the density and texture of the concrete mix. This modification also leads to a more homogeneous mix, reducing the porosity and increasing the concrete's resistance to factors such as chloride penetration. Thorough testing and evaluation, accounting for mix proportions, casting conditions, curing conditions, and the use of admixtures, remain essential to determining the best cement type for a given UWC application.

2.2.1.2 Supplementary Cementitious Materials (SCMs)

To improve both the eco- efficiency and performance of concrete, using supplementary cementitious materials in UWC to partially substitute cement is becoming increasingly popular. This section discusses the utilization of different SCMs, also known as mineral or pozzolanic admixtures in UWC. Fly ash, slag, and silica fume, metakaolin and nano silica are the most used SCMs in underwater concrete mixtures. The effects of some SCMs on the performance of AWC and their optimal contents are summarized in Table 1 [39-44].

Table 1. Influence of SCM dosage on underwater concrete properties.

SCMs	Recommended Dosage (% Weight of Cement)	Slump	Setting Time	Washout Resistance	Chloride Diffusion Resistance
Silica Fume	5–15	↓	↓	↑	↑
Fly Ash	20–30	↑	↑	↑	↑
Slag	20–50	↑	↑	↑	↑
Nano Silica	1–5	↓	↓	↑	↑
Metakaolin	10–20	↓	↓	↑	↑

The up and down arrows reflect increasing and decreasing effects, respectively, as a result of increasing the SCM dosage within the recommended ranges.

Fine filler materials such as limestone can also be utilized as SCMs in UWC mix solutions. Although limestone powder does not exhibit high pozzolanic reactivity in concrete mixtures – lacking a silica-rich composition essential for forming cementitious compounds like calcium silicate hydrate (CSH) during hydration, a hallmark of pozzolanic materials – it can still interact with cement hydration products during the later stages of cement hydration. This interaction leads to the formation of compounds in the calcium aluminate hydrate family, which are secondary hydration products known for their strong affinity for superplasticizer admixtures. Leveraging this property can enhance the workability and flowability of concrete mixtures. Moreover, limestone powder is a cost-effective and desirable filler material for controlling the viscosity of concrete. However, other highly active pozzolanic cementitious materials such as silica fume, slag, and fly ash that react with the by-products of the cement reaction are essential for achieving desirable performance properties in both the fresh state—providing workability, resistance to segregation, slump retention, lower heat of hydration, reduced bleeding potential, and better control of setting time—and in the hardened state—enhancing mechanical strength, boosting durability, mitigating chloride ingress, and reducing shrinkage. Underwater concrete casting presents unique challenges, distinct from those encountered in conventional concrete applications. One of the primary issues is the potential for mass loss and segregation, exacerbated by the dynamic nature of water flow. These challenges become even more pronounced when employing SCCs for underwater applications. SCCs, known for their high flow rates, amplify the risk of flow control complications and increase the likelihood of segregation during the underwater casting process. To mitigate these issues, the incorporation of SCMs such as fly ash, slag, and silica fume is essential. These materials play a pivotal role in enhancing the concrete mix, providing improved cohesion, stability, and durability. Besides these pozzolanic supplementary materials and their viscosity-modifying effects, chemical VMAs can also be added to improve cohesiveness and minimize the washout of fresh concrete in water [45-49].

The use of SCMs in cement-based systems, regardless of the w/c ratio and high-range water-reducing admixtures (HRWRAs) dosage, generally increases plastic viscosity and yield point, thereby altering their rheological properties. SCMs with a high loss-on-ignition (LOI) content can increase water demand, leading to rapid slump loss and erratic air void contents in concrete. SCMs with less than 5% LOI are preferable. Pozzolanic material replacement in cement affects UWC flowability, workability, and strength gain over time, depending on the replacement percentage, chemical composition, and particle size of the SCMs. Recent research indicates that SCMs like bottom ash, metakaolin, and nano silica, as well as ternary or quaternary concrete mixtures with multiple pozzolanic admixtures, can also be effectively used in underwater concrete construction. These mineral admixtures impart properties such as workability, homogeneity, resistance to segregation, slump retention, reduced heat of hydration, and better control of setting time [50-53].

Fly Ash. Fly ash enhances AWC flowability due to its spherical particles but can slow down the hydration reaction, and slightly postpone compressive strength. The use of fly ash also reduces the water demand in AWC due to its lower yield stress and the viscosity of the mix designed with it. The optimal content for fly ash ranges from 20-30%, balancing workability, washout resistance, and compressive strength. Research shows that substituting 20% of cement with fly ash improves the corrosion protection of steel bars in marine environments. Both Class F and Class C fly ashes are beneficial for long-term high-strength concrete production and viscosity modification. Class F fly ash is recommended to replace 15% to 25% of portland cement, while Class C fly ash should replace 20% to 30%. Class F fly ash can slightly slow down strength gain, whereas Class C fly ash reacts faster in the early stages. Both types improve workability without compromising cohesion, attributed to the densified microstructure from secondary pozzolanic reactions and improved adhesion between rebar and AWC. The fly ash dosage in underwater concrete typically does not exceed 40% of the total cementitious materials [54-60].

Ground Granulated Blast Furnace Slag. Anti-washout properties are enhanced by incorporating ground granulated blast furnace slag, which triggers pozzolanic reactions. The reactivity of the slag is influenced by its grain size and chemical composition, with underwater concrete typically requiring slag with a maximum Blaine fineness of more than 4,000 cm^2/g. Finer particles of GGBFS result in a larger exposed surface area, facilitating hydraulic reactions.

To regulate the heat of hydration, it is crucial to optimize the amount of slag replacement and the concrete temperature during placement. The utilization of finely ground slag promotes prolonged flow retention and setting time. As the substitution ratio of GGBFS increases, the early-age compressive strength decreases. However, the long-term compressive strength of AWC tends to increase with a higher substitution ratio of GGBFS. The pozzolanic reactions of GGBFS also contribute to the higher steel bar corrosion resistance and chloride penetration resistance of AWC. The optimal dosage of GGBFS for AWC has been found to be 30% when combined with fly ash, as it leads to better anti-washout properties, flowability, and compressive strength compared to other reference groups. However, the excessive substitution of slag may result in insufficient washout resistance and postpone the setting time in UWC mixtures [61-65].

Silica Fume. Silica fume is a widely utilized additive in AWC to prevent washout. It serves as an effective admixture for underwater concrete, improving cohesion and providing high early strength development while minimizing bleeding and segregation. When incorporating silica fume, it is advisable to use a superplasticizer or an HRWRA to compensate for the decrease in the slump of the mixture due to the utilization of silica fume. Compared to fly ash and GGBFS particles, silica fume particles are much smaller in size. The high specific surface area of silica fume improves the viscosity and cohesiveness of AWC, which changes its rheological properties. As a result, decreased slump and flowability are observed, and water resistance is improved. Moreover, the small size of silica fume particles facilitates the formation of a denser microstructure, resulting in higher compressive strength values at both early and late ages in AWC. A substitution ratio of between 5% and 15% silica fume alone might be effective, or a substitution ratio of around 5% silica fume coupled with 20% fly ash has been suggested as the optimum dosage for silica fume in AWC [12,54,66-71].

Metakaolin. Since metakaolin is a highly reactive supplementary cementitious material, it can help speed up the rate of cement hydration and consequently accelerate the setting time of concrete, meaning that the concrete may begin to set and harden more quickly. Additionally, metakaolin can improve rheological performance, control slump and flowability, and increase the compressive strength of AWC. The dosage of metakaolin in anti-washout concrete can vary depending on several factors, including the specific application, the type of cement used in the mix, and the desired performance characteristics of the UWC. The recommended dosage range for metakaolin is between 5% and 20% by weight of cementitious materials in the concrete mix [72-74].

Nano silica. In recent studies, nano silica has gained significant attention due to its potential to enhance the rheological and mechanical properties of concrete, especially in the underwater environment. Nano silica particles are known for their extremely small size and high surface area, which facilitate their interaction with the cement hydrates and their ability to fill the voids in the microstructure of concrete. As a result, nano silica can significantly improve the workability, strength, and durability of underwater concrete. One of the most significant benefits of incorporating nano silica into underwater concrete is its ability to enhance the anti-washout properties of concrete. Due to the high water pressure and flow rates in the underwater environment, traditional concrete mixes are prone to segregation and washout of cement particles, resulting in weaker and less durable concrete structures. However, the addition of nano silica can improve the viscosity and cohesiveness of concrete, reducing the risk of washout and improving the workability of the concrete mix. Moreover, nano silica can facilitate the formation of a denser and more impermeable concrete microstructure, which enhances the water resistance and durability of underwater concrete. Thus, the use of nano silica at a dosage of 1% to 3% by weight of cement in underwater concrete mixtures has the potential to improve the performance of concrete structures in harsh marine environments [75-78].

2.2.2 *Aggregates*

The selection of aggregates plays a crucial role in the anti-washout characteristics and overall performance of underwater concrete. Key factors such as size, shape, surface texture, and water absorption capacity significantly influence UWC's performance and durability. Angular and crushed aggregates enhance washout resistance and cohesiveness due to better particle interlocking but reduced flowability, while rounded or river aggregates improve flowability but may reduce cohesiveness. Well-graded aggregate blends increase particle packing density, thereby improving workability, anti-washout properties, density, and compactness, which contribute to the strength and durability of the concrete.

In underwater construction, aggregates with higher densities are preferred to ensure structural stability and resistance to water-induced forces. While the benefits of lightweight concrete are notable in conventional applications, underwater conditions necessitate the use of denser and heavier concrete to overcome buoyancy and mitigate washout risks. The proportion of coarse and fine aggregates also affects UWC's characteristics. A higher proportion of coarse aggregates enhances anti-washout characteristics but may reduce workability and increase segregation and bleeding risks. On the other hand, fine aggregates improve cohesiveness but heighten the washout risk in highly flowable concretes. An optimal mix typically includes 40% to 60% coarse aggregates by total aggregate volume, with the remainder being fine aggregates. In lower slump underwater concrete applications, a higher fine aggregate proportion can be used [70,79-81].

Crushed sand, used as a substitute for natural sand, boosts strength, anti-washout properties, and durability, with a recommended proportion of 30% to 50% by volume of total sand content. The ideal fine-to-coarse aggregate ratio and the choice between river and crushed aggregates should be project-specific. Aggregates in UWC should produce a strong bond with a continuous cementitious matrix. The interaction between aggregates and paste underwater is affected by friction forces, which influence washout properties. Large, angular aggregates decrease workability and pose challenges in reinforcing cages, requiring higher water content to achieve workability compared to round aggregates. Well-graded aggregates enhance flowability and uniformity, while gap-graded aggregates risk segregation in self-consolidating concrete. ASTM C 33 provides gradation requirements for aggregates. Slightly increasing the sand-to-total aggregate ratio can significantly improve viscosity and resistance to washout in underwater concreting. To enhance the overall quality of underwater concrete, it is often advisable to raise the proportion of very fine aggregates that pass through sieves No. 100 and No. 200, typically up to 10% and 5%, respectively. This adjustment is crucial for achieving the desired level of plasticity in the concrete mix. Moreover, it can reduce the reliance on VMAs, potentially leading to cost savings in underwater concrete construction. In cases where the gradation lacks an adequate amount of filler or fine aggregates, incorporating fine fillers such as limestone powder can prove beneficial. A sand-to-total aggregate ratio of 50%, containing a sufficient quantity of fine particles, has been determined as the optimal balance between washout resistance and mechanical strength in underwater concreting applications [7,14,33,82-87].

Some commonly used aggregates and their effects on the performance of AWC are summarized in Table 2 [7,14,85-87].

Table 2. Pros and cons of aggregate types used in UWC mix designs

Type of Aggregate (Texture)	Positive Effect on UWC	Negative Effect on UWC
Natural Source/Riverbed Aggregates (Rounded Surface)	- Enhanced workability - Less effort is required during mixing and placing. - Reduction in cement consumption due to lower surface-to-volume ratio	- Weaker bond between the aggregate and the cement paste - Reduced overall compressive strength
Crushed Stone (Rough and Angular Surface)	- Stronger bond with the cement paste - Better interlocking of particles and improved overall strength. - Increased resistance of washout	- Less workability - More effort required during mixing and placing - A higher proportion of cementitious paste needed to achieve workable mixtures
Mineral Fillers (Fine Particles)	- Refined pore structure and reduced permeability - Dense microstructure resulting in better overall strength. - Improved workability and viscosity-modifying properties	- Increased water demand of mixtures - Reduced flowability and increased HRWRA demand - Increased risk of shrinkage and cracks

Gerwick [88] suggested a fine aggregate content of 42% to 45% of total aggregates by weight for underwater concrete, higher than typical ratios found in ground-placed concrete. While exceeding 45% fine aggregate content without high-range water reducers or superplasticizers might negatively impact flowability, underwater concrete mixtures often include 45% to 50% fine aggregate when using these additives. The influence of coarse aggregates on concrete rheology is complex, as it intertwines with the cement paste content and fines amount. General guidelines for aggregate selection in underwater concrete are derived from experimental observations. The maximum aggregate size is typically limited to 25.0 mm (1 in.) for mass underwater concrete and 19.0 mm (3/4 in.) for general applications, though it may be reduced to 12.5 mm (1/2 in.) in areas with dense reinforcement. Large-size aggregates can reduce the cement and water content in concrete but may increase the risk of segregation in highly flowable concrete, which is essential for UWC moderate-distance flow depositing without mass loss. The maximum percentage of flat and elongated coarse aggregates should be capped at 3% to avoid reducing workability, as flaky particles have a high surface area-to-volume ratio, increasing water demand and consequently a higher w/c ratio, which causes lower concrete strength. Moreover, flaky aggregates can obstruct concrete flow by getting stuck between forms and reinforcement bars [7,82,89].

2.2.3 *Additives*

Selecting appropriate AWAs like VMAs that are compatible with the concrete mix, accompanied by High-Range Water Reducers or superplasticizers, are essential for underwater applications. Traditionally, concrete mix design for underwater casting, especially with the tremie method, had to balance flowability and cohesion, limiting the slump to 100 to 150 mm (4 to 6 in.) and the maximum transport distance to about 5 meters. The introduction of HRWRAs and AWAs has revolutionized this approach, allowing for high flowability similar to SCC while maintaining cohesion to prevent segregation and bleeding, leading to the direct depositing of concrete underwater. AWAs, typically water-soluble organic polymers, enhance the concrete's cohesion, significantly reducing the washout of finer particles underwater. Available in both powder-based and liquid forms, AWAs are often used with superplasticizers to create flowable, self-leveling concrete mixtures suitable for underwater placement. These admixtures ensure optimal workability and compaction, improving the concrete's integrity and reducing environmental impacts like cement dispersion in water. Anti-washout admixtures are particularly effective in various water-related applications, including deep underwater and intertidal zones. They form a three-dimensional polymeric network that binds the concrete components, reducing mass loss from external water exposure. The interaction between the cement matrix and AWAs involves polymer-water adsorption, polymer-polymer interactions forming a gel-like network, and polymer-particle interactions, which increase surface tension and viscosity, creating a cohesive and sticky network. While they increase cohesion, these admixtures slightly reduce workability and flow, which can be offset by adding superplasticizers. For an optimal effectiveness of VMAs, it is recommended to use cementitious materials of at least 400 kg/m³ (650 lb/yd³) and combine fine SCMs like fly ash or silica fume with AWAs for increased cohesion. However, care must be taken to prevent concrete from clogging pump lines or tremie pipes, as turbulent underwater flow can cause segregation [34-37, 90-94]. This mechanism is illustrated in Figure 1.

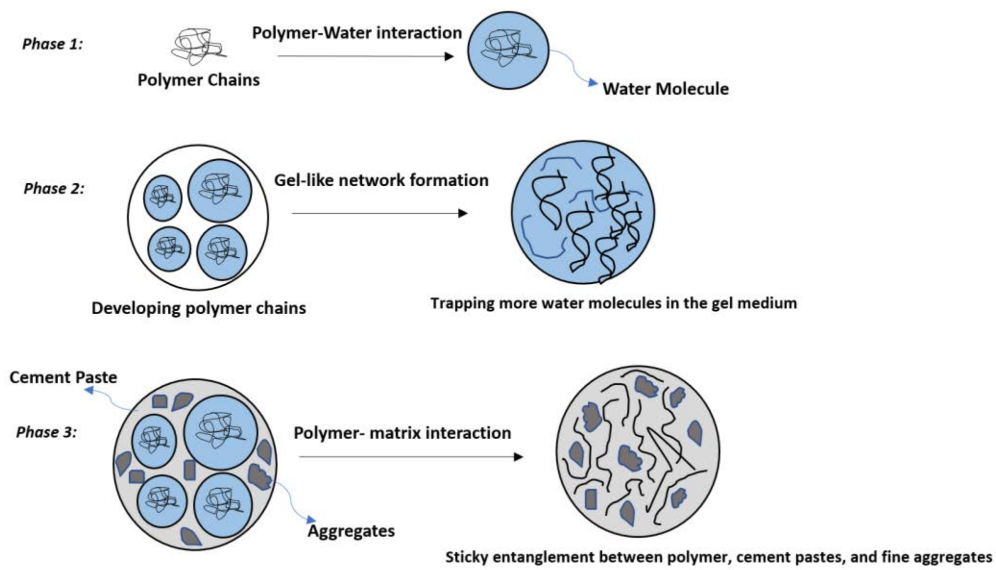


Figure 1. Mechanism of anti-washout admixtures in concrete

In underwater concrete mixtures, it is crucial to understand the role of chemical admixtures, especially in terms of their impact on the viscosity, workability, and overall performance of fresh concrete. These additives are typically categorized based on their function and composition. Commonly used types of polymers and additives that can enhance viscosity and other properties of fresh concrete are as follows:

1. **Water-Reducing Admixtures**. These additives, for example, polycarboxylate ethers (PCE), lignosulfonates, or naphthalene-based superplasticizers, can reduce the water content needed to achieve a given workability, thereby improving the viscosity and flowability of the concrete. Polycarboxylate-based HRWRA is the most commonly used.
2. **Air-Entraining Admixtures**. These additives, based on surfactants or synthetic resins, introduce microscopic air bubbles into the concrete mixture, improving its workability, freeze-thaw resistance, and durability. While they do not directly impact viscosity, they can increase the overall volume of voids in the concrete.
3. **Polymer-Based Viscosity Modifiers**. These additives, for example, acrylic polymers, styrene-butadiene latex, or ethylene-vinyl acetate copolymers, can enhance the properties of concrete as VMAs. They improve adhesion, reduce shrinkage and cracking, and enhance the workability and strength of the concrete.
4. **Organic Rheology Modifiers**. These additives, which act as VMAs, are specifically used to control the rheological properties of concrete, including its flowability, segregation resistance, and viscosity. They can also positively impact durability and mechanical strength and, in the case of additives such as limestone powder, zeolite, metakaolin, and very fine sand, may be employed based on their filler effects.
5. **Fibers**. Steel, polypropylene, or glass fibers can be added to concrete to improve its tensile properties, crack resistance, and overall mechanical strength. While they do not directly influence viscosity, they can affect the overall rheology and behavior of the concrete mixture in the fresh state.

The addition of viscosity-modifying agents to underwater concrete is essential for improving its resistance to washout. Among several available options to achieve washout resistance, chemically synthesized polymers are particularly preferred due to their beneficial properties, including easy water solubility, high molecular weight, and ability to be produced at a high level of quality and to be applied in accurate dosages. These polymers are also readily available in the concrete admixtures market. Over time, viscosity-modifying agents as rheology modifiers have undergone significant advancements, as shown in Figure 2 [94-97].

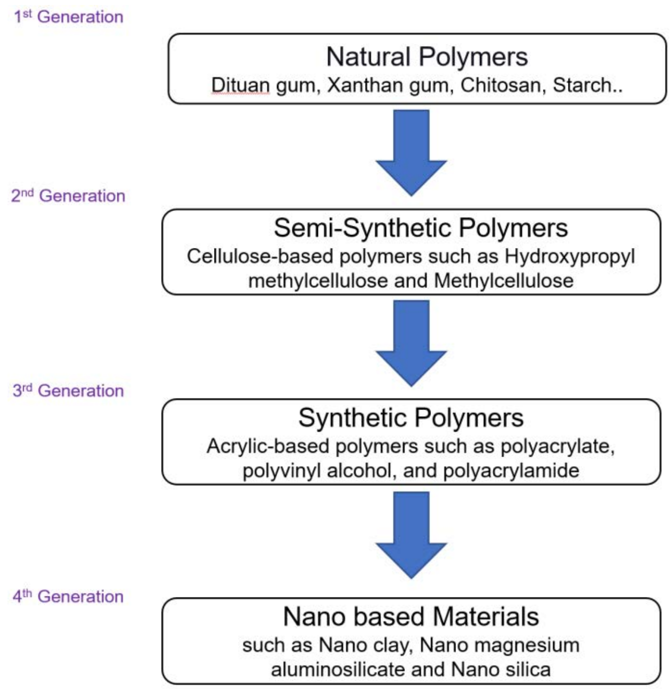


Figure 2. Progression of anti-washout admixtures over time

In the past, natural polymers obtained from tree gum, plant proteins, and anaerobic microbial fermentation (such as diutan gum, welun gum, Arabic gum, xanthan gum, chitosan, and starch) were used to some extent in concrete mix designs. However, their poor water solubility and chemical stability limited their use. Therefore, semi-natural or semi-synthetic polymers such as carboxymethyl starch and some cellulose-based polymers such as methylcellulose and hydroxypropyl methylcellulose were synthesized to improve their properties. However, these second-generation polymers were still difficult to use due to their limited solubility and chemical stability. To address these issues, synthetic polymers such as polyacrylate, polyvinyl alcohol, polyethylene oxide, and polyacrylamide gained increasing attention. They have excellent water solubility and chemical stability and are easily modified and prepared chemically. In contrast to natural and semi-synthetic polymers, synthetic polymers exhibit superior and customizable anti-washout properties. Furthermore, they offer greater ease of use, and their performance in UWC can be more readily adjusted and predicted.

In their 4th generation, VMAs and AWAs for concrete applications include nano-based materials. Such materials have the capability of modifying the concrete's viscosity due to their ultra-fine size and high reactivity. For example, nanomaterials like nano silica can significantly enhance the rheological properties of the concrete mix, making it more stable and workable. Moreover, the interactions of these nano-based materials with the cementitious matrix allow for improved adaptability, thus functioning similar to compatible pozzolans. This can result in a more cohesive mix with less potential for segregation or bleeding.

The incorporation of AWAs into concrete significantly influences various properties of the mix. The setting time and air content can be effectively adjusted by altering the type, dosage, and source of VMAs and superplasticizers used. Generally, the maximum dosage of AWAs is kept below 1% of the total weight of cementitious materials. Research has shown that in high-performance underwater concrete, increasing the AWA content to 0.5% of the cementitious material weight results in a marked reduction in slump flow (by about 50%), segregation (by 80%), and mass loss ratio (also by 80%), while simultaneously causing more than a twofold increase in air content. These changes illustrate the significant impact of AWAs on the performance characteristics of underwater concrete, which can be seen in Figure 3 [14,16,37,98].

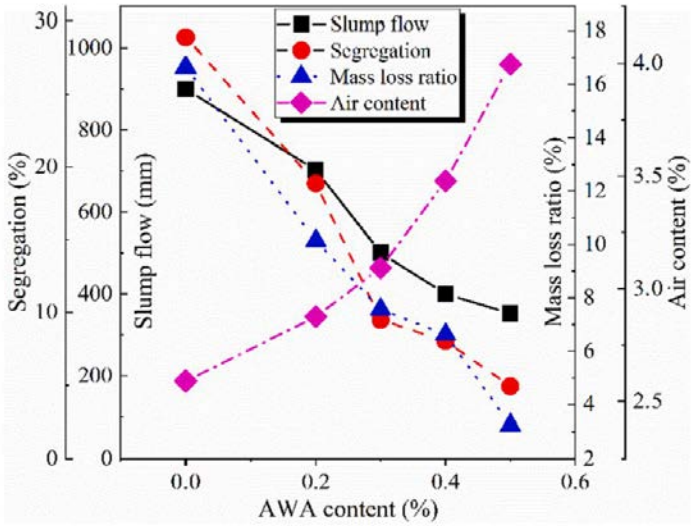


Figure 3. Correlation between AWA content and segregation, mass loss ratio, slump flow, and air content [14]

The performance of AWC is significantly influenced by the molecular characteristics of VMAs. AWAs with higher molecular weights or more side chains can form denser networks, enhancing washout resistance. Superplasticizers, especially polycarboxylate ether-based types, can offset the reduction in slump or fluidity caused by AWAs and are generally more compatible with AWAs than naphthalene-based superplasticizers. Balancing fluidity and washout resistance is achievable by combining polycarboxylate superplasticizers with AWAs. However, excessive AWA content can increase viscosity, necessitating higher superplasticizer dosages for desired flowability. The lowest effective dose of AWAs is recommended for optimal washout resistance, and compatibility evaluation between superplasticizers and AWAs is crucial before full-scale underwater concrete casting. Mixing time also significantly impacts AWA performance in concrete. Extended mixing reduces viscosity due to the alignment of polymer chains along the flow direction, which re-entangle upon ceasing mixing, restoring original viscosity. Therefore, a significant time interval between mixing and placement is essential for maintaining flowability. The recommended batching sequence involves adding AWAs after thoroughly mixing superplasticizers in the fresh mixture to ensure proper dispersion and optimal performance of AWAs. AEAs have been explored to control concrete viscosity, but their use in tremie-placed concrete can be problematic due to inconsistent air content and challenges in maintaining uniform consistency under field conditions. AEAs in underwater concrete should be limited to scenarios where the concrete will be exposed to freezing and thawing conditions due to difficulties like changing flowability and entrapping air in the mixtures [97-100,106-108].

2.2.4 *Mix Design and Related Considerations*

To meet the technical requirements of various underwater concrete applications, it is essential to have a properly optimized mix design. The mix design for UWC includes two types of variables: independent variables (like water-to-cement or water-to-binder ratios, types and quantities of cementitious materials, aggregates, and chemical admixtures) and dependent variables (such as flowability, washout resistance, setting time, and compressive strength). It should be noted that the "water to binder ratio" and the "water to cement ratio" are sometimes used interchangeably, while they have distinct meanings from a scientific standpoint. The water-to-cement ratio (w/c) typically refers to the ratio of water to cement (alone). In contrast, the water-to-binder ratio (w/b) refers to the ratio of water to all cementitious materials, including cement and SCMs such as silica fume and fly ash. The choice between "w/c" and "w/b" in specifications depends on design objectives and specific characteristics desired for the final concrete product. For example, if the design focuses on achieving durability characteristics or leveraging the benefits of some supplements like fly ash or silica fume for performance reasons, the w/b ratio provides a more representative measure compared to the w/c ratio. It should be noted that some of the studies reviewed and synthesized for the current research project have reported w/c, and some have reported w/b. Hence, w/c and w/b have been listed consistent with their corresponding references.

Underwater concrete differs from conventional concrete in workability requirements, as it needs to flow and compact under its own weight, while being highly viscous at the same time. UWC mixtures are primarily categorized into two types: standard mixtures, which are akin to conventional concrete, and high-performance mixtures, which are tailored for self-consolidating and anti-washout applications. These high-performance mixtures often involve customizing components and chemical admixtures to enhance specific performance-based applications. The process of proportioning these mixtures typically follows a methodical approach, often involving trial and error to achieve optimization. Initially, the focus is on optimizing the basic mixtures to ensure a solid base mix. Once the base mix is achieved, chemical admixtures are introduced. It is crucial to note that these admixtures are not intended to compensate for poor mix proportions or to fill the absence of some specific materials. Instead, their role is to refine and enhance the already established quality of the concrete mixture. Five key considerations impact UWC mix design:

- **Cementitious Materials**. UWC requires higher cementitious material content, with fly ash, GGBFS, and silica fume altering workability and performance. Optimal workability is achieved when fly ash (or slag) and silica fume together replace up to 40% of cement content.
- **Water-to-Cement Ratio**. This ratio affects VMAs' performance, directly influencing workability, strength, and durability. In UWC, a lower water-to-binder (w/b) ratio can result in reduced workability. Addressing this with a high dosage of superplasticizers may increase the risk of washout. Conversely, a higher w/c ratio tends to decrease the relative compressive strength of the concrete.
- **Coarse Aggregate Size**. Smaller aggregates improve workability and reduce segregation risk. The maximum aggregate size should ideally be no larger than one-fifth of the narrowest structural element dimension or half of the minimum clear spacing between reinforcing bars.

- **Water-to-Fines Ratio**. This ratio, including cementitious materials, limestone powder, and fine aggregates, is crucial for workability. The recommended range is between 0.8 and 1.0 by volume, balancing cohesion and flowability.
- **Chemical Admixtures**. The correct use of viscosity-modifying admixtures and superplasticizers enhances UWC's performance. Dosages should be balanced to maintain desired properties and meet project requirements.

Finalizing UWC mix design involves conducting trial batch testing to assess workability, strength, thermal stresses, and the suitability of placement procedures, ensuring overall concrete performance for specific underwater applications. Several recommendations have been developed for this purpose, as mentioned in previous sections, and are summarized in Table 3.

Table 3. Key underwater mixture parameters and their recommended ranges

Parameter	Recommended Ranges	Considerations
Water-to-binder ratio	0.30 to 0.45	Critical for strength gain and durability
Cementitious materials content	400–800 kg/m^3 (670-1350 lb/yrd^3)	Includes cement plus all other SCMs such as silica fume, fly ash, slag, nano silica
Sand-to-total aggregate ratio	45%–65%	Helps cohesiveness and filling ability
Maximum size of coarse aggregate	10–19 mm (1/2–3/4 in.)	Smaller aggregates enhance workability and minimize the risk of segregation.
Silica fume-to-cement ratio	Up to 12%	Acts as an inorganic anti-washout admixture
Fly ash-to-cement ratio	Up to 30%	Enhances workability and durability
Slag-to-cement ratio	Up to 50%	Enhances workability and durability and delays setting time
Anti-washout admixture	0.02%–0.7 % by weight of cementitious materials	Reduces mass loss of concrete mixtures and is preferably used after adding superplasticizer
Superplasticizer	0.5%–2% by weight of cementitious materials	Used for gaining desirable flowability between 400 and 650 mm (16 and 26 in) flow diameter

2.3 Fresh Properties

In various regions across the world, different standardized methods have been adopted to evaluate the fresh properties of underwater concrete, specifically in relation to its resistance to water exposure. In Japan, a prevalent method employs a suction system to determine the pH level of concrete upon contact with water. The procedure involves pouring 500 g of freshly mixed concrete into a beaker containing 800 mL of water. After a span of 3 minutes post-pouring, the pH of the water is measured. An increased pH reading suggests a greater degree of concrete washout, as the leaching of alkaline components from the concrete raises the pH level of the water [115]. In Canada, the spray test is the primary method of choice. This procedure is designed to gauge concrete's resistance to water-induced washout. The test is executed by subjecting 1 kg of fresh concrete to a continuous water spray for a duration of 4 minutes. Following this, the mass loss is measured, offering insights into the concrete's resistance to washout [116]. In the United States, the preferred method for evaluating underwater concrete is the USACE test method CRD-C61 [117], colloquially known as the "plunge test." The origins of the plunge test trace back to Belgium, specifically to research initiatives at the University of Ghent. The initial version of this test utilized a basket of compact dimensions with relatively small holes. However, the method underwent revisions when the USACE adopted it. The USACE made modifications, such as transitioning to a larger basket equipped with bigger hole diameters and integrated the updates into the CRD-C61 standard. The plunge test is distinguished by its ability to provide a quantitative assessment of washout. The test evaluates the relative loss of cement paste and fine mortar when a concrete sample housed in a perforated basket undergoes immersion in water. The procedure requires a 2.0 kg concrete sample to be placed inside the basket, which is then submerged three times in water to a depth of 1.7 m. After each immersion, the sample's mass variation is recorded. The final results, presented as a percentage, reflect the comparative mass loss from the sample's initial weight, thereby shedding light on the concrete's resilience when it comes into contact with water [24]. For testing the water resistance of AWC, the plunge test and pH test offer the most practical results among all tests. These methods, by measuring specific parameters such as the sample's mass loss ratio and pH value, provide direct insights into the AWC's resilience when exposed to water. Both tests offer the combined benefits of simplicity of execution, minimal equipment demands, and accurate results and have been widely accepted and incorporated into civil underwater concrete practices. A typical threshold for adequate water resistance has often been identified as a cement mass loss ratio under 1.5% and a pH value less than 12. In the spray test, the integration of an electric balance with a computer facilitates real-time monitoring of sample mass changes. While this technological advancement enhances measurement accuracy, the spray test might not always mirror real-world underwater conditions. Factors such as the spray nozzle type and its distance from the concrete's exposed surface can impact results, necessitating further validation or calibration [87,114].

AWAs affect how UWC concrete flows, mainly by changing its viscosity. Adjusting these chemical additives is crucial for the concrete's fresh properties. Superplasticizers are typically composed of various polymers that function by adsorbing onto the surface of the cement particles. When these molecules attach to the cement particle surfaces, they impart a strong negative charge. This electrostatic repulsion between particles prevents the cement particles from stacking up, leading to a more fluid mixture. However, this dispersion effect can interfere with the initial hydration reactions of the cement particles. The hydration of tricalcium silicate (C3S) and dicalcium silicate (C2S), the primary phases in portland cement, can be delayed due to the presence of these adsorbed superplasticizer molecules. Using larger quantities of superplasticizers can increase this delay. Additionally, higher air content can be observed in mixes that contain superplasticizers, likely because of the changed viscosity [118-120]. In underwater concrete applications, optimal fresh properties during casting are crucial. All fresh properties contribute to consistent concrete quality and an ideal setting time for efficient transport and casting. Balancing flowability and setting time is essential for meeting construction requirements. The integration of appropriate water-reducers or superplasticizers, and occasionally accelerators, can rectify variations in these attributes. Nevertheless, the complex dynamics among different chemical admixtures necessitate meticulous evaluation by AWC specialists. Modifying one attribute can inadvertently influence others. A profound grasp of concrete's rheological properties is vital to understanding the relationships among its fresh mix attributes. The Bingham model serves as a widely acknowledged rheological framework for analyzing AWC, particularly in establishing how rheological parameters correlate with washout resistance. According to this model, concrete has two main properties: yield stress and plastic viscosity. Yield stress is the force that must be applied to make the concrete start flowing. Plastic viscosity describes how easily the concrete flows once it starts moving. In this model, VMAs and superplasticizers play specific roles. VMAs increase both the yield stress and plastic viscosity, making the concrete thicker and more difficult to start moving but more stable once it does. This is useful for situations where the concrete must not flow away, like underwater applications. Superplasticizers do the opposite: they reduce yield stress and plastic viscosity, making the concrete easier to start moving and keep moving. This is useful for pumping concrete or getting it to fill complex forms. To summarize the Bingham model, VMAs make concrete more stable but more difficult to move, and superplasticizers make concrete easier to move but potentially less stable [71,86,121]. The Bingham model is illustrated in Figure 4.

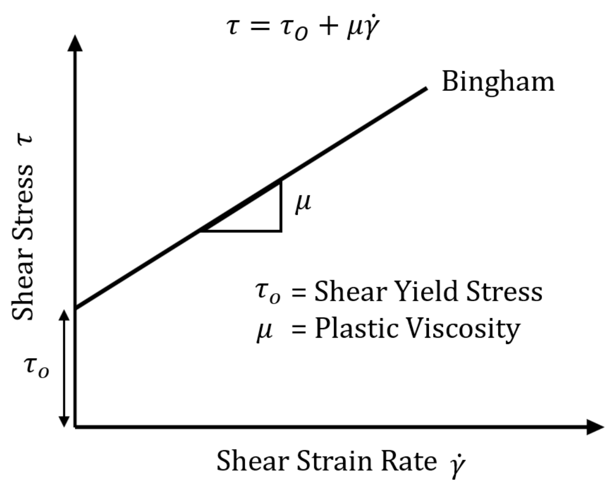


Figure 4. Bingham rheological model [118]

When VMAs are introduced into the concrete matrix, they usually elevate the concrete's viscosity and, depending on their chemical formulation, could induce either shear-thickening or shear-thinning phenomena. The addition of VMAs aids in fortifying the cohesiveness and stability of the concrete, attributes that are highly valued in applications like self-consolidating concrete and underwater concrete. In contrast, superplasticizers primarily focus on workability enhancement by lowering the mix viscosity and promoting shear-thinning characteristics. This reduction in viscosity facilitates the concrete's flow under applied shear forces, optimizing placement and pumpability. However, in the context of underwater concrete, where water currents and the risk of concrete washout are prevalent, the application of superplasticizers warrants meticulous consideration to ensure that enhanced workability does not compromise the material's stability or resistance to washout [118-121].

2.3.1 *Setting Time*

Setting time is a pivotal parameter for UWC, influencing both its ease of placement and ultimate performance. The rheology of UWC is significantly affected by setting time, particularly during and following placement. Challenges such as cement washout and material segregation due to factors such as water currents arise when setting times are extended. Conversely, overly rapid setting times can hinder the completion of the pouring and compaction processes. For UWC applications, a faster setting time is generally preferred to mitigate the risks of cement washout and segregation. However, setting should not occur instantaneously, because a certain amount of time is required for both placement and compaction. The optimal setting time varies based on job-specific conditions, including water currents, placement depth, and placement method. A widely accepted guideline suggests an initial setting time of less than one hour to strike a balance between placement needs and washout prevention. Various cementitious materials and SCMs, such as calcium sulfoaluminate cement, silica fume, and fast-setting grouts, can serve to accelerate concrete setting. Conversely, materials such as fly ash and slag tend to delay setting. In UWC scenarios where delayed setting is problematic, mixes containing significant amounts of pozzolanic materials such as slag, fly ash, or metakaolin can be coupled with fast-setting agents to extend the setting time. High dosages of superplasticizers may delay concrete setting by dispersing cement particles, thus impeding the hydration process temporarily. However, some new-generation superplasticizers possess the ability to control setting time. These can be customized by manufacturers to meet specific project requirements, adding an additional layer of flexibility in setting time management. Finally, while anti-washout admixtures primarily aim to modify viscosity, they can also influence setting time. Typically, the use of VMAs results in a slight extension of initial setting time due to slowed hydration. These admixtures are tailored specifically for UWC to improve mix cohesion and resist washout. Recent advancements in chemical admixture technology allow for the customization of properties like setting time, water reduction, and viscosity modification. Customized properties can be specified when VMAs are ordered from manufacturers, providing a versatile toolkit for underwater concreting applications [3,30,38,121,122].

Focusing on the parameters that affect the setting time of underwater concrete, especially in low-temperature environments, both ambient and water temperatures need to be considered. While “cold weather concreting” is well-documented for the situations that do not involve a direct exposure to water, additional attention is required for underwater concrete based on water temperature. Cold water temperatures can significantly slow down the hydration process, due to direct and immediate cooling effects on the concrete mix. This situation leads to an “extended setting time” because the chemical reactions essential for the concrete to set and harden are delayed. Longer setting times in cold water heighten the risk of material segregation and washout, especially in flowing water conditions. To mitigate the associated challenges, several strategies can be employed, including the use of accelerating admixtures. Incorporating chemical accelerators into the concrete mix can enhance the rate of hydration, thereby reducing setting times. When possible, pre-heating the water or aggregates before mixing, utilizing warm water as mixing water, or insulating the truck mixer or tremie buckets during placement can result in a favorable temperature for hydration. Alternatively, mix designs can be adjusted to include materials that perform better in cold conditions. Strategies may include increasing the cement content to generate more heat of hydration, utilizing calcium sulfoaluminate (CSA) cement, or reducing the water-to-cement ratio.

2.3.2 *Workability*

AWC's enhanced workability ensures better flow, filling, and passing abilities and prevents segregation at the same time. These traits optimize compaction and leveling when the concrete is poured into underwater formworks. Consequently, concrete becomes more resistant to the penetration of corrosive substances and naturally displays self-leveling capabilities. Workability refers to the ease with which concrete can be mixed, placed, compacted, and finished with minimal loss of homogeneity. In simple terms, concrete workability describes how easy a concrete mix can be placed, consolidated, and finished during construction. Various tests such as the slump test and flow table test are commonly employed to measure workability. Several parameters affect the workability of concrete, particularly in underwater casting. These include water-to-cement ratio, aggregate gradation, temperature, and the use of admixtures such as VMAs and superplasticizers. The effects of superplasticizers and VMAs on workability in underwater concrete casting are especially prevalent [60,121-123]. Superplasticizer admixtures enhance workability primarily by reducing the concrete mix's viscosity. Lower viscosity improves the flow of concrete, making it easier to pump and place, which is especially useful when trying to maneuver concrete in underwater settings. However, too much superplasticizer might make the concrete too fluid, increasing the risk of segregation and washout in underwater environments, where water currents can already pose challenges to concrete placement. VMAs or anti-washout admixtures are generally used to improve the concrete's stability by increasing its viscosity, thus making it less prone to segregation and washout, which are critical issues in underwater casting. VMAs help maintain homogeneity, allowing the concrete to better resist the disruptive effects of water currents. However, VMAs can make the mix harder to pump and place if used in excess. Superplasticizers and VMAs have opposing effects on the workability of underwater concrete. Superplasticizers make the concrete easier to place but could increase the risk of washout, while VMAs make the concrete more stable but could make it more difficult to handle. Therefore, a careful balance of these additives must be maintained to optimize workability for underwater concrete casting. The proportions of the concrete mix must also be meticulously calibrated, particularly with regard to the unique flowability demands imposed by underwater environments. Elevating the w/c ratio or the superplasticizer content can significantly increase the slump and slump flow values, thereby enhancing workability. However, this increase in workability could also elevate the rate of mass loss, especially when the concrete is exposed to aquatic conditions. Figure 5 elucidates the relationship between slump flow and mass loss as assessed through plunge tests utilizing small and large mesh baskets [7,27,104,124].

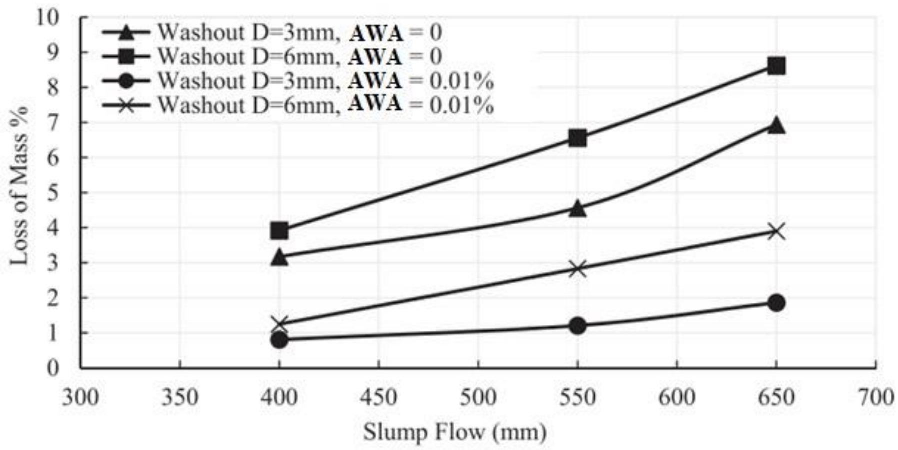


Figure 5. Mass loss percentage in relation to slump flow for various mesh basket diameters (D) and AWA contents [27]

In practical UWC applications, UWC mix design aims to strike a balance in the concrete's workability characteristics. While the concrete is designed to be placed easily with minimal or no mechanical effort, its slump should not exhibit the high flowability observed in fully self-consolidating concrete due to the increased potential for washout and risk of segregation underwater. The recommended value for workability as measured by the flow-slump method is a spread diameter of 450 to 550 mm (18 to 22 in.), which distinguishes UWC from SCC, the latter of which often exhibits values between 650 and 800 mm (26 and 32 in.). Such differentiation in workability metrics aligns with established practical experience and addresses the unique challenges of underwater concrete placement.

2.3.3 *Measurement Techniques*

In the realm of underwater concrete applications, the assessment of fresh properties such as workability, setting time, bleeding, and segregation is crucial for both optimal placement and long-term structural performance. The unique challenges posed by aquatic environments, most notably the heightened risk of material loss through washout, necessitate adaptations of standardized testing protocols to fit these specific conditions. Test methods ranging from the conventional slump test to more advanced methodologies employing equipment like the V-funnel, L-box, T-50, Urimet, and J-ring, all of which were initially designed to evaluate the fresh properties of SCC, can be adapted to assesses the fresh properties of underwater concrete. In this context, the following tests are applicable to measure the workability of underwater concrete: [19,35,57,76,125]

- **Conventional Slump Test**. This widely used workability assessment method employs a slump cone to measure the vertical subsidence of the concrete mix. Although reliable for conventional concrete, it is less effective for highly flowable mixes.
- **Slump Flow Test**. Specifically designed for self-compacting and high-flow concretes, this test measures the horizontal flow of concrete, offering additional workability data.
- **V-Funnel Test**. This test measures the flowability and filling ability of self-compacting concrete, providing valuable insights into the concrete's ability to flow through narrow openings or densely packed reinforcement.

- **L-Box Test**. This test evaluates the flow and passing ability of self-compacting concrete, especially in conditions mimicking those with obstructions such as rebar.
- **T-50 Test**. This test measures the time taken for the concrete to reach a spread diameter of 50 cm, which is critical for assessing the flow rate and, by extension, the workability of the mix.
- **J-Ring Test**. This test is specifically designed to measure the concrete's ability to flow around reinforcing bars without segregation or blockage.
- **Urimet**. This test measures the rheological properties of a concrete sample, offering an integrated view of the concrete's workability and setting time.

Table 4 outlines standard workability test protocols and requirements, as documented in the literature.

Table 4. Test methods and criteria for evaluating workability of UWC

Test Item	Standard Test Method	Standard Requirements	UWC Requirements
Slump tests after mixing	ASTM C 143	Slump = 180 ± 10 mm (7 ± 0.5 in.)	Slump = 255 ± 25 mm (10 ± 1 in.)
Slump flow after mixing	EFNARK	Slump flow > 550 mm (22 in.)	Slump flow > 400 mm (16 in.)
Slump tests at 30 min, 60 min, and 90 min	ASTM C 143	Slump at 60 min > 125 mm (5 in.)	Slump at 60 min >150 mm (6 in.)
Test of the time of setting	ASTM C 403	Initial set time > 45 min Initial set time < 120 min Final set time <480 min	Initial set time > 30 min Initial set time < 90 min Final set time < 360 min
Test of the concrete resistance to washout and erosion	CRD-C 61-89A	Cement washout loss < 12 percent by mass	Cement washout loss < 8 percent by mass
Bleeding test	ASTM C 232, method A	Bleed water < 2.0 percent	Bleed water < 0.5 percent

In some studies, the air content of concrete has been examined to gauge its impact on washout resistance. These studies suggest that a slightly elevated level of entrained air—achieved using air-entraining admixtures and falling within the 2% to 4% range—may serve as a viscosity modifier in concrete. For instance, a 2022 study by Kumar et al. [54] indicated a relationship between air content and washout loss. According to the data presented in the study (Figure 6), an increase in air content corresponded to a decrease in washout loss in UWC containing 0% to 15% silica fume. However, the variations in air content were marginal, with a difference between samples of less than 1%. While the data suggest a possible role for entrained air in affecting concrete's resistance to washout, more rigorous research is needed to establish any significant impact.

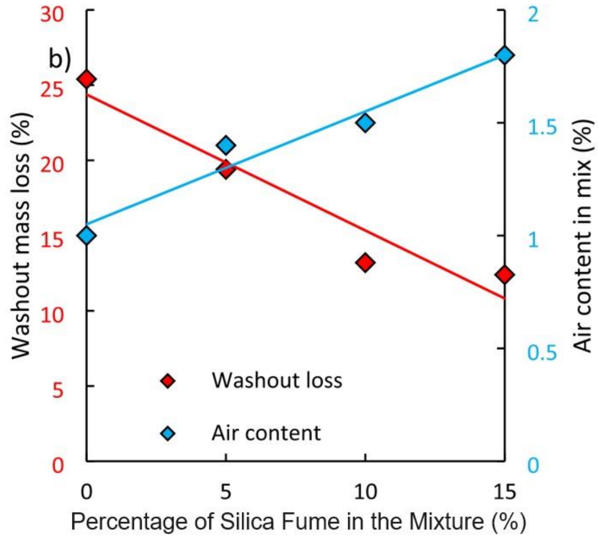


Figure 6. Variations in washout loss and air content with different percentages of silica fume in the concrete mix [54]

Another critical parameter that necessitates measurement in the fresh state is bleeding and segregation capacity. In underwater concrete applications, bleeding—a phenomenon where water ascends to the concrete's surface—has specific ramifications. Research by Sikandar et al. [11] supports the idea that VMAs can diminish the rate of bleeding by enhancing the concrete's viscosity. This is corroborated by Assad et al. [126], who employed EFNARK [127] test methods and ASTM C232 [128] to evaluate aggregate segregation and bleeding, respectively, in SCC. Based on these standards, segregation is assessed by pouring fresh concrete into a sieve with 5 mm (1/4 in.) square apertures and weighing the material passing through the sieve after a 2-minute resting period. Lower values indicate an SCC mix with stronger resistance to segregation, as evidenced by reduced separation of the cement paste and mortar from the concrete matrix. The bleeding test involves placing the fresh material in a container 75 mm (3 in.) in diameter and 150 (6 in.) mm in height. The container is tilted slightly, and free water is collected from the specimen's surface using a pipette. The percentage of bleed water is determined by dividing the collected water by the total mixing water in the tested specimen. It should be noted that the air content in all mixtures tested by Assad et al. [126] varied within a range of 3.1 ± 0.4%. Incorporation of VMAs into concrete mixtures has been shown to considerably reduce bleeding tendencies. These agents, along with anti-washout admixtures, likely augment the viscosity of the concrete mix, thereby enhancing its ability to suspend particles and minimize free water. This mitigates the risk of segregation. In a study by Benaicha et al. [129], the modified V-funnel test was utilized in conjunction with the sieve segregation test to measure the segregation resistance of concrete containing VMAs. This method can also assess resistance to segregation by measuring the concrete's flow time after a specific period. The inclusion of VMAs as admixtures and the use of silica fume as an SCM were found to simultaneously reduce the risks of segregation and bleeding while enhancing flowability and filling capability. In addition to laboratory testing, mock-up tests offer invaluable data for large-scale civil engineering projects, especially underwater concreting, by replicating complex environmental conditions not easily replicated in laboratory settings. These tests serve as practical rehearsals encompassing every critical aspect of a concrete mix, from its self-leveling capabilities and uniformity to its bond strength and mass loss potential. For instance, in tremie placements, a mock-up test can include a submerged box with pre-installed reinforcing steel cages and even a perforated precast plate cover to mimic real-world conditions. The aim is to address and optimize all variables, including flowability, washout resistance, temperature profiles, and setting time. Mock-up tests can also include in situ core tests to evaluate the hardened properties of concrete [125]. Figure 7 shows a mock-up test evaluating the flowability of UWC.

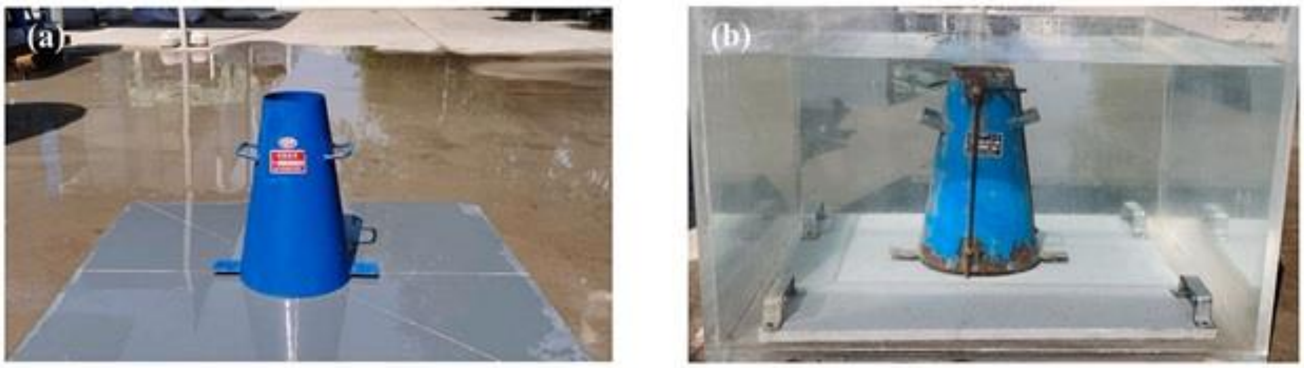


Figure 7. Mock-up tests assessing UWC flowability: (a) Slump flow test in the air and (b) Underwater slump flow test [125]

2.3.4 *Washout Loss*

The susceptibility of UWC to washout loss is a matter of grave concern for its performance and longevity in marine and offshore conditions. Washout loss refers to the dispersion or dilution of concrete materials when exposed to flowing water, which compromises the concrete's structural integrity. Factors such as mix composition, aggregate gradation, and chemical admixtures (Superplasticizer and VMA) content play a vital role in determining washout resistance [8, 131]. Figure 8 shows the effects of an anti-washout admixture.

Figure 8. Effects of AWAs on underwater concrete placement: Material washout in the absence of AWAs (left) and enhanced cohesion after the addition of AWAs (right) [132]

Fresh mixes of underwater concrete that exhibit low viscosity are inherently more vulnerable to washout and, consequently, both mass loss and compromised structural integrity. Another factor that can make a concrete mix susceptible to washout might be an insufficient amount of binder materials, such as cement or pozzolanic agents such as silica fume, which can hinder effective bonding between the aggregates and the cementitious matrix. A poorly optimized mix, characterized by a nonuniform distribution of materials or incorrect ratios of fine to coarse aggregates, can also exacerbate washout issues. Materials like silica fume and nano silica are highly effective in minimizing washout loss in underwater concrete mixes due to their excellent filler effects and high water demand, attributable to the large surface area of their particles. Studies such as that by Nasr et al. [149] underscore the significance of nano silica particles in bolstering a mix's resistance to washout. Both silica fume and nano silica serve to enhance the cohesiveness of the concrete mixture. Enhanced cohesiveness reduces susceptibility to washout because the particles within the mix are more strongly bonded. These materials also alter the rheological properties of the concrete, rendering it more thixotropic, a quality that reduces flow under stable conditions but allows for effective pumping or placement under shear forces. Additionally, the fine granules of silica fume and nano silica fill voids between larger aggregate particles, thereby increasing the mix's density. This in turn reduces the potential for segregation and bleeding, which are key contributors to washout. The high reactivity of silica fume and nano silica also accelerates the cement's hydration process, resulting in a quicker initial setting time for the concrete. A reduced setting time narrows the window during which washout is most likely to occur. Moreover, both silica fume and nano silica contribute to the formation of a more refined microstructure within the concrete. This leads to improved resistance against washout. Silica fume is frequently the preferred choice for enhancing washout resistance in underwater concrete thanks to its wide availability, cost-effectiveness over nano silica, and ease of use. However, it is worth noting that the effects of both silica fume and nano silica can be adjusted using chemical admixtures such as superplasticizers and HRWRAs. This synergistic combination not only maintains workability but also simultaneously boosts the concrete's resistance to washout. To optimize washout resistance, it may be necessary to modify other elements of the concrete mix design, such as the water-to-cement ratio and the types and quantities of other admixtures. These adjustments aim to maintain or even improve the mix's workability when silica fume or nano silica is incorporated [8,68,131,134].

As mentioned before, a definitive test for evaluating washout loss is the plunge test, conducted in accordance with the USACE CRD-C61 standard. Figure 9 illustrates the apparatus and process used to conduct this test [54]. In this test, a fresh UWC sample weighing approximately 2 kg is prepared and pre-wetted. It is then placed in a perforated stainless-steel container, which is subsequently tamped 10 times on the top and sides. The container is carefully sealed and weighed (M1) before being lowered into a washout tube made of either plastic or glass that is filled with water. After reaching the bottom of the tube, the container rests there for 15 seconds before being rapidly pulled out within a 5-second timeframe. The water from the container is allowed to drain back into the tube, and the container is weighed again (M2). The discrepancy between the initial and final weights (M1 and M2) indicates the washout loss for the UWC sample. This test is performed in triplicate for each set of conditions, and the average weight loss is calculated to determine the degree of washout. By understanding and implementing these measurement techniques and mitigating the contributory factors, it is possible to significantly improve the washout resistance of UWC, thus enhancing its structural robustness and longevity [117,119].

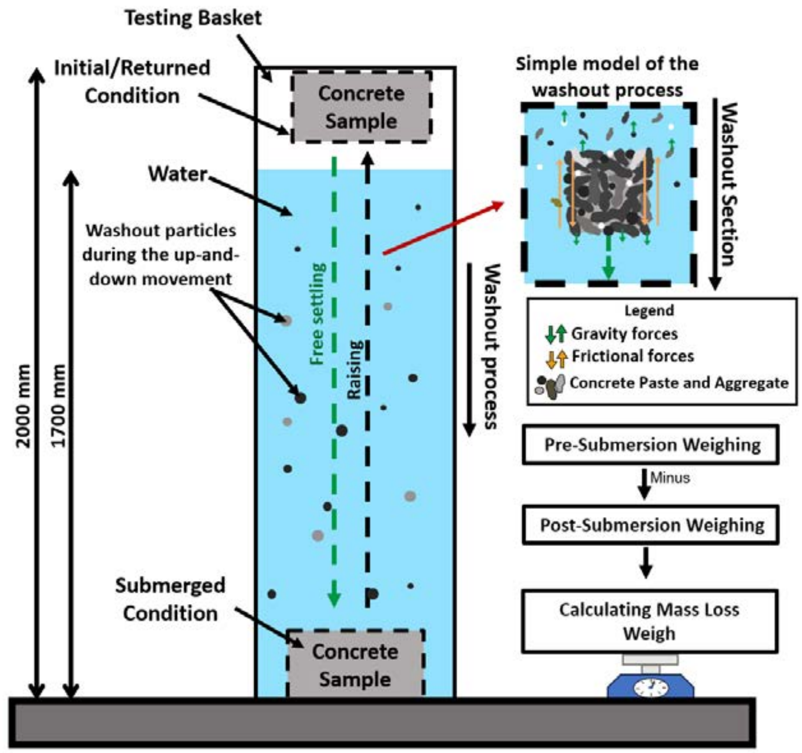


Figure 9. Schematic of washout (plunge) test for measuring concrete mass loss [54,117]

2.4 Hardened Properties

Evaluation of the hardened properties of concrete is indispensable for its use in structural applications. This evaluation becomes even more vital for UWC given the harsh and challenging environments it is exposed to. A comprehensive understanding of the mechanical, durability, and bonding properties of concrete is necessary for assessing the long-term performance, safety, and structural integrity of underwater concrete structures. These properties also inform mix design and quality control procedures, thereby guiding engineers in the successful application of UWC [13,27].

2.4.1 *Mechanical Properties*

Although some research suggests that concrete specimens maintain higher strength when consistently kept in a humid environment as opposed to being dried and stored in natural conditions, these findings may not fully translate to the unique circumstances of UWC. The process of underwater casting introduces additional variables, such as the potential for mass loss due to washout and dilution of the concrete mix due to interaction with water. These factors raise concerns about the mechanical properties of UWC, especially in terms of how the behavior of UWC may differ from that of conventionally cast concrete in controlled environments. In other words, there are concerns regarding the mechanical performance of UWC. Factors such as washout of cement, incomplete hydration, and difficulties in compaction during underwater casting can adversely affect UWC's mechanical properties. Adequate mechanical properties ensures the long-term durability of UWC, especially when the concrete is exposed to saltwater, freeze-thaw cycles, and sediment abrasion. Understanding these mechanical properties allows for refinements in the concrete mix design, ensuring better performance. Ongoing tests serve as a quality control mechanism to confirm that in situ UWC meets design specifications. The assessment of mechanical properties is paramount for ensuring the structural adequacy of UWC when failure could have catastrophic consequences [90-92,100].

Numerous studies have delved into the strength properties of underwater concrete, uncovering notable differences when compared to concrete cured in air. A landmark 1987 study by the U.S. Bureau of Reclamation [174] showed that certain sections of dams immersed in water achieved an average compressive strength about 20% greater than their counterparts cured under moist conditions. In a similar vein, research by Alaejos et al. [175] found that concrete submerged in seawater retained its compressive strength and durability for up to 90 days, showing comparable results to concrete in standard moisture conditions. In fact, these results affirm that the mechanical properties of submerged concrete either remains consistent or even experiences a slight increase over time compared to its 28-day compressive strength, despite exposure to saline water or various microorganisms underwater. To effectively differentiate underwater concrete casting sequences, it is crucial to understand that there is a difference between concrete that is first cast in a dry environment and then submerged after setting, as opposed to concrete that is directly cast underwater and remains submerged as it cures to gains strength. Some studies focused on concrete submerged for extended periods and noted the maintained or slight increase in strength compared to dry conditions. However, this shouldn't be misconstrued to mean that direct underwater casting always results in strength maintaining or growth. Challenges like potential paste loss or air bubble inclusion during casting can compromise the concrete's integrity and strength. Nevertheless, if cast without mass loss, it suggests that the concrete's density and strength underwater are reliable, contingent upon proper underwater casting methods. Notably, concrete mixes with mineral additives like fly ash and slag consistently showcased enhanced strength, especially after 90 days, surpassing traditional portland cement concrete in performance [86-89].

This body of research calls into question the common practice of relying on 28-day strength tests for structural design. Given the unique properties of UWC, it may be more appropriate to consider 90- or 180-day compressive strength as a basis for structural calculations. Additionally, the test cylinders used in strength compliance tests should ideally be subjected to conditions that mimic those of the in situ concrete, in that they should be maintained either in a fully immersed state or in an environment with 100% humidity. It is also worth noting that the method of concrete placement can significantly affect its final strength. According to several studies, concrete placed utilizing the tremie method demonstrates superior shape stability, filling ability and strength in comparison to concrete that is placed either by direct pumping or through the hydro valve methods. The latter techniques often lead to a less cohesive mixture and a higher prevalence of voids. Such disparities can be attributed to variations in the discharge method and the rate at which concrete exits the pipe [87,114,135]. AWAs are viscosity-modifying agents that inhibit cement hydration, potentially leading to long-term detrimental impacts on both the cement hydration process and the resulting concrete microstructure. This inhibition often results in an increase in capillary porosity. Additionally, concrete containing AWAs typically exhibits higher viscosity than conventional concrete, which can lead to a greater amount of entrapped air in the concrete mix. Due to these adverse factors, AWC generally demonstrates lower compressive and flexural strengths compared to its conventional concrete counterparts, as confirmed by multiple studies [13-18] and illustrated in Figure 10. In this context, "relative compressive strength" is defined as the ratio of AWC's compressive strength to that of AWA-free conventional concrete; "relative flexural strength" is similarly defined.

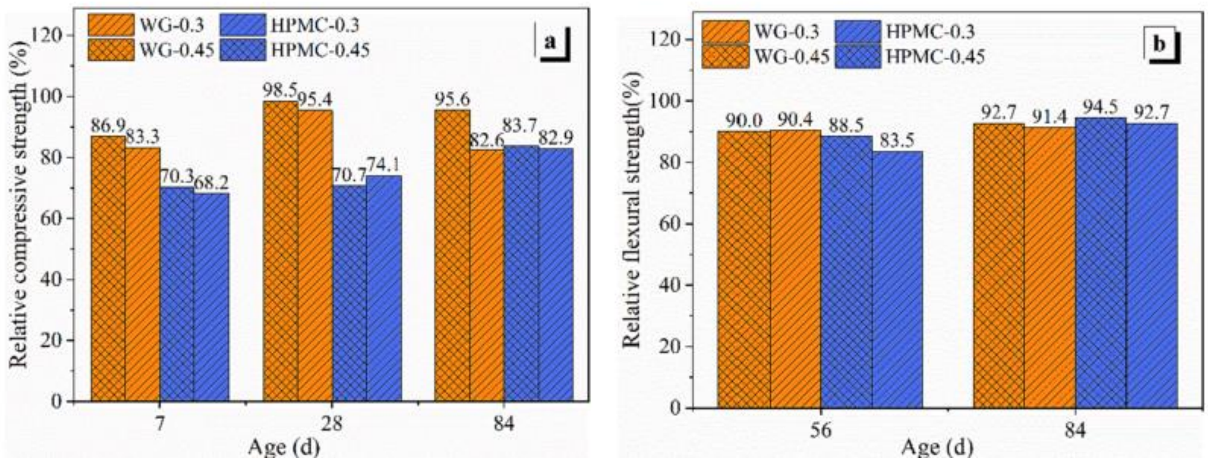


Figure 10. Relative compressive (a) and flexural (b) strength results for welan gum (WG) and hydroxypropyl methyl cellulose (HPMC) added AWC mixtures [13]

As shown in Figure 10, various concrete mixtures were tested featuring water-to-cement ratios of either 0.3 or 0.45 and different curing ages (7 days, 28 days, 56 days, and 84 days). The results indicate that both relative compressive and flexural strengths are typically less than 100%. Different countries have specific regulatory requirements for AWC's mechanical properties. For example, Chinese specifications mandate that the 28-day compressive and flexural strengths of AWC must reach at least 70% and 60%, respectively, of those of conventional concrete [136]. In South Korea, the regulation stipulates that the relative compressive strength of AWC should be more than 80% of its conventional concrete counterpart [137]. In a study conducted by Horszczaruk and Brzozowski [25], it was observed that the 28-day compressive strength of UWC was a relatively modest 7.5% below the average 28-day compressive strength values of specimens tested in conditions outside of water. This suggests that the effects of underwater casting on compressive strength may be less detrimental than commonly perceived, at least under certain conditions. According to the existing literature [11,13,138], the inclusion of AWAs appears to have a minimal impact on the stress-strain behavior and failure modes of concrete. In a study by Khayat et al. [13] it was confirmed that the use of welan gum as an anti-washout admixture in concrete with a w/c ratio of 0.30 led to an approximate 10% reduction in compressive strength. Furthermore, Khayat et al. observed that the incorporation of anti-washout admixtures into UWC generally results in a 10% to 15% reduction in flexural strength compared to similar concrete formulations that do not contain anti-washout admixtures [13,58].

2.4.2 *Durability Properties*

Durability is a key concept in engineering, epitomizing the resilience and longevity of materials and structures against various environmental factors. It is especially critical in underwater structures, where durability means the ability of concrete to resist weathering, chemical attack, and abrasion while maintaining its desired engineering properties. Concrete's popularity in marine construction stems from its economic benefits for building large structures and its general excellence in marine durability. The growing use of marine spaces for infrastructure highlights the importance of understanding concrete's durability in underwater applications. The future of marine construction will place even greater demands on concrete, pushing its limits in challenging environments like ocean depths, estuaries, and areas with extreme climates. Recent advances in concrete technology have introduced various options to enhance concrete properties. The use of cement blends with pulverized fuel ash, slag, and micro silica, along with admixtures like superplasticizers, retarders, and air entrainers, help control the properties of both fresh and hardened concrete. Innovations have led to the creation of high-strength concretes with normal and lightweight aggregates, and the development of fiber-reinforced concretes, which offer added ductility and cracking resistance, making them suitable for aggressive underwater environments. Several deterioration processes can affect underwater concrete, including chemical deterioration from harmful substances and physical degradation due to climatic extremes and harsh exposure conditions. While exposure to saltwater and splash and tidal zones are not critical concerns in Wisconsin, the properties of concrete and its hydration products play a significant role in underwater durability. Strategies to prevent deterioration involve selecting appropriate materials, which in turn affect concrete properties, offering a comprehensive view of the current knowledge and future directions in this field. Critical durability properties like impermeability, resistance to chloride ion penetration, and freeze-thaw resistance are essential for assessing the longevity of underwater concrete structures.

The durability of underwater concrete is influenced by environmental factors, material properties, and construction practices. In general, exposure zones in marine environments are critical in determining the type of degradation processes concrete will face. The splash zone, above the high tide level, is particularly hostile, exposing concrete to atmospheric conditions, salt spray, and wetting and drying cycles. This leads to risks like chloride-induced corrosion and freeze-thaw damage. The tidal zone, between low and high tide levels, subjects concrete to mechanical abrasion and chemical decomposition of portland cement hydrate. The submerged zone, always under water, faces less corrosion risks but is more prone to chemical attacks from underwater salts. The chemical composition of water bodies also affects durability. Factors like the concentration of dissolved oxygen, chloride ions, and the salinity of water bodies play a significant role. Different mechanisms of deterioration, such as magnesium attack, sulfate attack, and ettringite formation, can weaken concrete. Additionally, temperature variations significantly impact underwater concrete structures, especially in regions with considerable climatic fluctuations. Freeze-thaw cycles, surface spalling, and deterioration of joints are some of the challenges faced [68,135-141].

Marine fouling from aquatic microorganisms adds another layer of complexity, involving biological, chemical, and physical factors. While microorganisms like sulfate-reducing bacteria can lead to bio-corrosion, others may provide benefits, like forming barriers that limit corrosive substance penetration. Strategies to mitigate these effects include using bio-resistant coatings and selecting concrete types less susceptible to microbial corrosion.

In recent years, the use of AWAs and VMAs in underwater concrete formulations has gained attention for their impact on durability. AWAs have been found to improve durability by reducing chloride ion permeability and water permeability. However, VMAs can negatively impact air permeability and freeze-thaw resistance. The impacts of these admixtures require careful understanding and application, emphasizing the need for future research to optimize formulations and dosages for maximum benefit. Ensuring the durability of underwater concrete involves understanding and addressing a multitude of factors. From the composition of the concrete itself to the environmental conditions it faces, each aspect plays a crucial role in maintaining the structural integrity and longevity of underwater constructions [142-150].

2.4.3 *Bonding and Repair Mechanisms*

The durability and long-term structural integrity of underwater concrete structures, particularly drilled shafts and piers are critically threatened by the corrosion of steel reinforcement bars. This corrosion, exacerbated by surface cracks or minor spalling in aquatic environments, can significantly reduce the lifespan of these structures. To counteract this, several repair and rehabilitation methods have been developed, focusing on restoring structural strength, halting further damage, and extending the lifespan of these submerged structures. Key repair techniques include surface spalling repair, injection techniques, preplaced aggregate concrete methods, and steel sleeve coverage techniques. A crucial aspect of repairing underwater structures is the bonding properties of the concrete. Achieving a strong bond between existing and new materials is vital for the structural soundness and extended performance of the repair. This bonding quality is evaluated through adhesion tests, shear bond strength, and pull-out strength measurements. Factors influencing the bonding capabilities include the quality of the substrate, concrete mix design, surface preparation techniques, and environmental conditions such as temperature and humidity [135,151,152].

In underwater concrete casting and repair, attention is given to resistance to washout and the mass loss ratio. Research indicates that a higher mass loss ratio leads to reduced bonding strength. This finding is significant in understanding how pre-existing cracks can accelerate the corrosion cycle, leading to further deterioration. To address these challenges, innovative solutions such as styrene-butadiene rubber (used as priming coats) and light-curing resin cement have been utilized. These materials are modified for optimal film thickness, filler distribution, and curing times, making them suitable for underwater repairs. Additionally, anti-washout admixtures are studied to enhance concrete's resistance to washout, thereby reducing the mass loss ratio and improving bonding strength. When selecting materials for underwater concrete repair, it is essential to consider factors that might cause debonding due to stresses at the interface, such as drying shrinkage, thermal strain, water pressure, and elastic mismatch. The key properties for a durable repair include addressing drying shrinkage by using expansive cement or additives like Type K cement, matching the coefficient of thermal expansion of the repair material with the original concrete, and ensuring that the elastic modulus of the repair material aligns closely with that of the existing concrete. Core sampling and laboratory testing, including ultrasonic pulse velocity (UPV) testing, play a crucial role in achieving this compatibility. The transport properties of concrete, encompassing characteristics such as permeability, porosity, diffusivity, and capillarity, are also critical. These properties control the extent to which corrosive agents can penetrate the concrete, thus determining its durability. For underwater concrete structures, repair materials must be impermeable to prevent water intrusion and either highly resistive to conductivity or entirely nonconductive to protect against reinforcement steel corrosion. The repair and bonding of underwater concrete structures involve a comprehensive approach that considers material properties, environmental factors, and the specific challenges of underwater conditions. This approach ensures the compatibility, bonding strength, and longevity of repair endeavors, aiming to restore and prolong the life of these vital structures. Table 5 summarizes the requirements of patch repair materials that are compatible with existing underwater concrete structures [71,135,152,155].

Table 5. Requirements for patch repair materials in relation to the properties of the concrete substrate.

Property	Relationship of repair material (R) to concrete substrate (C)
Shrinkage strain	R < C
Creep coefficient (for repairs in compression)	R < C
Creep coefficient (for repairs in tension)	R > C
Thermal expansion coefficient	R = C
Modulus of elasticity	R = C
Poisson's ratio	R = C
Tensile strength	R > C
Fatigue performance	R > C
Adhesion	R > C
Porosity & resistivity	R = C
Chemical reactivity	R < C

2.5 Underwater Concreting Practices

In traditional construction practices in aquatic environments, cofferdams have long been a preferred method for creating a dry work environment. These structures, often formed by installing sheet piles around the desired work area or submerging prefabricated units, require water to be pumped out to make the area suitable for activities such as concrete casting. However, while cofferdams have been instrumental, they come with their own set of challenges. The alteration of water paths, for instance, can have detrimental effects on aquatic ecosystems. The installation time for cofferdams, especially on large-scale projects, can be lengthy, leading to extended project timelines. Additionally, there is always an inherent risk associated with cofferdams, in that any failure can result in catastrophic consequences for both the project and the environment [101,156]. The contemporary alternative to cofferdams is underwater concreting. Recognized as a more efficient option, underwater concreting eliminates many of the logistical and environmental challenges posed by cofferdams. For starters, there is no need to divert water paths or pump out vast amounts of water. As mentioned in previous sections, modern advancements in concrete chemistry and admixtures have ensured that concrete can set and cure efficiently underwater, maintaining its durability and strength. Cost-effectiveness is another major advantage. Underwater concreting reduces the need for extensive machinery and infrastructure, like that required for cofferdams, translating to substantial cost savings on large-scale projects. Numerous projects, ranging from the construction of bridge piers and deep drilled shafts to repair and restoration of bridge substructures, can successfully employ underwater concrete pours and non-segregating concrete casting methods. The outcomes often include reduced project timelines, minimal environmental impacts, and a level of structural integrity that matches, if not exceeds, the results obtained from more conventional methods [71,101,135].

For the casting of underwater concrete, precision in the initial production step is crucial. It involves measuring water and liquid admixtures by volume or weight and weighing solid components. Contemporary practices largely utilize ready-mix concrete plants with automated or semi-automated systems, combining batching, mixing, and transportation. While truck mixers are common for their convenience, central mixing is preferred for better homogeneity and uniformity. High-speed mixers are used for enhanced cohesiveness in fresh concrete and improved strength in hardened concrete, and the sequence of batching components significantly impacts the final product. It is important to ensure the de-flocculation of cement particles and mineral admixtures in the dry mix before introducing water and superplasticizers. For high-slump concretes, a portion of the superplasticizer dosage is often added at the site to combat slump loss during transportation. Testing for compatibility of superplasticizers and other additives in trial batches is also crucial. Specialized mixing procedures are employed to optimize air entrainment, which is particularly vital for underwater concrete. Speedy transportation of freshly mixed concrete is essential to prevent significant consistency loss, ensuring smooth placement, consolidation, and finishing. In milder or colder conditions, consistency loss within the first 30 minutes is minimal. However, in hotter climates, this can be more pronounced. The proximity of the batching plant to the job site offers benefits in preserving concrete's fresh properties, transportation cost-efficiency, and consistent quality control. Various equipment types like truck mixers, conveyors, cranes, chutes, and elevators are used for transporting concrete, with the primary goal being to maintain the mixture's integrity and prevent segregation. Regular inspections of mixer blades in trucks are necessary to avoid segregation. Underwater concrete placement requires specialized techniques for inspecting conditions and assessing concrete surfaces needing repairs. These inspections are typically conducted visually by divers or ROVs. After assessing conditions, selecting the most appropriate casting methods is crucial. Key areas in the technical specifications for underwater concreting include:

- Method and technique of placement
- Sequence of placement
- Equipment layout for placement
- Concrete finishing process
- Protective measures for the concrete

The ideal placement plan depends on site-specific conditions, engineering demands, desired concrete properties, concrete volume and thickness, water currents during placement, presence of reinforcement or obstructions, equipment availability, technical viability, and cost. One of the main challenges in underwater concreting is the potential for washout, leading to segregation. Techniques like the tremie method and pumping minimize direct contact with water, preventing segregation. Anti-washout additives are also used to counteract segregation, allowing for more flexible placement methods. To maintain structural integrity, it is vital to minimize concrete's direct contact with water and use anti-washout admixtures. Ideally, new concrete should be placed at the center of previously poured concrete, and single-pass pouring methods are preferred. The concrete used must possess self-compacting and self-leveling qualities, as underwater compaction tools can compromise the mix. Challenges like high water velocities may require timing adjustments or flow diversion. Limited visibility and control over the pour site necessitate simple reinforcement designs with wide spacing and larger bars to facilitate concrete flow and reduce voids. The following are the major methods of underwater concreting [71,87,135,157]:

- Tremie method

- Pumping technique
- Preplaced aggregate concrete
- Bags and bucket methods

2.5.1 *Tremie Method*

The tremie placement method is a widely known technique for placing underwater concrete. Underwater concreting using the tremie method is convenient for pouring a large amount of highly flowable concrete. The concrete is moved to the hopper by either pumping or using a belt conveyer or bucket. Tremie pipe, whose upper end is connected to a hopper and whose lower end is continuously submerged in fresh concrete, is used to place concrete at a precise location from the hopper at the surface. The reason to immerse the tremie pipe's lower end is to prevent intermixing of both concrete and water. The typical arrangement for a tremie pipe is shown in Figure 11. A number of factors should be considered when using the tremie pipe technique for underwater concreting, as summarized in the sections below [9,135,158].

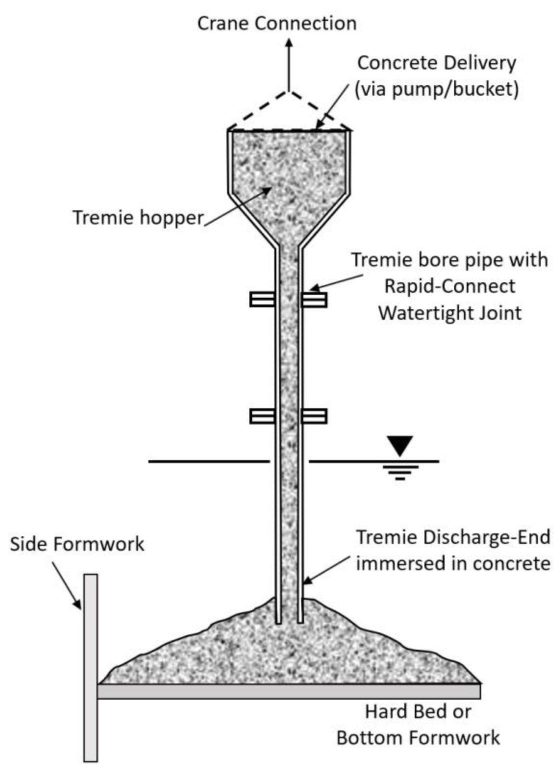


Figure 11. Underwater concrete placement using tremie technique [177]

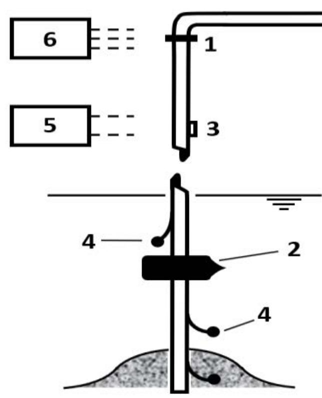
2.5.1.1 Tremie Equipment

The tremie pipe might be configured in three different ways. The pipe can be set at a constant length and raised during concreting, the pipe can have different sections that are dismantled during concreting, or a telescoping pipe can be used. Irrespective of the configuration, understanding the operation and management of the tremie pipe is vital for the successful execution of the tremie method. A tremie pipe is a watertight pipe used to place concrete underwater in a way that prevents the concrete from being contaminated by water. The commonly used diameter for a tremie pipe ranges from 150 to 250 mm (6 to 10 in.). However, in instances where the aggregate size is considerably large, such as a maximum size of 38 mm (1.5 in.), diameters can extend up to 400 mm (16 in.). The selection of the pipe diameter should consider the aggregate size in the concrete mix. Furthermore, for deep drilled shafts or foundations, the pressure and weight of the concrete might demand a larger diameter. This ensures a consistent and uninterrupted flow, tailored to the specific needs of the project. The tremie pipe must be made of durable materials that can handle the weight and abrasiveness of the concrete mix while also withstanding underwater conditions [101,114,160]. The most commonly used materials for tremie pipes are as follows:

- **Steel**. This is the most common material used for tremie pipes. Steel is durable and resistant to abrasion and can handle the weight of the concrete mix effectively. Steel pipes usually come with watertight joints to ensure that there is no ingress of water during the concrete placement process [114,135].
- **Aluminum**. Lighter than steel, aluminum tremie pipes are easier to handle, especially for smaller projects or in situations where the handling equipment has weight limitations. They are also resistant to corrosion, but they may not be as robust as steel when it comes to handling very heavy loads or aggressive concrete mixes. An aluminum alloy pipe can adversely affect the concrete due to chemical reactions between the pipe and concrete materials and therefore should be avoided. The pipe should have an adequate diameter to prevent blockage because of aggregate size [1, 87,135,157-159].

The integrity of the concrete seal at the bottom of the tremie pipe is paramount. A broken seal can lead to the pouring of fresh concrete atop a previously laid layer, which, especially when water is present, results in the formation of a weak layer within the pour and compromises the integrity at the water-concrete interface. Therefore, it is essential to submerge and pour the concrete within the previous layer rather than on top of it. Loss of charge in the tremie pipe necessitates a full restart of the operation. If the seal breaks, pouring should cease immediately. To resume pouring, the end of the tremie pipe must be repositioned within the already poured concrete to avoid the inclusion of weak material. Recharging should be carried out with an end-plate on the tremie pipe to prevent water intrusion. In the case of a broken seal, the tremie pipe should be lifted and an end-plate attached, and then the pipe should be repositioned using kentledge. Once the pipe is positioned and charged, the end-plate is removed and pouring continues. The primary concern with a broken seal is the potential damage to the poured concrete. Ascertaining the damage during the pour is challenging, and using divers to inspect the pour could lead to more harm. If extensive damage is suspected, halting the work to let the concrete set is advisable. Post-set, the extent of the damage can be gauged, and, after necessary repairs and surface preparation, pouring can recommence.

A significant advancement in tremie pipe design is the introduction of a hydraulically operated valve at the pipe's lower end. A system detailed by Yamaguchi et al. includes a crushing valve that operates hydraulically and is equipped with pressure (level) sensors (Figure 12). This tremie setup dramatically reduces the likelihood of seal loss and accommodates interruptions in the supply of concrete to the tremie hopper. The crushing valve serves as a one-way mechanism, allowing concrete to flow out but preventing water or slurry from flowing back into the pipe. This feature is particularly crucial when initiating the Tremie method, where the pipe is originally filled with water or bentonite slurry to prevent the entry of air. As concrete placement begins, the valve ensures the concrete displaces this initial filling without it re-entering the pipe, thus reducing the risk of segregating the concrete mix. Furthermore, by maintaining hydrostatic pressure, a continuous flow of concrete is ensured, preventing the potential formation of voids or inclusions in the placed concrete. Additionally, the valve simplifies the concrete placement process, especially during moments of repositioning or relocating the Tremie pipe. On the other hand, the pressure sensors embedded in the setup offer real-time monitoring of the hydrostatic pressure within the Tremie pipe. As the concrete is poured, the weight of the concrete column inside the pipe generates hydrostatic pressure. This pressure should remain relatively stable to ascertain continuous and consistent placement. A sudden drop or spike in this pressure can be indicative of a problem, such as an unsealing of the Tremie pipe from the concrete below or potential blockages in the pipe. These sensors enhance safety by supplying real-time data, allowing swift action upon detecting unexpected pressure variations. They also play a pivotal role in upholding the integrity of the placed concrete. Keeping a close eye on the pressure ensures that the Tremie pipe remains submerged in the freshly placed concrete. This is paramount to avoid the inclusion of air or water, which can lead to potential weaknesses or defects in the concrete structure [1,71,87,135].



	Part Name	Recommended Specification
1	Tremie pipe	150-250 mm (6-10 in) diameter
2	Crushing valve	150-250 mm (6-10 in) diameter
3	Pressure sensor	Gauge with 0-500 psi range, ±0.5% Full Scale accuracy, IP68 protection
4	Level sensor	Tilt switch
5	Control unit	Hydraulic
6	Lamp indicating panel	LED indicators for operational status
7	Flexible delivery hose	200 mm (8 in) diameter, 10-meter (33 ft) length

Figure 12. Specifications for tremie with crushing valve and pressure sensor [135]

The tremie method offers a robust solution for underwater concrete placement. Ensuring the maintenance of the concrete seal in the tremie pipe and understanding how to manage interruptions are critical for the method's success. Advancements such as the incorporation of a hydraulically operated valve further enhance the reliability and efficiency of this method.

2.5.1.2 Tremie Seal

To prevent water from mixing with concrete in the tremie pipe, a wooden plug or metal plate is inserted at the end. This ensures that as the pipe is lowered to its desired location, water is kept out, maintaining the pipe's interior dry. Once positioned, pouring the concrete displaces and opens the plug or plate, often referred to as a "loose plate." This design ensures the plate only opens outward, preventing water ingress. The newly poured concrete then forms a seal around the pipe's bottom end, ensuring a consistent and uncontaminated flow.

2.5.1.3 Placement and Flow Pattern

As soon as concreting begins, the pipe's mouth should be submerged as much as 1 to 1.5 m into the fresh concrete to prevent water from entering the pipe. The concrete flow rate is controlled by lowering and raising the pipe, and either a decrease or increase in concrete discharge indicates the loss of the seal. Therefore, the flow of concrete should be continuous and carefully monitored.

Two types of flow patterns are recognized, namely, layered and bulging. A bulging flow is desired because it displaces the concrete uniformly, which leads to less laitance deformation and flatter slopes [71, 87, 126, 135].

2.5.2 *Pumping Technique*

The pumping technique for underwater concreting is a developed version of the tremie method and is more effective for concreting in areas that are difficult to access, such as under piers. Pumping provides several advantages over the tremie method. For example, concrete is poured from the mixer directly into formworks, blockages in the pipe are minimized because the concrete is placed through pumping instead of gravitational force, and the risk of segregation is decreased. Figure 13 shows a typical pipeline configuration for the pumping method.

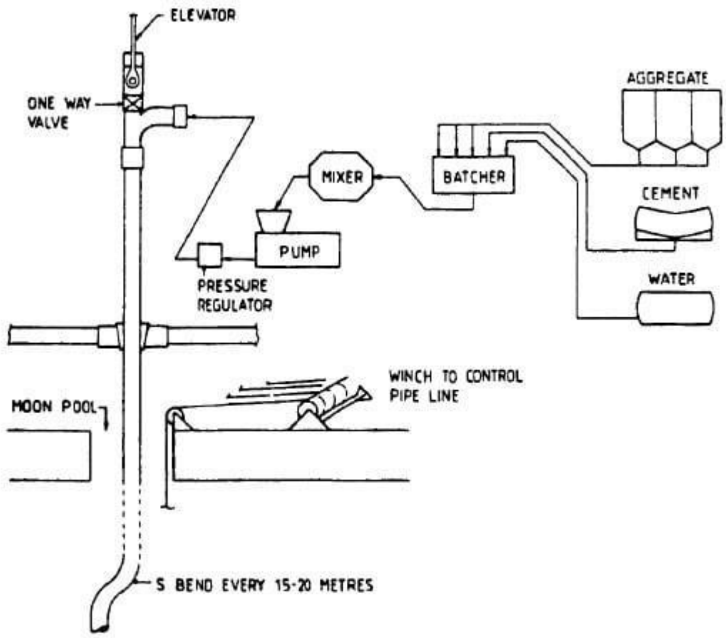


Figure 13. Pump system for underwater concrete placement [177]

While the conventional tremie technique is widely used, it often presents logistical challenges due to its reliance on cranes to hold the tremie hopper. The need to raise and lower the tremie pipe to regulate the pouring process, coupled with the method of filling the hopper with concrete via skip, can be cumbersome. In contrast, advanced concrete pumping techniques reduce the operation's dependence on cranes. One of the primary benefits of using pumping techniques is the rapid and virtually continuous delivery of concrete to the pour site. Modern pumping systems, utilizing static pipe runs, can transport concrete over impressive distances of up to 1,000 m. Further, the hydraulic booms found on most mobile units add a significant degree of versatility in terms of concrete placement. The use of hydraulic booms allows for two primary modes of concrete placement underwater: through a tremie system or direct pumping to the desired site. If a tremie system is used, a concrete pump becomes the optimal way of feeding the hopper, thanks to the steady flow of concrete and the ease of repositioning the delivery pipe using the hydraulic boom. This setup ensures that operators can efficiently manage multiple-term pipes. A standout feature of the pumping method is its ability to deliver concrete underwater without reliance on gravity. This feature helps avoid issues such as segregation. However, it is crucial to maintain the same placement principles as used with the traditional tremie method. A major point to consider is the minimization of the water-concrete interface. Freshly poured concrete should ideally settle at the core of the previously placed mass. Given the complexity of the operation, blockages can occasionally occur, making it prudent to have a backup pump ready on-site. When placement depths surpass 35 m, incorporating a non-return valve into the pumping line becomes essential. The pump's delivery rate is intrinsically linked to the head loss within the pipeline. The greater the length of the pipe, the higher the pumping head required, with the pumping head restricted by both the pump unit's capacity and the delivery pipe's seals. Pressure loss due to friction is a factor when conveying a fluid, or in this case concrete, through a pipeline. Typically, a concrete pump can dispatch concrete at a rate of around 90 m^3/hour. However, a pump has operational constraints tied to pressure, with a peak delivery pressure of around 300 psi. The friction-caused head loss for standard pumped concrete is roughly 0.06

kg/cm^2/m. Factors like back-pressure from the overlying water and concrete play a pivotal role in influencing pumping pressures and, consequently, the delivery rate. When the pipe is submerged into the concrete to a depth ranging from 100 to 200 mm (4 to 8 in.), the pump's working pressure remains within acceptable bounds. For open-form concrete delivery, a trailing pipe can efficiently place the concrete [157-161]. A challenge faced during vertical downward concrete pumping is the risk of the concrete freefall, leading to segregation. This can be curtailed by employing a plug akin to that used in the tremie method. Introducing a sponge plug at the top of the delivery line before the pumping process can effectively support the concrete. In scenarios involving deep pours, it might be necessary to incorporate pairs of 90-degree bends in the line every 15 to 20 m to manage the flow.

2.5.3 *Preplaced Aggregate Concrete*

The preplaced aggregate concrete method, also known as the two-stage concrete placement method or the grouted aggregate concrete method, is a contemporary underwater placement technique offering significant benefits, particularly in challenging underwater conditions. This technique is ideal for areas subjected to high water velocities or waves or for places with limited access, where conventional placement methods are not feasible. The preplaced aggregate concrete method differs from traditional concreting in both its placement process and the materials used. The steps involved in this method can be summarized as follows: [79,80,166]

1. **Aggregate Placement**. Initially, coarse aggregates are positioned at the desired underwater location. It is essential to note that this method heavily relies on the coarse aggregate content of the concrete, which is present in higher proportions compared to traditional concrete.
2. **Grouting**. Once the aggregate is in place, the cavities or voids between the aggregate particles are grouted. This grouting is achieved using specialized anti-washout concrete or mortar. The pumping tubes used for this process extend to the bottom of the form, ensuring that the grout fills the voids effectively and uniformly.
3. **Displacement of Water and Air**. In the two-stage concrete placement method, the water and air present between the aggregate particles are pushed upwards by the advancing grout front. The grout injection continues until grout emerges free of contaminants from the pour's top, indicating that the voids between the aggregate particles are entirely filled.
4. **Starting from the Bottom**. One of the crucial aspects of this method is that concreting commences from the bottom. This bottom-up approach is vital to prevent air and water from becoming trapped. Consequently, tubes are strategically positioned in the forms before the aggregate is placed.

This method is illustrated in Figure 14.

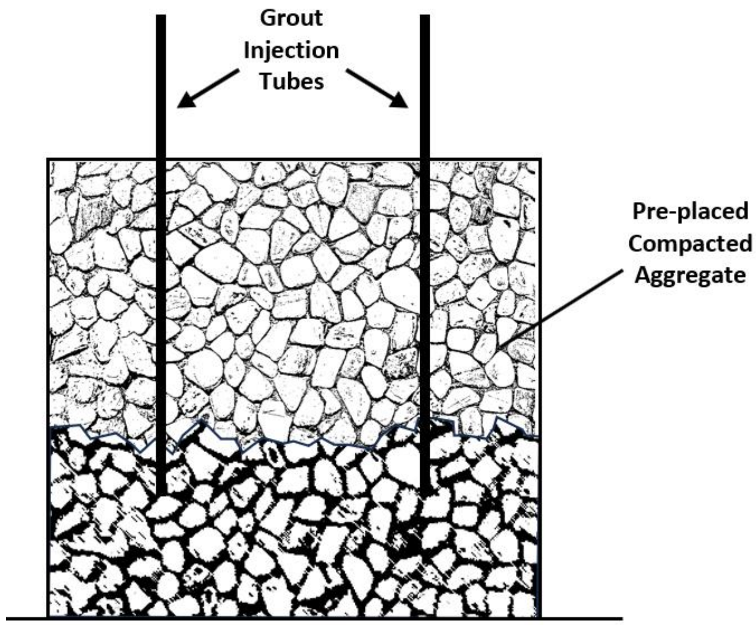


Figure 14. Simplified view of preplaced aggregate method [177]

The advantages of the preplaced aggregate concrete method are as follows:

- **Quality Control**. Because this method involves a systematic two-stage process, there is a greater scope for quality assurance. By placing the aggregates first, their uniform distribution can be ensured, which in turn subsequently ensures an even distribution of the grout.
- **Reduction in Aggregate Segregation**. Given that the aggregates are placed before the grout is pumped, the chances of segregation are significantly reduced, resulting in a homogenous concrete mix.
- **Better Bonding**. The preplaced aggregate method often results in better bonding between the aggregates and the grout, contributing to a concrete structure with enhanced strength and longevity.
- **Efficient Air and Water Displacement**. The systematic bottom-up approach ensures that trapped air and water are effectively displaced, leading to a more compact and defect-free concrete [53, 79, 80, 166].

A concrete strength of about 70% to 100% of that of conventional concrete can be obtained using this technique. The pipes are distributed at a maximum distance of 1.5 m (5 ft) from each other, and their diameters range from 20 to 35 mm (0.8 to 1.4 in.). The preplaced aggregate concrete method offers remarkable adaptability in terms of application, catering to both repairs and large-scale underwater concrete placement. For repair purposes, especially in areas necessitating precise application and delicate handling, finer aggregates are predominantly used. This allows for a smoother finish, ensuring that the repaired section seamlessly integrates with the existing structure without causing any inconsistencies. More details about the use of this method for repairs can be found in Section 2.5.8. For large-scale underwater concreting projects, the method can accommodate aggregates as large as 63 mm (2.5 in.). The use of larger aggregates provides a robust framework for the concrete, enhancing its structural integrity and ensuring its longevity.

These larger aggregates also expedite the placement process, proving to be cost-effective and efficient for vast underwater construction projects [53, 135, 166].

2.5.4 *Bucket Method*

Utilizing the Bucket Method for underwater concrete placement ensures precision and control, combining the reliability of a watertight box or bucket with a hydraulic double-door mechanism at its base, resembling a bottom jaw. After preparing a concrete mix with the desired flowability, it is poured into the bucket. This loaded bucket is then methodically lowered to the target placement location, often with the assistance of divers in deeper waters to guarantee exact positioning. Upon reaching the correct spot, the hydraulic mechanism springs into action, opening the bottom doors for a measured release of the concrete directly into the formwork. This careful discharge process is what sets the Bucket Method apart, especially when large quantities of concrete need to be strategically positioned. The design ensures the concrete's consistency and quality, whether it is being placed close to the surface or in more challenging deep-water scenarios (see Figure 15).

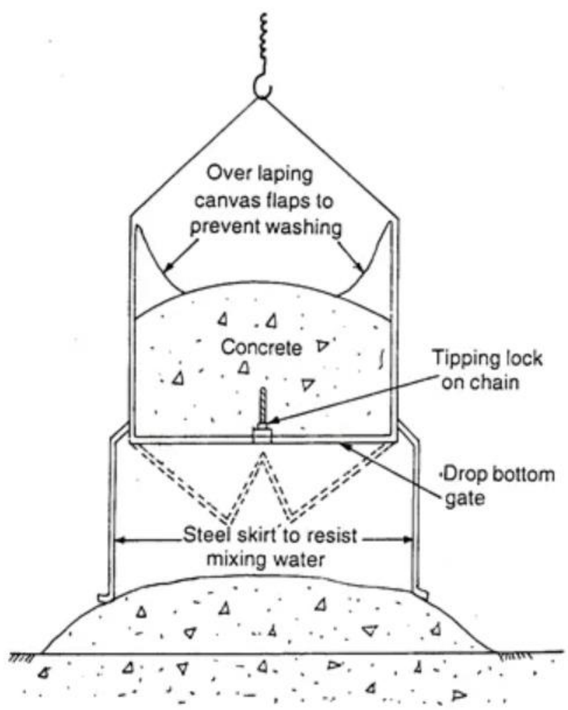


Figure 15. Bucket method for underwater concrete placement [177]

2.5.5 *Other Placement Methods*

While tremie and pump methods are the most widely used techniques for underwater concreting, there are several other methods that, depending on the specific conditions and requirements of the project, can be used alone or in conjunction with the more common methods. Here is a concise overview:

2.5.5.1 Valve methods

Various valve techniques have been developed to control the flow, prevent water ingress, and placement of concrete underwater. One such technique is the Hydro Valve, introduced by Dutch engineers, which employs a flexible hose that's hydrostatically compressed to pour concrete. The weight of the concrete counterbalances both internal friction and hydrostatic pressure, ensuring a consistent flow and preventing segregation. Another approach is the use of Pneumatic Valves, such as the Abetong-Sabema and Shimizu valves. These valves are designed to regulate the discharge rate, optimizing the efficiency of the placement. Notably, the Shimizu valve incorporates a sensor that halts the flow once the concrete achieves a certain thickness. There is also an innovative strategy where the Tremie and Valve methods are combined. This amalgamation takes advantage of the Tremie method's continuous pouring feature and the precision of the valve techniques, ensuring a more efficient and precise placement of concrete underwater.

2.5.5.2 Bagging Techniques

One of efficient techniques for shallow underwater placement is the use of toggle bags, where a mostly canvas bag, sealed at the top, is filled with concrete and carefully dropped into the intended location. Once positioned, the concrete is discharged through an opening at the bag's bottom. On the other hand, the Bagged Concrete Method serves a more specific purpose. Primarily used for temporary repairs such as renewing foundations or sealing underwater holes, divers transport bags crafted from robust fabric to the desired site. These bags, filled with concrete with desired characteristics, adhere to stringent specifications concerning slump and aggregate size to ensure optimal performance.

In conclusion, the choice of depositing method greatly depends on the specific needs of the project, and often, a combination of methods is employed to achieve the desired result efficiently and effectively.

2.5.6 *Quality Control of Underwater Concrete Works*

Underwater concreting is an intricate process that entails special techniques and methodologies distinct from those used for regular concreting. Given its complexity and the challenges posed by the aquatic environment, ensuring quality becomes imperative. In this context, quality control (QC) and quality assurance (QA) play a pivotal role. Quality control refers to the procedures and activities aimed at ensuring the concrete's desired attributes during production and placement. It involves direct physical actions, such as inspection, testing, and verification, to ensure that the product meets the specified criteria. In underwater concreting, QC would encompass activities such as evaluating the concrete mix design, testing materials, checking the equipment, and monitoring the concrete placement. Quality assurance, on the other hand, is a broader framework encompassing all planned and systematic actions necessary to provide confidence that a product or service will satisfy given requirements for quality. It is more about process-oriented actions, ensuring that the approach to the entire project—from design to completion—is sound and that all processes are designed to achieve the desired quality. In underwater concreting, QA would involve setting up protocols, training personnel, documenting processes, and setting up contingency plans. Both QC and QA work in tandem in underwater concreting to ensure that structures are not only designed optimally but are also executed to perfection, guaranteeing the safety, reliability, and durability of marine structures [87, 135].

2.5.6.1 Before Casting

Underwater concreting is a specialized field that demands meticulous attention to detail. Its complexity is compounded by the challenges posed by the aquatic environment, such as poor visibility and unstable bases. Site inspections are paramount, ensuring that the placement site is free from debris and potential impediments. The stability of the riverbed or seabed is essential; it must be capable of bearing the weight and pressure of the fresh concrete. Equally essential in the pre-casting phase is equipment verification. When the tremie method is used, the tremie pipes should be inspected meticulously. Potential leakages at the joints or any malfunction can sabotage the whole operation. The quality of raw materials also cannot be overlooked. Before concrete placement, materials such as cement, aggregates, and admixtures should be tested rigorously to meet specified standards. The designed concrete mix should be vetted for its suitability in underwater conditions, with special attention given to its workability, setting time, and resistance to washout. Training is pivotal for underwater placement, as the involved crew should be thoroughly familiarized with all the key aspects of underwater concreting. This ensures not only quality but also safety during the casting process. Establishing a comprehensive quality control plan specific to the marine project is a fundamental step. This plan should outline the overall quality objectives, the procedures to be used, and the responsibilities of the project team. Clearly defined quality standards are crucial and should comply with relevant industry codes, regulations, and client requirements. In preparation, a robust document control system is also needed to manage and track quality-related documentation and to ensure that all documents are up-to-date and accessible.

2.5.6.2 During Casting

As casting commences, dynamic monitoring becomes the primary focus of QA/QC activities. One of the foremost concerns during this phase is the rate of concrete placement. It is vital to ensure that the concrete is placed at a consistent rate to avoid cold joints and to ensure even distribution. Depth is another significant concern. Using soundings, one can ascertain that the concrete is placed to the desired level. The sounding data provide real-time insights into the consistency and level of the poured concrete, allowing adjustments as needed. Concomitant with the placement process, concrete testing remains paramount. Regular assessments of parameters such as slump, temperature, unit weight, and compressive strength are indispensable. Contractor and supplier qualifications need strict evaluation and verification. Monitoring critical activities throughout the construction process ensures compliance with approved plans and quality standards. Nondestructive testing (NDT) methods, such as ultrasonic testing and magnetic particle inspection, offer invaluable insights into the structure’s integrity. Furthermore, when the tremie method is used, following the tremie protocol, a vital aspect of concrete placement underwater, ensures a continuous flow and prevents detrimental water intrusion.

2.5.6.3 After Casting

After casting, the QA/QC process continues. Core sampling is undertaken to give a tangible assessment of the in-place concrete’s quality. Soundings, even after casting, retain their importance for validating the final depth and consistency of the placed concrete. Diver-led visual inspections are part of the post-casting checks, providing invaluable information once the concrete has settled. A comprehensive review of records, encompassing sounding data, concrete test results, and placement logs, offers a holistic view of the entire operation. A post-project assessment of all equipment used can highlight wear and tear, ensuring longevity and operational readiness for subsequent projects. Performance tests on completed structures, such as load testing and pile integrity testing, verify the structures' functionality and safety. Establishing procedures for documenting and addressing nonconformities is critical. These procedures guide the corrective actions that may need to be taken, ensuring that the quality remains uncompromised. Concluding the process, a comprehensive final inspection of the completed work is conducted to ensure that all quality requirements have been met. It is essential to note that the aforementioned guidelines provide a general overview. Specific quality control procedures might vary, necessitating adaptations to meet the project's unique requirements and to adhere to industry standards and regulations [56,114,163,173].

NDT also plays a vital role in the QC of drilled shafts, an essential component in underwater construction. NDT methods are employed to evaluate the constructed (after casting) quality of these shafts without causing any damage, ensuring their integrity and suitability for the intended structural loads. NDT can be conducted to check for defects like voids, cracks, or inconsistencies in the concrete or other materials (like reinforcement bars) used in the shafts. Techniques such as ultrasonic testing and radiography provide detailed insights into the shaft's condition, offering a reliable means of ensuring that the construction meets the required standards and specifications, or needs rehabilitation. The specific NDT methods commonly used for drilled shafts include the following:

- **Crosshole Sonic Logging (CSL)**. CSL is widely used for evaluating the integrity of concrete in drilled shafts. It involves inserting probes into parallel access tubes embedded in the shaft. The probes transmit and receive ultrasonic pulses, detecting flaws like voids, cracks, or inclusions in the concrete.
- **Thermal Integrity Profiling (TIP)**. TIP assesses the quality of drilled shafts by measuring the heat generated from curing concrete. Sensors embedded in access tubes monitor the temperature profile over time. This method helps in identifying anomalies like necking, bulging, or variations in concrete quality.
- **Pile Integrity Test (PIT)**. PIT is used to check the physical dimensions, continuity, and consistency of pile materials. It involves striking the pile head with a hammer and recording the resulting stress waves. The test can identify defects like cracks, voids, or areas with poor material properties.
- **Gamma-Gamma Logging (G-G)**. G-G is a radiographic method where a gamma source and detector are lowered into an access tube within the shaft. This method measures the density of the concrete, helping to identify areas of lower or higher density, which could indicate quality issues.

For underwater and marine structures, these NDT methods are essential for ensuring the safety and durability of the foundations. When direct human access is challenging or dangerous for conducting these tests, they are often performed by remotely operated vehicles.

3. SURVEY OF STATE DEPARTMENTS OF TRANSPORTATION

In the realm of bridge construction and maintenance, ensuring the integrity of concrete when placed underwater is a critical task. The process of pouring concrete underwater, whether for the construction or repair of bridge substructures and bridge piles, presents significant challenges. Notably, aggregate segregation during concrete placement in deep drilled shafts stands out as a major concern. Traditional methods, such as the use of cofferdams, which involves pumping out water to create a dry environment for construction, can be time-consuming, physically demanding, and costly. However, in a promising shift, innovations in chemical admixture technologies now offer the potential to engineer concrete mixes that drastically minimize washout and segregation during direct underwater pouring.

Given the magnitude of the challenges posed by underwater concrete placement and the urgency to adopt progressive methods, a nationwide survey was distributed to key personnel in 50 state DOTs to garner a deeper understanding of current practices, difficulties, and solutions regarding underwater concreting. Based on the 35 insightful responses to the survey, this chapters aims to provide a comprehensive perspective on current and past practices, insights from key personnel, and challenges faced by various DOTs, highlighting trends, differences among DOT practices, and potential directions for the future.

Given WisDOT's recent policy shift toward implementing restrictions on underwater concrete pours for pile-encased piers, it is imperative to highlight the significance of the challenges posed by underwater concrete placement and to understand the experiences and practices of other DOTs in managing their underwater concrete projects. Consequently, this chapter provides insights into two primary areas:

1. Mix design, material selection, mix proportions, and detailed considerations regarding materials and specific concrete mixes
2. Placement techniques, casting methodologies, formwork strategies, specialized practices, inspections, and similar issues

3.1 Overview of the Survey and Results

For the purpose of gaining a comprehensive understanding of underwater concrete practices and related challenges across various jurisdictions, a detailed survey was administered via Qualtrics to 50 state DOTs. The results are summarized below.

3.1.1 *Distribution and Response Rate*

Of the 50 DOTs targeted, the total number of responses received was 35, a response rate of 70%. Note that this rate was achieved after a series of follow-ups, emphasizing the commitment to gather comprehensive data (Figure 16).

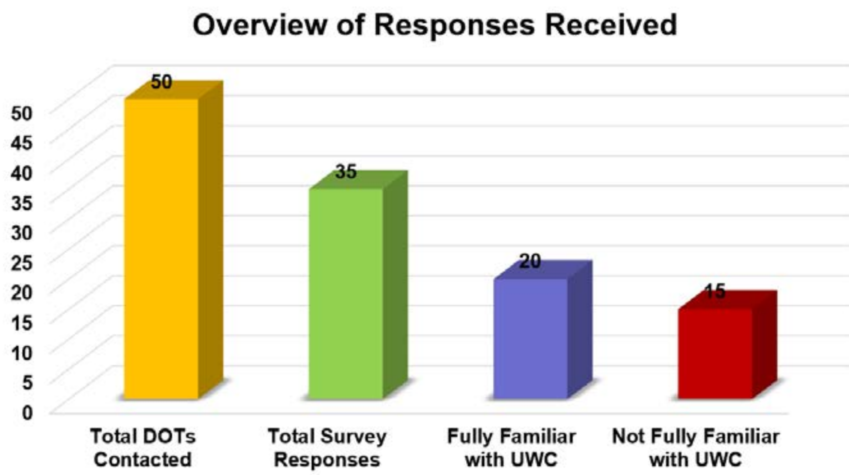


Figure 16. Summary of responses from the DOT survey

3.1.2 *Depth of Responses*

- **Fully Informed Responses**. Detailed information was provided by 20 of the DOTs, showcasing a robust familiarity with the subject matter. These respondents not only answered the questions thoroughly but also supplemented their responses by providing relevant documentation.
- **Partial Familiarity**. The remaining 15 DOTs expressed a more limited familiarity with the subject at hand. While their responses provided some insights, they were not as detailed as the ones from the more informed group and were not supplemented with additional resources.

3.1.3 *Implications*

The high response rate, especially after the follow-up efforts, indicates a keen interest and recognition of the topic's importance among the DOTs. The detailed responses from 20 DOTs offer a rich dataset, potentially revealing best practices, challenges, and innovative solutions. On the other hand, the 15 less informed DOTs might be less engaged with underwater concrete placement due to their specific environmental conditions or possibly because they fully outsource such tasks to contractors.

3.1.4 *Breakdown of Underwater Concrete Projects: New Construction versus Repairs*

Based on the gathered responses, the predominant focus of the respondents concerning underwater concrete pertained to the construction of **new underwater structural elements, accounting for 74%** of responses**.** Meanwhile, the **repair of existing underwater structural elements was the focus of 26%** of responses**.**

3.2 Mix Design, Material Selection, and Mix Proportions

Understanding the uniqueness and peculiarities of UWC mix designs compared to traditional on-ground concrete mixtures is imperative for successful underwater construction projects. In this section, the key distinctions reported by the various DOTs in terms of mix design, material selection, and mix proportions are discussed.

3.2.1 *Key Differences Reported Between UWC Mix Designs and Other Concrete Mixes Used by DOTs*

3.2.1.1 Additives and Chemical Admixtures (50% of Respondents)

The majority of respondents, representing 50% of DOTs, highlighted that the additives and chemical admixtures used for UWC are distinctively different from those used in other concrete mixtures. The additives identified included the following:

- **Superplasticizers** improve workability without affecting the water-to-cement ratio.
- **Anti-washout Admixtures** reduce washout of cement and fines.
- **Accelerators** hasten the setting time, especially in colder water.

These specific additives ensure that the concrete maintains its integrity and strength when placed underwater.

3.2.1.2 Aggregate Type and Size (20% of Respondents)

A fifth of DOTs emphasized that the type and size of aggregates used in UWC mixtures differ from those of conventional concretes. Such variations might be essential for the following:

- **Reducing Segregation**. Fine aggregates can help reduce the risk of segregation during underwater placement.
- **Enhancing Cohesiveness**. Specific aggregate types can promote a more cohesive mix suitable for underwater placement.

3.2.1.3 Similar Materials but Different Proportions (18% of Respondents)

Interestingly, 18% of respondents noted that while UWC uses materials akin to those used in on-ground concrete, particularly those potentially used for the above-water portions of bridges and decks, the proportions differ significantly. This distinction can be attributed to the following:

- **Enhancing Durability**. Underwater structures might require higher cementitious materials contents for less permeability and long-lasting durability.
- **Optimized Workability**. Modifying proportions can ensure that the concrete is more workable and less susceptible to washout underwater.

3.2.1.4 No Particular Differences (12% of Respondents)

A smaller segment, 12% of DOTs, reported no significant differences between UWC and on-ground concrete mixtures in terms of mix design. They emphasized that the key to successful UWC projects is not necessarily in the mix design, but in the placement methods.

The DOTs’ responses are summarized in Figure 17.

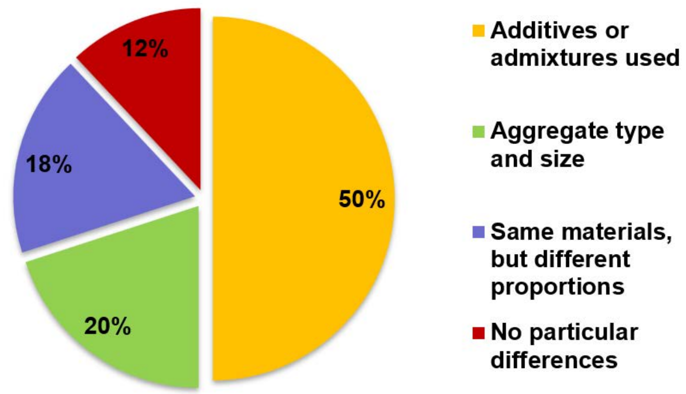


Figure 17. Reported differences between UWC mix designs and other DOTs' concrete mixes

3.2.2 *Choice of Aggregates in UWC Mix Designs*

3.2.2.1 Dominance of Coarse and Fine Aggregates (90% of Respondents)

A significant majority of the respondents highlighted the predominance of both coarse and fine aggregates in UWC mix designs. Their choice aligns closely with the gradation used for on-ground concrete, emphasizing the following:

- **Consistency in Strength**. A mix of coarse and fine aggregates ensures a balance, providing a consistent matrix that offers structural integrity.
- **Workability**. This well-graded combination ensures that the concrete remains workable, which is crucial for underwater placement, where handling can be especially challenging.
- **Minimized Porosity**. A well-graded mixture of fine and coarse aggregates helps reduce the porosity of concrete, a critical factor for underwater applications to prevent water intrusion.

3.2.2.2 Other Choices (10% of Respondents)

A minority, 10% of DOTs, indicated that other choices, specifically natural fillers, could be effective for UWC. The reasons behind this preference might include the following:

- **Enhanced Cohesiveness**. Natural fillers, given their finer gradation, can enhance the cohesiveness of the concrete mix, thus reducing risks associated with segregation underwater.
- **Economic Benefits**. In some regions, using locally available natural fillers could be a more available and economical choice, reducing the overall project costs.

While the majority leans toward the traditional blend of coarse and fine aggregates, understanding the potential benefits and application areas of alternative materials such as natural fillers can open avenues for more optimized UWC mix designs in specific scenarios.

3.2.3 *Recommended Water-to-Binder Ratios for UWC*

3.2.3.1 Predominance of 0.35 to 0.45

The largest segment, 72% of respondents, recommended a w/b ratio ranging from 0.35 to 0.45. This recommendation aligns with the following considerations:

- **Balance Between Strength and Workability**. A w/b ratio within this range strikes a balance between achieving desired strength properties and maintaining necessary workability. This is particularly critical for UWC, where the ease of placement and the structural robustness of the set concrete are both crucial.
- **Manageable Admixture Usage**. Within this w/b range, there is not an urgent need for high dosages of superplasticizers. This makes the modification and control of the mix more straightforward and reduces the chances of unpredictability in the mix behavior.

3.2.3.2 Lower Water-to-Binder Ratios (<0.35) and Potential Challenges

Approximately 20% of respondents leaned toward a w/b ratio of less than 0.35. While this can yield high strength, it also presents challenges in terms of increased admixture dependency. Extremely low w/b ratios often necessitate the use of high dosages of superplasticizers to maintain workability. This, in turn, can make it challenging to manage the simultaneous use of viscosity-modifying agents or anti-washout admixtures. The resulting mix can become highly sensitive to slight variations in admixture dosage or type.

3.2.3.3 Higher Water-to-Binder Ratios (>0.45)

Only 8% of respondents recommended a w/b ratio of more than 0.45. This higher ratio might be suited for specific niche applications, but generally higher w/b ratios might compromise the strength and durability of the concrete, especially in demanding underwater conditions. These results are shown in Figure 18.

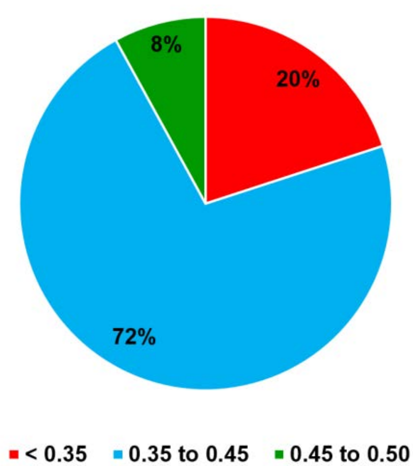


Figure 18. Recommended water-to-binder ratios for UWC.

3.2.4 *Preferred Chemical Admixtures in UWC*

3.2.4.1 Combined Use of Viscosity-Modifying Agents and Superplasticizers: The Predominant Choice

With nearly half (47%) of the respondents advocating for the combined use of VMAs, also known as AWAs, with superplasticizers, it is evident that this pairing is favored for UWC. This combination ensures that the concrete behaves as follows:

- Retains its cohesiveness and does not segregate underwater, thanks to the VMAs
- Maintains good workability and flow characteristics due to the presence of superplasticizers

3.2.4.2 Standalone Admixture Choices

- **VMAs as Sole Admixture (11%)**. While VMAs prevent washout and maintain cohesion in underwater conditions, using them as the only admixture might result in a mix that is somewhat rigid. For certain applications, however, this could be adequate or even preferred.
- **Superplasticizer Only (26%)**. Some DOTs seem to favor mixes similar to those used for SCC. Using only superplasticizers ensures excellent workability, but there might be some concerns regarding washout if these are not paired with VMAs.

3.2.4.3 Inclusion of Air Entrainers: Considerations for Cold Climates

- **Superplasticizer + Air Entrainer (5%)**. The addition of air-entraining agents alongside superplasticizers, as indicated by 5% of respondents, underscores the importance of freeze-thaw resistance in colder regions. Air entrainers introduce tiny air bubbles into the mix, offering protection against the detrimental effects of freezing and thawing cycles.
- **Triple Combo: Superplasticizer + Air Entrainer + VMA (11%)**. An all-encompassing approach, this combination addresses workability, underwater cohesion, and freeze-thaw durability. It is a comprehensive mix strategy suitable for challenging environments.

To summarize, the preference for combining VMAs with superplasticizers indicates a focus on ensuring both workability and underwater stability in UWC mixes. Meanwhile, the addition of air entrainers in some mixes reflects the tailored approach that some DOTs adopt based on specific environmental challenges.

The Venn diagram in Figure 19 summarizes the chemical admixtures preferences.

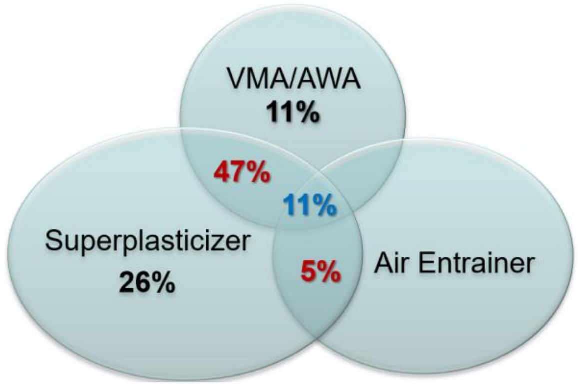


Figure 19. Chemical admixtures used or recommended by DOTs for UWC mixtures

3.2.5 *Preferred SCMs in UWC*

3.2.5.1 Fly Ash: The Leading Choice

As the preference of 42% of the DOT respondents, fly ash is the most recommended SCM for UWC mixes. Its popularity can be attributed to several advantages:

- **Workability and Reduced Heat of Hydration**. Fly ash contributes to enhanced workability and reduced heat of hydration, making it suitable for underwater conditions.
- **Improved Durability**. The pozzolanic reaction of fly ash with the calcium hydroxide in the cement paste can lead to a denser, more durable concrete matrix.

3.2.5.2 Silica Fume: Focus on Strength and Durability

Approximately 26% of DOTs recommended the use of silica fume. It is highly pozzolanic and contributes to the following:

- **Increased Strength**. Silica fume refines the concrete's microstructure, leading to significant strength enhancement.
- **Enhanced Durability**. By reducing concrete permeability, silica fume boosts resistance to chloride ingress, a vital consideration for underwater structures.

3.2.5.3 Combined SCM Approaches

- **Fly Ash + Silica Fume (11%)**. This combination seeks to harness the benefits of both SCMs, ensuring improved workability from fly ash and enhanced strength and durability from silica fume.
- **Slag + Fly Ash (21%)**. Pairing slag, which offers long-term strength gains and improved workability, with the properties of fly ash can result in a balanced mix ideal for UWC applications.

The Venn diagram in Figure 20 illustrates the supplementary cementitious materials recommended or utilized by DOTs for UWC mixtures.

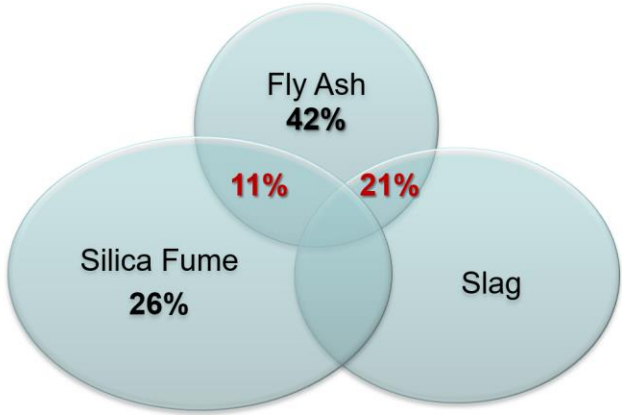


Figure 20. Supplementary cementitious materials used or recommended by DOTs for UWC mixtures.

3.2.6 *Fibers in UWC Mixtures: A Surprising Absence*

In the context of UWC mixtures, the survey revealed an intriguing outcome: none of the DOT respondents reported the incorporation of fibers. These finding warrants attention for several reasons:

- **Workability Concerns and Placement Challenges**. Fibers can impact the workability of the mix, which is critical in underwater concrete placement. Ensuring a homogenous, non-segregating mix might become challenging with fibers.
- **Cost Implications**. The addition of fibers might increase the material costs. Given tight budgets, DOTs might prioritize other solutions that ensure the durability and integrity of the mix.

3.2.7 *General Challenges in UWC Mix Design Development*

Upon synthesizing the responses from DOTs, the following primary obstacles were identified:

- **Determining Appropriate Mix Design Ratios**. A significant 43% of respondents noted the intricacy involved in determining the right mix design ratios. Balancing the constituents to achieve the desired properties while ensuring workability, strength, and durability remains a pressing challenge for these DOTs.
- **Optimizing Admixture Selection and Dosage**. Closely following, 39% of DOTs cited challenges associated with identifying suitable admixtures for underwater concrete and optimizing their dosages. The multitude of available admixtures and the interplay between them necessitate meticulous research and testing.
- **Suitable Aggregates and Their Gradations**. Approximately 9% of respondents mentioned difficulties in finding the appropriate aggregates and ensuring their precise gradations. The integrity of underwater concrete is profoundly influenced by the type and gradation of the aggregates used, making this a critical area of consideration.
- **Identifying Compatible Supplementary Cementitious Materials**. Another 9% of DOTs pointed toward challenges in determining and sourcing supplementary cementitious materials

that synergize well with other mix components. The right choice in this regard can enhance the durability, strength, and other desirable properties of underwater concrete.

Such insights underline the necessity for continuous research, knowledge exchange, and technical advancements in the domain of underwater concrete mix designs. The DOTs' responses are summarized in Figure 21.

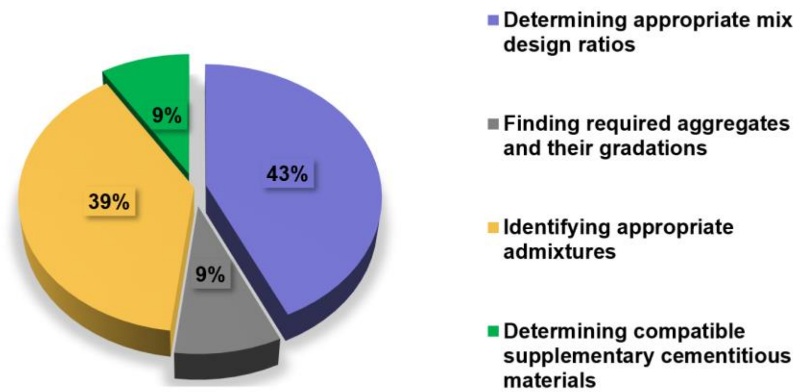


Figure 21. Main challenges for the development of appropriate underwater concrete mix designs

Figures 22 and 23 present two real-world mix design examples utilized in Connecticut and Idaho, respectively. They are not intended to provide either "good" or "poor" examples. Instead, they show the details that need to be designed and included, depending on project-specific requirements (e.g., SCC for pier repair).

PARAMOUNT CONSTRUCTION, LLC
49 Hollow Tree Lane
Newington, CT 06111

DESCRIPTION

Span Pole & Mast Arm Foundation Tremie Concrete mix 3/8" stone Builders Concrete

Customer : PARAMOUNT CONSTRUCTION	Contractor : PARAMOUNT CONSTRUCTION
Project : CT DOT 172-444	

Class :	F (4400 PSI)	Source of Concrete : BUILDERS CONCRETE EAST
Aggregate size :	3/8" -- 9.5 mm	Construction type : EXTERIOR CONCRETE
Air :	4.5 to 7.5 %	Placement : MIXER TRUCK
Water/Cement ratio :	0.397	Unit Weight : 148.23 pcf
Slump :	3.00 to 6.00 in	Design Date : 04/12/2019
Slump after SP:	6.00 to 9.00 in	Cement type: Type I/II

Sieve Size	Percent Passing	ASTM C-33
⅜" (9.5mm)	100	100
#4 (4.75mm)	95	95-100
#8 (2.36mm)	82	80-100
#16 (1.18mm)	68	50-85
#30 (600µm)	47	25-60
#50 (300µm)	22	10-30
#100 (150µm)	8	2-10
#200 (75µm)	1.8	0-3
Fineness Modulus	2.78	2.3-3.1

MasterGlenium® 7500
Full-Range Water-Reducing Admixture

MasterSure® Z 60
Workability-Retaining Admixture

Figure 22. Example material and mix design description used in Connecticut

Marine Professionals Since 1919
BRENNAN

IDAHO TRANSPORTATION DEPARTMENT

Mix Description	Usage
5000 PSI 3/4" SCC	SCC FOR PIER REPAIR

Material Code	Material Supplier	Material Description		Design Quantity
MDTN-SND	IMC	....MIDDLETON READY MIX SAND		1425 lb
MDTN-#8	IMC	....MIDDLETON 3/8" PEAGRAVEL		610 lb
MDTN-#67	IMC	....MIDDLETON #67 3/4" ROCK		825 lb
AGD-I/II	ASHGROVE	....ASHGROVE I/II DURKEE		700 lb
BRIDGER	HEADWATERS	....ISG BRIDGER		70 lb
WATER	WATER	....WATER		36.0 gal
GLEN3030	BASF	....GLENIUM 3030 HIGH RANGE WATER REDUCER		60 lq oz
P-322N	BASF	....POZZOLITH 322N		31 lq oz
			Total	3930 lb

Sieve	% Passing	Spec Limits C-33
3/8"	100	**100**
#4	97	**95-100**
#8	82	**80-100**
#16	71	**50-80**
#30	49	**25-60**
#50	15	**5-30**
#100	3	**0-10**
#200	.9	**0-3**
FM = 2.86		**2.4-3.2**

GLENIUM® 3030 NS
Full-Range Water-Reducing Admixture

MasterMatrix® UW 450
Anti-Washout Admixture

	Slump in	Air Content %	Concrete Temp deg F	Air Temp deg F	7 Str psi	Strength28 psi	Str 28 Run Avg 3 psi
Average	25.46	3.26	74	71	5820	7500	7460
Range Min	23.00	1.30	61	30	5070	6760	6880
Range Max	28.50	6.10	88	94	7070	8630	8020

Figure 23. Example material and mix design description used in Idaho

3.3 Analysis of UWC Placement Methods

3.3.1 *Pre-Placement Inspection Techniques*

Understanding pre-placement inspection techniques provides foundational insights into the initial steps taken by DOTs in their underwater concrete projects. These practices play a pivotal role in shaping the success of the subsequent placement or repair endeavors. The survey shed light on the diverse inspection techniques employed by different DOTs.

3.3.1.1 Diving (50% of Respondents)

A majority, half of the surveyed DOTs, rely on diving as their primary method of inspection. This hands-on approach enables direct observation and assessment of the underwater conditions, offering a vivid understanding of the environment.

3.3.1.2 Underwater Imaging (25% of Respondents)

A quarter of the respondents employ underwater imaging techniques, which might include tools such as sonar and ROVs. These tools provide visual insights into the underwater environment and offer the advantages of safety and possibly broader coverage.

3.3.1.3 Wading (18% of Respondents)

It not always essential to perform deep underwater inspections. Some DOTs, precisely 18%, choose wading as their inspection method, which is typically relevant in shallow water conditions. Inspectors can walk through or stand in water to assess and inspect the areas of interest.

3.3.1.4 Others (7% of Respondents)

The remaining 7% of DOTs employ other inspection techniques, which might be context-specific or driven by unique challenges or constraints faced by the respective DOTs.

3.3.2 *UWC Placement Methods*

The act of placing underwater concrete necessitates unique methods, given the intricate challenges posed by the aquatic environment. The choice of method can significantly affect the quality, efficiency, and cost of the placement. As per the survey, the following are the prevalent methods adopted by the DOTs.

3.3.2.1 Tremie Method (27% of Respondents)

Utilized by over a quarter of the respondents, the tremie method involves using a watertight pipe to pour concrete underwater. This method ensures that the concrete can be placed without coming into direct contact with water, which can lead to washout of the cement and a reduction in concrete quality.

3.3.2.2 Pumping (10% of Respondents)

A small percentage of DOTs use direct pumping to cast concrete underwater. This method involves the use of concrete pumps to convey and place concrete directly in submerged areas.

3.3.2.3 Combination of Tremie and Pumping (63% of Respondents)

A significant majority of the DOTs opt for a combined approach. Here, concrete is pumped into a tremie pipe, which is then used to cast the concrete into molds underwater. This hybrid technique capitalizes on the strengths of both methods. Pumping the concrete into the tremie pipe ensures a consistent and continuous flow, while the tremie pipe ensures that the concrete's quality is not compromised by direct exposure to water.

The data suggest a clear inclination toward leveraging the combined strengths of both the tremie and pumping methods. This combined approach appears to offer a blend of efficiency and quality assurance, making it the preferred choice for many DOTs in their underwater concrete projects. The DOTs' responses are summarized in Figure 24.

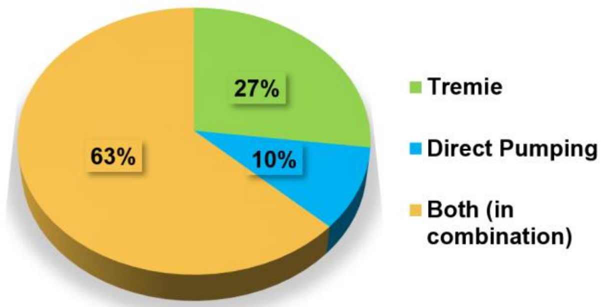


Figure 24. UWC placement methods

3.3.3 *Formwork Choices for UWC Placement*

The choice of formwork is important for underwater concrete. The formwork not only gives shape to the concrete but also must resist the pressure and movements of water, ensuring that the poured concrete remains uncontaminated and achieves the desired strength and finish. The survey data are summarized below.

3.3.3.1 Metal/Steel Formwork with Sealed Joints (79% of Respondents)

The overwhelming majority of DOTs prefer metal or steel formwork with sealed joints for underwater concrete placement. This preference can be attributed to several factors:

- **Durability and Strength**. Metal formwork, especially when made of steel, is robust and can withstand the hydraulic pressures of deep-water placements.
- **Precision**. Metal formwork provides sharp, clear lines and retains its shape, ensuring that the final structure closely aligns with the design specifications.
- **Sealed Joints**. Crucial for underwater placement, sealed joints prevent water ingress, ensuring that the mix remains uncontaminated and unaffected by washout.

3.3.3.2 Other Choices (21% of Respondents)

The remaining respondents mentioned alternatives such as lumber and rubber. These choices might be influenced by the following:

- **Budget Considerations**. Lumber, for instance, can be cost-effective, especially for one-time use scenarios.
- **Flexibility**. Rubber formwork, due to its flexibility, might be preferred for shapes that are intricate or geometrically irregular.

3.3.4 *Strategies to Shield Fresh Underwater Concrete from Water Action*

The successful placement of concrete underwater necessitates intricate methods to safeguard the freshly cast material from potential water action. Without these protective measures, the quality of concrete can be compromised, leading to weaknesses in the finished structure. The survey data are summarized below.

3.3.4.1 Use of Plastic Sheets, Tarps, and Shields

Employing these materials to cover the non-formed surfaces of fresh underwater concrete is the preferred strategy among nearly 95% of DOTs. The following reasons were cited:

- **Barrier Creation.** These materials act as an effective barrier, minimizing the ingress of water and reducing the risk of washout and aggregate segregation.
- **Versatility**. These materials are versatile and can be tailored to fit various forms and configurations, ensuring that even irregularly shaped placements can be adequately shielded.
- **Cost-Efficient**. Plastic sheets and tarps are relatively inexpensive, making them a cost-effective solution for large-scale projects.

3.3.4.2 Placement of Extra/Sacrificial Thickness

Another strategic measure adopted by DOTs involves casting an additional layer of concrete, which acts as a buffer against potential water interference. The benefits include the following:

- **Additional Protection**. This extra layer absorbs the initial shock of any water action, safeguarding the underlying primary structure.
- **Flexibility in Finishing**. Once the concrete achieves sufficient strength, the superficial layer can be removed if it is deemed unnecessary, allowing for flexibility in achieving the desired finish and structural thickness.
- **Reduction in Repairs**. If water action compromises the extra layer's quality, that layer can be removed, minimizing the need for extensive and costly repairs to the primary structure.

3.3.5 *Addressing the Deterioration of Underwater Concrete: Repair Methods in Focus*

The resilience of underwater concrete structures is of paramount importance. However, even with meticulous construction processes and protective measures, deterioration can and does occur over time. According to the survey data, a significant majority of the respondents have observed the degradation of existing UWC structures. Degradation necessitates the adoption of efficient repair methods that can not only restore structural integrity but also extend the lifespan of these structures.

The primary repair methods used by the various DOT respondents are summarized below.

3.3.5.1 Concrete Replacement (52% of Respondents)

This method involves the removal of deteriorated sections of the concrete structure and subsequent replacement with new concrete. It is akin to a "replacement rather than repair" approach.

Forming and pouring concrete over deteriorated sections guarantees renewed structural integrity and longevity. It is particularly effective when the deterioration is extensive or when the underlying causes of the initial degradation have been addressed. This method can be more time-consuming and costly than other repair options, especially when large sections are affected. Furthermore, casting new concrete underwater comes with its own set of challenges, such as preventing washout.

3.3.5.2 Concrete Grouting (24% of Respondents)

Concrete grouting involves filling voids or cavities underwater with a concrete mixture. This method is used for filling voids and sealing gaps, offering both structural stability and water resistance. Concrete grout is generally more robust than other grouting materials, ensuring that the repaired section remains firm and resistant to further damage. It also provides good adhesion to existing concrete.

3.3.5.3 Epoxy Injection (24% of Respondents)

This is a targeted method wherein epoxy resin is injected directly into cracks or fissures in the concrete. It is suited for addressing fine cracks where traditional fill methods might not be effective. Injecting epoxy resin under pressure ensures deeper penetration and thorough sealing. This method restores both structural strength and water resistance. Moreover, the method can be customized based on the crack's width and depth, making it versatile.

3.3.6 *Participant Roles in Underwater Concrete Construction and Repair Projects*

For UWC construction and repair, the capabilities and expertise of the teams performing the task are of the utmost importance. The individuals and crews handling these projects must be adept, considering the unique challenges associated with underwater environments. The survey sought to identify who shoulders this significant responsibility. The findings and analysis are summarized below.

3.3.6.1 Contractors Hired by Agencies (70% of Respondents)

A significant majority of the DOTs prefer to outsource UWC construction and repair projects to specialized contractors. This trend might be indicative of several factors:

- Specialized contractors often possess equipment, expertise, and experience specific to underwater concrete projects.
- Hiring external experts can often be more cost-effective than training and maintaining an in-house team, especially if UWC projects are sporadic or infrequent.
- The risk associated with underwater projects might make DOTs more inclined to rely on seasoned professionals who are well versed in dealing with the complexities of UWC.

3.3.6.2 Combination of Agency Crews and Hired Contractors (30% of Respondents)

A notable proportion of DOTs adopt a hybrid approach, employing both in-house teams and external contractors.

This preference can be attributed to a desire to maintain oversight or control over critical aspects of projects while still benefiting from the specialized skills of contractors. This approach also provides an opportunity for skill transfer, where in-house teams can learn and gain experience from seasoned contractors. Some phases of the project might be straightforward, making it feasible for the in-house team to handle them, while more complex aspects are entrusted to external experts.

3.3.6.3 Crew from Agencies (0% of Respondents)

None of the surveyed DOTs rely exclusively on their in-house crews for UWC construction or repair. The challenges and risks associated with underwater projects, coupled with the need for specialized equipment and expertise, might make it impractical for agencies to rely solely on internal resources.

3.4 Overall Analysis

The results derived from the survey align with the findings from the extensive literature review described in Chapter 2, which covered numerous research articles and scientific publications. This agreement emphasizes general consistency in underwater concrete mix designs and placement methods (despite differences and variations).

4. WISDOT POLICIES, DOCUMENTS, AND PRACTICES

4.1 Introduction

WisDOT has meticulously crafted an extensive array of policies, documents, and practices that serve as benchmarks for the state's transportation infrastructure development. Among the elements of this framework, there is Section 502.3.5.3, "Depositing Concrete Underwater," which offers guidance for concreting bridge substructures and preventing aggregate segregation in deep drilled shafts. This section on technical operations is crucial and has the potential for further expansion, as it ensures the structural integrity and durability of bridges—essential components of Wisconsin's transportation network.

The challenges of underwater concrete placement and deep drilled shaft construction are multifaceted, involving environmental, durability, and material considerations. Recognizing the importance of these issues, this chapter explores the relevant specifications in detail, outlining the protocols for underwater concrete deposition, as detailed in Standard 502.3.5.3. This standard includes the procedures for tremie usage, concrete layering, and cofferdam design, emphasizing the need for a well-designed approach that prevents disturbance to the newly placed concrete and ensures the avoidance of cold joints and other potential defects.

WisDOT's proactive approach extends beyond maintaining current standards; the department has actively sought to evolve its methodologies through research and comparative analysis. To further these efforts, this research synthesis report was initiated to consolidate knowledge on effective placement methods, tackle the complications associated with pile-encased piers, and formulate strategies for non-segregating concrete used in underwater applications and deep drilled shaft projects. This section reviews the guidelines in the WisDOT Bridge Manual's "Concrete Bridges" section with a focus on applying the insights obtained through the research synthesis. The section also incorporates insights derived from interviews with contractors and field experts, offering an exhaustive analysis of the construction factors that can impact underwater concrete pouring operations. The WisDOT Bridge Manual primarily provides guidance for constructing concrete bridges and the concrete components of other structures, focusing on enhancing the application process for pile-encased piers and similar structures, such as abutments. By considering the variables experienced in real concrete placement—variables that contractors report can affect the strength and durability of concrete, such as water velocities, depth of water, and mix design—detailed information was obtained.

Ultimately, the insights presented in this section lay the ground for possible revising and improving WisDOT's policies, standards, and specifications. The proposed updates, based on a thorough examination of current practices and comparative benchmarks, tackle the challenges of depositing concrete underwater compared to dry placements, offer recommendations for specifications to control aggregate segregation, and introduce innovative techniques for the excavation and shaping of substructures in aquatic environments. These advancements have the potential to be incorporated into the updated WisDOT Bridge Manual and Construction and Materials Manuals and will likely influence the specifications and standards that govern the construction of concrete piers and abutments in aquatic settings nationwide.

4.2 Current Bridge Manual and Specification Review of WisDOT

Within the framework of WisDOT's Bridge Manual, the guidelines for underwater concrete placement are both meticulous and precise, ensuring the structural integrity of bridge substructures. Key points from this section indicate the following:

1. Deposit concrete underwater only if the engineer orders, the plans show, or the contract specifies.
2. Provide concrete as specified in Section 501, except increase the slump to 5 to 9 in. without exceeding the maximum mix water allowed for that grade.
3. For concrete deposited underwater, place it carefully in a compacted weight in its final position using a tremie. The tremie consists of a tube that has a diameter of not less than 10 in. and is constructed in sections having flanged couplings fitted with gaskets. The tremie support must allow free movement of the discharge end over the entire work surface and allow its rapid lowering if necessary to choke off or retard the flow. Keep the discharge end sealed at all times and the tremie tube full to the bottom of the hopper. If dumping a batch into the hopper, raise the tremie slightly, but not out of the concrete at the bottom, until the batch discharges to the bottom of the hopper. Then stop the flow by lowering the tremie. Ensure a continuous uninterrupted flow until the work is complete. The contractor may use a tremie equipped with a suitable mechanical seal or valve at the discharge point instead of the open tube tremie, if the engineer approves of the design, method of operation, and control of the device.
4. Exercise special care not to disturb concrete deposited underwater and to maintain still water at the deposit point. Do not place concrete in running water. Ensure watertight formwork.
5. Place the concrete in a way that precludes developing a cold joint between successive layers or placement stages. Accomplish this by either placing the concrete layers deep enough to accommodate satisfactory tremie operation, while ensuring that the previously layer does not take initial set by pouring at a rate sufficient to raise the concrete level between 1½ to 2 ft per hour, or by placing the concrete full depth in one continuous operation and completing the work to grade progressively from one end of the cofferdam to the other.
6. Design cofferdams to accommodate appropriate and planned pour rates. The contractor may place underwater concrete by pumping, if the engineer approves.
7. Do not dewater the cofferdam until at least 3 days pass from the time placed and not before the concrete hardens and is strong enough to withstand the hydrostatic pressure.
8. After dewatering, remove laitance or other unsatisfactory material on the top of seals and underlying proposed substructure units by scraping, chipping, or other means.

In addition to Section 502.3.5.3, "Depositing Concrete Underwater," in WisDOT's Bridge Manual, there is a comprehensive appendix dedicated to drilled shafts, which provides detailed specifications and guidelines. This appendix addresses the work conforming to the standard specifications outlined in Sections 501, 502, 701, 710, and 715 (QMP Concrete Structures) of the WisDOT Bridge Manual, except as modified in specific instances.

Key elements of the "QMP Drilled Shafts" appendix include the following:

A. General Requirements:

Adherence to the standard specifications is mandated, with specific exceptions or additional stipulations outlined.

B. Materials:

- **Concrete Mix Requirements.** High compressive strength concrete with 590 to 675 pounds of cement per cubic yard is required for drilled shaft construction. The concrete mix should be flowable, non-segregating, and exhibit minimal rapid slump loss.
- **Unit Weight of Concrete.** Must be between 140 to 160 lb/ft³ as per AASHTO T 121.
- **Aggregates.** Both fine and coarse aggregates must conform to specific gradation requirements outlined in the standard specification in Section 501.2.5, with detailed sieve size percentages. Maximum size of gravel (coarse aggregate) must be limited to ½ in.
- **Admixtures.** Usage of chemical admixtures, other than approved air-entraining agents or water reducers, requires prior approval and must meet AASHTO M 194 standards. Dosage rate adjustments of concrete admixtures are permissible without necessitating a new mix design.
- **Slump.** Trial mix designs for drilled shaft concrete must be conducted with the aim of assessing slump loss over time, or for determining the Slump Loss Graph, which represents Slump versus Time after Batching. Slump Ranges in Inches for Concrete Placement in Drilled Shafts (for both Uncased or/and Cased Excavations) are as follows:

  Dry Installation Method:

  - Concrete Placed by Free Falling: 7 to 9 in.
  - Concrete Placed by Tremie: 8 to 9½ in.
  - Concrete Placed by Pump: 7 to 9½ in.

  Wet Installation Method:

  - Concrete Placed by Free Falling: Not Applicable
  - Concrete Placed by Tremie: 8 to 9½ in.
  - Concrete Placed by Pump: 7 to 9½ in.

- **Slurry.** If slurry is used for drilled shafts, it must be a stable suspension of mineral or polymer in potable water, meeting specific requirements for density, viscosity, pH, and sand content. The appendix outlines various tests for the slurry's density, viscosity, sand content, and pH, along with detailed procedures and equipment specifications. This information is a vital component of the WisDOT Bridge Manual, offering specific guidelines to ensure the structural integrity and longevity of drilled shaft foundations.

4.3 Insights from Contractors on Underwater Concrete and Drilled Shaft Practices

In this section, recent experiences and issues identified during construction and regular inspections in Wisconsin are explored. These insights have been gathered through interviews conducted with in-service inspection staff and regional construction contractors who possess extensive experience in Wisconsin. The focus of this section encompasses both underwater concrete practices and drilled shaft concreting. For systematic analysis, their insights are categorized into three primary divisions: first, perspectives on mix design, proportions, and admixtures are considered; second, the techniques employed in concrete placement are examined; and third, the strategies for quality control activities are discussed. Additionally, this section presents any needs, wish lists, or promising technologies that these professionals suggested could enhance or address existing challenges in these critical construction areas. This approach provides a comprehensive overview of the current practices and challenges in underwater concrete placement and drilled shaft construction, as observed from the perspective of industry professionals. The insights gathered from these experienced contractors and inspection staff are summarized in the following sections.

4.3.1 *Mix Design, Proportions, and Admixtures*

- **Similarity to Ordinary Concrete**. The majority of contractors reported no significant differences in mix design between underwater concrete and ordinary concrete. This similarity in formulation suggests a level of familiarity and confidence in handling UWC projects.
- **Water-to-Cement Ratio**. In almost all cases, this was limited to 0.45.
- **Use of Superplasticizers and Water Reducers**. Almost all contractors mentioned the inclusion of superplasticizers or high-range water reducers in their concrete mixes. This addition was essential for enhancing the workability and flowability of the concrete without compromising its strength.
- **Air-Entraining Agents for Freeze-Thaw Durability**. Where there was a potential for freeze-thaw cycles, contractors commonly added air-entraining agents. This choice underscored the importance of durability in challenging weather conditions.
- **Limited Use of Viscosity-Modifying Agents**. Very few contractors reported using VMAs, and none mentioned the use of anti-washout admixtures. Despite awareness of these additives, their practical application seemed limited.
- **Choice of Supplementary Cementitious Materials**. The selection of supplementary cementitious materials was mostly dependent on the supplier of the ready-mixed concrete. Most contractors preferred using fly ash over silica fume, due to silica fume's higher prices. Some reported using slag or a combination of slag and fly ash. However, fly ash emerged as the predominant choice in most UWC and drilled shaft mix applications.
- **Increased Flowability**. Almost universally, contractors noted that the concrete used in their UWC and drilled shaft projects was more flowable than ordinary concrete, typically with a slump range of 7 to 9 in. This higher slump was indicative of the need for concrete that can be easily placed and compacted in underwater or deep-shaft environments.

These insights from contractors provided a valuable understanding of the current practices and preferences in mix design for UWC and drilled shaft applications, highlighting the trends and commonalities in material choices and mix properties.

4.3.2 *Placement Techniques*

- **Preferred Methods of Placement**. A majority of contractors preferred pumping methods for placing concrete, especially in drilled shafts with dense reinforcement bars. Pumping is particularly effective because it allows additional control over the concrete flow, ensuring

that the mix uniformly fills all spaces around the reinforcement bars without leaving gaps. Additionally, the tremie method was noted to be widely utilized, with some contractors employing a hybrid approach that combines both pumping and tremie methods. This combination involved using the pump to feed the tremie, optimizing the placement process.
- **Use of Formworks**. For UWC casting, metallic formworks were almost universally used. This choice, particularly considering the sealed joints, indicated a preference for robust and reliable containment methods that can withstand underwater conditions.
- **Monitoring Placement**. Video or camera monitoring during or after placement was not too common, though some contractors did utilize these technologies for overseeing the placement process. This indicated that while technological monitoring is known, it is not widely adopted in practice yet.
- **Adaptations for High Water Flow**. In situations of high water flow, one contractor reported the use of innovative measures like installing shields in the direction of the water flow. This approach was not meant to create a dry environment like a cofferdam but rather to divert the water's direction and reduce its speed. Such a technique is instrumental in reducing the speed of the water, thereby minimizing the washout risk of fresh concrete.
- **Post-Placement Protection and Curing**. The use of tarps for protection after placement was mentioned by some contractors. In one specific instance, hot air was blown onto the concrete after it had been set to facilitate better curing. These methods highlighted the attention to detail and the importance of protecting concrete during its critical early stages.

These insights reflected a blend of traditional and innovative techniques in the placement of UWC and drilled shafts, illustrating the contractors' adaptability and problem-solving skills in aquatic construction environments.

4.3.3 *Strategies for Quality Control*

- **Pre-Placement Quality Control**. Contractors typically prioritized pre-placement checks to ensure concrete quality, including interactions with the ready-mix concrete supplier. It was essential that the supplier meets all necessary standards and specifications to ensure the quality of the concrete mix.
- **During Placement Quality Control**. The primary method of quality assessment during concrete placement was the testing of slump. This was typically done through samples collected at the time of placement. The slump test was vital for assessing the consistency and workability of fresh concrete.
- **Post-Placement Quality Control**. This step of the QC included the use of divers for inspecting underwater concrete, assessing firmness, and identifying repair needs. However, there was generally a lack of systematic post-placement quality control plans, especially those involving NDT methods.
- **Common Tests for Concrete Quality**. The most widely used tests for evaluating concrete quality were as follows:

    1. The slump test for fresh concrete, which provides insight into the mix's consistency and water content.

2. The compressive strength test for hardened concrete, usually using cylindrical samples measuring 4 by 8 in. These samples aim for a target 28-day compressive strength ranging from 4,000 to 8,000 psi, depending on specific project requirements.
3. Additional tests, like measuring air content and density, were also mentioned but were less common.

4.3.4 *Wish List and Improvement Opportunities*

- **Flexibility in Mix Design and Depositing Methods**. Contractors expressed potential opportunities that can be introduced by using less prescriptive mix designs and depositing methods, advocating for some approaches that are not overly restrictive. Experienced professionals mentioned that there are innovative ideas regarding the use of certain materials, changes to mix designs, the addition of admixtures, and the application of new methods. However, these are often not acceptable due to strict adherence to guidelines by DOTs. Essentially, contractors are advocating for a shift toward performance-based criteria for UWC mix proportions, material selection, and casting methods.
- **Training for Contractors and Engineers**. There was a recognized need for specialized training for contractors, in-charge staff, and engineers who participate or oversee UWC or drilled shaft projects. Most of these professionals base their approach on standard ground placement techniques, but underwater concrete placement involves additional details. These include understanding the negative pressure or vacuum effects in pumping, the use of specific additives in UWC, and the sealed process of formworks or tremie pipes. Enhanced training in these and other related areas can potentially lead to better quality underwater construction.
- **NDT Post-Casting**. Some contractors suggested the adoption of NDT or digital imaging methods for monitoring concrete after casting to assess its condition. NDT can provide a more comprehensive understanding of the concrete's structural integrity without being invasive or destructive.
- **Use of Precast Elements**. The idea of using precast elements for underwater or drilled shaft projects was also proposed. The rationale behind this suggestion was that precast elements typically undergo more rigorous quality control compared to in situ concrete placed underwater, potentially leading to higher quality and more consistent outcomes.

These insights highlight contractors' desire for more flexibility and innovation in practices, alongside a keen interest in adopting new technologies and methods that can further enhance the quality and efficiency of underwater construction projects.

5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The extensive research comprising a literature review, database analysis, and survey of practices, combined with input from various DOTs and experienced contractors who work in UWC and drilled shafts, has led to significant insights into UWC and drilled shaft construction.

5.1 Overall Guidelines and Requirements

This section provides a comprehensive overview of best practices and preferences across different states regarding underwater concrete placement.

5.1.1 *Commencement of Underwater Placement*

In underwater concrete placement, there exists a widespread consensus among numerous state guidelines regarding the initiation of the process. It is generally agreed that concrete placement should only commence when the tremie or the designated placement apparatus has been accurately positioned at the correct base or shaft elevation. This precise positioning is essential to ensure a consistent and controlled flow of concrete, which is critical to achieving the desired structural integrity and durability. Adhering to this protocol mitigates the risks of premature washout and potential contamination of the concrete, thus laying a solid foundation for the subsequent phases of construction.

5.1.2 *Tremie Specifications*

- Most states require a minimum diameter of around 10 in. for the tremie.
- The end of the tremie must always remain submerged in the concrete throughout the operation. A consistent depth of 5 ft is commonly mentioned, but some states suggest up to 10 ft.
- Tremies should be watertight, movable, and designed for rapid lowering.
- There is universal emphasis that aluminum or materials that react with concrete should be avoided in tremie construction.

5.1.3 *Underwater Placement Process*

- A continuous and uninterrupted flow of concrete during placement is critical. Any interruption should not be prolonged.
- Concrete should ideally be placed directly in its final position, without any disturbance or vibration after placement.
- Concrete should be compact and free of voids once placed.

5.1.4 *Quality and Mix of Concrete*

- **Concrete Classes**. Different states specify distinct classes or types of concrete ideal for underwater placement. Common mentions include sealed concrete and drilled shaft concrete.
- **Cement Content**. An increase in cement content, typically around 10%, is advised when placing concrete underwater.

- **Slump Adjustments**. Various states recommend adjusting the slump, with a range usually falling between 5 to 9 in. Chemical admixtures often facilitate this enhancement.
- **Water-to-Cement Ratio**. While the water-to-binder ratio fluctuates from 0.4 to 0.6, a majority of the recommendations hover between 0.4 and 0.48.
- **Compressive Strength**. The 28-day compressive strength varies between 3,000 and 4,500 psi, with a predominant focus around 4,000 psi.
- **Aggregate Composition**. The proportion of fine aggregate should not dip below 45% of the total aggregate. The maximum aggregate size ranges from ½ inch to 1 inch, with a prevalent preference for about ¾ inch (19 mm).
- **Vibration**. A unanimous point across various DOTs is that underwater concrete should be non-vibrated.
- **Supplementary Cementitious Materials**. The use of supplementary materials, especially fly ash, is considered in dosages up to 20%. The next most common recommendations include silica fume and slag.
- **Placement Methods**. The tremie and pump methods are predominantly recommended by most DOTs for underwater concrete placement.

5.1.5 *Safety and Precautionary Measures*

- Several states stress the importance of pre-placement notifications and ensuring that all equipment and forms are clean and free of contaminants.
- Still water conditions are ideal for concrete placement, and running water or disturbances should be avoided.
- Dewatering, if necessary, should be done cautiously to ensure that the concrete has set and can handle hydrostatic pressure.

5.1.6 *Inspection and Post Placement*

- After placement, a thorough inspection of the concrete structure is mandatory.
- Unwanted materials, laitance, or unsatisfactory concrete layers need to be removed to ensure the structural integrity of the deposited concrete.

5.1.7 *Alternative Placement Methods*

- Besides the use of tremies, placement methods such as the use of bottom dump buckets and concrete pumps are acceptable, provided they meet specified standards.
- For concrete pumps, the need to use watertight joints, avoid the use of aluminum pipes, and meet specific diameter requirements is emphasized.

5.1.8 *General Requirements*

- **Approval**. One of the prevailing directives across guidelines is the essentiality of securing approval before initiating underwater concrete placement. Typically, this approval is sought from the supervising engineer or the overseeing agency. This step underscores the significance of coordination and ensuring that all safety and technical standards are met.
- **Environmental Considerations**. Recognizing and adapting to the placement environment is pivotal. For instance, concrete should not be placed against frozen ground, as this could

compromise the structural integrity and durability of the concrete. Such directives highlight the importance of understanding and adjusting to site-specific challenges.

- **Importance of Proper Formwork**. Adequate preparation of the site, especially in terms of ensuring the right formwork, is emphasized. Proper formwork guarantees that the concrete retains its desired shape, maintains uniformity, and meets the structural requirements. It also plays a role in preventing wastage and spillage of materials.

5.1.9 *Summary of State Guidelines and Requirements*

The collated guidelines from various states paint a comprehensive picture. There is a consistent focus on the following:

- **Quality Assurance**. The quality of concrete used is non-negotiable. This encompasses its mix, consistency, and strength, ensuring the structure's longevity and durability.
- **Equipment Standards**. Using the right equipment, whether it is for mixing, transporting, or placing the concrete, is paramount. The emphasis is on efficiency, precision, and safety.
- **Placement Conditions**. Every phase, from preparation to placement, needs to account for prevailing environmental and site conditions. This ensures that external factors do not adversely affect the quality of the placed concrete.

In conclusion, underwater concrete placement is a pivotal and complex task for DOTs involved in projects that include drilled shafts in aquatic settings. This intricate process demands meticulous planning, precise execution, and stringent oversight to ensure the structural integrity and durability of the resulting constructions. The guidelines set forth by DOTs serve as an essential navigational aid, leading these detailed projects to successful completion while upholding strict safety protocols and environmental conscientiousness.

As specifications are refined across all 50 state DOTs, the goal is to delve deeper into the specifics of materials, mix designs, and placement techniques. This will enhance the methods of direct underwater concrete casting, advancing practice with the accumulated wisdom of experience and the fresh perspective of innovation.

5.2 Final Conclusions and Recommendations

The conclusions of this study regarding the use of underwater concrete are categorized into three parts and are presented in the following sections.

5.2.1 *Mix Proportions and Material Selection*

- The balance in mix design for AWC is critical. The selection of chemical admixtures, especially water reducers and, in some cases, VMAs, is vital for improving construction quality in underwater projects due to the admixtures' impact on washout resistance and rheological behavior.
- The compatibility of multiple chemical admixtures requires careful attention. Interactions between admixtures such as water reducers, VMAs, air entrainers, and anti-washout admixtures, particularly for sealed applications, can significantly affect anti-washout capacity

and potentially increase air and void formation, necessitating comprehensive studies and trial mix designs.
- Water-to-binder ratios should be judiciously controlled, with a consensus in almost all references pointing toward ratios between 0.35 to 0.45 for optimal UWC performance. Higher ratios may lead to segregation or reduced durability.
- A common approach used by several DOTs involves increasing the cement content by (at least) 10% for underwater concrete applications (compared to conventional concrete mixes). This adjustment generally increases the cement content from a typical range of 540-575 lb/cy to 600 lb/cy (or more) for achieving enhanced performance in underwater conditions.
- The use of SCMs is beneficial for underwater concrete applications. Silica fume, for example, is recommended in the literature for its ability to enhance anti-washout characteristics and improve strength properties. However, its higher cost often restricts its widespread use in large-scale projects, as confirmed by contractors. This cost consideration frequently leads to a preference for more cost-effective alternatives such as fly ash and slag, which also help improve the concrete's resistance to washout and its overall performance in underwater applications.

5.2.2 *Fresh and Hardened Properties*

- The interplay between fluidity, setting time, and mechanical strength in AWC with multiple chemical additives necessitates advanced rheological models for predicting and optimizing fresh properties.
- The effort for achieving optimal fresh and hardened properties lies in balancing the use of VMAs or AWAs. While they enhance cohesiveness and workability, they may also impact compressive strength. Finding this balance necessitates trial batches before large-scale field deployment. For VMA types and proportions, the use of synthetic polymer-based VMAs with a dosage below 1% of the cement weight has been recommended in the literature. According to the DOT specifications, the inclusion of VMAs is appropriate if tailored to the unique requirements of each underwater concrete project. It should be noted that specific dosage ranges vary from one VMA product to another, and thus, it is commonly prescribed by the supplier. Despite the promises, feedback from contractors indicated that VMAs are still not widely used in real-world applications.
- Compressive strength is a key performance indicator for underwater concrete, whether in new placements or repair situations. Besides providing load-bearing capacity for underwater concrete structures such as piers and drilled shafts, there is an imperative need to ensure enhanced rebar protection and overall concrete durability. Most references suggest a compressive strength exceeding 4,000 psi to meet the outlined performance requirements.

Table 6 summarizes the main recommendations related to the mix proportions, as well as fresh and hardened properties, of underwater concrete.

Table 6. Recommendations for mix proportion and ratios for underwater concrete

Parameter	Possible Ranges*			Recommended Considerations
	Literature	DOTs	Contractors	
Water-to-cementitious materials ratio	0.30 to 0.40	Up to 0.50	0.40 to 0.45	Current WisDOT specifications do not indicate a specific water-to-cementitious materials ratio for underwater concrete or drilled shaft applications. However, they require the water-to-cementitious materials (w/cm) ratio not to exceed 0.45 for all concrete constructions within the state. Despite overall adequacy, an increase of up to 10% can be justified for underwater concrete and drilled shaft applications, depending on project-specific needs.
Cementitious materials content (lb/yd^3)	Minimum 600	Minimum 600	Decided often based on the concrete class provided by the project's ready-mix concrete supplier	WisDOT recommends Grade A for structural concrete, which contains a minimum cement content of 565 lb/yd^3. For specific applications, such as underwater concrete, an engineer-approved mix design with a potentially higher cementitious materials content is permissible. WisDOT's structural concrete mix design may allow an increase in cementitious materials by including up to 25% fly ash or 30% ground granulated blast-furnace (GGBF) slag by weight. When combining fly ash and GGBF slag, the total proportion must not exceed 30 percent. To ensure quality, an increase of cementitious materials content to a minimum of 600 lb/yd^3 can be considered for underwater concrete and drilled shaft applications.
Sand-to-total aggregate ratio	45% to 65%			WisDOT specifies that the oven-dry weight of fine aggregates shall constitute up to 45% of the total oven-dry weight of aggregates in concrete mixtures, which aligns well with the recommended ranges. However, increasing this

				ratio to at least 50% can be considered for underwater concrete and drilled shaft applications.
Maximum size of coarse aggregate (in.)	1/2 to 3/4	Up to 1	Decided often based on the concrete class provided by the project's ready-mix concrete supplier	For structural concrete mixtures, WisDOT specifies the maximum size of aggregate to be 1 inch. WisDOT also recommends that well-graded coarse aggregates should conform to the ASTM C33 gradation requirements for size number 67 aggregates. Notably, size number 67 refers to limestone gravel stone, which is a crushed angular limestone aggregate with a size ranging from 1/2 to 3/4 in. This maximum size of aggregate is deemed appropriate for underwater concrete and drilled shaft applications.
Anti-washout and viscosity-modifying admixtures	0.02% to 1.00% by the weight of cementitious materials	Approved viscosity modifying admixtures (VMA) can be used if they are included in the approved mixture design.	Open to consider but not commonly used	WisDOT allows the use of alternative supplementary cementitious materials (ASCM) or new chemical admixtures. Such mix designs must detail the sources and quantities of materials and be submitted for WisDOT review. Accompanying the submission, a certified report that outlines the chemical composition, physical properties, and performance test results—verified by a certified laboratory—is necessary. All sampling and testing procedures must comply with the manufacturer's specifications and receive the DOT engineer's approval. This flexibility helps with the consideration of anti-washout admixtures (AWAs) and viscosity-modifying admixtures (VMAs). To further facilitate the use of such admixtures, they are suggested to also be included in the WisDOT Approved Products List.

Superplasticizer (SP)	0.5% to 2.0% by the weight of cementitious materials, depending on the type of SP	Conventional superplasticizer or a high-range water reducer can be used, conforming to the provided specifications.	Superplasticizer is commonly employed in underwater concrete applications	WisDOT permits the use of water-reducing agents and air-entraining admixtures in all specified concrete grades, unless the contract dictates otherwise. Additionally, the use of self-consolidating concrete (SCC) is permissible. Such flexibility facilitates improved mix designs, ensuring both fresh and hardened properties for underwater concrete and drilled shaft applications.
Slump	A slump flow of greater than 18 in. for SCC	A range of 7 to 9 in. from the conventional slump test	A range of 7 to 9 in. from the conventional slump test	WisDOT permits increasing the slump for depositing concrete underwater to a range of 5 to 9 in. without exceeding the maximum mix water allowed for that grade of concrete. This range is consistent with other references, while it can be narrowed down toward higher values.
Compressive strength (psi)	4,000 and above	Minimum 3,000	4,000 and above often targeted	WisDOT requires a minimum 28-day compressive strength of 3,500 psi for all structural concrete, unless the project requires a different compressive strength. This aligns well with the requirements for underwater concrete and drilled shaft applications.

5.2.3 *Placement, Pouring, or Casting Methods*

- The pump and tremie methods are commonly used for underwater concrete placement. Their use in combination is also recognized for its practicality and effectiveness in underwater construction scenarios. Recommendations related to the placement and depositing concrete underwater in the Midwest region are summarized in Table 7, along with a set of recommended considerations.

Table 7. Recommendations for placement and depositing concrete underwater

	Illinois	**Nebraska**	**Minesota**	**Missouri**	**Kansas**	**North Dakota**	**South Dakota**	**Iowa**	**Recommended Considerations**
Sealing Conditions	At discharge end, pipe joints, and formwork	At discharge end, pipe joints, and formwork	At discharge end and watertight gaskets in pipe joints	At discharge end	At discharge end, pipe joints, and formwork	At discharge end	At discharge end and pipe joints	At discharge end and pipe joints	WisDOT similarly requires them at discharge end, pipe joints, and formwork.
Tremie pipe Diameter	Minimum of 10 in.	Minimum of 10 in.	Minimum of 10 in.	Minimum of 10 in.	Minimum of 8 in.	Minimum of 4 in.	Minimum of 8 in.	Maximum of 12 in.	WisDOT requires a minimum of 10 in, which falls in the range and is consistent with the other state practices.
Pouring Stoppage	Not exceeding 30 minutes	Not allowed. The flow of concrete must be continuous until the work is complete.	Not discussed	Not allowed	Concrete placement should not be disturbed once begun	Not allowed or drilled core is needed to show no horizontal joint is present	Not exceeding 30 minutes or the setting time of concrete	Not discussed	WisDOT requires continuous placement without stopping. It also recommends concrete to be poured at a rate that raises the level by 1.5 to 2.0 ft. per hour. The explanation is detailed enough and consistent with other state practices.

Additional Details	Maximum rebar spacing must be increased to 8 times of the aggregate size.	Tremies must not be made from aluminum or aluminum alloys that could react with concrete. The discharge end must be sealed at the start to prevent water ingress and kept sealed throughout the operation, with the tremie tube remaining full at all times.	The tremie tube should be of sufficient length to ensure the hopper remains above water when the tube's bottom is underwater.	The tremie discharge end must remain immersed in the concrete by at least 5 ft. throughout the operation to prevent water intrusion. Both tremie and pump lines must be positioned at the shaft base elevation before the start of concrete placement.	Shaft base cleanliness is critical, with less than 0.5 in. of sediment. Concrete must be deposited by methods that avoid freefall through water, such as tremie, pumping, or bottom dump bucket.	Tremie should be filled completely.	Slow vertical movement is critical to avoid the loss of pipe seal.	Tremie pipe should be long and heavy enough to stay at the bottom.	WisDOT allows both pumps and tremies for underwater concrete placement. Tremie support must permit free movement of the discharge end over the entire work area and allow quick lowering to control the flow as needed, and the tremie tube must be filled to the bottom of the hopper to prevent the ingress of water or contaminants. These requirements align well with other DOT specifications and current practices employed by contractors in the field.

- The role of underwater nondestructive tests (NDT) and monitoring technologies is emphasized. These technologies are vital for pre-construction inspections and for identifying construction and post-construction defects, thereby ensuring the safety and longevity of underwater structures.
- Sustainable development in UWC construction is a key focus area. This involves the design of environmentally friendly mix proportions and the evolution of placement methods to minimize ecological impacts, aligning construction practices with the principles of environmental stewardship.

APPENDIX A: UNDERWATER CONCRETE SPECIFICATIONS OF STATE DOTS

State departments of transportation (DOTs) across the United States adhere to a diverse set of specifications, crafted to address both general and specific local challenges. In this appendix, related DOT specifications and wet construction techniques are compiled from all 50 states. The majority of the information available about drilled shaft construction indicates employing the tremie method, an established method in the field of underwater concrete placement, as well as the cofferdam and its associated techniques, which are enduring yet resource-intensive solutions.

Despite the established nature of these guidelines, there is an emerging need to reevaluate and update these specifications in light of the latest global practices and technological advancements. The tremie method, while effective, is often bounded by regulations that may require modifications to enhance efficiency and adapt to the nuanced demands of modern construction environments. Similarly, cofferdams, though reliable, impose significant costs in terms of investment, time, and resource utilization. These considerations are particularly salient in states where aquatic challenges are a constant reality in bridge construction projects.

Therefore, this report initiated a comprehensive examination of the current DOT specifications related to underwater concrete placement, with the objective of analyzing and synthesizing this information into a cohesive narrative.

A1. Alabama

Section 501.02 – Materials. Class of Concrete Required for Specific Structures

As depicted in Table 8, Class D concrete, which has a maximum aggregate size of 1 inch and a water-to-binder ratio limited to 0.45, is appropriate for use in underwater construction practices.

- **Class A**. Used for retaining walls, concrete safety barriers, headwalls, and inlets.
- **Class B**. Used for box culverts, bridge substructures (poured in place), and bridge superstructures.
- **Class C**. Used for machine-laid curbs, gutters, combo curbs and gutters, slope paving, and miscellaneous concrete units.
- **Class D**. Specifically for underwater concrete.

Table 8. Prequalification requirements for concrete mix design in Alabama DOT

PREQUALIFICATION REQUIREMENTS FOR CONCRETE MIXTURE DESIGN				
Concrete Class	Class A	Class B	Class C	Class D
Minimum 28-Day Compressive Strength (psi) {Mpa}	3,000 {21}	4,000 {28}	3,000 {21}	3,000 {21}
Maximum Water/Cementitious Materials Ratio	0.50	0.45	0.55	0.45
Range of Total Air Content (%)	2.5 - 6.0	2.5 - 6.0	2.5 - 6.0	2.5 - 6.0
Slump (in) {mm}	3.0 {75}	3.5 {90}	3.0 {75}	7.0 {180}
Maximum 28-Day Drying Shrinkage (%)	--	0.04	--	--
Largest Nominal Maximum Aggregate Size (in) {mm}	1.0 {25}	1.0 {25}	1.0 {25}	1.0 {25}

Section 504.03 – Construction Requirements. Encasements Constructed in Wet Conditions

Underwater Inspection

- Inspection is required after excavation, cleaning, and placement of reinforcing steel for at least one Bent.
- 48-hour notice required for the ALDOT Underwater Inspection Team.
- Divers perform various and final inspections.

Placement of Concrete

- The bottom of an encasement form should be sealed with epoxy mortar.
- Concrete is pumped into the form to ensure it fills the entirety of the encasement.

Section 506.09 – Tremie Concrete Placement

- Tremies, tubes used to place concrete, should be of a specific length, weight, and diameter. No aluminum parts can touch the concrete.
- The inner diameter should be at least 6x the aggregate size, a minimum of 10 in.
- Tremie tubes must have clean and smooth surfaces.
- Concrete placement methods:
  - The tremie should be watertight, and the placement only starts when it reaches the base.
  - The tremie end should always be submerged in concrete.
  - If the tremie line orifice is removed from the concrete column, the shaft is deemed defective.
  - In such a case, there are protocols to follow, including possible removal and repouring, with all costs borne by the contractor.

Pumped Concrete Placement

- Concrete pumps can be used in both wet and dry excavations.
- Equipment for pumping must be watertight and of a specific diameter.

- There are specific protocols regarding the position of the pump line during concrete placement.
- If the pump line orifice is improperly positioned, the shaft is deemed defective, and there are stipulated remediation measures.

A2. Alaska

Alaska Division 500 – Concrete Placement in Wet-Shaft Conditions

Wet-Shaft Process

- A method of placing concrete using a tremie (a tube or pipe) or a concrete pump.

Continuous Placement

- Ensure that concrete is placed continuously until it meets the Engineer's criteria for good quality at the top of the shaft or the nearest construction joint.

Laitance Removal

- Remove any concrete laitance immediately or during concrete placement operations.

Environmental Protection

- Prevent contaminants from entering waterways, including water, drilling aids, and concrete overflow.

Discharge

- The tremie or pump line's end should be constructed to allow free flow of concrete and prevent water intrusion. Devices like caps, bottom plates, or pigs can be used to separate the concrete from the excavation fluid during the initial charging process. The discharge pipe should be long and heavy enough to rest on the shaft base.

Handling of Tremie

- Proper support should be provided, allowing the tremie to be raised or lowered to regulate concrete discharge. Avoid rapid movements or vibrations of the tremie.

Setting Head of Tremie

- Maintain a higher level of concrete inside the tremie or pump line compared to the excavation fluid. The discharge orifice should be positioned close to the shaft base and should remain submerged by at least 8 ft of concrete during the placement. If the orifice rises above this, the shaft may be considered defective, warranting immediate halt of operations and consultation with the Engineer.

Concrete Flowability

- Ensure a minimum slump of 6 in. for the concrete throughout the placement to maintain flowability. Sampling and testing from the first batch of concrete are required, with immediate reporting of results to the Supervising Engineers.

Table 9, comprising two screenshots from the Alaska DOTs specification, outlines the slump requirements and specific compressive strength for concrete designated for drilled shaft applications.

Table 9. Fresh and mechanical properties for drilled shaft (DS) concrete type.

TABLE 501-5
SLUMP REQUIREMENTS

Condition	Slump
Concrete without a water-reducing admixture	4" max.
Concrete with a Type A, D, or E water-reducing admixture	6" max.
Concrete with a Type F or G high-range water-reducing admixture	9" max.
Class DS concrete, wet-shaft process	7" min. 9" max.
Class DS concrete, dry-shaft process	6" min. 9" max.

TABLE 501-6
COMPRESSIVE STRENGTH REQUIREMENTS

Class of Concrete	Specified Compressive Strength (f'_c) *(psi)*
A	4000
A-A	5000
P	8000
DS	4000

Class DS: Concrete for drilled shaft foundations.

A3. Arizona

Placing Concrete in Water (Tremie Concrete)

Tremie concrete shall be deposited in water only if either specified in the project plans or when directed and then only under the Engineer's supervision. When depositing in water is allowed, the concrete shall be carefully placed in a compact mass in the space in which it is to remain by means of a tremie, bottom dump bucket, or other approved method that does not permit the concrete to fall through the water without adequate protection. The concrete shall not be disturbed after being deposited. No concrete shall be placed in running water, and forms that are not reasonably watertight shall not be used for holding concrete deposited under water.

A4. Arkansas

Depositing Concrete Under Water (Section 802.11)

General Regulation

- Concrete should not be deposited underwater unless explicitly shown on construction plans or approved by the Engineer.

Type of Concrete

- Seal concrete must be used when depositing underwater.

Placement Rate

- Maintain a continuous supply of concrete, aiming for a placement rate that raises the concrete's elevation by at least 1 ft (0.3 m) per hour. Use approved retarders if working at slower rates.

Continuous Placement

- For underwater structures, seal concrete should be placed continuously, with a horizontal surface. The Contractor must provide means to sound the top of the seal to ascertain its location at all times. Adjacent concrete should be placed before the initially placed concrete sets.

Method of Placement

Tremie:

- An approved method of placing concrete underwater, which involves a tube of at least 10 in. (250 mm) diameter, designed in sections with gasketed flanged couplings and a foot valve.
- The tremie should be manipulable for quick lowering to control concrete flow.
- Initially, the discharge end of the tremie must be sealed to prevent water ingress.
- The tremie tube should remain sufficiently filled to maintain the concrete seal.
- Aluminum tremies are prohibited.
- If the concrete seal is lost at any point, adjust the tremie appropriately before continuing.

Water Conditions:

- Maintain still water at the point where concrete is deposited, ensuring that the planned horizontal flow of concrete does not exceed 15 ft (4.5 m).

Dewatering:

- Dewatering is allowed after the seal concrete has cured for at least 72 hours, given that water temperatures remain above 45°F (7°C). Remove any unsatisfactory material, including laitance, from surfaces bearing structural loads.

Contractor's Responsibility:

- Before placement, the Contractor must communicate the methodology for complying with these regulations to the Supervising Engineers.

Concrete Consolidation:

- Seal concrete should not be thoroughly consolidated either during or after it is deposited.
- Concrete is delineated according to its air entrainment characteristics. Importantly, Seal concrete, often utilized for underwater concrete applications, is distinct in that it does not have intentionally added air-entraining agents (Table 10).

Table 10. Classification of concrete types based on air entrainment properties

Non Air-entrained Concrete	Air-entrained Concrete	Miscellaneous Concrete
Class A	Class S(AE)	Class M
Class B		
Class S		
Seal		

- An alternative gradation for coarse aggregates in various concrete classes based on AASHTO M43 #57 specifications comes in Table 11. For a 1 in. sieve, it suggests that 95% to 100% of the aggregates should pass through.

Table 11. Suggested alternative coarse aggregate gradation in Arkansas DOT for seal concrete utilized in underwater applications

Class A, S, S(AE), and Seal Concrete:

	% Passing	
Sieve (mm)	**Standard Gradation AHTD**	**Alternative Gradation AASHTO M43 #57**
1½" (37.5)	-	100
1¼" (31.5)	100	-
1" (25.0)	60-100	95-100
3/4" (19.0)	35-75	-
1/2" (12.5)	-	25-60
3/8" (9.5)	10-30	-
#4 (4.75)	0-5	0-10
#8 (2.36)	-	0-5

A5. California

Guidelines for Concrete Placed Under Water (Section 51-1.03D(3))

- Only seal course concrete is permitted for underwater placement.
- If dewatering of excavations proves infeasible or is not recommended, a seal course should be placed underwater using either a tremie or a concrete pump.

Tremie Specifications

1. The tremie should be a watertight tube of at least 10 in. in diameter equipped with a hopper at its top.
2. The flow of concrete is induced by raising the discharge end of the tremie.
3. Both discharge and tremie tubes must possess a mechanism to prevent water from entering during the charging process.
4. The tubes must be supported such that there is free mobility of the discharge end across the entire work surface, coupled with the capacity for rapid lowering.

Underwater Concrete Placement

1. The method used to deposit concrete should prevent the washing away of the mixture.
2. The discharge end of the tube must remain submerged in concrete throughout the operation.
3. The tube must be consistently filled with enough concrete to avoid water entry.
4. Concrete placement should be meticulous and in a compact form.
5. Ensure continuous flow of the concrete until the seal course is completed, ensuring it remains monolithic and homogeneous.
6. After placement, the concrete should remain undisturbed.
7. Remove any local elevated points to ensure the specified gap for reinforcing steel before the placement of fresh concrete.

8. For underwater concrete placement, the utilization of high-frequency vibrators for concrete consolidation is prohibited.

A6. Colorado

Guidelines for Depositing Concrete Under Water (Section 601.12)

Concrete, except for cofferdam seals, shall not be deposited under water, unless approved by the Engineer. If approved, care shall be exercised to prevent the formation of laitance. Concrete shall not be deposited until all laitance, which may have formed on concrete previously placed, has been removed. Pumping shall be discontinued while the foundation concrete is being deposited if pumping results in a flow of water inside the forms.

Concrete deposited under water shall be carefully placed in a compact mass in its final position by means of a concrete pump and tremie. The discharge or bottom end of the tremie shall be lowered to contact the foundation at the start of the concrete placement and shall be raised during the placement at a rate that will ensure that the bottom or discharge end of the tremie is continuously embedded or buried in fresh concrete at a minimum depth of 12 in.

Air and water shall be excluded from the tremie pipe by keeping the pipe continuously filled. The continuity of the placement operation shall be maintained without breaking the seal between the concrete mass and the discharge end of the tremie until the lift is completed. The placed concrete shall not be disturbed after it has been deposited.

A7. Connecticut

Section 6.01.03-(f) Underwater Placement

- Concrete can be placed underwater only within a cofferdam unless otherwise specified in the Contract or permitted by the Engineer.
- Before concrete placement, the Engineer must inspect and accept the foundation material's depth and character.
- Underwater concrete mixes are considered non-standard and must be submitted to the Engineer for approval. They typically need at least 10% more cement than non-underwater mixes.
- The concrete should be placed continuously, with its surface kept as horizontal as possible. The subsequent layer must be placed before the previous layer begins to set.
- For significant concrete placements, using more than one tremie or pump is necessary.
- To prevent segregation, concrete should be placed compactly in its final position using a tremie, concrete pump, or another approved method. The water at the point of deposit should remain still, and cofferdams need to be vented during concrete placement and curing to balance hydrostatic pressure.
- If a tremie is used, the method used to deposit the concrete needs to be detailed and submitted to the Engineer for review as a working drawing. The tremie should have watertight couplings and allow free movement over the work area.

Section 6.01.04

- The volume of underwater concrete will be measured in cubic yards.

A8. Delaware

- Submit a detailed placement plan when placing concrete underwater.
- Ensure that the foundation area is level before placing tremie concrete.
- Clean all forms and surfaces to remove mud and silt.
- Use a minimum 8 in. diameter tremie tube with the following features:
  - Smooth interior face
  - Watertight discharge
  - Length reaching the bottom of the placement
  - Markings in 1 ft intervals
- Connect the tremie tube to a funnel or hopper with at least ½ yd3 capacity.
- Ensure that a tight-closing valve is present at the tube's lower end or use a foam rubber plug in the hopper.
- Keep at least two tremie tubes on hand to ensure continuous concrete placement.
- Use equipment allowing free vertical movement of the tremie tube's discharge end.
- Avoid lateral movement of the tremie during concrete placement.
- Keep the discharge end submerged in freshly deposited concrete at all times.
- Deposit tremie concrete in a single, continuous operation while
  - Preventing aggregate segregation,
  - Ensuring consistent flow over the entire placement area, and
  - Maintaining a stable concrete level inside the tremie tube.
- Keep the top surface of the concrete as level as possible.
- Maintain balanced hydrostatic pressures to prevent form failures.
- Do not pump concrete directly to the bottom of the placement.
- Place tremie concrete only in the presence of the engineer.
- Cure test specimens under similar conditions until the specified requirements are met.
- After placement, remove unsatisfactory material from the concrete surface without causing damage.
- Chip off high spots on the concrete surface that might interfere with steel reinforcing bar placement.
- For concrete placed underwater, the recommended nominal slump range is between 5 to 8 inches, with the maximum allowable slump being 8 inches, ensuring optimal workability and performance for underwater applications (Table 12).

Table 6. Delaware DOT's concrete consistencies specifications

Table 1022.5: Concrete Consistencies[1]	
Type of Work	**Nominal Slump (inches)**
Formed Elements:	
Sections < 12 inches	1 to 3
Sections ≥ 12 inches	1 to 4
Concrete placed under water	5 to 8
Filling for riprap	3 to 7
Slip-formed elements	0.5 to 2.5

[1] Use only Type F or Type G admixtures for slumps greater than 4 inches. The maximum allowable slump is 8 inches.

A9. Florida

Section 400-8.2 Method of Placing

- Place concrete deposited under water with care in the designated space.
- Use a tremie, a closed-bottom dump bucket (minimum 1 yd3 capacity), or other approved method.
- Avoid disturbing the concrete after depositing.
- Ensure that seal concrete is deposited in one continuous placement.
- Do not place concrete in running water.
- Ensure the watertightness of form work designed to retain concrete underwater.

Section 400-8.3 Use of Tremie

- The minimum inside diameter of the tremie tube must be 10 in.
- The tremie tube must have watertight joint sections.
- Avoid allowing aluminum parts to come in contact with concrete.
- Always keep the discharge end of the tremie seated.
- Keep the tremie tube full to the bottom of the hopper.
- When adding a batch to the hopper, slightly raise the tremie (without it leaving the concrete at the bottom) until the batch reaches the bottom of the hopper.
- Choke off or retard the flow of concrete by lowering the tremie.
- Allow free movement of the tremie tube's discharge end over the entire top surface of the work.
- Enable rapid lowering of the tremie tube when necessary.
- Ensure a continuous, uninterrupted flow of concrete until completion.

- Exercise caution to maintain still water at the deposit point.

A10. Georgia

Underwater Placement Equipment

Place concrete under water using the following underwater placement equipment.

Tremie

Use a tremie when depositing concrete in water above 10 ft (3 m) deep. Ensure that the tremie is

- At least 8 in. in (200 mm) diameter and
- Constructed in sections with watertight couplings.

Bottom Dump Bucket

Where the Engineer permits, use a bottom dump bucket in water up to 10 ft (3 m) deep. Ensure that the bottom of the bucket opens only when it touches the surface that receives the charge and that the top of the bucket has a lid or cover.

A11. Hawaii

Depositing Concrete Underwater (Sections 503.03 and 511 – Drilled Shafts)

- Avoid depositing concrete underwater except for cofferdam seals, tremie concrete, and drilled shaft concrete.
- For concrete deposited underwater, use seal concrete conforming to Section 601 – Structural Concrete.
- As outlined in Table 13, the “SEAL” class of concrete and concrete designated by specific strength are eligible for underwater applications if they meet the necessary strength specifications for the project. The 'SEAL' class must attain a minimum 28-day compressive strength of 3,000 psi, and the specially designed mixes should meet or exceed the specified strength requirements. Both options must contain at least 610 lbs of cement per cubic yard to ensure the fresh and hardened properties of concrete in underwater conditions are achieved.

Table 7. Concrete mix design specifications in Hawaii DOT

TABLE 601.03-1 - DESIGN OF CONCRETE			
Class of Concrete	28-Day Strength f'_c, psi	Minimum Cement Content lbs./c.y. (800 Maximum)	Maximum Water-Cement Ratio, lb./lb.
A	3000	560	0.55
B	2500	500	0.62
C	2000	440	0.71
D	1500	400	0.80
BD	3750	610	0.49
SEAL	3000	610	0.55
Designated by Strength f'_c or $^*f'_r$	As Specified	610	0.49
$^*f'_r$ = Specified Modulus of Rupture			

- Place concrete underwater in a compact mass in its final position using either a tremie or a closed-bottom dump bucket.
- Once placed, do not disturb the concrete.
- Always maintain still water at the point of deposit.

Tremie Specifications

- The tremie should be of sufficient length, weight, and diameter to discharge concrete at the shaft base.
- Avoid allowing aluminum parts to come in contact with the concrete.
- The tremie tube should have the following features:
  - An inside diameter at least 6 times the maximum aggregate size in the concrete mix
  - A minimum diameter of 10 in.
  - Clean and smooth inside and outside surfaces
  - Wall thickness preventing crimping or sharp bends
- For wet excavation concrete placement, use a watertight tremie. Begin placement after the tremie is set at the shaft base elevation.
- Use valves, bottom plates, or plugs to keep drilling water separate from fluid concrete.
- Start concrete discharge within one tremie diameter of the base.
- Ensure that the discharge end of the tremie allows the free radial flow of concrete during placement.

- After starting the concrete flow, keep the discharge end of the tremie immersed at least 5 ft below the surface of the fluid concrete.
- Place concrete continuously, ensuring a positive head of concrete in the tremie.
- If the tremie discharge end is removed from the fluid concrete column during placement, causing concrete to be discharged onto the rising concrete surface, the shaft will be considered defective and rejected.

Pump Specifications for Concreting

- Use a pump and discharge line of sufficient capacity, length, weight, and diameter to discharge concrete at the shaft base elevation.
- Avoid allowing aluminum parts to come in contact with the concrete.
- The discharge line should have the following features:
    - A minimum diameter of 4 in.
    - Watertight joints
- Start concrete placement only after the discharge line orifice reaches the shaft base elevation.
- In wet excavations, use plugs to separate the concrete from any fluids in the hole until pumping starts.
- Always keep the pump discharge line orifice at least 5 ft below the surface of the. fluid concrete.
- Reduce the line pressure temporarily while lifting the discharge line during concreting until it is repositioned at a higher level.
- If the discharge line is removed from the fluid concrete column during placement, leading to concrete being discharged onto the rising concrete surface, the shaft will be considered defective and rejected.

Concrete Seal Design and Construction

- Submit concrete seal design calculations and working drawings stamped and signed by a Hawaii Licensed Structural Engineer.
- The exact concrete seal thickness will depend on factors such as hydrostatic head, bond, pile spacing, and cofferdam size.
- Construct the concrete seal after the Engineer accepts the design.
- Before depositing fresh footing concrete, remove any local high spots to ensure proper clearance for the footing reinforcing steel.

A12. Idaho

Section 502.03

- Use seal concrete in or underwater. The “Seal Concrete” class has a minimum cementitious content of 660 lb/yd^3, a maximum water-cement ratio of 0.60, and an air content percentage ranging from 0 to 6.0% (Table 14).

Table 8. Overview of basic mix design parameters in Idaho DOT

Concrete Class in (100 psi) (28 day)[a]	Minimum Cementitious Content lb/yd³ [b][c]	Maximum Water Cement Ratio	Air Content Percent
45 and greater [d][e][f][g]	660	0.44	0 - 6.0
35 to less than 45 [d][e][f][g]	560	0.44	0 - 6.0
30	560	0.49	6.5 ± 1.5
Seal Concrete	660	0.60	0 - 6.0

- Carefully place concrete in a compact mass, in its final position, by means of a tremie, a bottom dump bucket, or other approved method to prevent segregation. Do not disturb concrete after it is deposited.
- Do not place concrete in running water. Construct the forms for underwater concrete in a way that provides still water inside the forms. Continuously place the concrete until the required depth is reached and keep the surface of the concrete as nearly level as possible.

Comply with the following requirements for placement if a tremie is used:

1. Use a watertight tube having a diameter of at least 10 in. with a hopper at the top.
2. Provide a device that will prevent water from entering while the tube is being charged with concrete.
3. Support the tremie to permit free movement of the discharge end over the entire top surface and to permit rapid lowering when necessary to slow or stop the flow of concrete.
4. Use a method to fill the tremie that will prevent the concrete from washing away.
5. Completely submerge the discharge end in concrete and maintain sufficient concrete in the tremie tube to prevent water entry.
6. When concrete is dumped into the hopper, induce the flow of concrete by slightly raising the discharge end, always keeping it in the deposited concrete.

A13. Illinois

Depositing Concrete Underwater (Part 503.08)

General Requirement

- Concrete should not be exposed to water before it sets and should not be deposited in water unless approved and supervised by the Engineer.

Method of Deposit

- Use a tremie to place concrete in its final underwater position.
- Once deposited, the concrete must not be disturbed.
- The area where concrete is being deposited should have still water.
- All formwork designed for underwater concrete must be watertight.

Concrete Quality

- Consistency of the concrete must be regulated.
- Prevention of material segregation is mandatory.
- The method used to deposit concrete should ensure approximately horizontal surfaces.

Tremie Specifications

- **Diameter**. No less than 10 in. (250 mm).
- **Construction**. Sections with flanged couplings and gaskets.
- **Support**. Allow free movement over the work surface and rapid lowering when needed.
- **Sealing and Flow**. The discharge end must be sealed. The tremie tube should remain full up to the bottom of the hopper. Adjust the tremie height to manage the flow, ensuring that the bottom remains submerged during batch discharge.
- **Alternate Option**. Contractors can opt for pumping equipment instead of a tremie. Such equipment and its piping require prior approval from the Engineer.

Portland Cement Concrete Types (Part 1020)

Within subsections 1020.05 and 1020.15, specific guidelines pertain to the mix design for underwater concrete:

- **Water-Cementitious Material Ratio.** For all underwater concrete placement, the ratio lies between 0.32 and 0.44.
- **Central-Mixed Concrete.** The minimum for cement and finely divided minerals is set at 550 lb/yd^3 (326 kg/m^3).
- **Truck-Mixed or Shrink-Mixed Concrete.** The prescribed minimum for cement and finely divided minerals is 580 lb/yd^3 (344 kg/m^3).
- **Class Drilled Shaft (DS) Concrete.** Use one of the following mixtures when the coarse aggregate (CA) grade is 11 (with a maximum size of 19 mm):
    - **Regular Mixture**. Cement and finely divided minerals combined should be a minimum of 605 lb/yd^3 (360 kg/m^3).
    - **Underwater or Self-Consolidating Mixture**. Cement and finely divided minerals combined must be at least 635 lb/yd^3 (378 kg/m^3).
- **Class Sealed Concrete (SC) and Other Underwater Placements**. Allowable cement and finely divided minerals should be increased by 10%.

Note that a reduction in the cement factor is not permissible for any class of concrete placed underwater.

A14. Indiana

Depositing Concrete Underwater (Section 702.20d)

General Requirements

- Concrete, excluding foundation seals, must not be deposited underwater without written permission.
- If allowed, concrete must be deposited with caution to avert laitance formation.
- Laitance formed on previously placed concrete must be removed before new concrete is deposited.
- If pumping triggers water flow within the forms, pumping should be halted during the depositing of foundation concrete.

Concrete Quality

- When concrete (except foundation seals) is deposited underwater, there is a stipulation for at least a 25% increase in cement content, without extra payment. This augmentation accounts for potential losses to water.

Method of Deposit

Concrete deposited underwater must be

- Positioned compactly in its ultimate spot;
- Placed via a tremie, a closed-bottom dump bucket, or another approved method; and
- Undisturbed after it is deposited.

Tremie Specifications

- **Diameter**. No less than 10 in.
- **Construction**. Comprises sections with flanged couplings complemented with gaskets.
- **Support**. Tremie support should
  - Facilitate free movement of its discharge end across the entire top surface of the area where the concrete is deposited and
  - Allow quick lowering to modulate or halt concrete flow.
- **Operation and Sealing**:
  - The discharge end must remain closed until the immediate moment at which concrete is deposited to bar water entry.
  - The discharge end should be sealed in its entirety, barring periods when concrete is actively being deposited.
  - The tremie tube should be kept full, right up to the bottom of the hopper.
  - When the flow of concrete is initiated via the tube, the discharge end should be minimally raised (ensuring that it remains within the previously deposited concrete) to maintain a steady flow until the complete required volume of concrete is deposited.

Note that no specific recommendations were found in the Indiana DOT standard specifications regarding the mix design and proportions.

A15. Iowa

Underwater Concrete Placement (Section 2403.03b)

Underwater Placement Equipment Requirements

- Utilize a tremie, pump, or other equipment that meets the Engineer's approval for underwater concrete placement.

Tremie Specifications

- **Water Tightness and Discharge**. Ensure that the tremie is constructed to be watertight and to discharge concrete efficiently.
- **Diameter**. The tremie should be no more than 12 in. in diameter.
- **Material**. The tremie must have no aluminum parts that come in contact with the concrete.
- **Discharge End**. The discharge end should be designed to prevent water intrusion while permitting a free flow of concrete during placement operations.
- **Weight and Length**. The tremie should be heavy and long enough to rest on the bottom of the placement area before starting concrete placement.
- **Support and Movement**. The tremie's support system should allow it to be raised or lowered to adjust the concrete discharge rate.

Pipe and Fittings for Underwater Crossings (Section 2554.03)

General Requirement

- When crossing watercourses greater than 15 ft in width, the following specifications are to be adhered to:
  - **Cover**. There should be a minimum cover of 5 ft over the pipe unless otherwise specified in the contract documents.
  - **Pipe Specifications**. Use pipes with flexible, restrained, or welded watertight joints.
  - **Valves**. Install valves at both ends of water crossings, allowing the section to be isolated for testing or repair. Ensure that these valves are easily accessible and not susceptible to flooding.
  - **Testing and Sampling Provisions**. Integrate permanent taps or other systems to facilitate the insertion of a small meter. This allows for the detection of leakage and the acquisition of water samples on each valve side closest to the supply source.

Note that in the Iowa DOT specifications consulted, the focus is predominantly on placement methods and equipment. There are no specific recommendations or details found regarding the mix design for underwater concrete.

A16. Kansas

Drilled Shaft (Section 703)

Shaft Cleanliness Prior to Concrete Placement

- At the time of concrete placement underwater, ensure that a minimum of 75% of the base of the shaft has less than ½ in. of sediment.
- The Engineer will determine shaft cleanliness using one of the following methods:
  - Visual inspection
  - Underwater probes
  - Downhole television camera and video recordings
- An engineer's review and inspection before concrete placement does not exempt the Contractor from the responsibility of delivering a defect-free shaft per specifications.

Concrete Structure Construction (Section 710)

Forms

- Use forms that are adequately watertight for holding concrete placed underwater.

Cement Factor and Slump

- Increase the minimum cement factor for the concrete grade being deposited underwater by 10%. This aims for a slump of approximately 6 in.

Method of Depositing Concrete

- Carefully deposit the concrete to achieve a compact mass.
- Use methods like a tremie, pumping through piping, or a bottom dump bucket. Ensure that the method does not allow concrete to freefall through the water.

Water and Concrete Disturbance

- Do not pump out water from inside the foundation forms during concrete placement.
- Do not disturb concrete once deposited.
- If there is a risk of flooding, place a concrete seal using a closed chute or tremie and let it set.

A17. Kentucky

Placing Concrete Under Water (Section 601.03.09)

- Do not expose concrete to water before it sets. Only deposit concrete in water with written permission from the Engineer.
- When concrete is deposited underwater, use concrete mixed in the proportions specified for Class A Modified concrete.
- Ensure that concrete is placed in its final position using a tremie or other approved method.
- Do not disturb the concrete after it has been placed.

- Use a sufficient number of tremies or approved devices to distribute concrete evenly across all parts of the seal.
- Ensure that the water is calm at the point where concrete is being deposited.
- Do not place concrete in flowing water.
- Ensure that underwater formwork, such as interlocking sheeting, is watertight.
- Adjust the consistency of the concrete to prevent segregation.
- Try to keep the surface of the concrete as horizontal as possible.
- To ensure that the concrete layers bond properly, place each successive layer before the one beneath it starts setting.
- Start work with the discharge end of the tremie closed to prevent water from entering.
- Start the flow of concrete by slightly raising the tremie, keeping the discharge end within the deposited concrete. Stop the flow by lowering the tremie.
- Aim for continuous flow, avoiding interruptions until the work is complete.
- Dewatering is permissible when the concrete can resist hydrostatic pressure but not before three days after placement, or longer if directed by the Engineer.
- Remove unsatisfactory material such as laitance from the exposed surfaces as directed by the Engineer.

Concrete Seal in Foundation

- A concrete seal in foundation is the volume of concrete placed underwater using a tremie or other approved method. Its purpose is to seal the bottom area of the excavated pit within the cofferdam against hydrostatic pressure. This allows the excavation to be dewatered and the foundation to be built in dewatered forms.
- The "A Mod" class, utilized for sealed concrete and suitable for underwater applications, is characterized by a slump range of 4 to 7 inches to ensure optimal workability, and the water-to-cement ratio is required to be limited to 0.47, as shown in Table 15.

Table 9. Proportioning and requirements for different concrete classes

INGREDIENT PROPORTIONS AND REQUIREMENTS FOR VARIOUS CLASSES OF CONCRETE							
Class of Concrete	Approximate Percent Fine to Total Aggregate		Maximum Free Water by W/C Ratio(14) (lb/lb)	28-Day Compressive Strength (1) (psi)	Slump (4) (inches)	Minimum Cement Factor (lb/yd^3)	Air (11) Content (%)
	Gravel	Stone					
A(5)	36	40	0.49	3,500	2-5(7)	564	6 ± 2
A Mod	36	40	0.47	3,500	4-7	658	6 ± 2
AA(2)	36	40	0.42	4,000	2-5(12)	620	6 ± 2
B	40	44	0.66	2,500	3-5	451	6 ± 2
D(3)	35	39	0.44	4,000	3-5(6)	639	6 ± 2
D Mod(3)	35	39	0.42	5,000	3-5(6)	733	6 ± 2
M1(8) w/ Type 1 Cement or blended hydraulic cement	36	40	0.33	4,000(9)	7 max.	800	6 ± 2
M2(8) w/ Type III Cement	36	40	0.38	4,000(9)	7 max.	705	6 ± 2
P(5)	35	38	0.49	3,500	---(13)	564(10)	6 ± 2

- Typically, the thickness of the seal course should be 0.43 times the hydrostatic head exerting pressure on the foundation bottom, or as specified in the plans.
- The corners of the seal should be placed at a lower elevation than the rest of the seal surface for dewatering purposes. The elevation difference between the corners and the rest of the seal surface should not exceed 6 in.

A18. Louisiana

Part 805.05.7 Depositing Concrete Underwater

When specified in the project plans or permitted by the agency engineering team, concrete placement can occur underwater. This process must be completed in a manner that prevents segregation and should be executed in a single, uninterrupted operation using a tremie pipe. The specifics for tremie use are outlined in section 803.05.9. Efforts should be made to ensure the surface for underwater concrete placement is as level as practicable. Before any subsequent concrete layers are added, it is necessary to clear away any laitance and undesirable materials from the surface of the construction joint, taking care not to harm the fresh concrete. For applications involving drilled shafts, seals, and underwater placement, Class S concrete is introduced, as detailed in Table 16.

Table 10. Classification and applications of concrete types

Concrete Class	Use
A1, A2, A3	Concrete exposed to sea water, and all other concrete except as listed herein.
MASS(A1), MASS(A2), MASS(A3)	Mass concrete
P1, P2, P3	Precast concrete
S	Drilled shafts, seals and underwater placements
M	Minor structure

The "S" class, designated as Seal Concrete, has an average compressive strength of 4,500 psi at 28 days, and has a slump range of 6 to 8 inches for non-vibrated applications, it cannot be vibrated during placement (Table 17).

Table 11. Master proportion table for portland cement concrete

	Average Compressive Strength, psi at 28 days	Grade of Coarse Aggregate[1]	Surface Resistivity[2] (kΩ-cm)	Maximum Water/Cementitious Ratio, lb/lb	Air Content (Percent by volume)[3]	Slump Range [5], inches		
						Non-Vibrated[4]	Vibrated	Slip Form Paving [6]
Structural Class [7]								
A1	4,500	57M, 67, 89M[9], B,D	22	0.45	2 - 7	2-5	2-4 [4]	N/A
A2	6,500 [11]	57M, 67, 89M[9], B,D	22[11]	0.45	2 - 7	2-5	2-4 [4]	N/A
A3	9,000 [11]	57M, 67, 89M[9], B,D	22[11]	0.36	2 - 7	2-5	2-4 [4]	N/A
P1	6,000 [8]	57M, 67, 89M[9], B,D	22	0.44	2 - 7	N/A	2-6 [10]	N/A
P2	8,500 [8]	57M, 67, 89M[9], B,D	22	0.40	2 - 7	N/A	2-6 [10]	N/A
P3	10,000 [8]	57M, 67, 89M[9], B,D	22	0.40	2 - 7	N/A	2-6 [10]	N/A
S	4,500	B, D	22	0.53	2 - 7	6-8	N/A	N/A
MASS(A1)	4,500	B, D	22	0.53	2 - 7	N/A	2-4 [4]	N/A
MASS(A2)	6,500 [11]	B, D	22[11]	0.46	2 - 7	N/A	2-4 [4]	N/A
MASS(A3)	9,000 [11]	B, D	22[11]	0.36	2 - 7	N/A	2-4 [4]	N/A

A19. Maine

Depositing Concrete Under Water

- No concrete shall be deposited underwater except for cofferdam seals.
- Pumping water to outside of formworks or within the cofferdam will not be allowed while concrete is being placed.
- The concrete shall be placed carefully in a compact mass in its final position by means of a tremie or by other approved means and shall not be disturbed after being deposited. Bottom dump buckets will not be permitted.
- Particular care must be exercised to maintain still water at the point at which concrete is deposited. Concrete shall not be placed in running water.
- The method of depositing concrete shall be so regulated as to produce approximate horizontal surfaces.
- Each seal shall be placed in one continuous operation.
- When a tremie is used, it shall consist of a tube not less than 10 in. in diameter.

- The means of supporting the tremie shall be such as to permit free movement of the discharge end over the entire seal and to permit its being lowered rapidly when necessary to choke off or retard flow.
- The tremie shall be filled by a method that will prevent washing of the concrete. The discharge end shall be completely submerged in concrete at all times, and the tremie tube shall be kept full to the bottom of the hopper. The flow shall be regulated by raising or lowering the tremie.
- When the horizontal area of the tremie seal is large, several tremie hoppers shall be provided and positioned strategically to allow placement of concrete near the point where it is needed, to avoid moving concrete horizontally through the water. The number of tremie hoppers and the work plan shall be approved by the Resident.
- All laitance or other unsatisfactory material shall be removed from the surface of the seal before placing additional concrete. The surface shall be cleaned by scraping, chipping or other means that will not injure the concrete.

A20. Maryland

Depositing Concrete Under Water (Section 420.03.05)

- Do not deposit concrete in water or expose it to water before setting unless specified or approved.
- Use a tremie pipe of at least 10 in. in diameter with a watertight plug.
- Fit the bottom of the tremie pipe with a baffle or deflector plate.
- The number and location of tremie pipes will depend on the size of the pour.
- Do not disturb tremie concrete after placement.
- Do not place successive layers on previously placed concrete until it has attained the necessary strength as determined by the Engineer.
- Concrete should not be deposited in water colder than 35°F. For water temperatures between 36°F and 45°F, heat the concrete and place it within a range of 60°F to 80°F.
- Pumping of water is prohibited during concrete placement.
- Regulate concrete consistency to prevent segregation.
- Trim any portions of the tremie concrete that stand more than 6 in. above the planned elevation.

A21. Massachusetts

Section 901.63: D. Placing Concrete Under Water

- Concrete may be deposited in water only when stipulated in the plans or in the Special Provisions or when approved in writing by the Engineer, and only under the direct supervision of the Engineer.
- The concrete shall be of the designation required except that an additional 10% of cement shall be added to all concrete deposited under water except that mass concrete shall be placed with the cement content required by any Special Provisions.

- The method and equipment to be used shall be approved by the Engineer before work has begun. Concrete deposited under water shall be carefully placed by the tremie method in a compound mass in its final position and shall not be disturbed after being deposited.
- Special care must be taken to maintain still water at the point of deposit. No concrete shall be placed in running water, and all form work designed to retain concrete under water shall be watertight.
- The consistency of the concrete shall be carefully regulated, and special care shall be taken to prevent segregation of the materials. The concrete shall be distributed uniformly over the entire area between forms in order to maintain a level surface.
- The work shall be carried out in a continuous operation with sufficient rapidity to prevent the formation of layers or inclined seams. Concrete shall not be placed in water having a temperature below 35°F.
- Pumping of water will not be permitted while the concrete is being deposited nor before it is sufficiently hardened. The tremie shall be watertight, consisting of a tube constructed in sections with flange couplings fitted with gaskets, and the inside diameter shall be sufficiently large to permit the free flow of concrete.
- The spacing of the tremie tubes shall not exceed 20 ft on centers or 10 ft from the forms. The tremie tubes shall not be moved horizontally or the seal purposely broken once placing of concrete has started. The radius of influence of a tremie shall not be assumed to exceed 10 ft.
- The means of supporting the tremie shall be such that the tremie can be rapidly lowered when necessary to retard or stop the flow of concrete. The discharge end shall be closed at the start of the work so as to prevent water from entering the tube and shall be kept entirely sealed at all times and the tremie tube kept full to the bottom of the hopper during the depositing of the concrete.
- When a batch is dumped into the hopper, the tremie shall be slightly raised, but not out of the concrete at the bottom, until the batch discharges to the bottom of the hopper. The flow shall then be stopped by lowering the tremie. Special care shall be taken to maintain as nearly as practicable a uniform flow and to avoid dropping the concrete through the water.
- The flow shall be continuous until the work is completed. If the charge is lost during depositing, the tremie shall be withdrawn and refilled. Dewatering may start when the concrete seal has reached a compressive strength of 1,200 psi.
- All laitance and scale shall be removed so that sound, durable concrete is exposed to the area on which the construction is to be based and shall be leveled off with epoxy-bonded concrete or mortar.

A22. Michigan

Concrete Placement Methods for Drilled Shafts (Section 718)

Underwater Placement

- For wet methods of construction, concrete should be placed in one continuous operation from the bottom to the top of the shaft.
- Continue placing concrete until clean concrete appears at the top of the shaft.
- Do not vibrate the concrete except for the top 5 ft in dry placements.

Underwater Placement Methods

Tremie Tubes:

- The tremie method is suitable for wet or dry excavations.
- Tremie tubes must be of a certain length, weight, and diameter to effectively discharge concrete.
- Tremie tubes should have an inner diameter of at least 10 in.
- Ensure that the tremie tubes are watertight and smooth.
- Tremie tubes should be immersed at least 10 ft into the concrete after initiation of flow.
- If the concrete flow is interrupted during placement, the tube needs to be resealed, reinserted, and recharged before continuing.

Pumped Concrete:

- Pumped concrete is suitable for use in either wet or dry excavations.
- Use pipes with a minimum diameter of 4 in. and watertight joints.
- Minimize bends in pipes conveying the concrete.
- Ensure that pipes are anchored.

Environmental Precautions:

- Use a sump or other approved method to divert displaced fluid and concrete away from the excavation.
- Do not discharge these displaced fluids into waterways, wetlands, floodplains, or sewers.
- If concrete is poured over water, a system to capture the slurry and the top portion of overflowing concrete must be used.

A23. Minnesota

Sections 5.393.104 and 5.393.352 of the Minnesota DOT specifications offer some guidelines related to underwater concrete placement.

Tremie Specifications

- The tremie system must use a watertight metal tube with a minimum diameter of 250 mm (10 in.).
- The tremie tube must be strong enough for the intended work.
- The lower end of the tremie tube must have a valve or a device that meets the following requirements:
  - The valve can be closed tightly while charging and positioning the tremie.
  - The valve can be fully opened when the tube is lowered.
  - A typical tube may have a 300 mm (12 in.) steel shell pile section with a welded hopper (either conical or rectangular with a sloping bottom).
  - Control cables for the valve might run through the tremie tube up to the top of the hopper.
  - If sectional tubes are utilized, they must have watertight gaskets where sections are bolted together.

- o The tube should be long enough that the hopper remains above water when the bottom of the tube is at the bottom of the excavation.

The schematic process and details of tremie method has depicted in Figure 25.

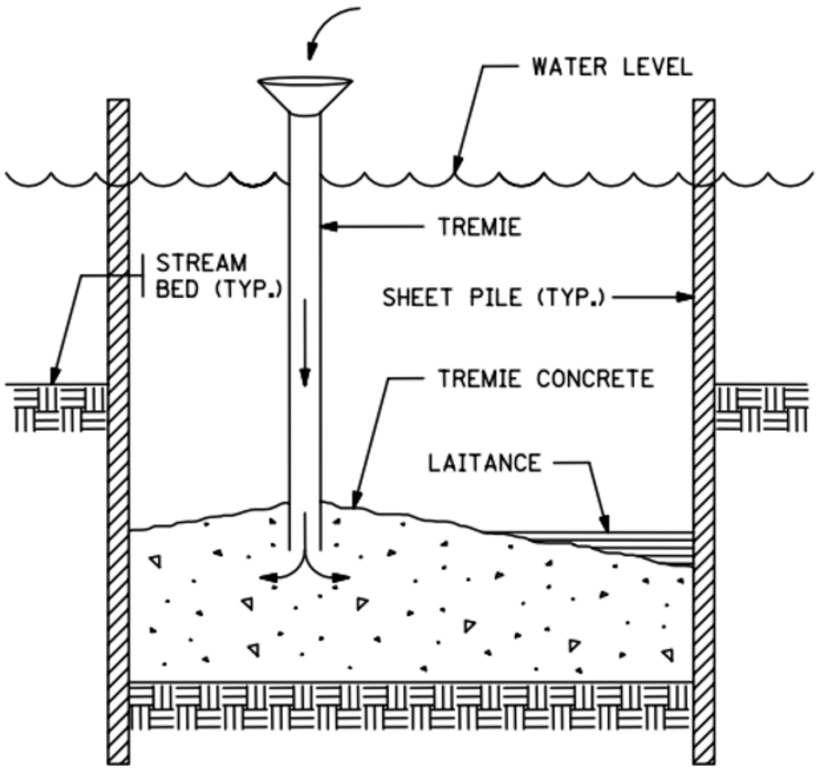


Figure 25. Tremie underwater concrete placement

Underwater Foundation Precautions

- After underwater foundation excavation and before pile driving, it is essential to check the bottom elevation of the excavation thoroughly.
- Ensure that no dirt mounds are present, especially under struts, walers, or bracing.
- After pile driving operations, a similar check is necessary.
- If the bottom of the underwater foundation is too high after pile driving, excess material might be removed by scouring the area using a water jet and pumping the material while still in suspension.

A24. Mississippi

Depositing Concrete Under Water (Section 804.03.09)

General Guidelines

- Concrete should not be deposited in water without the Agency Engineer's approval.

- When deposited under water, the concrete type used should be Class S, other requirements of this class has outlined in Table 18.

Table 12. Master proportional table for concrete mix design

Class	Application	Coarse Aggregate Size No.	Maximum w/cm Ratio	Specified Compressive Strength (f'_c) psi	Maximum Permitted Slump, or Slump Flow inches[3]	Nominal Total Air Content (%)	Maximum Static Segregation (%)
AA	General and Structural	57 or 67	0.45	4000	3 [-1.5] 4-8 [-2.5]	4.5±1.5	N/A
BD	Bridge Deck[1]	57 or 67	0.43-0.45	4000	5 [-2.5]	4.5±1.5 6.5±1.5	N/A
S	Seal concrete deposited under water	57 or 67	0.45	3000	8 [-2.5]	4.5±1.5	N/A
DS[2]	Drilled shaft	67	0.45	4000	8±1	See note[2]	N/A
DS[2]	Drilled shaft SCC	67	0.45	4000	24 [-6]	See note[2]	15

[1] For Class BD concrete for bridge decks, the water/cementitious material ratio range shall be 0.43-0.45 and the maximum cementitious material content shall be 550 pounds per cubic yard.

Depositing Process

- When concrete is deposited underwater, it should be meticulously placed in a compact mass in its final position using methods such as the tremie method, bottom dump bucket method, or other sanctioned methods.
- Once deposited, the concrete should remain undisturbed.
- It is crucial to ensure still water at the deposit point and avoid placing concrete in running water.
- All formwork designed to retain underwater concrete must be watertight.
- The concrete’s consistency must be carefully controlled, with particular emphasis on preventing material segregation.

Concrete Seals

- Concrete seals should be placed continuously from start to end.
- The surface of the concrete should remain as horizontal as feasible at all times.
- Each succeeding layer of a seal should be placed before the preceding layer starts to set.

Tremie Usage

- If the tremie method is employed, the tremie tube should have a diameter of at least 10 in.
- The tremie tube should be constructed in sections with flanged couplings fitted with gaskets.
- The setup should allow for the free movement of discharge across the whole top surface of the work and should facilitate rapid lowering when necessary.
- The discharge end should be sealed at the beginning of work to prevent water entry and should be entirely sealed throughout the operation.
- The tremie should always be full up to the bottom of the hopper.
- To facilitate the flow of concrete, slightly raise the discharge end while ensuring it stays submerged in the deposited concrete.
- Lowering the tremie can stop the flow, which should remain uninterrupted until the task is complete.

Drop Bottom Bucket Method

- The top of the bucket should be open during casting.
- The bottom doors of the bucket should open freely downward and outward when activated.
- The bucket should be filled completely and lowered slowly to prevent backwash.
- The concrete should not be dumped until the bucket is on the surface where the concrete is intended to be deposited. Once emptied, the bucket should be withdrawn slowly until it is well above the concrete.

A25. Missouri

Section 701.4.13.2.2 – Tremie Operation

- The underwater placement process should not commence until the tremie reaches the shaft base elevation.
- The discharge end of the tremie must be designed to allow for the free radial flow of concrete during placement.
- The discharge end of the tremie must remain submerged in the concrete to a minimum depth of 5 ft throughout the operation.
- The tremie should be supported to enable free movement of the discharge end across the work surface and quick lowering when required to manage the concrete flow.
- The discharge end of the tremie should be sealed initially to keep water out until the tremie tube filled with concrete.
- Once placement begins, the level of the concrete inside the tremie should always be maintained above the level of the slurry or water in the borehole to ensure that no water or slurry gets into the shaft concrete.
- If water does penetrate the tremie after placement is initiated, the tremie should be removed and resealed at its discharge end and the placement process should be restarted.
- The concrete flow should be maintained continuously until completion.

Section 703.3.3.6 – Underwater Concrete Placement

- Depositing concrete underwater is allowed either if stated in the contract documents or upon written approval from the engineer.
- The concrete should be placed using methods such as tremie, bottom dump bucket, or mechanically applied pressure.
- The concrete needs to be placed in its final position in still water and should not be subjected to any vibration or disturbance after it is deposited.

Section 501 – Seal Concrete

- The maximum aggregate size for seal concrete should not exceed 19 mm.
- Apart from Type I and II ordinary portland cement (OPC), Type IL and IS cements are also acceptable.
- The minimum cement content required for seal concrete is 660 lb/yd^3.

A26. Montana

Depositing Concrete Underwater (Section 552.03.5)

- For seals mentioned in the contract, utilize Class General or Drilled Shaft concrete.
- All expenses associated with placing concrete beyond the plan's dimensions or altering the seal mix design for the contractor's convenience are borne by the contractor.
- Concrete should not be placed underwater without the approval of the Project Manager.

Requirements for drilled shaft concrete depicted in Table 19.

Table 13. Requirements of different concrete classes

Class	Nominal Maximum Aggregate Size inches (mm) [6 & 9]	Cementitious Materials Content, lbs./yd^3 (kg/m^3) [11]	Indicated Compressive Strength, 7-Day, PSI (MPa)	Minimum Required Compressive Strength, 28-Day, PSI (MPa) [5]	Water / Cement Ratio (W/C) [5]	Maximum Target Value for Slump, inches (mm) [2]	Slump Tolerance, inches (mm)	Required Air Content, (%) [7]
General[8]	1½ (37.5) - ¾ (19)	658 (390) max	—	4000 (28)	0.45 max	5 (130)	+1½ (37) to -2 (50)	5.0-8.5
Pave	1½ (37.5) - ¾ (19)		Note 3			3 (75)		
Pre[1]	¾ (19)	—	—	Note 1	0.40 max	—	—	—
SCC	¾ (19)	—	—	Note 4	0.42 max	See Special Requirements for SCC Concrete		5.0-8.5
Deck	1½ (37.5) - ¾ (19)	564 (334) max	—	4000 (28)	0.42 – 0.45	5 (130)	+1½ (37) to -2 (50)	
Overlay-SF	½ (12.5)	580 (344) max	Note 10			5 (130)		
Overlay-LM	½ (12.5)	660 (392) min	Note 10		0.30 - 0.40	5 (130)		3.0-6.5
Structure	1½ (37.5) - ¾ (19)	580 (344) max	—		0.42 max	6 (150)		5.0-8.5
Drilled Shaft	¾ (19)	—	—		0.45 max	See Special Requirements for Drilled Shaft Concrete		—
Lean	1½ (37.5) - ¾ (19)	—	—	—	0.53 max	—		Note 12

Notes:

1. The strength for transfer of pre-stress and the 28-day strength requirement vary with beam length and design. Check plans and specifications for each project.
2. The field target value for slump may be changed, within requirements, when necessary to facilitate proper placement.
3. For full-depth concrete pavement, the flexural strength requirement to open to traffic is 350 psi (2.4 MPa) minimum determined by AASHTO T 97 or 2500 psi (17.2 MPa) compressive strength.
4. For self-consolidating concrete, the 28-day strength may vary with the class of concrete specified. Check plans and specifications for each project.
5. Maximum water cement ratios and minimum 28-day design strength requirements do not relieve the contractor of supplying concrete producing adequate freeze-thaw protection.
6. Mix designs with other nominal maximum aggregate sizes may be requested based on certain placement and design scenarios.
7. If 1½-inch (37.5 mm) nominal maximum aggregate is used in the design, the air content requirement is reduced to 4.0% - 7.5%.
8. When class General is specified for seal concrete, air entrainment is not required.
9. Nominal Maximum aggregate size is defined as one sieve size larger than the first size to retain more than 10%.
10. Compressive strength must reach a minimum of 3,000 psi (21 MPa) before opening to traffic.
11. When high-early strength concrete is required by contract, higher cement contents may be submitted with the mix design for approval.
12. The minimum required air content is 3%. Tests will be conducted as required by the Project Manager.

Seal Placement

- If it is impractical or not advisable to remove water from an excavation before concrete placement, put a seal course underwater to seal the cofferdam.
- This seal should be placed in a continuous operation and should adhere to the following:
  - Use a tremie system as follows:
    - Directly pump concrete into a tremie hopper or to the deposit point.
    - The tremie system should be constructed and deployed as follows:
      - Construct tremie systems from rigid, watertight steel tubing with a minimum diameter of 10 in. (255 mm) and a hopper on top.
      - Always submerge the discharge end of the tremie in the deposited concrete and maintain it full up to the bottom of the hopper during placement.
      - To initiate concrete flow, raise the tremie when a load is poured into the hopper until the load reaches the bottom of the hopper.
      - The tremie support should permit free movement of the discharge end and allow quick lowering to control or halt the flow.
  - Pump seal concrete as follows:
    - Always have a backup concrete pump or tremie at the site to guarantee continuous placement of the entire foundation seal.
    - Pumped concrete should meet the requirements for tremie-placed concrete.
    - When concrete is directly pumped, the discharge tube should be a rigid pipe extending at least 5 ft (1.5 m) above the water level during placement, and the top discharge line can be flexible.

Concrete Placement Requirements

- Ensure that water does not enter the tube during placement.
- Place concrete as a consolidated mass and avoid disturbing it after it is deposited.
- Avoid placing concrete in running water or exposing it to water actions before its final set.
- Ensure that water remains still at the deposit point.
- Refrain from pumping water out of the cofferdam while underwater concrete is being deposited.
- All formwork used to retain underwater concrete should be practically watertight.
- Deposit concrete in a way that generates horizontal surfaces.

A27. Nebraska

Placing Concrete Under Water (Section 704.03)

General Requirements

- All underwater concrete placements need approval from the Engineer.
- The class and mix of the underwater concrete should be identical to those of the rest of the structure but with a 10% increase in cement content.

Tremie Methods

- The tremie must be a watertight tube with a diameter of at least 10 in. (250 mm).
- The tremie is to be constructed in sections with flexible, watertight couplings.
- Aluminum or aluminum alloy materials that react with concrete should not be used for constructing tremies.
- Tremies should be supported to permit free movement of the discharge end across the top surface of the work and should facilitate rapid lowering if required to manage the concrete flow.

Concrete Placement

- The discharge end of the tremie should be sealed at the beginning of work to ensure that no water enters the tube, and the tube should remain sealed throughout the process.
- The tremie tube should always be kept full.
- Concrete flow is induced by slightly raising the discharge end while ensuring that the end remains submerged in the concrete being placed.
- Concrete flow should be uninterrupted until the operation concludes.
- Concrete placement should be continuous, maintaining a near-horizontal surface as much as feasible.
- Once placed, the concrete should be compact, free of voids, and undisturbed.
- The water at the deposit point should be still, and the forms used must be watertight.

Post-placement Procedures

- A thorough inspection of the concrete is mandatory. Any unsatisfactory material or laitance on the surfaces should be removed.

A28. Nevada

Concrete Deposited Under Water (Section 502.03.10)

- In situations where it is impossible or not advised to dewater the excavation (as per the Engineer's opinion), concrete must be deposited underwater using a tremie or a concrete pump.
- The objective is to deposit a sealed course of concrete that is thick enough to thoroughly seal the cofferdam.
- During the process, the concrete should be deposited in a compact manner and should remain undisturbed after it is deposited.

Tremie

- Avoid the use of an aluminum tremie when placing concrete.
- The tremie tube should be watertight, and its diameter should not be less than 250 mm (10 in.). This tube should have a hopper at the top.
- To initiate the flow of concrete, slightly raise the discharge end whenever a batch is dumped into the hopper. It is essential to always keep the concrete in the deposited state.

Concrete Pumping

- The discharge tubes of the concrete pump and the tremie tubes should be equipped with a device that effectively prevents water from entering the tubes.
- Such tubes should be supported in a manner that allows the free movement of the discharge end across the entire top surface of the work.
- Rapid lowering of the tubes should be feasible when necessary to slow or halt the concrete flow.
- It is crucial to always ensure that the discharge end remains submerged in the concrete throughout the operation.
- It is also vital to fill the tubes in such a way that the washing away of concrete is prevented.
- The tubes should contain ample concrete to block any water ingress, and they should offer a continuous flow until the concrete seal becomes monolithic and uniform in structure.

Concrete Class

- The concrete deposited in water should belong to either Class A or Class AA, with an extra 10% of cement added, as shown in Table 20.
- The exact thickness of the seal will depend on several factors, including the hydrostatic head, bond, spacing of piles, size of the cofferdam, and o on. However, the seal should have a minimum thickness of 600 mm (2 ft).
- After the seal concrete is placed, it should be allowed to cure for a minimum of 5 days before dewatering commences.

Table 20. Specifications for various classes of concrete mix design in Nevada DOT

Class of Concrete	Cement Range kg/m^3 (lb/yd^3)	Grading Limits of Combined Aggregates mm (in.)	Maximum Water Cement Ratio kg/kg (lb/lb)	Minimum Compressive Strength MPa (psi)	Slump Range mm (in.)	Entrained Air Range %
A and AA	330-420 (564-705)	37.5 (1 1/2)	0.45 (0.45)	21 (3000)	25-100 (1-4)	4-7 (AA only)
B BA	300-420 (517-705) 300-420 (517-705)	37.5 (1 1/2) 37.5 (1 1/2)	0.47 (0.47) 0.47 (0.47)	21 (3000) 21 (3000)	25-125 (1-5) 25-100 (1-4)	--- 4-7
C CA	280-360 (470-611) 300-390 (517-658)	37.5 (1 1/2) 37.5 (1 1/2)	0.60 (0.60) 0.51 (0.51)	17 (2500) 17 (2500)	25-125 (1-5) 25-125 (1-5)	--- 4-7
D DA	330-420 (564-705) 330-450 (564-752)	19 (3/4) * 19 (3/4) *	0.45 (0.45) 0.45 (0.45)	21 (3000) 21 (3000)	25-100 (1-4) 25-100 (1-4)	--- 4-7
PAA	330-450 (564-752)	19 (3/4) *	0.45 (0.45)	See Plans	25-100 (1-4)	See Plans
A and AA Modified	330-450 (564-752)	37.5 (1 1/2)	0.45 (0.45)	See Plans	25-100 (1-4)	4-7 (AA only)
D and DA Modified	330-450 (564-752)	19 (3/4) *	0.45 (0.45)	See Plans	25-100 (1-4)	4-7 (DA only)
E and EA Modified	330-420 (564-752)	19 (3/4)	0.40 (0.40)	See Plans	13-100 (1/2-4)	4-7 (EA only)
S and SA	380-545 (639-925)	19 (3/4) *	0.40 (0.40)	28 (4000)	N/A	4-7 (SA only)
PCCP	360-420 (611-705)	See 409.02.01	0.45 (0.45)	28 (4000)	25-125 (1-5)	4-7

A29. New Hampshire

Section 520-3.5.5 Depositing Concrete Under Water

- Unless otherwise specifically permitted, all concrete placed in water shall be placed by tremie. Slump shall for tremie concrete which mostly employed underwater and other types of concrete must comply with Table 21:

Table 21. Recommended slump ranges for different concrete applications

Footings and mass concrete	1 - 3”
Columns and pedestals	2 - 4”
Decks and sidewalks	2 - 3”
Tremie concrete	6 - 8”
Walls over 18” thick	2 - 3”
Walls 18” thick and under	2 - 4”
Concrete with High Range Water Reducer	8” max.

- **Section 3.5.5.1**. Pumping for underwater placement of concrete shall also be into a tremie unless specific permission is given for direct placement by pump lines. Placement by direct pumping, if permitted, will require the hose to be securely fastened to the cofferdam frame at all times to eliminate surging of the hose in the concrete. If at any time the procedure becomes unacceptable, the remainder of the concrete shall be placed by a tremie. Tremie equipment shall be available on site prior to start of pumping operations.
- **Section 3.5.5.2**. A tremie shall consist of a watertight tube attached to a hopper of approved size with an adequate working space provided around the hopper. The tremie shall be attached to a crane or other approved hoisting equipment to permit lifting and lowering of the tremie with sufficient rapidity to control and stop the flow of concrete as required. The equipment shall be capable of moving the tremie over the entire surface of the placement area.
- **Section 3.5.5.3**. At the start of placement operations, and at any time thereafter that the tremie is withdrawn from the concrete, an approved watertight plug shall be inserted into the discharge end of the tremie. The tremie shall be lowered until it rests on the bottom or in freshly deposited concrete. It shall then be checked for leaks. If watertight, the tremie tube and hopper shall immediately be filled with concrete. The hoisting mechanism shall then raise the tremie to permit the discharge of the concrete without removal from freshly deposited concrete. The tremie shall then be lowered to stop the flow of concrete before the level of the concrete has dropped below the level of the bottom of the hopper. The hopper shall again be filled and the process repeated until the desired intermediate or final grade is attained. Top concrete surfaces shall be approximately horizontal.

A30. New Jersey

The New Jersey specifications predominantly cover general details about underwater inspection. However, specific to Underwater Concrete (UWC) in section 27, the specs reference Table 22, which categorizes structural concrete items by their concrete class and design compressive strength. Notably, drilled shafts necessitate a Concrete Class A (or SCC) with a strength of 4000 psi, while tremie concrete, used for underwater applications, is assigned Concrete Class S with a strength of 2000 psi.

Table 14. Classes of concrete in New Jersey DOT

Structural Concrete Items	Concrete Class	Design Compressive Strength (f'c)
Cast-in-Place Items		
Nonreinforced Footing	B	3000 psi
Reinforced Footings	B	3000 psi
Abutments, Walls	B	3000 psi
Concrete Barrier Curb, Bridge	B	3000 psi
Piles	B	3000 psi
Drilled Shafts	A (or SCC)	4000 psi
Columns and Caps for Piers, Arch Spans, Rigid Frames, Culverts, Approach Slabs	A	4000 psi
Decks, Sidewalks, Concrete Patch, Parapets, Curbs, Pylons	HPC-1	4000 psi
Seal (Tremie) Concrete	S	2000 psi

A31. New Mexico

Section 511.3.5.4 Placing Concrete Under Water

If placing concrete under water, the Contractor shall submit a mix design and procedure plan to the Project Manager. The Project Manager may require up to 30 days to approve the design and plan. The Contractor shall allow time in the schedule to accommodate this approval process.

Section 511.3.5.4.2 Concrete Placement with Tremie or by Pumping

The Contractor shall use rigid tremie pipe and/or concrete pumps for concrete placement in either dry or slurry displacement shafts. The Contractor shall place a plug within the tremie or pump line to ensure that the concrete does not segregate prior to developing a concrete pressure head within the tremie or pump line and shall ensure that the plug does not discharge from the tremie or pump line prior to the concrete developing a continuous flow. The Contractor shall not begin underwater placement before placing the tremie or pump line within one (1) tremie or pump line diameter of the shaft base elevation. The Contractor shall remove plugs from the excavation if the Project Manager does not specifically approve them to remain in the shaft. The Contractor shall keep the discharge end continually immersed at least five (5) ft in concrete after starting the flow of concrete. The Contractor shall keep the concrete flow continuous. The Contractor shall maintain the concrete in tremies or pump lines continuously at a positive pressure differential to prevent water or slurry intrusion into the shaft concrete. When lifting pump lines during concrete placement; the Contractor shall temporarily reduce the line pressure until the orifice has been repositioned at a higher level in the excavation. If at any time during the concrete pour the orifice is removed from the fluid concrete column and discharges concrete above the rising concrete level, the Department will consider the shaft defective. The Contractor may, at its own risk and cost, remove the reinforcing cage and concrete to complete the necessary sidewall removal as directed by the State Geotechnical Engineer.

A32. New York

Section 555-3.05 Depositing Structural Concrete Under Water

- Use a tremie tube, pipeline, or similar method for concrete placement under water at temperatures between 32°F to 90°F.
- "Tube" refers to both tremie tube and pipeline unless specified.
- For Classes G and GG, which are applicable for underwater applications, there is a requirement for the replacement of portland cement with 20% pozzolan. This substitution can be accomplished using Class F Fly Ash. See Table 23.

Table 15. Concrete classification and recommended pozzolan substitutions

TABLE 501-3A POZZOLAN SUBSTITUTIONS		
Concrete Class Specified	**Substitute Cement by Mass With**	**Class Substitution Allowed**
A, C, E, H	15-20% Class F Fly Ash (711-10)	HP[1]
I, J	15-20% Class F Fly Ash (711-10)	-
D	15-20% Class F Fly Ash (711-10)	DP[1]
G[2] and GG[2]	20% Class F Fly Ash (711-10)	-
F	No Substitution Allowed	-

NOTES:
1. Class HP and DP concrete may be substituted to mitigate ASR as listed above. Classes HP and DP require the replacement of portland cement with 20% pozzolan and 6% microsilica. The pozzolan may be either Class C or F Fly Ash (§711-10) or Ground Granulated Blast Furnace Slag (§711-12).
2. Classes G and GG require the replacement of portland cement with 20% pozzolan. The mitigation of ASR in Classes G and GG must be accomplished using Class F Fly Ash (§711-10).

- Table 24 details the concrete mixtures based on design mix guidelines. Specifically for Classes G and GG, both are designed for underwater applications. Class G has a total cementitious material content of 727 lb/yd^3, 45.0% sand, a water-to-cementitious material ratio of 0.45, and a slump range of 6-7 inches using coarse aggregate (CA) 2, which has a maximum aggregate size of 1 in. In contrast, Class GG, designated for special underwater use, has a content of 800 lb/yd^3, the same sand percentage, a ratio of 0.45, with a slump range of 6 to 7 in., but utilizes coarse aggregate (CA) 1, which has a maximum aggregate size of ½ in.

Table 16. Guidelines for concrete mix designs

TABLE 501-3 CONCRETE MIXTURES							
Design Mix Guidelines (where sand fineness modulus = 2.80)[1]							
Concrete Class	**T.C.M.[5] Content (lb/cy)**	**Sand % Total Agg. (solid volume)**	**Water/ cement-itious mat'ls (by weight)**	**Air Content % desired (Range)**	**Slump Range (in)**	**Type of Coarse Aggregate Gradation**	**Primary Use**
A	606	36.2	0.46	6.5 (5.0 - 8.0)	2 1/2 - 3 1/2	CA 2	general purpose structural
C[6]	605	35.8	0.44	6.5 (5.0 - 8.0)	1 - 3	CA 2	Pavement: slipform paving, form paving
D	725	45.8	0.44	7.5 (6.0 - 9.0)	2 1/2 - 3 1/2	CA 1	thin structural applications
DP [2]	725	45.8	0.40	7.5 (6.0 - 9.0)	3 - 5	CA 1	thin structural applications, overlays
E	648	35.8	0.44	6.5 (5.0 - 8.0)	3 - 4	CA 2	structural slabs and structural approach slabs
F	716	34.6	0.38	6.5 (5.0 - 8.0)	2 - 3	CA 2	high early strength for pavement or structural applications
G [3]	727	45.0	0.45	6.0 (4.0 - 8.0)	6 - 7	CA 2	underwater
GG [3]	800	45.0	0.45	6.0 (4.0 - 8.0)	6 - 7	CA 1	underwater (special)
H	675	40.0	0.44	6.5 (5.0 - 8.0)	3 - 4	CA 2	pumping applications

- Concrete must be placed on areas cleaned of debris, mud, etc.
- Provide a list of equipment and a schedule to the Engineer 20 days before placement.
- The minimum vertical rise is 1 ft/hour; the minimum placement rate is 40 yd^3/hour.
- Avoid delays to ensure the bond and to prevent cold joints.

Methods of Placement

- Common methods include tremie tube and pump and pipeline.
- Other methods require approval.

Tremie Tube Method (Open System):

- This method uses a vertical tube open at the top.
- The tube size depends on the delivery system.
- Use a hopper or funnel to transfer concrete into the tube.
- A safe work platform is required at the top of the tremie system.

Pump and Pipeline Method (Closed System):

- This method uses a vertical tube attached to a closed system.
- The minimum inside diameter of the pipe should be 5 in.
- An air vent/valve connection is required.
- Class G concrete or “cement-water” grout must be used for pipeline lubrication.

Placement Tubes:

- Mark tubes in 1 ft intervals to show the depth of placement.
- Use watertight joints.
- Place tubes 15 ft from forms, 30 ft on center.
- Install a separate tube at each placement point.
- Do not relocate or remove tubes until concrete placement is complete.
- Maintain the seal even when the tube end is removed from fresh concrete under water.

A33. North Carolina

In section 1000 of the North Carolina specifications, the reference to underwater concrete was identified in Table 25. It states that the drilled pier concrete requires a maximum water-cement ratio of 0.450, applicable for angular and round aggregates. The slump for underwater (wet) construction is set between 7 and 9 in., and the cement content is prescribed at 640 to 800 lb/yd^3 for non-vibrated mixtures.

Table 17. Requirements for different concrete classes

Class of Concrete	Min. Comp. Strength at 28 days	Maximum Water-Cement Ratio				Consistency Max. Slump		Cement Content			
		Air-Entrained Concrete		Non Air-Entrained Concrete		Vibrated	Non-Vibrated	Vibrated		Non-Vibrated	
		Rounded Aggre-gate	Angular Aggre-gate	Rounded Aggre-gate	Angular Aggre-gate			Min.	Max	Min	Max.
Units	*psi*					*inch*	*inch*	*lb/cy*	*lb/cy*	*lb/cy*	*lb/cy*
AA	4,500	0.381	0.426	-	-	3.5	-	639	715	-	-
AA Slip Form	4,500	0.381	0.426	-	-	1.5	-	639	715	-	-
Drilled Pier	4,500	-	-	0.450	0.450	-	5-7 dry 7-9 wet	-	-	640	800
A	3,000	0.488	0.532	0.550	0.594	3.5	4	564	-	602	-
B	2,500	0.488	0.567	0.559	0.630	1.5 ma-chine placed 2.5 hand place	4	508	-	545	
Sand Light-weight	4,500	-	0.420	-	-	4	-	715	-	-	-

A34. North Dakota

Requirements relevant to underwater concrete can be found in Section 602.04.

Pre-placement Notifications and Preparation

The following methods should be used during concrete placement, whether underwater or on the ground:

- Notify the Engineer at least 24 hours prior to concrete placement.
- Ensure that all forms are clean and free from any deleterious material.
- Do not place concrete on or against frozen ground.
- Remove temporary supports such as struts, stays, and braces as fresh concrete rises and renders them unnecessary.

Concrete Placement

- Concrete should be placed in such a way as to avoid aggregate segregation and ensure complete consolidation.
- Place concrete in successive horizontal layers.
- Pour the next layer before the prior layer begins to set.
- Endeavor to place concrete directly into its final position.
- If chutes or tremies cannot be used due to form dimensions or placement location and if there is a need for a freefall of concrete beyond 5 ft, adopt methods that prevent concrete segregation. Freefall only is acceptable for dry drilled shafts.

Use of Tremies

- Ensure that tremies remain filled with concrete throughout the placement operation.
- The lower end of the tremie must always be submerged in the concrete during the pour.
- Specifically for caisson foundations, keep the lower end of the tremie submerged a minimum of 5 ft into the concrete during the entire pour.

A35. Ohio

Concrete Type and Requirements for Underwater/Wet Concrete Placement

- Use Class QC 5 or QC 4 concrete for drilled shafts over 7 ft (2.1 m) in diameter, as depicted in Table 26.

Table 18. Concrete mix design requirements

TABLE 499.03-1 CONCRETE MIX DESIGN REQUIREMENTS

Quantities per Cubic Yard (Cubic Meter) Provide Concrete with 7±2% Air Content				
Class	**Design Strength psi (MPa)**	**Permeability [1] Maximum (Coulombs)**	**Cementitious Content [2] Minimum. lbs (kg)**	**Aggregate Requirements**
QC 4 Mass Concrete	4,000 (28.0) or as per plan [3]	2,000 or as per plan	470 (213) [4] [5] or as per plan	Well-Graded or as per plan
QC 5 [8]	4500 (31.0) at 28 days	N/A	520 (236)	1 inch or 3/8-inch nominal maximum size

[3] Strength for Mass Concrete (QC 4) may be tested at either 28 or 56 days.
[4] Do not use Type III cement or accelerating admixtures in mass concrete.
[5] The maximum fly ash, natural pozzolan, or slag cement content may be increased up to 50%.
[6] For QC Misc. mixes only –Water/Cementitious ratio limited to 0.50 maximum.
[7] Cement or a combination of cement and up to 15% fly ash or natural pozzolan; or up to 30% slag cement.
[8] For QC 5 and QC SCC mixes with 3/8-inch nominal size, provide an air content of 8±2%.
[9] Portland cement concrete pavement mix design.

- The required slump is 6 ± 1 in. (150 ± 25 mm). Additional slump may be achieved using chemical admixtures Type F or G. For tremie placement, increase the slump to 8 ± 1 in. (200 ± 25 mm).
- The maximum water-to-cement ratio is 0.44.
- For underwater concrete placement, add 10% more cement to the mix.

Wet Method Construction

- Place the concrete in one continuous operation from the bottom to the top of the shaft.
- After the concrete reaches the top of the shaft, continue pumping and remove any contaminated concrete until high-quality concrete is evident.
- Do not vibrate the concrete.
- When the top of the shaft is below ground during concrete placement, use a casing to prevent material from caving into the fresh concrete.
- Do not place concrete without acceptance from the Engineer.

Tremie Placement

- A gravity tremie can be used instead of a concrete pump.
- For uncased wet holes, ensure the shaft excavation remains filled with slurry or water to avoid any water infiltration.
- The tremie should have a diameter of at least 10 in. (250 mm) and be constructed to ensure the smooth flow of concrete and unimpeded withdrawal.
- The tremie should not contain aluminum parts that contact the concrete.

- Use a watertight tremie and ensure that it is at the shaft base elevation before the underwater placement begins.
- The discharge end of the tremie should be immersed at least 10 ft (3 m) in concrete at all times after starting the flow of concrete.

Pumped Concrete

- For uncased wet holes, maintain the shaft excavation full of slurry or water to prevent water inflow.
- Use a concrete pump pipe with a minimum diameter of 4 in. (100 mm) and watertight joints.
- Ensure that any vibrations from the pump equipment do not damage the fresh concrete.
- Do not use aluminum pipes for concrete conveyance.
- Pump lubricating grout, mortar, or concrete (without coarse aggregate) ahead of the specified concrete.
- The outlet end of the pumping system should ideally be approximately 10 ft (3 m) below the top of the fresh concrete. Once the concrete reaches the top of the shaft, remove all laitance.

A36. Oklahoma

Section 509.04

- Underwater placement is allowed for seal concrete and drilled shafts.
- Seal concrete is used to protect structures from water.
- For concrete placed underwater, increase the cement content by 10%.
- Place drilled shafts as per Section 516, Drilled Shaft Foundations.
- Concrete should be compact underwater and avoid segregation.
- Maintain still water at the deposit point.
- Underwater forms should be watertight.
- Vent cofferdams during placement and curing to maintain hydrostatic pressure and prevent water intrusion.
- Maintain a continuous flow of concrete underwater and keep the surface level.
- Ensure bonding by placing each new layer of seal concrete before the previous layer sets. For large pours, use multiple tremies or pumps.

Tremies

- The tremie tube must be watertight and have a diameter of at least 10 in. (250 mm).
- Fit the top of the tremie with a hopper.
- Multiple tremies may be required as per the Contract.
- The tremie should be capable of rapid lowering to control concrete flow.
- Seal the discharge end of the tremie tube at the start of placement and keep it full during placement.
- If water enters the tremie tube, remove the tremie, reseal the discharge end, and maintain a continuous concrete flow.

Concrete Pumps

- Avoid pumping concrete directly into drilled shafts.
- Pump concrete into a tremie as outlined in Section 516.04.C.(6), Tremies.
- Pump concrete into footings and other structures as approved by the Engineer.
- Pumps should prevent water entry as concrete fills the tube.
- When concrete starts flowing, the end of the discharge tube should be full and remain below the surface of the deposited concrete.

A37. Oregon

In the Oregon specifications, two tables in section 02001.20 pertinent to underwater concrete were identified. Table 27 indicates that the Drilled Shaft Concrete class and seal concrete class, suitable for underwater applications, specifies a slump range of 8 1/2" ± 1 1/2". Similarly, Seal Concrete, which also can be used for underwater contexts, prescribes a slump of 8" ± 2".

Table 19. Slump requirements for different concrete conditions

Concrete Slump	
Condition	**Slump**
Concrete without WRA	4" max.
Concrete with WRA	5" max.
Concrete with HRWRA	6" ± 2"
Precast Prestressed Concrete with HRWRA	10" max.
Seal Concrete	8" ± 2"
Drilled Shaft Concrete	8 1/2" ± 1 1/2" [1]
[1] Maintain a minimum slump of 4 inches throughout drilled shaft placement, including temporary casing extraction.	

The drilled shaft concrete, used for structural purposes, is designed with a strength of 4000 psi and requires a maximum water-to-cementitious material (w/cm) ratio of 0.48, as detailed in Table 28.

Table 20. Strength and w/cm ratio for various concrete types

Concrete Strength and Water/Cementitious Material (w/cm) Ratio		
Type of Concrete	**Strength f'_c (psi)**	**Maximum w/cm Ratio**
Structural	3300	0.50
	3300 (Seal)	0.45
	4000	0.48
	4000 (Drilled Shaft)	
	HPC4500	0.40
	HPC (IC) 4500	
	5000 +	
Paving	4000	0.44
	5000	0.48
PPCM's (with cast-in-place decks and no entrained air)	5500	0.44
	6000 +	0.42

A38. Pennsylvania

Section 1006.03-h

Employ the tremie method for deploying Class A cement concrete for structural uses in underwater, casing-supported excavations. For all underwater placements, Self-Consolidating Concrete (SCC) should also be placed using the tremie method regardless of conditions. Additional information and guidelines can be found in Table 29.

If the top elevation of the shaft is below the ground level at the time of concrete placement, provide an oversized casing from the ground elevation to a point below the top of the shaft to prevent extraneous material from falling into the fresh concrete during and after placement. Keep the oversized casing in place until the concrete has cured at least 24 hours.

For permanently cased drilled caissons that carry lateral loads, grout the area between the casing and the excavation to provide adequate bearing capacity.

Table 21. Criteria for various classes of cement concrete

Class of Concrete	Use	Cement Factor(2)(4) (lbs./cu. yd.)		Maximum Water Cement Ratio(5) (lbs./lbs.)	Minimum Mix(1,7) Design Compressive Strength (psi)				28-Day Structural Design Compressive Strength (psi)
					Days				
		Min.	Max.		3	7	28(8)	56(8)	
AAAP	Bridge Deck	560	640	0.45	—	3,000	4,000	—	4,000
AAA(3)	Other	634	752	0.43	—	3,600	4,500	—	4,000
AAAP LW	Bridge Deck	600	730	0.45	---	3,000	4,000	---	4,000
AA	Slip Form Paving	587	752	0.47	—	3,000	3,750	—	3,500
AA	Paving	587	752	0.47	—	3,000	3,750	—	3,500
AA	Accelerated(6)	587	800	0.47	—	—	3,750	—	3,500
AA	Structures and Misc.	587	752	0.47	—	3,000	3,750	—	3,500
AA LW		587	752	0.47	---	3,000	3,750	---	3,000
ASC(9)		587	846	0.47	---	---	4,000	---	4000
A		564	752	0.50	—	2,750	3,300	—	3,000
C		394	658	0.66	—	1,500	2,000	—	2,000
HES		752	846	0.40	3,000	—	3,750	—	3,500

(1) Test Procedures: Slump—AASHTO T 119; Compressive Strength—PTM No. 604, or Maturity Meter Method—PTM No. 640. The upper age limit and lower age limit are defined by the values listed for 7-day and 28-day compressive strength.
(2) For use in miscellaneous or structural concrete, if the Fineness Modulus (FM) is between 2.3 and 2.5, increase the minimum cement factor for the class of concrete 47 pounds per cubic yard. This requirement may be waived after adequate strength data is available and analyzed according to the mix-design section in ACI 211.
(3) AAA concrete is not allowed to be used for new bridge decks.
(4) For exception, see Section 704.1(c). Cement factor may be increased to a maximum of 690 pounds per cubic yard with the approval of the DME/DMM.
(5) If a portion of the cement is replaced by SCM, use a water to cement plus SCM ratio by weight. The minimum water cement ratio for AAAP is 0.40 pounds per pounds.
(6) For accelerated cement concrete, submit mix design, as specified, Section 704.1(c), having a minimum target value compressive strength of 1,500 pounds per square inch at 7 hours if tested according to PTM No. 604. (1,500 pounds per square inch at 7 hours is for mix design acceptance only). The required compressive strength for opening to traffic is specified in Section 501.3(q).
(7) Trial Mix Designs for Class AAAP, AAAP LW, ASC and all concrete paving mixtures are required to meet a minimum 28-day compressive strength overdesign requirement of 28-day Minimum Mix Design Compressive Strength plus 500 pounds per square inch.

A39. Rhode Island

Placing Concrete Under Water (Part 808.03 — Bridge Structures)

- Do not place concrete underwater without the Engineer's approval and supervision.
- Use methods specified by the Engineer for underwater placement.
- Use a tremie for underwater concrete placement.
- Once the concrete is placed, do not disturb the concrete.
- Ensure still water at the placement point and watertight underwater forms.
- Continuously place concrete seals for underwater structures when feasible.

- Maintain a nearly horizontal concrete surface.
- Ensure thorough bonding by placing each new layer before the previous layer's initial set.

Tremie Specifications

- Tremie tubes should have a diameter of at least 10 in.
- Tremie tubes should be constructed in sections with flanged couplings fitted with gaskets.
- Tremie tubes should be supported to allow free movement over the entire top surface of the work.
- Use a foot valve to close the discharge end when placement begins to prevent water entry into the tube.
- All joints should be sealed before concrete is discharged into the empty tube.
- Keep the tremie tube filled to the bottom of the hopper.
- Ensure a continuous concrete flow by slightly raising the discharge end within the placed concrete mass.
- Place concrete underwater continuously from start to finish.
- For large pours, use multiple tremies or pumps to maintain a continuous flow and to ensure that bonding requirements are met.

A40. South Carolina

Section 702.4.2.6 Depositing Concrete Underwater

- When concrete is permitted to be deposited in water by the Plans or Special Provisions or with the written approval of the Supervising Agency, ensure that the concrete and procedure conform to the requirements of Subsection 712.4.13 for depositing Class 4000DS concrete in water.
- For drilled shaft construction, utilize Class 4000DS concrete, designed with specifications that include a minimum of 625 lbs. of cement per cubic yard, a slump range of 7 to 9 inches, and a 28-day minimum compressive strength of 4000 psi. The mix does not require an air-entraining admixture and should have a nominal coarse aggregate size of ¾ inch, as depicted in Table 30.

Table 30. Structural concrete types

Structural Concrete Table					
Aggregate Type	Minimum Cement Content (lbs./CY)	Other Cementitious Material (lbs./CY)	Min. 28 Day Mix Design (psi)	Percent Fine to Coarse Aggregate Ratio	Max. Water to Cementitious Material Ratio
Class 3000					
Crushed stone	588	--	3000	35:65	0.46
Gravel	588	--	3000	34:66	0.44
Marine Limestone	588	--	3000	39:61	0.47
Class 4000					
Crushed stone	611	--	4000	35:65	0.40
Gravel	611	--	4000	34:66	0.40
Class 4000S					
Crushed stone	682	--	4000	38:62	0.45
Gravel	682	--	4000	38:62	0.45
Class 4000DS (See Notes 2 & 4)					
Crushed stone	625	--	4000	40:60	0.44
Gravel	625	--	4000	39:61	0.43

- Make certain that Class 4000S concrete has a slump of approximately 8±1 in.
- When considered desirable, use a water-reducing retarder to delay the initial set of the concrete deposited under water.
- To prevent segregation, carefully place the concrete in a compact mass in its final position by means of a tremie or other method accepted by the Bridge Construction Engineer (BCE) and do not disturb the concrete after it has been deposited.
- Maintain still water at the point of deposit.
- Unless otherwise permitted, place concrete seals continuously from start to finish and keep the surface of the concrete as nearly horizontal as is practicable at all times. Ensure thorough bonding by placing each succeeding layer of a seal before the preceding layer has initially set.
- Remove all laitance and foreign matter from the top surfaces before any concrete is placed upon them in the dry.

A41. South Dakota

Underwater Placement of Concrete (Section 465.3 M. Drilled Shaft Construction)

Tremie Method

- The tremie pipe must be made of steel with a minimum wall thickness of 0.25 in. and a minimum inside diameter of 7¾ in.
- The pipe must be clean and free of rust, hardened concrete, or other contaminants.
- The pipe should be marked to determine its depth.
- Joints in the tremie pipe should be watertight.
- Concrete placement via tremie should be continuous. If interrupted, the wait must not exceed 30 minutes or the initial set time of the concrete.
- To start or restart concrete placement, the bottom of the tremie should be sealed, lowered to the shaft bottom (or at least 5 ft into the concrete), and then filled with concrete.
- The mouth of the tremie should always remain embedded at least 5 ft into the fresh concrete.
- Concrete should not fall through water.
- The tremie pipe should not be moved horizontally during concrete flow.
- All vertical movements of the tremie must be made slowly. If the seal is lost, the tremie must be resealed, replaced, and restarted.

Concrete Pump Method

- Concrete pumps are suitable for underwater concrete placement as long as the pump line surging can be controlled.
- The pump line must be at least 4 in. in diameter, with the part that penetrates the deposited concrete being a rigid steel line.
- An approved plug is inserted into the pump line in such a way that the fresh concrete pushes against the plug without any intervening air or water.
- The pump line must start within 6 in. of the shaft bottom and be kept embedded at least 5 ft into the fresh concrete.
- Concrete should not fall through water.
- Concrete placement should be continuous, with interruptions not exceeding 30 minutes or the initial set time of the concrete.
- If the pump line is removed or comes out of the concrete, placement should be restarted by sealing the end of the pump line, filling it with concrete, and embedding it at least 5 ft into the concrete.

A42. Tennessee

Depositing Concrete Under Water (Section 604.18)

- Do not deposit concrete underwater except for cofferdam seals and drilled shafts.
- Prepare foundations per Section 204.10 before placing foundation seals.
- Inspect foundations for seal *concrete* as follows:
    - Use an experienced diver with a diving suit and two-way telephonic equipment.

- Have the necessary equipment for underwater inspections.

Placement of Concrete for Seals

- Place seal concrete only in still water.
- Ensure cofferdams or cribs meet the requirements in Section 204.09.
- Maintain a near-horizontal concrete surface throughout the operation.
- Use a tremie for placement, unless otherwise approved.
- Do not disturb the concrete after placement and prevent the concrete's exposure to water before final setting.

Concrete Specifications

- Use the proportions designated for Class S concrete.
- Do not use extra compensation (such as increases in water, aggregate, or other components) for additional cement added in S class.
- Regulate the consistency of the concrete to avoid segregation.
- Place underwater concrete continuously until completion.

Technical requirements of class S and other types of concrete are shown in Table 31.

Table 22. Requirements of various classes of concrete

Class of Concrete	Min 28-Day Compressive Strength (psi)	Min Cement Content (pound per cubic yard)	Maximum Water/Cement Ratio (pound/pound)	Air Content % (Design ± production tolerance)	Slump (inches)
A	3,000	564	0.45	6 ± 2	3 ± 1 (1)
D, DS (2, 3)	4,000	620	0.40	7 (3)	8 max (4)
L (3, 5)	4,000	620	0.40	7 (3)	8 max (4)
S (Seal)	3,000	682	0.47	6 ± 2	6 ± 2
X (6)					

(1) For slip forming, the slump shall range from 0 to 3 inches.

(2) Use Class D concrete in all bridge decks except box and slab type structures unless otherwise shown on the Plans. Use Class DS concrete in bridge decks with polish-resistant aggregate described in **903.03** and **903.24**.

(3) Design Class D, Class DS, and Class L concrete at 7% air content. Acceptance range for pumping and other methods of placement is 4.5-7.5%. Sampling will be at the truck chute.

(4) Water reducing admixtures are acceptable; however, do not exceed the maximum water/cement ratio in order to achieve the required slump.

(5) The unit weight of air dried Class L concrete (lightweight concrete) shall not exceed 115 pounds per cubic foot as determined according to ASTM C567.

(6) Plan specific requirements

Tremie Specifications

- The tremie should be made of metal and attached to a suitable hopper.
- The tremie should be designed to withstand stresses.
- The tremie tube should have a minimum inside diameter of 10 in.
- Tremie sections should be joined with flanged couplings fitted with gaskets.
- The tremie should be supported in a way that allows free movement and rapid lowering.
- Equip the lower end of the tremie with a valve or similar device.
- Keep the valve closed while charging and lowering the tremie and keep the valve fully open when the tremie is in the lower position.
- Prevent water entry by keeping the tremie filled with concrete.
- Induce flow by raising the tremie while keeping the discharge end within the concrete.

A43. Texas

Place concrete through a closed tremie or pump it to the bottom of the excavation. The minimum tremie diameter will be at least six times the maximum size of the aggregate used in the concrete mix but not less than 10 in. Initially seal the tremie or pump line to positively separate the concrete from the slurry or water. Place concrete continuously from the beginning of placement until the shaft is completed.

If using a tremie, keep the tremie full of concrete and well submerged in the previously placed concrete at all times. Raise the tremie as necessary to maintain the free flow of concrete and the stability of any casing used. If a pump is used, keep the discharge tube submerged in the previously placed concrete at all times.

Place additional concrete to ensure the removal of any contaminated concrete at the top of the shaft. Allow the top portion of concrete to flush completely from the hole at the completion of the pour until there is no evidence of slurry or water contamination. Do not attempt to remove this concrete with shovels, pumps, or other means. Level the top of shaft with hand tools as necessary.

According to item 416 of Texas DOT specifications, three different concrete types are deemed acceptable for use in drilled shafts, as detailed in Table 32. Specifically, Class SS concrete is designated for underwater placement. Table 33 further outlines the specific requirements for each of the various concrete classes.

Table 23. Concrete for drilled shafts

Drilled Shaft Type	Concrete
Non-reinforced	Class A
Reinforced	Class C
Slurry and underwater concrete placement	Class SS

Table 24. Requirements for various concrete classes

Class of Concrete	Design Strength,[1] Min f'_c (psi)	Max w/cm Ratio	Coarse Aggregate Grades[2,3,4]	Cement Types	Mix Design Options	Exceptions to Mix Design Options	General Usage[5]
F[6]	Note 8	0.45	2–5	I, II, I/II, IP, IS, IT,[7] V			Railroad structures; occasionally for bridge piers, columns, or bents
H[6]	Note 8	0.45	3–6	I, II, I/II, III, IP, IS, IT,[7] V	1–5	Do not use Type III cement in mass placement concrete. Up to 20% of blended cement may be replaced with listed SCMs when Option 4 is used for precast concrete.	Precast concrete, post-tension members
S[6]	4,000	0.45	2–5	I, II, I/II, IP, IS, IT,[7] V	1–8		Bridge slabs, top slabs of direct traffic culverts, approach slabs
P	See Item 360, "Concrete Pavement."	0.50	2–3	I, II, I/II, IL, IP, IS, IT, V	1–8	When the cementitious material content does not exceed 520 lb./cu. yd., Class C fly ash may be used instead of Class F fly ash.	Concrete pavement
CO[6]	4,600	0.40	6	I, II, I/II, IP, IS, IT,[7] V	1–8		Bridge deck concrete overlay
LMC[6]	4,000	0.40	6–8	I, II, I/II, IP, IS, IT,[7] V	1–8		Latex-modified concrete overlay
SS[6]	3,600	0.45	4–6	I, II, I/II, IP, IS, IT,[7] V		Use a minimum cementitious material content of 658 lb./cu. yd. of concrete.	Slurry displacement shafts, underwater drilled shafts

A44. Utah

Place Concrete Under Water (Section 03310)

- Ensure watertight forms.
- Avoid disturbing the concrete for at least 24 hours or until it reaches 50% of its 28-day compressive strength.
- Maintain horizontal surfaces during placement.
- Start placement from one end and progress in a zig-zag movement across the form.
- Use tremie or concrete pumping equipment for placement.

Tremie Specifications

- Utilize an 8 to 12 in. steel tube tremie with watertight connections, a receiving hopper, and a device to prevent water entry.
- The tremie should be supported to allow movement over the entire work surface and rapid lowering when needed.
- Minimize tremie location shifts to ensure continuous placement.
- Always keep the tremie tube filled with concrete.
- Raise the tremie slightly for new batches but keep it submerged in concrete. Reseal and refill if the seal around the tube is lost.

Pump Concrete

- Engage a prequalified concrete pumping contractor (refer to Utah Department of Transportation [UDOT] Quality Management Plan 511).
- Replace any pump that causes air entrainment issues.
- Ensure a continuous stream of concrete that is free from air pockets.
- Avoid adding water to the concrete in the pump hopper.
- Prevent pump vibrations from damaging the fresh concrete.
- Avoid using concrete that becomes contaminated during pump priming or cleaning.

Concrete in Drilled Shafts (Section 02466)

- Use Class AA(AE) for drilled shaft concrete, unless specified differently.
- Aim for a target slump of at least 6½ in.
- When placing concrete underwater, employ high-range water reducers.

Table 34 presents the mix requirements and specifications for various classes of concrete

Table 25. Concrete classes and mix requirements.

Concrete Classes and Mix Requirements							
Class	Coarse Aggregate Size	Maximum Water / Cementitious Ratio****	Maximum Percent Shrinkage at 28 days AASHTO T 160	Chloride Ion Penetration AASHTO T 358 Table 1	Air Content Percent (%) *	Mix Design Compressive Strength f'cr (psi)	28 Day Minimum Compressive Strength f'c (psi) **
AAA(AE)	1" to No. 4 ¾" to No. 4	0.40	N/A	N/A	5.0 - 7.5	6,200 or f'c +1200	5,000 or as shown
AA(LSF)	1" to No. 4 ¾" to No. 4	0.42	0.035	Low to Negligible	5.0 - 7.5	5,200	4,000
AA(LS)	1" to No. 4 ¾" to No. 4	0.40	0.035	Low to Negligible	5.0 - 7.5	5,200	4,000
AA(P)	2" to No. 4 1½" to No. 4 1" to No. 4	0.44	0.042	N/A	4.0 - 7.0 4.5 - 7.5 5.0 - 7.5	5,200	4,000
AA(ES)***	1½" to No. 4 1" to No. 4 ¾" to No. 4	0.42	0.035	Low to Negligible	4.5 - 7.5 5.0 - 7.5 5.0 - 7.5	5,200	4,000
AA(AE)	2" to No. 4 1½" to No. 4 1" to No. 4 ¾" to No. 4	0.44	N/A	N/A	4.0 - 7.0 4.5 - 7.5 5.0 - 7.5 5.0 - 7.5	5,200	4,000
A	1½" to No. 4 1" to No. 4 ¾" to No. 4	0.53 0.53 0.48	N/A	N/A	N/A	3,900	3,000
A(AE)	1½" to No. 4 1" to No. 4 ¾" to No. 4	0.53 0.53 0.48	N/A	N/A	4.5 - 7.5	3,900	3,000
B or B(AE)		0.62	N/A	N/A	N/A 3.0 - 6.0	3,250	2,500

Table 2 Notes:

* Values listed represent in-place air content. Make necessary adjustments for impacts to air content due to placement.

** For f 'c over 4,000 psi, design and proportion mixes according to ACI Manual of Concrete Practice 301: Specifications for Concrete and project specific criteria. Use air content percent in Table 2 for these mixes according to the class specified and the coarse aggregate size.

*** For Class AA(ES), achieve at least 3,000 psi at 24 hr.

****The Water/Cementitious ratios in this table are the maximum allowed. The mix design w/c ratio is established in the trial batch and will remain within the tolerances of this Section Article 2.6 during production.

Acronym Definitions:

AE = air-entrained
LSF = low shrinkage with fiber
LS = low shrinkage
P = pavement
ES = high early strength

A45. Vermont

Vermont offers very good recommendations on the use of underwater concrete.

Section 501.10 Depositing Concrete Under Water

(a) General Requirements

- Only deposit concrete under water if specified or approved by the Supervising Engineer/Agency.

- Use Class SCC concrete for underwater deposits unless otherwise approved.
- Include an anti-washout admixture for underwater concrete. (Anti-washout admixtures shall conform to the requirements of the U.S. Army Corps of Engineers standard CRD-C 661.)
- Ensure a minimum air content of 3% for underwater concrete with an anti-washout admixture.
- Be aware that the anti-washout admixture might cause a delay in set times.
- The anti-washout admixture does not need to be included in the mix during mix qualification testing. If absent, provide an administrative submittal for its addition.

(b) Placement

- Use a tremie or another approved method to minimize the mixing of concrete and water.
- Tremies must be made of heavy-gauge steel, have watertight joints, be a minimum of 10 in. in diameter, and have a hopper on top.
- Ensure that the tremie hopper can hold at least ½ yd^3.
- Ensure that the discharge end of the tremie has a device to seal out water initially. An inflatable ball is not acceptable as a sealing device.
- Place concrete continuously to achieve a monolithic and homogeneous result.
- Do not deposit concrete in water colder than 35°F. When depositing concrete in water ranging from 35°F to 40°F, heat the mixing water or aggregates.
- When dumping a batch of concrete, raise the discharge tube slightly while keeping the end of the tube submerged.
- Prevent water from entering the tube.
- Monitor the elevation difference between the concrete and the end of the tube.
- Avoid horizontal movement of the discharge tube.
- For minor quantities of concrete, a direct pumping method might be approved by the Engineer.
- If pumping, the pipe should be made of heavy-gauge steel sections.
- Cured cylinders should have the same temperature as the water covering the concrete.

Section 501.11 Pumping

- Ensure that the pumping equipment is suitable for the project and has adequate capacity.
- The pump should be appropriate for concrete within specified slump limits.
- Aluminum pipe conveyances are not permitted.
- The pump should produce a continuous concrete stream without air pockets.
- When pumping concludes, ensure that the leftover concrete in the pipeline is ejected properly without contamination.
- Arrange equipment to prevent vibrations from damaging the fresh concrete.

A46. Virginia

Section 404.03—Procedures (f)

Depositing Concrete Under Water: Concrete shall not be deposited in water except with the approval of the Engineer.

Concrete placed in water shall be Class T3. Concrete shall be carefully placed in a compact mass in its final position by means of a tremie or another approved method and shall not be disturbed after being deposited except as specifically provided herein. Still water shall be maintained at the point of placement. Table 35 illustrates the detailed requirements and specifications for various classes of concrete based on their specific applications and characteristics. Class T3 requires a compressive strength ranging between 3,000 to 3,500 psi, a maximum water/cementitious material ratio of 0.49, and an air content percentage of 4±2%. Such specifications underscore the importance of Class T3 for certain structural and underwater purposes.

Table 26. Requirements for hydraulic cement concrete

Class of Concrete	Design Min. Laboratory Compressive Strength at 28 Days (f'c) (psi)	Aggregate Size No.[6]	Design Max. Laboratory Permeability at 28 Days (Coulombs)[5]	Design Max. Laboratory Permeability at 28 Days - Over tidal water (Coulombs)[5]	Nominal Max. Aggregate Size (in)	Min. Grade Aggregate	Min. Cementitious Content (lb./cu yd)	Max. Water /Cementitious Mat. (lb. Water /lb. Cement)	Consistency (in of slump)	Air Content (percent)[1]
A5 Prestressed and other special designs[2]	5,000 or as specified on the plans	57, 68, 78, or 7	1,500	1,500	1	A	635	0.40	0-4	4 1/2 ± 1 1/2
A4 General	4,000	56 or 57	2,500	2,000	1	A	635	0.45	2-4	61/2 ± 1 1/2
Low Shrinkage A4 Mod.	4,000	56 or 57	2,500	2,000	1	A	N.A.	0.45	2-4	61/2 ± 1 1/2
A4 Post & rails	4,000	7, 8 or 78	2,500	2,000	0.5	A	635	0.45	2-5	7 ± 2
A3 General	3,000	56 or 57	3,500	2,000	1	A	588	0.49	1-5	6 ± 2
A3a Paving	3,000	56 or 57	3,500	3,500	1	A	564	0.49	0-3	6 ± 2
A3b Paving	3,000	357	3,500	3,500	2	A	N.A.	0.49	0-3	6 ± 2
B2 Massive or lightly Reinforced	2,200	57	N.A.	N.A.	1	B	494	0.58	0-4	4 ± 2
C1 Massive Unreinforced	1,500	57	N.A.	N.A.	1	B	423	0.71	0-3	4 ± 2
T3 Tremie seal	3,000	56 or 57	N.A.	N.A.	1	A	635	0.49	3-6	4 ± 2
Latex hydraulic cement concrete overlay[3]	3,500	7, 8 or 78	1,500	1,500	0.5	A	658	0.40	4-6	5 ± 2
Silica fume, silica fume / Class F Fly Ash or silica fume / slag concrete overlay[4]	5,000	7, 8 or 78	1,500	1,500	0.5	A	658	0.40	4-7	6 ± 2
Class F Fly Ash or slag overlay	4,000	7, 8 or 78	1,500	1,500	0.5	A	658	0.40	4-7	6 ± 2

A tremie shall consist of a tube having a diameter of at least 10 in., constructed in sections having flanged couplings fitted with gaskets. The discharge end shall be closed at the start of work and entirely sealed at all times. The tremie tube shall be kept full to the bottom of the hopper. When a batch of concrete is dumped into the hopper, the flow of concrete shall be induced by slightly raising the discharge end, always keeping it in the placed concrete. Concrete seal shall be placed continuously from start to finish. Concrete shall be placed at a rate of at least one vertical foot per hour over the entire area of the seal course. The surface of the concrete shall be maintained in a horizontal plane within a tolerance of 6 in. at all times during placement. The tremie shall be supported so that its discharge end is freely movable over the entire work area, or multiple tremies shall be used. Vibration shall be used only when deemed necessary by the Engineer. Supports for tremies shall permit rapid lowering of discharge ends when necessary to retard or stop the flow of concrete. The method of placing the seal shall be subject to the approval of the Agency engineer prior to concrete placement.

A47. Washington State

Section 6-19.3(7)D Requirements for Placing Concrete Underwater

- Underwater concrete placement, including in shaft excavations with a water depth over 3 in., requires pressure feed placement using a concrete pump.
- The concrete pump should have a watertight tube of at least 4 in. in diameter.
- The discharge end of the tube must have a device to seal out water when the tube is initially filled with concrete.
- An alternative is to use a plug placed at the pump's hopper that travels through the tremie, ensuring that the concrete remains separate from water and slurry.
- Gravity feed concrete placement is prohibited.
- During placement, the discharge end of the tube should stay submerged at least 5 ft into the concrete, and the tube must contain sufficient concrete to prevent water ingress.
- Before removing the tremie, ensure that all liquid above the shaft construction joint is eliminated.
- The concrete placement should be continuous, ensuring a uniform and seamless shaft.

Section 6-19.3(7)E Testing and Repair of Shaft Concrete Placed Underwater

- If underwater concrete placement is interrupted, the Agency Engineer might request the Contractor to verify the shaft's integrity using core drilling or other tests to ensure that no voids or horizontal joints have formed.
- If testing identifies voids or joints, the Contractor must repair them or replace the shaft at no additional cost to the Contracting Agency.
- Preparing surfaces underwater for repairs involves removing dirt, oil, grease, loose paint, rust, and marine growth from the area to be repaired.
- Any sound paint around the damaged region must be roughened to align with the manufacturer's specifications.

Section 6-02.3(1) Classification of Structural Concrete

In Table 36, concrete classes are denoted by their minimum compressive strength in psi at 28 days, accompanied by a suffix for specific applications. The "P" suffix refers to piling and drilled shafts, while "W" is for underwater placements. Class 4000P, tailored for piling and shafts, has a cementitious content of 600 pounds. It allows for a 15% minimum and 35% maximum replacement of Fly Ash or Ground Granulated Blast Furnace Slag for Portland Cement, with a 50% maximum replacement of the latter. Class 4000W, designed for underwater use, has a cementitious content of 564 pounds. Its replacement guidelines are akin to 4000P, but without a specified minimum for Fly Ash or Ground Granulated Blast Furnace Slag.

Table 27. Cementitious requirements for different classes of concrete

Class of Concrete	Minimum Cementitious Content (Pounds)	Minimum percent Replacement of Fly Ash or Ground Granulated Blast Furnace Slag for Portland Cement	Maximum percent Replacement of Fly Ash for Portland Cement	Maximum percent Replacement of Ground Granulated Blast Furnace Slag for Portland Cement
4000	564	*	35	50
4000A	564	*	25	30
4000P	600	15	35	50
4000W	564	*	35	50
3000	564	*	35	50
Commercial Concrete	**564	*	35	50

*No minimum specified.

**For Commercial Concrete, the minimum cementitious content is only required for sidewalks, curbs, and gutters.

When both ground granulated blast furnace slag and fly ash are included in the concrete mix, the total weight of both these materials is limited to 40 percent by weight of the total cementitious material for concrete class 4000A, and 50 percent by weight of the total cementitious material for all other classes of concrete.

The water/cement ratio shall be calculated on the total weight of cementitious material. Cementitious materials are those listed in Section 5-05.2. With the Engineer's written concurrence, microsilica fume may be used in all classifications of Class 4000, Class 3000, and commercial concrete and is limited to a maximum of 10 percent of the cementitious material.

A48. West Virginia

Section 601.10.5 – Depositing Concrete Under Water

Concrete shall not be placed until all laitance that may have formed on previously placed concrete has been removed. Still water shall be maintained at the point of deposit. While depositing foundation concrete, pumping shall be discontinued if it results in a flow of water inside the forms. All concrete deposited under water shall have the minimum cement content increased by at least 10%. Concrete deposited under water shall be carefully placed in a compact mass in its final position by means of a tremie, a closed-bottom dump bucket, or other approved method and shall not be disturbed after being deposited. Use of following supplementary cementitious materials is acceptable using in drilled shaft concrete with recommended percentage in Table 37.

Table 28. Acceptable mass of a SCM can substitute with portland cement

Material	Class of Concrete	Quantity
Fly Ash	All Classes Except H	20%
Slag Cement	All Classes Except H	50%
Silica Fume	All Classes Except H	8%

In Table 38, the classification of concrete is detailed for specific applications. Class H concrete is designated for bridge elements, while Class DC is tailored for drilled shafts, predominantly utilized for underwater placements. The guidelines for mix designs are provided within this table.

Table 29. Mix design criteria for different classes of concrete

Class of Concrete	Design 28 Day Compressive Strength	Target Cement Factor	Maximum Water Content	Standard Size of Coarse Aggregate***	Entrained Air
	Pounds per Square inch	lbs./c.y.*	lb. of water / lb. of cement **	Number	Percent
A	3500	682	0.51	7, 78, or 8	7.5
K	4000	658	0.44	57, 67	7.0
B	3000	564	0.49	57, 67	7.0
C	2500	494	0.58	57, 67	6.0
D	2000	400	0.62	57, 67	5.5
H	4000	See Table 601.3.1C	0.40	57,67	6.5
DC	4500	705	0.44	7, 78, 8	6.0

* An equal mass of a SCM may be substituted for Portland cement up to the maximum amount in Table 601.3.1B. Only one SCM is permitted in a mix design, except for Class H concrete. The target cement factor of Class H concrete shall consist of Option 1 or Option 2 from Table 601.3.1C. The Contractor may choose either option.

** When using a SCM, masses of these materials shall be considered as cement for purposes of establishing maximum water content.

*** A number 67 coarse aggregate may be used in Class DC concrete, provided the Engineer approves the use of that size aggregate for the specific project on which it is to be used. That approval will depend on the minimum spacing of the reinforcing steel in the drilled shaft foundation.

A49. Wisconsin

Depositing Concrete Underwater (Section 502.3.5.3)

Conditions for Depositing Concrete Underwater

Only deposit concrete underwater if

- Ordered by the supervising engineer/agency,
- Indicated in the plans, or
- Specified in the contract.

Concrete Specifications

- Abide by the specifications in Section 501.
- Adjust the slump to 5 to 9 in. but do not surpass the maximum mix water allowed for the grade.

Tremie Usage

- Deploy a tremie for underwater concrete placement.
- The tremie should have a minimum diameter of 10 in. and be assembled using flanged sections fitted with gaskets.
- Ensure that the tremie is freely movable and can be rapidly lowered.
- Always keep the tremie sealed and filled up to the bottom of the hopper.
- Maintain a continuous flow of concrete.
- An alternative tremie with a mechanical seal or valve might be used, subject to the engineer's approval.

Precautionary Measures

- Avoid disturbing the deposited concrete.
- Maintain still water at the concrete deposit point.
- Refrain from placing concrete in running water.
- Use watertight formwork.

Placement Considerations

- Prevent the occurrence of cold joints between successive concrete layers.
- Pour concrete deep enough to suit the tremie operation, ensuring a rise between 1½ to 2 ft per hour, or fill the concrete in one continuous process.

Dewatering Considerations

- Only dewater the cofferdam after a minimum of three days from concrete placement and once the concrete is sufficiently solid to handle *hydrostatic* pressure.
- After dewatering, eliminate any laitance or substandard material on the tops of seals or proposed substructure units.

A50. Wyoming

Section 513.4.11.6 Cofferdam Seals

- Construct an underwater concrete cofferdam seal at least 24 in. (600 mm) thick from concrete enhanced with 25% extra cement when excavations cannot be dewatered before concrete placement.
- Ensure that the top of the seal does not surpass the predetermined bottom of the footing.
- Place the concrete compactly using a tremie and ensure that the water at the point of deposit is still.

- Always keep the discharge end of the tremie submerged in concrete to prevent water intrusion.
- To initiate the concrete flow, slightly elevate the discharge end while ensuring that it remains submerged.

Section 506.4.4 Concrete for Drilled Shaft

- Utilize class “S “concrete per Subsection 513.4.4, Mix Design, maintaining a slump of 8 in. ± 1 in. (200 mm ± 25 mm) for drilled shaft applications, which is outlined in Table 39.

Table 30. Concrete classification in Wyoming DOT

Parameter	Class		
	A	B	S
Ultimate Design Strength—f_c @ 28 d (psi [MPa])	4000 [28]	3500 [24]	4000 [28]
Min. Cement Content (lb/yd^3 [kg/m^3])	611 [362]	564 [335]	611 [362]
Max. Water : Cement Ratio	0.45	0.45	0.45
Max. Water: (Cement + Fly Ash) Ratio	0.45	0.45	0.45
Percent Entrained Air Content—Range	4.5 - 7.5	4.5 - 7.5	4.5 - 7.5
Consistency—Max. Slump (in [mm])(1)	6 [150]	6 [150]	6 [150]
Percent Fine Aggregate(2)	41 ± 3	41 ± 3	41 ± 3

(1) Ensure that concrete with slump greater than 4 in [100 mm] contains a water-reducing admixture.

(2) Percent by weight [mass] of the total aggregate.

- Present trial mix test results before concrete placement and ensure that the concrete retains its required slump for a two-hour placement limit.
- The method of placement should prevent aggregate segregation.
- Initiate placement from the bottom and proceed upwards.
- Cap the placement duration to two hours.
- In vertical holes deeper than 25 ft (7 m), employ an enclosed chute or pump.
- Keep the discharge end of the tremie pipe immersed at least 5 ft (1.5 m) in concrete after the flow initiates.
- The tremie pipe should be clearly marked in 1.0 ft (0.3 m) intervals to ensure its minimum embedment.
- Equip the tremie pipe with a hopper that drains into a watertight tube with a diameter of at least 10 in. (250 mm).
- For pumps, use a tube with a minimum diameter of 4 in. (100 mm).
- Ensure that the discharge end of the tremie or concrete pump line has a sealing device.
- Alternatively, a “pig” or “rabbit” device can be inserted into the hopper and propelled by the concrete to expel water or slurry from the tremie.
- If the tremie or pump line orifice is dislocated from the fluid concrete column, deem the shaft defective.

- Removal of defective shafts, including the reinforcing cage, concrete, and any sidewalls, is the contractor's responsibility.
- If concrete placement is interrupted, the engineer may demand proof via core drilling or other tests to verify the drilled shaft's integrity.
- For each wet shaft poured using the tremie method, draft a concrete yield plot and submit it to the department within 24 hours after concrete pouring.

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