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Assessment of Underwater Concrete Technologies for In-the-Wet Construction of Navigation Structures

by Sam X. Yao, Dale E. Berner, Ben C. Gerwick,
Ben C. Gerwick, Inc.

Prepared for Headquarters, U.S. Army Corps of Engineers

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Preface

This report was prepared for Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Innovations for Navigation Projects (INP) Research Program. The study was conducted under Work Unit 33142, "Underwater Concrete and Grout," managed at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. Dr. Tony C. Liu was the INP Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Don Dressler, HQUSACE, was the Research Area Coordinator. Dr. Reed L. Mosher, ERDC Structures Laboratory (SL), was the Laboratory Manager for the INP Program; Dr. Barry D. Fehl, ERDC, was the INP Program Manager.

This report was prepared by Drs. Sam X. Yao, Dale E. Berner, and Ben C. Gerwick, Ben C. Gerwick, Inc., under contract DACW39-98-M-0342. The work was monitored at ERDC by Mr. Billy D. Neeley under the general supervision of Dr. Bryant Mather, Director, ERDC SL; Mr. John Q. Ehrgott, Assistant Director, SL; and Dr. Paul F. Mlakar, Chief, Concrete and Materials Division (CMD), SL. Direct supervision was provided by Mr. Anthony A. Bombich, Acting Chief, Engineering Mechanics Branch (EMB), CMD. Mr. Neeley and Mr. Brian H. Green, EMB, were the Principal Investigators.

At the time of publication of this report, Dr. Lewis E. Link was Acting Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

1 Introduction

Background

In recent years, the U.S. Army Corps of Engineers (USACE) has launched major developments in underwater construction of locks and dams, the so-called "in-the-wet" or "offsite prefabricated" construction method. This innovative method uses precast concrete modules as the *in situ* form into which tremie concrete is placed directly without use of a cofferdam. The tremie concrete is designed to work in composite with the precast concrete.

In 1993, the USACE's Task Force on Design and Construction Innovation issued a feasibility study report (USACE 1993) that outlined the background and concepts of the in-the-wet method. Since then, comprehensive feasibility studies and preliminary design of navigation locks and dams have been carried out for various potential sites of the U.S. inland waterways. In-depth studies have shown that the in-the-wet construction method will lead to substantial savings in cost and construction time, in addition to minimizing the effect on river traffic during construction and substantially reducing or eliminating the impact on navigation during rehabilitation.

The experience with the design and feasibility studies highlighted the importance of underwater concrete construction as a major component of the new construction method. Many outstanding examples exist of high-quality concrete placed underwater by the tremie process. However, a significant number of failures have occurred which have resulted in excessive cost overrun and delays. These failures have been due in large part to improper concrete mixtures and improper placement procedures. These problems may have occurred because proper underwater concrete construction techniques and experience have not been widely disseminated to engineers and contractors. Thus, a review of the state-of-the-art underwater concrete technology is important for successful implementation of the USACE's program for in-the-wet construction.

Objectives

The objectives of this report are as follows:

a. To establish the basic performance requirements of underwater concrete for the in-the-wet construction of navigation structures.

b. To review the current technology in underwater concrete mixtures and provide a basis for proportioning concrete mixtures.

c. To review the current technology in underwater concrete construction and provide recommendations for the underwater construction of major navigation structures.

d. To provide a basis for developing specifications of underwater concrete for in-the-wet construction of navigation structures.

Scope

This report covers two areas of underwater concrete technology. The first part of the report focuses on underwater concrete materials. The relevant subjects include the performance requirements of underwater concrete, mass concrete properties, the effects of concrete mixture proportions on the workability and rheology, and the basis for proportioning underwater concrete mixtures. Emphasis is placed upon the practical construction issues, such as concrete workability, development of the form pressure from underwater concrete, and the effects and reduction of laitance, bleeding, and segregation of the concrete.

The second part of the report addresses underwater concrete construction procedures. Specific topics include a review of underwater concrete projects, production methods for underwater concrete, the tremie concrete placement schemes and techniques, construction inspection and quality control, and a critical examination of the pump method for placing concrete under water. A general checklist for underwater concrete specifications is also provided.

2 Concrete Materials

Performance Requirements of Underwater Concrete

Performance requirements discussed in this section include general requirements for underwater concrete for all purposes and the special requirements pertaining to the underwater construction of navigation structures.

The concrete performance requirements may be best presented with a typical example of in-the-wet construction of a tainter-gate dam. The key elements of the construction sequence are illustrated in Figure 1. The construction will start with dredging and preparing the dam foundation site. After piles and landing pads are installed underwater, each precast concrete module will be transported to the site, positioned, and lowered down onto the landing pads. The concrete module is typically a box containing one or several compartments. The module may or may not have a bottom plate, depending on the method of transportation and installation. These precast modules will serve as in situ form for underwater concrete. Once the module is locked into position, concrete will be delivered through tremie pipes to fill the compartments of the module. If the precast modules have bottom slabs, the space between the bottom slab and the riverbed will be filled with flowable, low-strength grout. The placement of tremie concrete usually starts from the lower end of the precast form and moves toward the upper end. When the tremie concrete completely fills the precast modules and hardens, it results in a composite, monolithic structure.

Placement of underwater concrete is one of the critical aspects in this construction method. Because of the difficult accessibility and poor visibility of underwater work sites, there is uncertainty with the quality and integrity of underwater concrete operations. Concrete placed underwater is inherently more susceptible to segregation, laitance, cement washout, voids, cold joints, and water entrapment. To successfully complete the underwater construction, the tremie concrete must possess several essential characteristics.

First, the concrete must easily flow out and around any obstruction (e.g., piles) until it completely fills the entire placement area. Good flowability of concrete is a prerequisite of the tremie operation.

When the concrete flows out over a distance, coarse aggregates have a propensity to segregate from the cement paste and to settle down. Serious

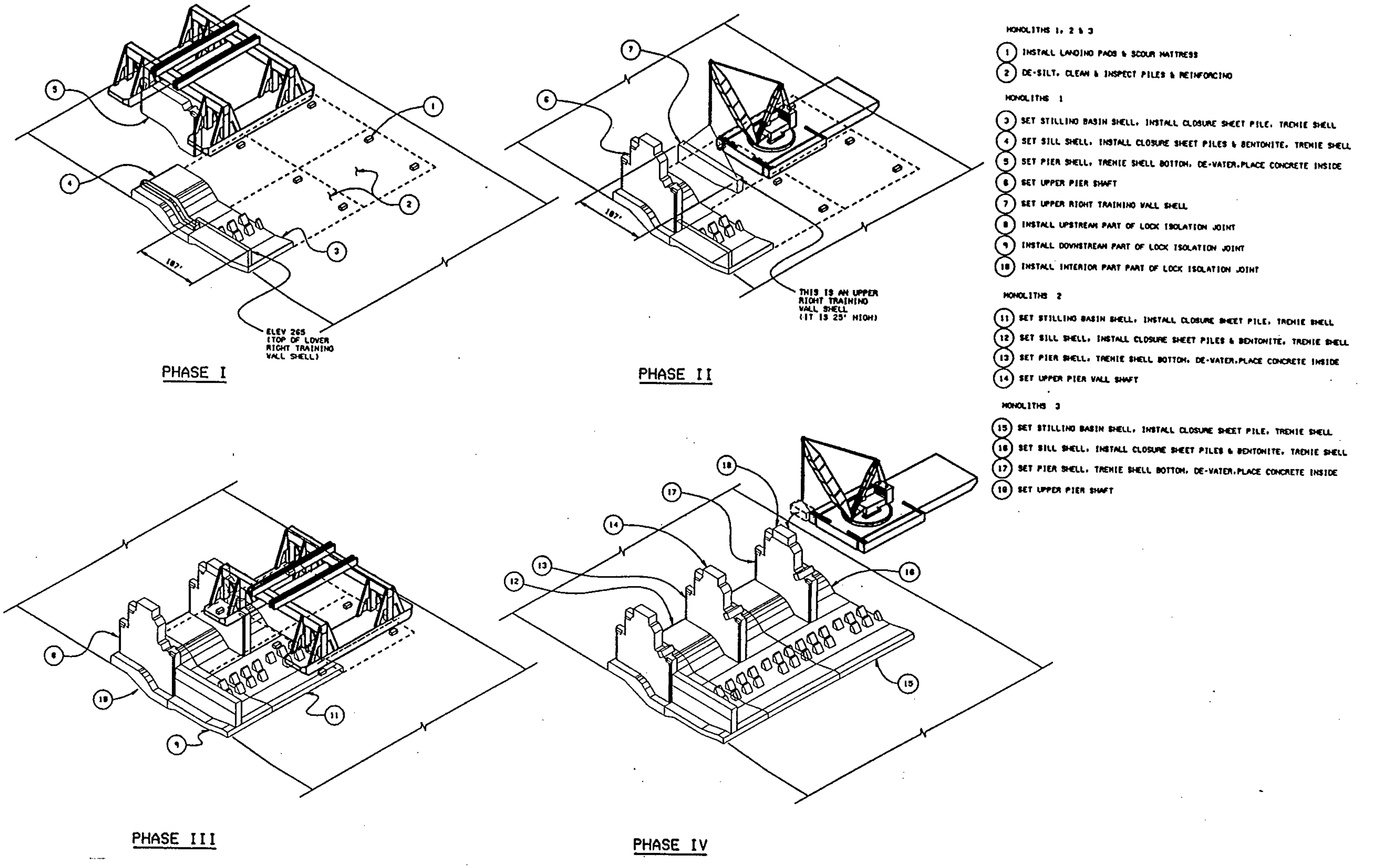

Figure 1. Erection plans

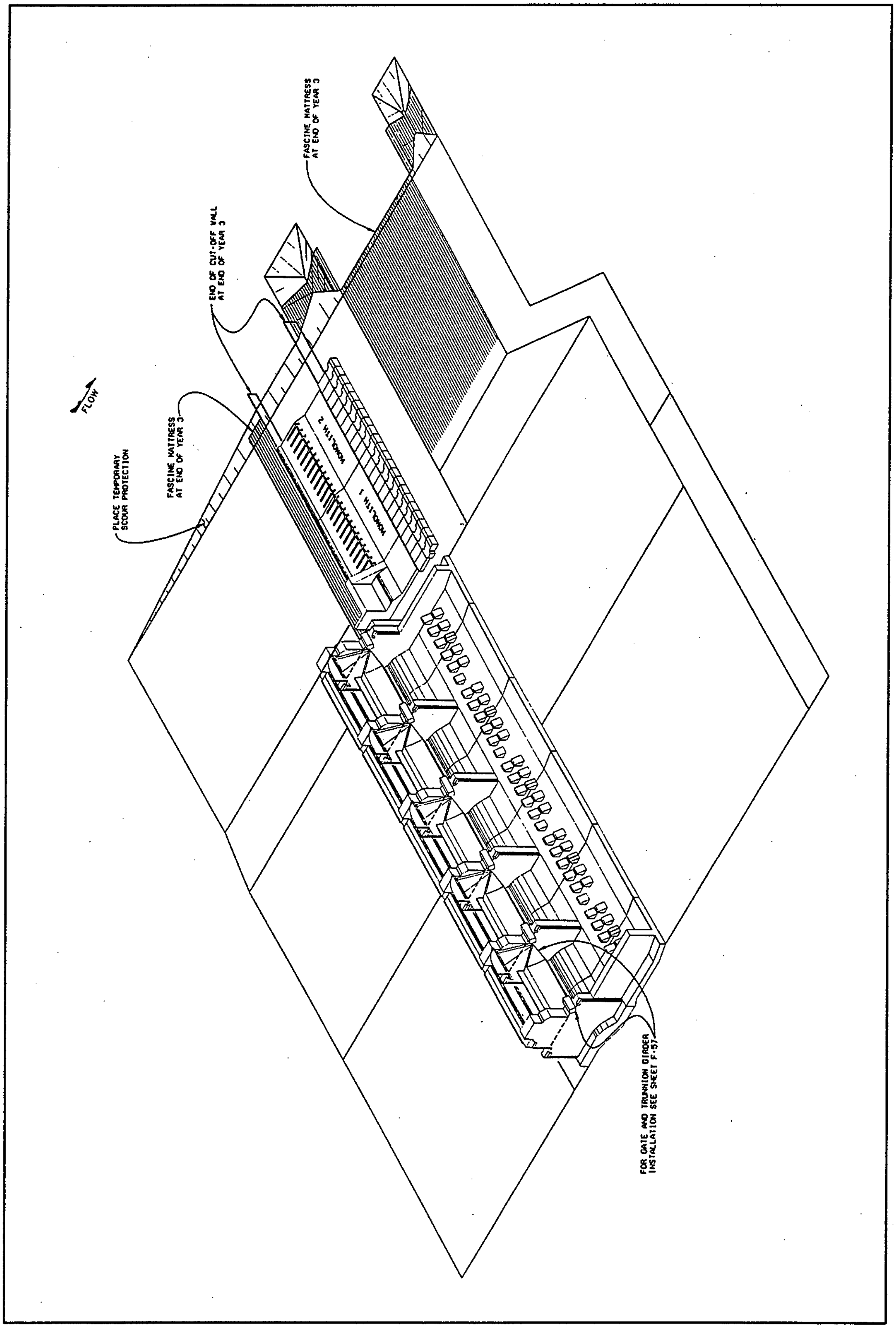

Figure 1. (Sheet 2 of 3)

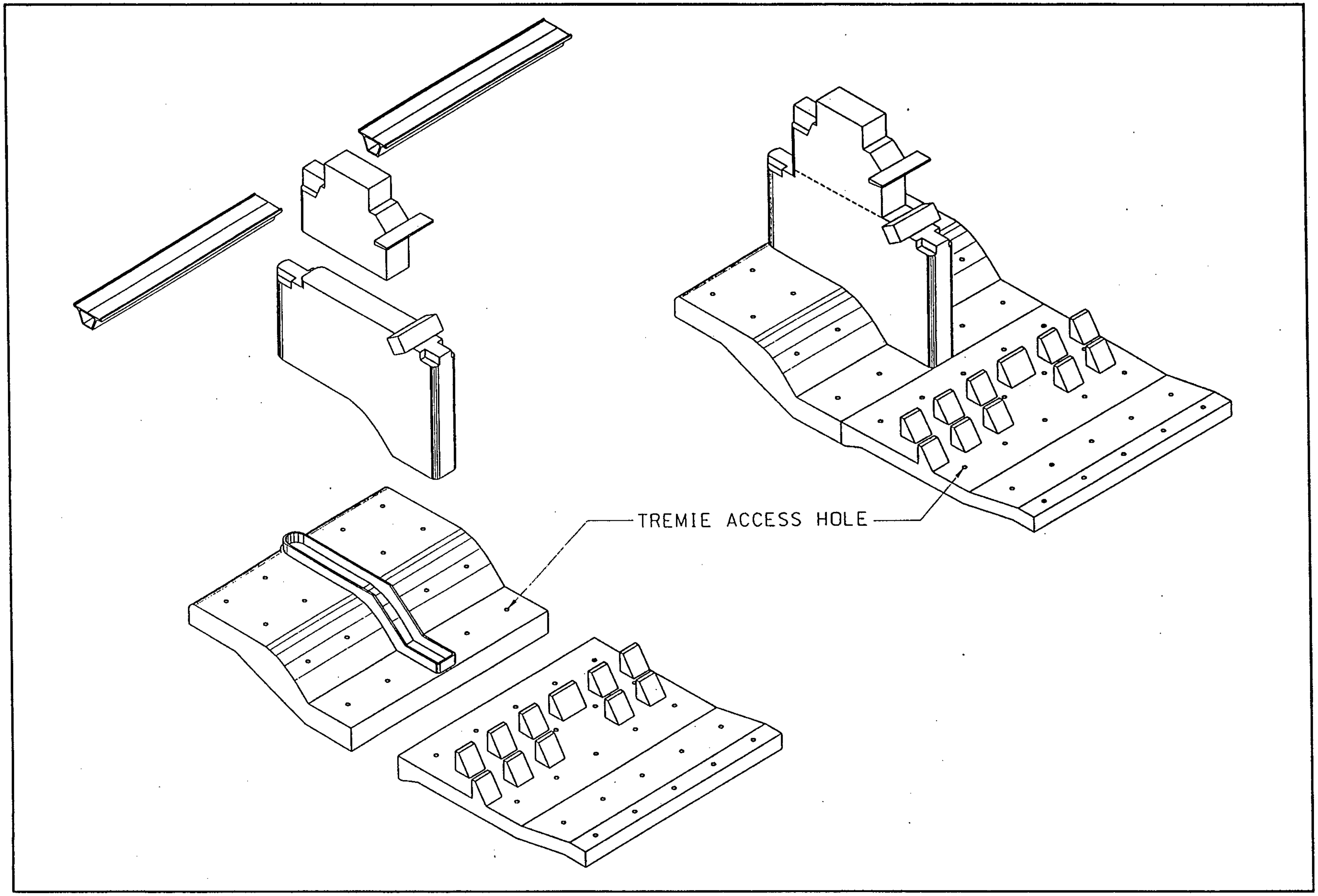

Figure 1. (Sheet 3 of 3)

segregation is a common cause of poor quality and nonhomogeneity of concrete. Thus, concrete must be cohesive enough to prevent excessive segregation.

Because it is generally impractical to compact concrete underwater with mechanical means, the concrete should have self-compacting characteristics, i.e., the concrete should be able to consolidate itself under its own net buoyant weight without trapping water inside. Furthermore, it is often desirable for the concrete to level out to a nearly flat surface, i.e., the concrete is self leveling.

Underwater concrete construction often entails transportation of a large quantity of materials over water. This often creates logistical problems with regard to the time lapse between concrete mixing and concrete placement. In such cases, the concrete mixtures must be able to maintain all the desirable properties (such as flowability, cohesiveness, and self-compacting characteristics) over a reasonable work window.

Concrete placed underwater tends to form a layer of weak, diluted cement paste on the top surface of the concrete mass, because of the diluting effect of the water into which it is placed and bleed water from the concrete itself. This weak cement paste, often referred to as "laitance," is potentially detrimental to the quality of the concrete. To illustrate this point, a typical arrangement of the tremie concrete operation is shown as Figure 2. As tremie concrete rises inside the precast concrete module, laitance and bleed water can easily be entrapped underneath the top slab. Such laitance and bleed water will create a weak bond or even voids between the precast concrete slab and the tremie concrete, thereby reducing the structural integrity of the monolith. Furthermore, improper placement of underwater concrete may lead to excessive mixing of cement with water and increases in the water-to-cement ratio and, hence, loss of strength. Therefore, underwater concrete for navigation structures must be cohesive enough so that it can displace the water into which it is placed without being significantly diluted, and bleeding of the concrete itself is minimized.

In massive concrete structures such as dams and locks, the heat of hydration may cause the tremie concrete to expand and induce thermal stresses within the precast concrete form. Furthermore, temperature gradients will develop within the concrete mass due to differential rates of cooling. The lateral pressure and temperature gradients may cause cracking of the concrete shell. Therefore, underwater concrete used in navigation structures should be treated as mass concrete. Concrete mixtures should be proportioned to develop low heat of hydration and a relatively slow rate of heat release.

Unlike conventional tremie concrete seal placements, the concrete placed inside the precast concrete forms is often structural concrete. The concrete strength development and other long-term properties in such applications are important design criteria. Both compressive strength and bond strength of the concrete are critical. Long-term creep and shrinkage of the concrete should be established at acceptable levels. Navigation structures are susceptible to damages of abrasion and erosion. The concrete that is permanently exposed to flowing water should be designed for resistance to abrasion. Previous research

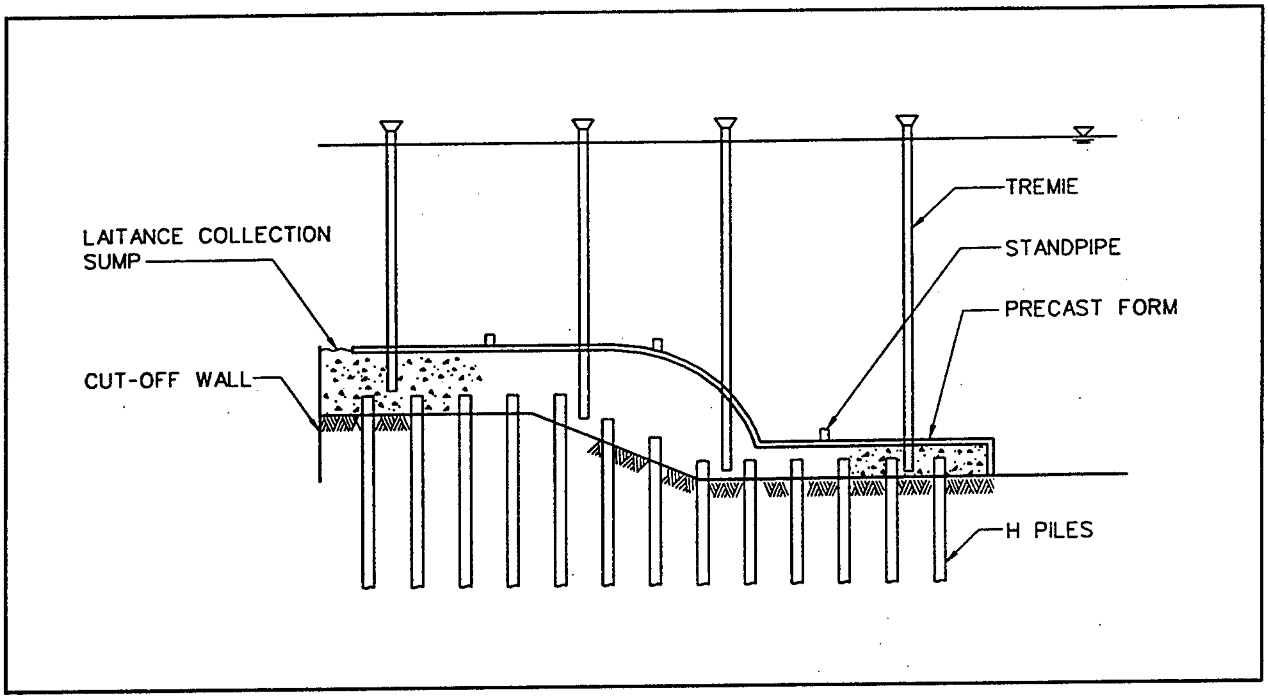

Figure 2. Tremie concreting into precast concrete form

study at WES (Liu 1980, McDonald 1980, Neeley 1988) provides excellent guidance for design of abrasion-resistant underwater concrete.

In summary, successful placement of mass concrete under water imposes special demands on the properties of concrete. The important properties of the structural underwater concrete include the following aspects:

a. Ability of concrete to flow around piles and reinforcing steel bars.

b. Self-compacting, and sometimes self-leveling properties.

c. Retention of workability over a reasonable work window of time.

d. Adequate cohesion to avoid excessive segregation and laitance.

e. Low heat of hydration.

f. Low bleeding.

g. Controlled set times.

h. Development of adequate compressive strength and bond strength.

i. Low creep and shrinkage.

j. Resistance to cement dilution and washout by flowing water during concrete placement.

k. Abrasion resistance, if exposed to flowing water.

Workability and Rheology of Underwater Concrete

According to the definition in ACI 116R (American Concrete Institute 1997c), workability of concrete is "that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished." In practice, the interpretation of concrete workability is inevitably project-specific. What represents workable concrete in one condition may become unworkable in another condition. Unless the level of concrete workability is specifically defined in the project specification and fully understood by all the parties involved in the design and construction, the project will face major risks of construction failure.

In large-scale underwater concrete construction, workability of the concrete can be interpreted as being flowable, cohesive, and self-compacting within a specified period of time. In some projects, workability may also include additional requirements such as the ability of the concrete to pass obstacles without segregation, self-leveling, and antiwashout characteristics. These fundamental characteristics of fresh concrete are most often evaluated on the basis of past experience, trial batching tests, and mock-up tests.

The behavior of fresh concrete is closely linked to complex relationships among many concrete mixture variables, such as cement content and percentage of fines. Effects of one variable on the concrete workability are highly dependent on the other variables. The relationships between the concrete workability and concrete mixture variables may be best explained with the theory of rheology.

Rheology describes flow and deformation of materials. Rheology of concrete is based on the notion that the behavior of fresh concrete can be described by two rheological parameters—yield stress and plastic viscosity. To move a concrete mass at rest, external force must be imposed upon the concrete to overcome the internal cohesion and friction. The minimum stress required to mobilize the concrete is called yield stress. Once the concrete starts to deform, the rate of deformation is linearly proportional to the stress imposed. The proportionality factor of stress versus rate of strain is called plastic viscosity. Past experience and experimental studies have shown that concrete approximately conforms to the two-parameter model, or so-called Bingham model. At present, however, a comprehensive knowledge base has not yet been established to quantitatively correlate the rheological parameters with the workability of concrete. Nevertheless, a general qualitative understanding of the concrete rheology is essential for proper design of underwater concrete mixtures.

In common terms, "stiff" concrete implies a high yield stress value; "sticky" concrete implies a high plastic viscosity value. A "wet" concrete mixture has relatively low yield stress and low viscosity. The yield stress of concrete is often associated with the workability under pseudostatic conditions, while the plastic viscosity is associated with the workability under pseudodynamic condition, such as concrete flow under pumping pressure. In reality, concrete placed underwater typically undergoes a wide range of kinetic states. For example, tremie concrete usually falls through the upper part of the tremie pipe at relatively high speed, resulting in potential segregation, followed by remixing as it impacts the previously placed concrete in the lower part of the pipe. Then, it flows out at relatively slow shear rates, either displacing or flowing up and over the previously placed concrete. Finally, concrete consolidates and levels out under a pseudostatic condition. Therefore, of critical importance are not only the yield stress, but also the plastic viscosity at various shear rates, typically ranging from 0.1 to 100 per second.

In essence, the influences of various concrete mixture variables on the rheological behavior of concrete can be summarized into five underlying mechanisms:

a. The free water content of the concrete.

b. Dispersion characteristics of solid particles in concrete.

c. Particle packing as determined by particle size distribution.

d. The amount and rate of the early hydration of C_3A.

e. Beginning of the acceleration of alite hydration.

While the first four mechanisms govern the rheology of concrete at the beginning, the last factor affects the time of set. In the following, each individual component of underwater concrete will be examined from the above five aspects.

Influence of the water content

Concrete may be perceived as a highly concentrated suspension in which water is the medium that carries aggregates and binders as suspended particles. The water coats and lubricates the suspended particles, resulting in the plasticity or flowability of concrete. In this regard, the water content is the single most important factor affecting the rheology of concrete.

The water content in a mixture can be classified into two categories. The first category is the water absorbed in the aggregate. The second category is the free water, that provides workability, and is the amount used in calculating water-cement ratio.

The absorbed water generally does not contribute to the workability of concrete. The larger the total surface area of solid particles, the higher the water demand. In a typical concrete mixture, surface area of the coarse aggregates and sand represents only about 5 percent of total surface area of the solids. Therefore, physical binding of water is almost directly proportional to the surface area of fines. The surface area of the binder is commonly measured by the Blaine Air Permeability method in ASTM C 204.

Free water is the interstitial water existing between binders and aggregates. It disperses and lubricates the solid particles in a mixture to create fluidity and plasticity of concrete. Therefore, it is the quantity and quality of free water in a mixture that determines much of the rheological behavior of fresh concrete. The quality of free water refers to the yield stress and the viscosity of the water.

As cement hydration progresses, more water is chemically bound in the hydrates and the free water gradually decreases. The loss of concrete workability over time, as often measured by loss of slump, is the direct result of loss of the free water in concrete. Maintaining adequate slump is essential when the construction logistics indicates the possibility of substantial time lapse between concrete mixing and concrete placing.

In essence, the fines content in concrete determines the amount of the bound water. The fines content is defined as the total amount of cementitious materials, limestone power (if any), and aggregates finer than 150 μm (Sieve No. 100). The free water depends on the relative proportion of the total water and fines content. The workability of concrete, therefore, largely depends on the ratio of water to fines content. In underwater concrete, the ratio of water to fines usually ranges from 0.9 to 1.0 by volume. When the ratio falls within this range, the concrete can be made to be very flowable by use of water-reducing agents, while still maintaining adequate cohesion to prevent segregation.

For a given water content, a high fines content leads to more cohesive concrete, and thus less bleeding and segregation. On the other hand, adding extra water to a concrete mixture will reduce the yield value and viscosity, thereby increasing the slump and propensity of segregation.

Influence of cement

Portland cement influences the behavior of fresh concrete in at least three fundamental ways. The first aspect is related to cement hydration. The second aspect is its influence on water demand. The third aspect is related to the cement paste. This subsection discusses the first two aspects, while the next subsection discusses the third aspect.

Cement hydration refers to the chemical and physical processes taking place between cement and water. A study on portland cement produced by 35 different plants worldwide (Gebauer and Schramli 1974) showed that the water demand varies greatly among the cements. According to the study, three important parameters of cement determine the water demand: (a) the gradation of cement particles, (b) the C3A content, (c) the alkali content.

The size of the cement particles affects the rate of cement hydration and water absorption. Cement particles have large surface areas with substantial unsaturated electrical charges. As a result, cement particles tend to flocculate once they are in contact with water. A large amount of water can be entrapped in the cement flocs, resulting in high water demand. The finer the cement, the higher the water demand. In general, the water demand is mostly influenced by cement particles within the size of 10 to 30 μm. Cement particles greater than No. 325 sieve size (45 μm) are difficult to hydrate, and those greater than No. 200 sieve size (75 μm) may not hydrate at all.

At the early stage of hydration, the rate of the chemical reactions is dictated by the balance of the calcium, sulfate, sodium, and potassium ions in the solution. A change in relative proportions of these ions can significantly change the hydration rate and the water demand. Cement containing high C_3A content usually causes rapid hydration of cement and consumption of free water in the paste, resulting in loss of slump with time.

Underwater concrete usually contains relatively high cementitious materials content in a range of 356 to 415 kg/m^3 (600 to 700 lb/yd^3). High-performance underwater concrete often needs even higher cementitious materials content to meet special performance requirements. The high cementitious materials content is essential to enhance the cohesion and flowability of concrete, thereby reducing laitance and propensity of segregation.

In massive underwater construction, the workability of concrete and the heat of hydration are the two most important concerns. In this regard, Type II portland cement is generally most preferable for use in underwater construction. Blended cement has been recently used in some underwater construction projects. However, blended cement is generally not recommended for underwater concrete, because of the difficulties of adjusting the relative proportions and fineness of cement and mineral binders.

Influence of cement paste

Cement paste is a mixture of cement, mineral binders, fines, and water in concrete. In a static condition, cement paste is in a state of flocculation as cement particles attract each other. The extent of the flocculation determines the flow characteristics of the paste. The cement flocs can be "deflocculated" by either agitation (mixing) or chemical influence (water-reducing admixture). In general, agitation will temporarily destroy a part of interparticle attraction of the paste, while water-reducing admixtures will increase the repulsion among cement particles.

Cement paste affects the workability of concrete in the following three ways: (a) the volume of cement paste, (b) the rheology of cement paste, and (c) the interactions between cement paste and aggregates.

Concrete can be perceived as a suspension in which the cement paste is the continuous matrix that carries aggregates as suspended particles. Cement paste separates, disperses, and lubricates coarse aggregates. A high volume of the cement paste inhibits or reduces point-to-point contact among coarse aggregates and the internal friction of concrete. Thus, an increase in the cement paste often leads to more flowable concrete. If the ratio of water-to-cementitious materials is held constant, increasing cementitious materials often improves concrete workability.

Besides the cementitious materials content, the chemistry of cement paste also plays a significant role. Once cement contacts water, cement hydration immediately begins. The most rapid reactions are the hydration of tricalcium aluminate (C_3A) and dissolution of gypsum and alkalies. Following the initial reactions, cement will experience a "dormant" period for a few hours during which sulfate ions suppress rapid dissolution of aluminates and promote slow reactions of calcium silicates. As calcium silicates gradually hydrate, the cement paste stiffens to reach the initial set and the final set. Figure 3 represents a typical history of the cement hydration over time.

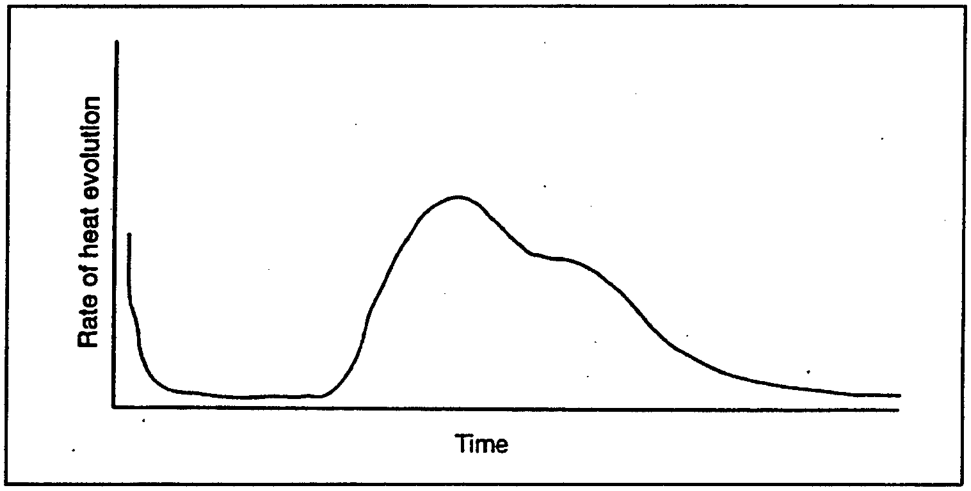

Figure 3. History of cement hydration

Due to the special placement condition, underwater concrete requires different rheological parameters than those of the conventional concrete. For placements in the dry, the cement paste usually has the yield stress ranging between 10 Pa (0.0014 psi) and 100 Pa (0.014 psi) and the plastic viscosity ranging between 0.01 and 0.1 Pa·sec (10 and 100 centipoise). Underwater concrete must be flowable and highly cohesive. The driving force that causes flow of tremie concrete is the buoyant weight of the concrete, roughly 60 percent that of concrete in air. Therefore, the workability of underwater concrete often requires that the yield stress of the cement paste be below 1.5 Pa (0.0002 psi) and the plastic viscosity above 1 Pa·sec (1,000 centipoise). In either case, the yield stress of cement paste reaches 2×10^4 Pa (3.0 psi) and 1×10^5 Pa (14 psi) at the initial set and at the final set, respectively.

Rheology of cement paste generally determines the cohesiveness and flow characteristics of concrete after the concrete overcomes its internal friction and starts to move. However, it does not uniquely determine the concrete workability. The size, angularity, gradation, and proportion of coarse aggregates play an equally important role. The effects of aggregates on the rheology of concrete mainly stem from their internal friction within the concrete. In general, the frequency of contact between aggregates decreases as the volume of cement paste increases.

Influence of mineral admixtures

The term "mineral admixture" in this report refers to ground granulated blast furnace (GGBF) slag and pozzolanic materials such as fly ash and silica fume. GGBF slag more or less participates in the initial hydration process, while pozzolans react only with the by-products of the cementitious reaction at a later age.

For massive underwater construction, adding mineral admixtures to the concrete mixture as partial replacement of portland cement is important. At present, it is fair to say that the performance requirements of high-performance mass underwater concrete cannot be reliably met without using mineral admixtures.

In essence, proper use of mineral admixtures will improve the quality of concrete in almost all the important aspects. The general improvement to the workability and rheology of underwater concrete may be summarized as follows:

a. Improving workability, flowability, and pumpability.

b. Improving homogeneity and uniformity of concrete mixtures.

c. Enhancing the resistance to segregation and erosion.

d. Extending flow time (slump retention).

e. Lowering total heat of hydration.

f. Slowing the rate of the hydration heat release.

g. Low bleeding.

h. Better control of set time.

At present, fly ash, GGBF slag, and silica fume are the three most popular mineral admixtures used in concrete mixtures. Recent research has shown that rice husk ash is promising for use in underwater concrete. Ternary or quaternary concrete mixtures containing several types of mineral admixtures have recently found wide applications in underwater concrete construction. The following sections discuss the selection and proportion of these materials in concrete materials.

Fly ash consists mainly of silica-alumina materials that will react with calcium hydroxide to produce the same hydrate product as that of portland cement. ASTM C 618 provides the standard specification for fly ashes used in concrete. The specification classifies fly ashes into Class F and Class C. Class F fly ash is a pozzolanic material that reacts with calcium hydroxide only at later ages of cement hydration. Class C fly ash has some cementitious ingredients that react directly with water. The cementitious reactivity of Class C fly ash depends mainly on its calcium oxide content. The higher the CaO content, the more active the fly ash is with water. ASTM C 618 does not directly specify CaO content for classification. Rather, it specifies the limits of silica, alumina, and iron oxides. It implicitly assumes that fly ashes with low silica/aluma/iron oxides contain high CaO content. In terms of cementitious reactivity, there is substantial diversity among Class C fly ashes satisfying the ASTM C 618 specification, depending on the CaO content. Class F fly ash typically contains 0.7 through 7.5 percent CaO, while the CaO content in Class C fly ash often ranges from 11 to 29 percent.

Replacing cement with Class F fly ashes reduces the heat of hydration and slightly retards the setting time of concrete. On the other hand, adding high calcium fly ash to concrete may even increase the heat of hydration of the concrete. Use of fly with over 20 percent CaO content may lead to rapid slump loss. For mass concrete construction where heat of hydration is an important consideration, an upper limit of 15 percent CaO content is generally recommended.

Using fly ash with high loss-on-ignition (LOI) in concrete with increase water demand, and may lead to rapid slump loss and erratic air void content. High LOI is primarily due to the presence of many unburned carbon particles in fly ash. LOI of fly ashes used in concrete must be less than 6 percent. Quality control of fly ash production is an important consideration in selection of fly ash. Before using fly ash from an unknown source, its effect on concrete workability and the setting time should investigated.

On average, fly ash is 30 percent lighter than cement. Therefore, if 30 percent cement is replaced with fly ash on the equal weight basis, the volume of cement paste will increase by 9 percent. The replacement has two opposite effects on the workability of concrete. On one hand, increasing the cement paste will enhance the lubrication around the coarse aggregates. On the other hand, an increase in fines content will increase the water demand. The net effects of the replacement on the workability of concrete depend on the replacement percentage, the chemical composition and the particle size of fly ash.

In general, replacement of 10 to 25 percent cement with fly ash by weight will effectively enhance the workability and cohesion of concrete. These beneficial effects stem mainly from the fact that fly ash consists of spherical glassy particles and participates little, if any, in the early hydration process. As a rule of thumb, replacing 10 percent cement with Class F fly ash improves the concrete workability to the same extent as a 4 to 6 percent increase in water content. Using Class C fly ashes also improves the concrete workability to some extent. Unlike adding water, the increase in workability from fly ash does not correspond to a decrease in cohesion of the concrete. In general, adding fly ash at a high dosage (above 40 percent) provides little extra benefit to the concrete workability. Therefore, the dosage of fly ash in underwater concrete rarely exceeds 40 percent of total cementitious materials.

Ground granulated blast furnace slag consists primarily of calcium silicates and calcium aluminosilicates. When GGBF slag is added to concrete, both cementitious and pozzolanic reactions take place. Hydration of slag occurs immediately upon contacting water and lasts for many years. ASTM C 989 defines commercial slag in three grades according to their initial chemical reactivity in concrete: Grade 80, Grade 100, and Grade 120.

The chemical reactivity of slag is highly influenced by its grain size and chemical composition. The finer the slag particles, the more rapid the slump loss and the greater the heat of hydration. To limit the initial chemical reaction, the maximum Blaine surface area of slag used in underwater concrete is normally specified as 4,400 cm^2/g.

In mass concrete placement, the control of the heat of hydration is a major concern. Grade 80 slag is generally less reactive than cement at room temperature. Figure 4 shows a typical example of the adiabatic temperature variations in mortar as a percentage of slag replacement (Malek 1993). However, it is found that slag will react faster than portland cement at high temperature ($T > 60$ °C). To effectively control the heat of hydration, it is essential to optimize the amount of slag replacement and to control the concrete temperature at placement. For underwater concrete, the optimum quantity of slag is frequently found to be between 60 and 80 percent of cement content by weight. In addition, the Blaine surface of the slag should be kept within 4,400 cm^2/g to minimize the heat of hydration.

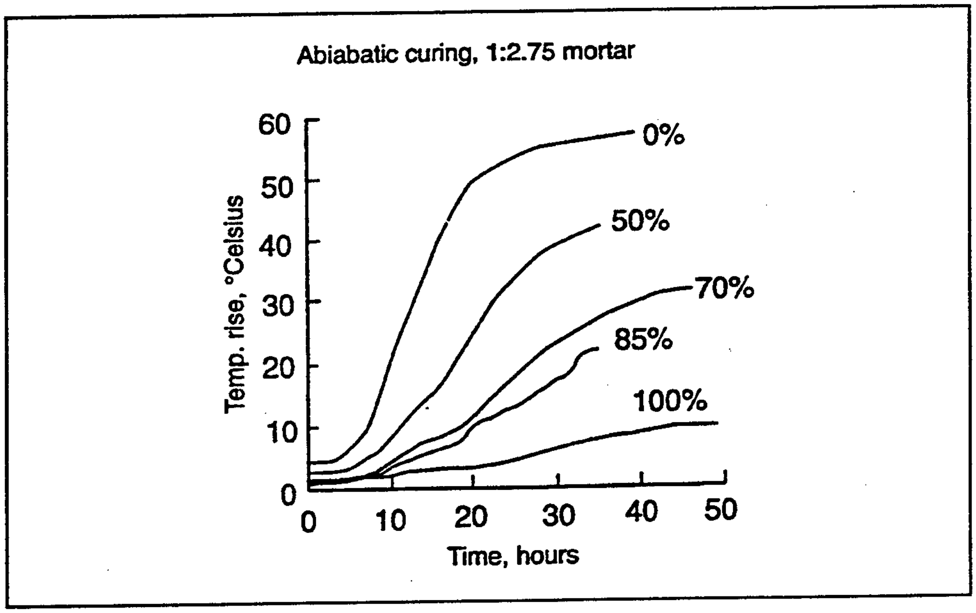

Figure 4. Adiabatic temperature rise for various percentages of slag replacements by weight

The Grade 80 slag retards the early hydration of C_3A. Therefore, slag normally extends the flow retention and the set time of the concrete. As a rule of thumb, the set time of concrete may be delayed by 10 to 20 min for every 10 percent cement replacement with slag by weight.

The Grade 100 and Grade 120 slags are normally not recommended for underwater concrete. However, a recent Japanese study (Tanaka et al. 1993) showed that use of finely ground slag (Blaine surface area of 6,000 cm^2/g) and control of calcium sulfate content can extend the flow retention and, at the same time, effectively reduce the set time.

Since Grade 80 slag contains relatively coarse grain, it tends to promote bleeding. If bleeding is a main concern for a project, there are many effective ways to alleviate the problem, such as use of a low water-to-cementitious materials ratio, use of silica fume, use of antiwashout admixture, or use of finely ground limestone powder.

Silica fume consists primarily of noncrystallized silica and, thus, is a pozzolanic binder. Its effects on concrete workability are highly dependent on the dosage of silica fume as a percentage of the cementitious materials. Figure 5 illustrates the correlation between silica fume content, cementitious materials content, and rheological parameters. Replacement of 2 to 5 percent cement with silica fume by weight reduces plastic viscosity up to 50 percent, while the yield value is nearly constant. Therefore, adding a small amount of silica fume to concrete usually improves the workability of concrete. Once the amount of silica fume in concrete exceeds about 5 percent of cement, the yield stress will increase drastically with the silica fume content.

The complex relationship may be explained by the influence of silica fume on cement dispersion and water absorption. The silica fume particles are on average about 100 times smaller than cement particles. In fresh concrete, microsilica particles tend to attach to cement particles, thereby promoting dispersion and deflocculation of the cement. As a result, concrete becomes "fluid." However, as the silica fume content increases beyond a threshold level (about 5 percent), microsilica particles themselves start to flocculate, resulting in high water demand and less workability. As shown in Figure 5, increasing cement content will amplify this "stiffening" effect.

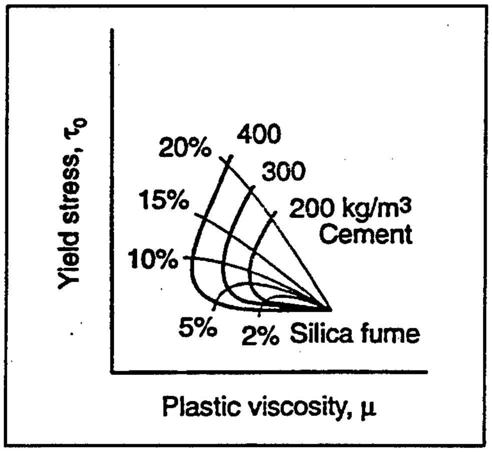

Figure 5. Effects of silica fume on rheology

The net effect of silica fume on concrete is high early strength gain, less bleeding, and segregation. Because silica fume can effectively enhance the cohesion of concrete, it is an excellent admixture for underwater concrete. On the other hand, due to its strong propensity of flocculation, silica fume should be used together with water-reducing admixture (preferably high-range water-reducing admixture).

Influence of limestone powder

Limestone powder primarily consists of calcium carbonates that are chemically inert in concrete. For many years, it has been a common practice in Europe to add fine limestone powder to portland cement as filler. European Cement Standard ENV 197 (European Committee for Standardisation 1992) allows addition of up to 35 percent limestone to commercial cement, provided that the limestone contains more than 75 percent $CaCO_3$, less than 1.2 percent clay, and less than 0.2 percent organic materials. In the United States, limestone powder is commonly used in the mining industry where the requirement for purity of limestone powder is not as restrictive. Nevertheless, sources of limestone powder that meets the ENV 197 requirements for concrete are abundant.

In recent years, limestone powder has been used in major underwater concrete construction projects in Japan. In these applications, the objective of using limestone powder is to improve the rheological behavior of concrete. Since limestone powder has a large surface area that absorbs the mixing water, it increases the cohesion and reduces bleeding of concrete. The finer the limestone powder, the higher the water demand of the concrete mixture, which therefore requires more water-reducing admixture to obtain high flowability.

It is recognized that the ratio of water-to-cementitious materials, as commonly used to evaluate the strength of concrete, does not directly control the workability of concrete. It is the total fines content, including limestone powder, that determines the amount of bound water in concrete and, therefore, its workability. When local sand available for making concrete is deficient in fine grains, limestone powder is recommended as a supplement to the sand. In a typical underwater concrete mixture, water-reducing admixtures are normally used to adjust the water demand, while limestone powder is used to improve workability of the concrete.

Limestone powder also provides beneficial effects on cement hydration and concrete durability. In fresh concrete, the finely ground limestone powder tends to attach to cement particles, improving the dispersion of cement. These limestone particles later become the "nucleation" sites for deposition of hydrates. It has been found that using limestone powder to replace a portion of sand increases the strength of concrete (Kanazawa 1992, Detwiler 1996).

In the United States, certain limestone powders were found to be beneficial in resisting alkali-silica reaction and alkali-carbonate reaction. Long-term tests (Matthews 1994) on concrete containing limestone powder as a partial replacement of cement were conducted in the United Kingdom to evaluate the effects on the strength, freeze-thaw resistance, sulfate resistance, and chloride permeability. The tests showed that the concrete containing 5 percent limestone as a replacement of cement has essentially the same performance as the control mixture.

Long-term tests (Kanazawa, Yamada, and Sogo 1992) in Japan showed that replacing 5 percent and 10 percent fine aggregates with limestone powder led to 50 and 85 percent reduction of bleeding, respectively. The concrete-containing limestone powder had higher plasticity, faster set time, and higher compressive strength. The increase in the concrete strength can be explained by microscopic observations which show that the fine limestone powder improves dispersion of cement particles and bridges between calcium silicate hydrates.

In the selection of limestone powder for concrete mixture, the gradation and chemical components of the powder are to be examined. If the limestone powder has no previous record for use in concrete mixtures, it is recommended that petrographic analysis (ASTM C 295) and alkali reactivity (ASTM C 227 or ASTM C 289) be conducted to identify the existence of potential detrimental materials. To safeguard the concrete from alkali carbonate reaction, limestone powder should contain less than 3 percent dolomite ($MgCO_3$).

Influence of aggregates

Concrete may be perceived as a highly concentrated suspension in which cement paste is the continuous matrix that carries aggregates as suspended particles. As concrete flows, the aggregates will contact each other to impose friction force in resistance. The higher the friction force, the lower the slump. Thus, concrete containing large and angular aggregates tends to be less workable and often has difficulty flowing through reinforcement cages. For the same reason, crushed aggregates require higher water content than round aggregates for the same workability.

The relative proportion of fine aggregates to coarse aggregates also has significant effect on the workability. High content of fine aggregates tends to reduce segregation and bleeding. In 1965, Gerwick recommended 42 to 45 percent fine aggregates of total aggregates by weight, which is significantly higher than the fine/total aggregates ratio of 36 percent commonly found in concrete placed in the dry. Without effective water reducers, fine aggregate content higher than 45 percent may adversely affect the concrete flowability. With use of high-range water reducers, modern underwater concrete usually contains fine aggregates in the range of 45 to 50 percent of total aggregates.

The amount of coarse aggregates in concrete is found to be a critical parameter to the workability of concrete. It is measured as the volume ratio of coarse aggregates to the total solids in concrete. A high ratio results in high yield stress and high viscosity. Since underwater concrete must be flowable and self-compacting, this ratio is usually limited within the range of 0.37 to 0.50.

In practice, it is difficult to quantify the influence of coarse aggregates on the concrete rheology, because their effects are intrinsically interlinked with the cement paste and percentage of fines in a concrete mixture. General guidelines for selection of aggregates are based upon past experience with underwater concrete. For example, the maximum size of aggregates is often limited to 25.0 to 37.5 mm (1- to 1-1/2-in.) for mass concrete, and 19.0 mm (3/4-in.) for general applications. Use of large size aggregates can considerably reduce the cement content and, consequently, the water content in concrete. However, precaution should be taken that increasing the maximum size of coarse aggregates may significantly increase the propensity of segregation of highly flowable concrete that is required to flow a moderate distance. Maximum percentage of flat and elongated aggregates should be limited to 2 to 3 percent. Optimum proportion of fine aggregates often ranges from 45 to 50 percent of the total aggregates. The percentage of fine aggregates passing 75 μm (#200) sieve is recommended to be about 10 percent of the aggregate volume. If the aggregates available for making underwater concrete lack the required amount of fine, it is desirable to add substitute fine materials, such as limestone powder or fly ash, as a part of the fines.

Influence of chemical admixtures

Antiwashout admixture (AWA) and high-range water-reducing admixture (HRWRA) are the two important chemical admixtures for high-performance underwater concrete. For many years, tremie mixture design had to be a compromise between the flowability and the cohesion of the concrete. As a result, the slump was limited to 100 to 150 mm (4 to 6 in.). The maximum flow distance of tremie concrete was often limited to about 5 m (15 ft). Rapid placement had to be used to overcome the lack of flowability. With the advent of HRWRA and AWA, modern concrete mixtures can achieve very high flowability and yet retain adequate cohesion to essentially eliminate segregation and bleeding.

The gradation of aggregates has a significant impact on the concrete workability. Well-graded aggregates improve flowability and homogeneity of the concrete. Gap-graded aggregates increase the risk of segregation of flowable concrete. The gradation of coarse aggregates should conform to the grading requirements in ASTM C 33. In order to produce a workable and cohesive concrete mixture, it is important that fine aggregates contain sufficient fine materials passing the 50- and 100-mesh sieves. ASTM C 33 specification requires that at least 10 percent fine aggregates pass the No. 50 sieve and 2 percent fine aggregates pass the No. 100 sieve. The fine aggregates should meet these minimum requirements, and a somewhat higher percentages of fines will be desirable under most circumstances.

In principle, chemical admixtures should not be used to compensate for poor mixture proportions, poor materials quality, or poor construction execution. Only when the concrete proportions are optimized can chemical admixtures effectively improve the performance of concrete.

Water-reducing admixtures are primarily dispersion agents that reduce cement flocculation and release bound water in concrete. The increase in free water consequently improves the workability of concrete. The effectiveness of water reducers can be measured in terms of the percentage of water reduction in concrete to achieve the same slump. According to ASTM standards, normal water-reducing admixtures and high-range water-reducing admixtures can achieve 5 to 7 percent and 12 to 30 percent water reductions, respectively. Although not described in ASTM C 494, admixtures achieving 7 to 9 percent water reduction are often referred to as midrange water-reducing admixtures.

Normal water-reducing admixtures are usually based upon lignosulfonate derivatives. At present, most commercial HRWRA's are either naphthalene sulphonate polymer or melamine sulphonate polymer. These two common water reducers consist of long chains of organic molecules. They have both hydrophilic and hydrophobic groups in their molecular chains. When mixed with water and cement, the admixture will coat cement particles in the form of bipolar groups to create electrical repulsion between cement particles.

As cement hydration progresses, the aluminate phase of hydrates can adsorb a significant amount of the dispersion agent. As a result, sufficient electrostatic repulsion between cement particles cannot be maintained. The net result is loss of flowability of concrete over time or slump loss. The heat of hydration accelerates this effect. This phenomenon is most conspicuous with some HRWRA's. In practice, slump loss of underwater concrete has caused many problems in construction. ACI Committee 211 report emphasizes the importance of verifying adequate slump life of underwater concrete containing HRWRA at the temperature that will occur in the actual mass placement (ACI 1997a).

One way to avoid the slump loss problem is by adding a portion of the water-reducing admixture onsite prior to placing concrete under water, especially if the time between mixing and placement is extended. In large-scale projects, however, this procedure may increase complexity of the operation and lead to difficulties in quality control. It should be pointed out that there is an essential difference between adjusting slump with water reducer and retempering concrete with extra water. Adding extra water to concrete onsite will increase the propensity of segregation. Most water-reducing agents reduce the yield stress only and have little effect on the plastic viscosity (see Figure 6). Therefore, the net effect of water reducers is an increase in slump, while maintaining a reasonable level of cohesion.

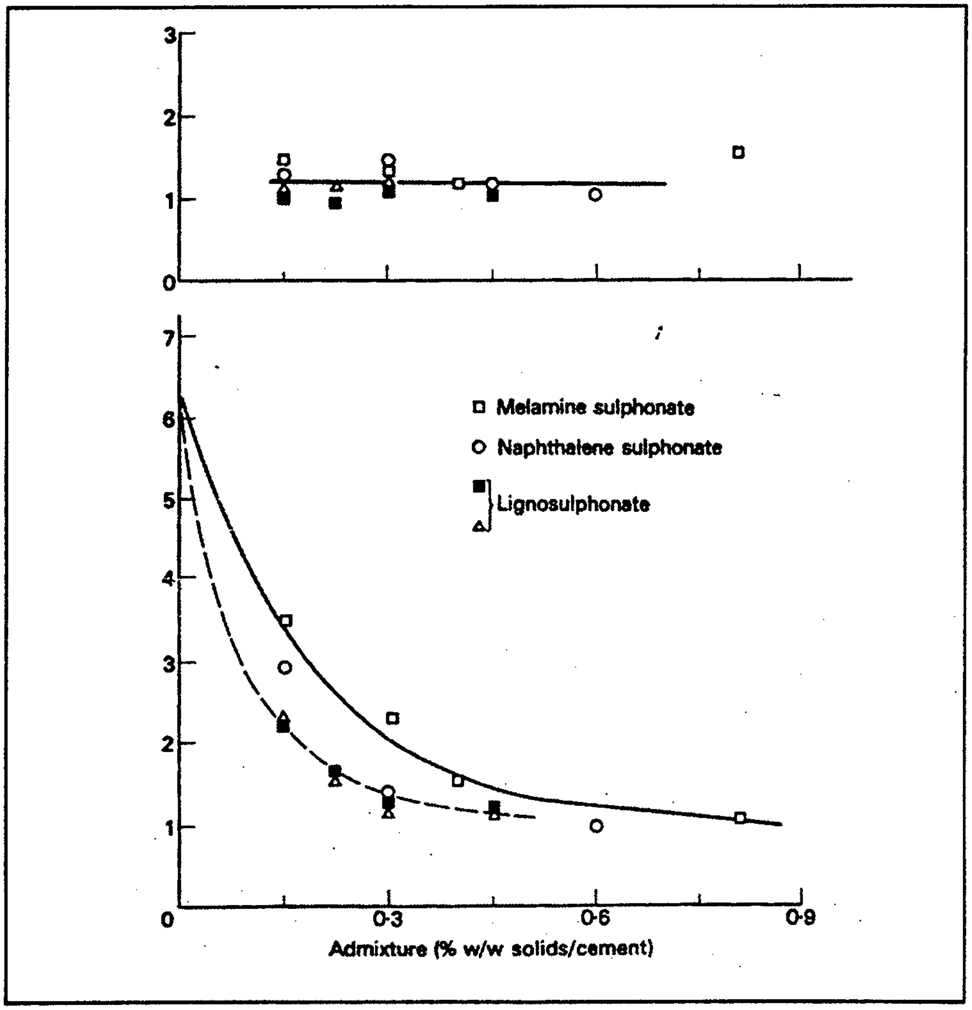

Figure 6. Effects of water-reducing admixtures on yield stress and plastic viscosity

Using set retarders or overdosing concrete with a water-reducing admixture can effectively offset rapid slump loss. But this approach frequently leads to a prolonged delay of the set. Such a situation may not be acceptable for certain projects where the construction schedule is very tight and site conditions can change drastically over time.

Recent experience in Japan (Kanazawa, Yamada, and Sogo 1992) appeared to indicate that using finely ground slag and careful control of calcium sulfate in cement can achieve satisfactory slump retention with adequate control of the set time. As previously discussed, the sulfate concentration in water suppresses the rapid rate of hydration of C_3A and, at the same time, promotes relatively slow reaction of calcium silicates. High sulfate concentration can retain the flowability, while calcium silicates in finely ground slag accelerate the setting of the concrete.

Recently, several new types of HRWRA's have attracted the attention of the engineering community. These new water reducers cannot be adsorbed or "consumed" by cement hydrates (Sakai and Daimon 1995, Billberg, Petersson, and Norberg 1996). Slump loss in the fresh concrete is consequently very small. These admixture appear to be promising for underwater concrete applications.

The effectiveness of a water reducer is also affected by the sequence of concrete mixing. A water-reducing admixture is found to be more effective if it is added to the concrete mixture after the mixing water is fully blended with other ingredients. It is postulated that C_3A in cement can quickly adsorb a portion of the water-reducing admixture, leaving less of the admixture to disperse cement. But if the addition of the admixture is delayed, C_3A quickly reacts with water to develop a protective layer of ettringite so that adsorption of the water reducer is minimized. It is found that the delayed addition of water reducer can enhance workability by 20 to 40 percent. For the same reason, if both regular water reducer and high-range water reducer are used in a mixture, it is advisable to add and mix regular water reducer before adding high-range water reducer.

Antiwashout admixture consists of long-chain saccharide polymers. When dissolved in water, the long-chain molecules form entanglement that partially restrains mobility of the water. Viscosity of the solution consequently increases. Upon agitation, the polymer chains tend to disentangle and align with the shear flow. Consequently, viscosity decreases with intensity of the agitation. The faster the shear flow, the lower the resistance to flow. When the agitation stops, the AWA polymer chains rapidly entangle again and the solution returns to the original viscosity. The thixotropic effects are pronounced in all the AWA solutions. For the same reason, when added to concrete, AWA "thickens" the interstitial free water in concrete, making it more cohesive and thixotropic.

AWA has been used as an antibleeding agent in posttensioning grout for many years. In the United States the use of AWA in underwater concrete was initiated by the Army Corps of Engineers for underwater repair of stilling basins (Saucier and Neeley 1985; Neeley 1988; Hester, Khayat, and Gerwick 1988). Since then, AWA has been successfully used in numerous small to moderate-size projects. However, the U.S. experience with using AWA in large-scale projects is still limited.

In general, flowable and self-compacting concrete mixtures can be made without AWA. The necessity of using AWA stems from the special performance requirements such as washout resistance and self-leveling characteristics. For reasons not yet fully understood, it seems that if AWA is fully hydrated it may not function properly in concrete unless high-range water reducers are also present. It is postulated that the cement particles need to be partially dispersed before AWA can form the necessary bridging between them. Therefore, in concrete production, it is preferable to add the AWA after the water-reducing admixture has been fully mixed with concrete.

Various test methods have been proposed to test the effectiveness of AWA. In Japan, for example, the PH level test method with a suction system has been standardized (Antiwashout Underwater Concrete Research Committee 1991). In North America, CRD-C61-89A, titled "Test Method for Determining the Resistance of Freshly Mixed Concrete to Washing Out in Water," has become the standard method. Past experience proved that CRD-C61-89A is a relatively simple and reliable way to measure the washout resistance. It also gives an indication of concrete resistance to segregation and laitance.

Liu (1990) found that use of AWA improves the bond strength between concrete and steel reinforcement due to reduction of bleeding from the concrete mixture. In underwater construction of navigation structures, AWA is expected to improve the bond strength and hence the monolithic behavior between the precast concrete forms and tremie concrete due to reduction or elimination of bleeding and laitance.

It has also been found in experiments (Skaggs, Rakitsky, and Whitaker 1994; Sakara, Maruyama, and Minami 1996) that certain types of AWA, such as welan gum, to a certain extent stabilize the rheological behavior of concrete with regard to variations of the concrete temperature and the water content of aggregates. For example, the measured slump and viscosity of concrete containing welan gum was found to remain near constant even if the moisture content of aggregates varies by plus or minus 1 percent. In practice, variations in quality and quantity of materials are inevitable on job site. These variations often change the flowability, slump retention, and the time of set of concrete. The experiments appear to show that, with proper use of AWA, more consistent performance of fresh concrete can be expected.

At present, two general types of AWA are found to be most effective for use in concrete. The first type is based on nonionic cellulose derivatives such as methyl cellulose and hydroxy ethyl cellulose. The second type of AWA is high molecular weight natural polysaccharide gum such as welan gum. Concrete containing welan gum appears to be more thixotropic than concrete containing cellulose-based AWA. Both types of AWA retard the reactions of cement hydration. When AWA is used together with high-range water reducer, the retardation effect is more pronounced.

Precaution should be taken when AWA and silica fume are added to a concrete mixture. Both admixtures can significantly increase the yield stress of concrete. If the type and dosage of water-reducing admixtures are not properly selected, rapid slump loss could occur.

Air-entraining admixture improves the workability of concrete. As a rule of thumb, each percent of entrained air in concrete allows approximately 3 percent reduction of water for the same level of workability. It has been reported that 5 percent entrained air reduces the yield stress by 70 percent and the plastic viscosity by 30 percent.

In practice, however, the stability of entrained air content in underwater concrete is a major concern. The actual air content inside the in-place concrete under water often experiences unpredictable variations, because it depends on interactions of many factors, such as concrete delivery and placement procedures, concrete temperature, concrete flow path and, especially, the depth of water for deposition of concrete. It is difficult to determine the exact influence of these factors on air entrainment. It is even more difficult to control these factors at the site so as to produce consistent air entrainment. Furthermore, it has been found that using air-entraining admixture as a replacement for water reducer causes greater than normal slump losses.

Both the slump retention and the flowability are critical to the success of underwater concreting. Air-entraining admixtures may increase the risk of failure. Therefore, air-entraining admixtures are generally not recommended for underwater concrete except that the concrete will later be exposed to freezing and thawing.

Practical methods for measurement of concrete workability

The slump test has been traditionally used to measure workability of fresh concrete. Engineering practice in the United States has shown that slump of concrete is a reliable indicator of workability of concrete and a convenient test method in the field. Experimental evidence has shown that the slump is directly related to the yield stress, as shown in Figure 7 (Tattersall 1991).

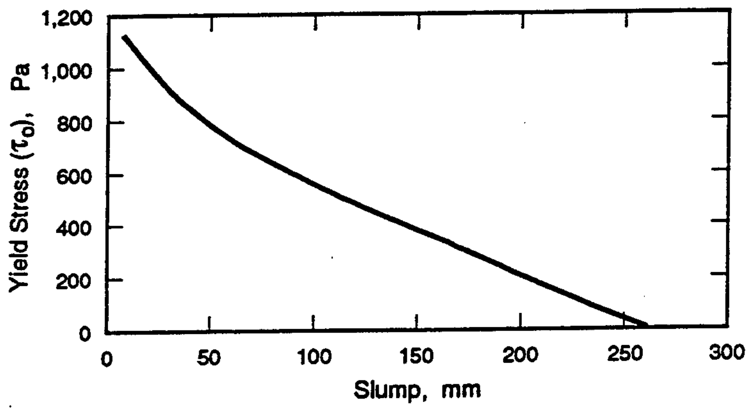

Figure 7. Yield stress versus slump (after Tattersall 1991)

When slump increases to 255 mm (10 in.) or above, concrete approaches a state of self-leveling consistency. Such concrete has a very small yield value. The plastic viscosity and friction with the slump test plate may influence the test results. Because it was perceived that the slump test for highly flowable concrete may be misleading, a slump flow test has been used in Japan and Europe. Slump flow is defined as the average number of two perpendicular slump spreads in a standard slump test. The slump flow test procedure is as follows: after taking the standard slump test, the tester then measures the diameter of the concrete in the direction of maximum spread and the diameter in the direction perpendicular to the direction of maximum spread to an accuracy of 0.5 cm (0.2 in.). The average of the two measured diameters of the concrete spread should be reported as the slump flow. Studies show that there exists a consistent correlation between slump and slump flow of concrete (Khayat et al. 1996) (Figure 8). For highly flowable concrete, the slump flow test produces more consistent and meaningful results. In Japan, the Antiwashout Underwater Concrete Research Committee (1991) recommended 450 to 500 mm (18 to 20 in.) slump flow for underwater concrete with good filling capability in complex shape, and 550 to 600 mm (22 to 24 in.) flow for concrete with self-leveling performance. Experience in the United States shows that underwater concrete may have a slump flow value in the range of 350 to 550 mm (14 to 22 in.) without excessive segregation and laitance. With further development of chemical admixtures, it is believed that the performance of underwater concrete can be further enhanced.

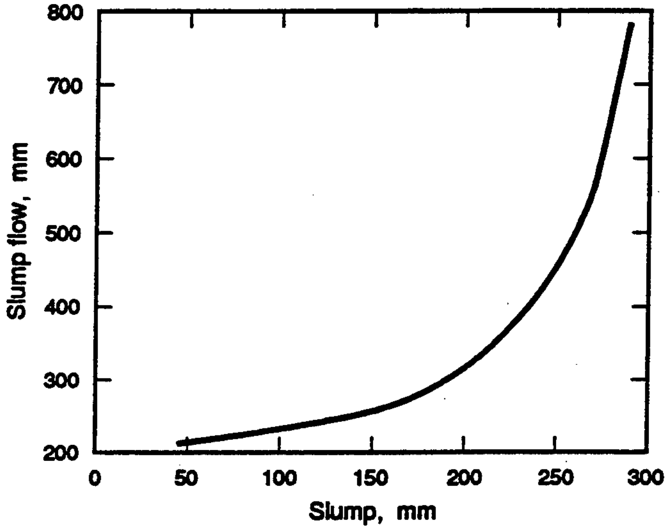

Figure 8. Slump versus slump flow

Both the slump test and the slump flow test measure the workability of concrete under a pseudostatic condition. There is a direct correlation between the slump value and the yield value calculated from a concentric viscometer test. To measure the workability under a dynamic condition, the DIN flow table test is often used in Europe (Deutsche Normen 1978).

The flow table consists of a wooden table connected to a baseboard by hinges. The top table can be raised to a standard height and then dropped. After a cone of concrete is placed over the top plate, the plate is lifted and allowed to free fall several times. The impact of the top plate causes the concrete to further spread under dynamic action. The diameter of the final spread is reported as the test result.

It is postulated that the plastic viscosity of concrete is related to shear rate and, therefore, is a time-related variable. In recent years, several simple test methods have been proposed on the basis of this postulation. Among them are slump flow speed method and V-funnel method.

The flow speed test can be conducted concurrently with a slump test. The flow speed is defined as the time for a concrete slump to reach a flow of 500 or 600 mm in diameter. Although a rigorous correlation between the slump flow speed and the viscosity has not been documented, some experimental work (Kuroiwa et al. 1993) indicated that the slump speed may be related to the rheological behavior of concrete under a dynamic condition.

A slightly more sophisticated test is the V-funnel method. The test measures the efflux time for concrete to flow out a funnel, as illustrated in Figure 9. The V-funnel test appears to be related to the concrete flowability and the capacity to pass reinforcement without segregation. A high efflux time (say, over 20 sec) indicates potential difficulty in flow. Some laboratory work (Okamura and Ozawa 1996) indicated that the efflux time is proportional to the volume ratio of coarse aggregates. When the volume ratio increases beyond the threshold value (above 0.5), the efflux time will increase drastically.

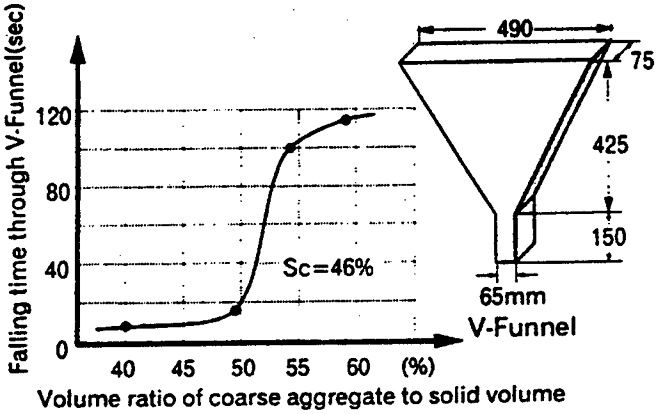

Figure 9. V-funnel test and the effect of volume ratio of coarse aggregates

Although numerous test methods have been proposed for directly measuring the propensity of concrete to segregation, none of the methods has received wide application in the industry. The resistance to segregation of concrete has been traditionally determined by experience and judgment. In practice, a simple and quite reliable method is visual observation of the consistency of the concrete and distribution of coarse aggregates. In the slump test, if substantial mortar surge accumulates around the edges of slump flow and coarse aggregates concentrate in the middle of the slump plate, the concrete has the propensity to segregation.

In review of the various test methods, the authors conclude that it is insufficient to depend only on laboratory tests to verify the concrete workability. For major civil work projects, mock-up tests are highly recommended to verify the construction procedures and determine important concrete properties that cannot be readily measured in the laboratory. The mock-up test should utilize a reasonably large-scale model. The concrete placement method and equipment used in the mock-up tests should be the same as planned for the construction. For example, to model tremie placement in precast concrete forms, a mock-up test would entail a precast concrete box container (e.g., 1.2 m by 1.2 m by 3 m) with a perforated precast plate cover. Reinforcing steel cage may be preinstalled inside the container as necessary. The container would be fully submerged, and tremie concrete would be placed into the box at a prescribed rate. The following properties of concrete can be determined:

a. Self-leveling capability and flow pattern.

b. Uniformity of the placed concrete, especially around preplaced objects (reinforcing steel and concrete blocks) and at the corners of a container.

c. Bond strength to precast concrete, especially to overhead precast concrete plates.

d. Capability to completely fill the box without trapped laitance and voids.

e. Development of hydraulic pressure on the form.

During the placement of underwater concrete, the following measurements should be made:

a. Soundings of concrete surface to determine the surface profile and the rate of concrete rise.

b. Temperature rise within concrete mass up to 90 days.

After concrete hardens, cores should be taken at various locations for the following:

a. Unit weight test of the in-place concrete compared with the fresh concrete.

b. Compressive strength test.

c. Pull-off test or direct shear test to determine bond strength between the precast concrete and tremie concrete.

d. Determination of existence of laitance and voids in the tremie concrete.

Mass Underwater Concrete Properties

Thermal behavior

One of the most critical problems with mass concrete is the thermal stress caused by heat of hydration. The problem is especially pronounced for in-the-wet construction of navigation structures, since the thermal expansion of mass concrete can lead to unacceptable cracks in the precast concrete form. The problem is exacerbated by the fact that underwater concrete usually has to be continuously placed without construction joints, giving little time for heat dissipation.

Conventional underwater concrete mixtures generally are not suitable for mass concrete construction due to their high cement content. Common means to control thermal stress include:

a. Use a large proportion of pozzolans or GGBF slag as replacement of portland cement.

b. Lower the concrete placement temperatures to slow down early cement hydration and lower the peak temperature rise of the concrete mass.

c. Plan concrete placement sequences to minimize temperature gradients within the concrete mass.

d. Use insulating covers to control temperature gradients within concrete mass.

e. Design the precast concrete forms in such a way as to minimize thermal cracking.

Past experience has demonstrated that it is most effective to combine several techniques in synergy to control the thermal problem. These techniques are discussed below.

Replacing a portion of portland cement with pozzolans and/or GGBF slag is the most cost-effective method to reduce the heat of hydration. Most pozzolans, such as low-calcium fly ash, do not actively participate in the early hydration process and also generate much less heat at later times during the pozzolanic reactions. Although GGBF slag and high-calcium fly ash do participate in the early hydration process, the reactions take place at a significantly slower rate than that of an equal quantity of portland cement.

As a rule of thumb, the contribution of low-calcium fly ash to the heat of hydration is about 15 to 30 percent of that of portland cement on a basis of equivalent mass. The heat of hydration from Grade 80 slag is approximately 60 percent that of portland cement. Bamforth (1980) reported an extensive field measurement program for mass concrete containing fly ash and slag. Temperature data were recorded within mass concrete placements of three concrete mixtures that contained 100 percent portland cement content of 400 kg/m^3 (680 lb/yd^3); 30 percent replacement of cement with fly ash by weight; and 75 percent replacement of cement with slag by weight. In comparison with portland cement concrete, the fly ash and slag concrete resulted in 11- and 16-percent reductions in maximum temperature rise, respectively.

Controlling the concrete temperature at placement is another way of reducing thermal stresses in mass concrete. Lowering placement temperature leads to an approximately equal amount of reduction in the peak temperature within the concrete mass. In modern dam construction practice, the maximum placement temperature is commonly specified for mass concrete (e.g., 10 °C or 50 °F at Glen Canyon Dam). For massive underwater concrete, the general recommendation is to limit the maximum placement temperature to 15 °C (60 °F). Placing concrete at a temperature higher than the upper limit often results in high thermal stresses and cracking of concrete as well as rapid slump loss.

The three primary ways of controlling the placement temperature in hot weather are to use precooling aggregates, chilled water or ice for batching and mixing, or liquid nitrogen to cool the concrete immediately after mixing. In hot weather, the mixing water may be replaced by up to 90 percent ice chips. All the silos or bins for storing aggregates and cementitious materials should be insulated/shaded from direct sun with wet tarps or equal. Aggregates may be immersed in chilled water. With injection of nitrogen, the concrete temperature can be as low as 5 °C (40 °F).

Finally, emphasis should be placed on the design of precast concrete forms to minimize any detrimental effects of thermal cracking. During in-the-wet construction, the precast concrete segments are installed underwater as in-situ form for tremie concrete. The form will experience steep temperature gradients when one side of the form is exposed to the water and the other side to the tremie concrete, which may lead to thermal cracking of concrete. The tensile stress imposed by both the thermal gradients and the lateral pressure of the tremie concrete becomes one of the critical load cases. As a general rule, the thicker the precast concrete wall of the form, the less the thermal gradient across the thickness of the form and the less potential of thermal cracking.

Placing small-sized, closely spaced reinforcement in the precast form helps distribution of the cracks. Since the reinforcing steel is under tension, it tends to close the cracks after the internal mass cools. The internal corner of the form should be chamfered to counteract the moment reversal as well as to avoid bleeding water at the location.

Laitance, bleeding, and segregation

In ACI 116R, laitance is defined as "a layer of weak and nondurable material containing cement and fines from aggregates, brought by bleeding water to the top of overwet concrete. In underwater concrete, laitance is mainly a result of the washing out of cementitious materials by water as well as bleeding and segregation of concrete.

Conventional construction of tremie seal requires that laitance accumulated on top of the placement be easily removed after dewatering. Laitance entrapped within a concrete mass constitutes a weak zone and is a potential source of leaking and cracking.

In "in-the-wet" construction of navigation structures, however, the laitance and bleeding are detrimental if underwater concrete has to be placed beneath an overhanging precast concrete slab so as to bond to the slab. As laitance and bleed water flow to the top surface of the mass concrete, a weak layer of concrete or possibly a gap will likely develop between the slab and the underwater concrete, resulting in a loss of structural integrity. Thus, vent holes and/or collection sumps should be provided to remove laitance wherever is possible. The formation of laitance should be kept to a minimum as discussed below.

An analysis of small-scale model tests (Strunge 1970) concludes that most of the laitance is produced in the first phase of tremie placement, and concrete surfaces formed at subsequent placements do not contribute as much to the total amount of laitance. This is why the starting procedure to place concrete is so important.

In a series of laboratory tests, Gerwick, Holland, and Komendant (1981) observed the following: "There was an immediate flow which occurred as soon as the tremie pipe was lifted. This flow was made up of two components. First, there was a flow of concrete which quickly established a mound around the mouth of the pipe. Second, there was a flow layer of a colloidal suspension of fine particles which traveled very rapidly to the far end of the placement box. These particles were apparently cement grains which were washed out of the concrete that initially flowed out of the tremie...The speed at which the colloidal layer traveled proved to be directly related to the speed at which the tremie pipe was raised to begin the placement."

To minimize laitance formation, the construction operation should cause as little disturbance to the concrete underwater as possible. Most of the disturbance occurs during starting and restarting of the placement, or results from loss of the seal or dragging the tremie horizontally while embedded in the concrete underwater. Therefore, the tremie mouth should be always embedded in the fresh concrete and, to the extent possible, the embedment depth should be moderately deep (0.7 m (2 ft) minimum). However, the tremie concrete must neither get stuck in nor be discharged under concrete that has taken its initial set. Vertical movement of the tremie pipe or pumpline should be limited to that absolutely necessary. Horizontal movement of embedded tremie or pumpline should be generally prohibited in mass underwater placement.

The starting and restarting of tremie placement is apparently critical to laitance formation. The amount of laitance can be reduced by raising the tremie slowly to start the placement. Concrete inside the tremie should be at the level of about 45 to 50 percent water depth so that tremie concrete flows out at a smooth and steady speed.

Bleeding and segregation is the second main cause of laitance formation. Therefore, developing a concrete mixture without bleeding and segregation is of significant importance to the in-the-wet construction.

Bleeding results in a gradual accumulation of water at the surface of fresh concrete or beneath the coarse aggregates. The main cause of bleeding is the sedimentation of solid particles and simultaneous upward migration of free water. Bleeding is commonly categorized into two types in terms of its mechanism. A uniform seepage of water over the entire concrete surface is commonly called "normal bleeding," while the term "channel bleeding" refers to streams of water flowing upward through localized channels in concrete mass. In conventional construction, normal bleeding is acceptable, although excessive bleeding is not desirable. In underwater concrete, both types of bleeding contribute to formation of laitance and, therefore, are undesirable.

Bleeding is commonly measured in three ways: bleeding capacity, rate of bleeding, and duration of bleeding. The bleeding capacity and rate are primarily controlled by concrete mixture proportions, especially the fines content and water content. The duration of bleeding is directly correlated with the rate of cement hydration and the time of set. The rate and duration of bleeding can also be affected by the chemical admixtures. Caution should be exercised in using set retarder, which may substantially increase the bleeding rate and duration. AWA and silica fume have been found to be effective in reduction and elimination of bleeding and laitance.

In developing proper concrete mixtures to reduce bleeding, a number of approaches can be taken in the trial batching stage. In general, the bleeding rate and bleeding capacity can be reduced by a combination of several approaches as listed below:

a. Use of silica fume and fly ash as a replacement of portland cement.

b. Use of low water-to-cementitious material ratios, preferably less than 0.45.

c. Increased proportions of fine aggregates, especially the particles smaller than 70 μm.

d. Adjustment of retarding admixture to reduce bleeding while keeping adequate slump retention.

It has been recognized that there is an optimum range of cementitious materials content in terms of minimizing the bleeding problem. Concrete mixtures with low cementitious materials content (e.g., less than 310 kg/m^3 or 520 lb/yd^3) often lead to excessive bleeding. On the other hand, increasing the cementitious materials content in a rich mixture beyond an optimum level also increases the total bleeding capacity of the concrete due to the reduced bridging effects of aggregates. For underwater concrete, the optimum cementitious materials content is commonly in the range of 385 to 505 kg/m^3 (650 to 850 lb/yd^3).

Studies show that use of water-reducing admixture will to some extent increase the bleeding rate and bleeding capacity. Therefore, when the bleeding problem is critical, precautions should be taken to avoid excessive use of water-reducing admixtures. To increase the workability of concrete, it is preferable to use water reducer together with a viscosity agent such as AWA.

In a typical concrete mixture, fines passing 300 μm (# 50) sieve have about 95 percent of the total surface area of solids in concrete. Therefore, these fines have the predominant effect on bleeding due to their high surface area. If local aggregate sources lack the desired fines content, limestone powder or other finely ground inert fillers can be added to reduce bleeding and segregation. Due to special performance requirements, underwater concrete may contain fine aggregates passing 300 μm (#50) and 150 μm (#100) sieves at a percentage higher than the specified limitations of ASTM C 33.

Bleeding and segregation of concrete should be carefully considered when determining the concrete placement rate and sequence and the design of the precast concrete form. The precast concrete shells should have weep holes on the overhanging or top slab to vent displaced water, bleed water, and laitance. If possible, the undersides of the top slabs should be sloped toward the weep holes to avoid trapping of bleeding water. The pressure of fresh concrete in the tremie pipes or standpipes will assist venting out bleed water and, thus, prevent forming of voids underneath the top slab.

Careful considerations should be given to the selection of the nominal maximum size of aggregates (NMSA). In flowable concrete, large aggregates tend to increase the propensity of segregation. As the NMSA increases, cohesiveness of the concrete should also increase in order to maintain an adequate level of resistance to segregation. Therefore, the common notion of using the largest NMSA possible to minimize the cementitious content in a mixture does not apply to the underwater concrete. The cementitious content of underwater concrete is primarily determined by its performance requirements, such as flowability, resistance to segregation, and heat of hydration.

Form pressure

Underwater concrete has been historically used for tremie seal of cofferdams where lateral form pressure is not a serious concern. In the past, only a limited number of underwater construction projects required consideration of the hydrostatic pressure of fresh concrete on formwork. For in-the-wet construction of navigation structures, accurate evaluation of the form pressure is critical. The construction method utilizes precast concrete segments as the in situ form for underwater concrete. As the concrete is being placed into the form, the hydrostatic pressures of the concrete on the form increase proportionally. Past experience shows that the form pressures in combination with the thermal expansion of the concrete often dictate the design of the precast form.

In principle, the form pressures decrease when the fresh concrete gradually transforms from a liquid state into a plastic state. If placement of concrete is slow enough to allow the concrete at the bottom to stiffen, the form pressure at the location will correspondingly decrease. Past experience shows that neglecting the time-dependent reduction of the form pressures often leads to overconservative and uneconomical design of the precast form.

In review of past experience and relevant experimental data, the authors conclude that design considerations for the time-dependent reduction of form pressure can be fully justified for underwater concrete, provided that the concrete placement is adequately controlled and properties of the concrete understood.

In comparison with conventional concrete, underwater concrete construction has several unique features that define the characteristics of the form pressure development:

a. Underwater concrete is characteristically fluid in order to develop a high degree of flowability. As a result, the form pressure is initially equal to equivalent hydrostatic head until the concrete gradually hardens. This head includes the height of concrete in the tremie, less the external water head at the elevation in question.

b. Underwater concrete needs extended slump retention because of the difficult construction conditions and the complex logistics and placement procedures. Extension of slump retention usually prolongs the set time, which in turn increases the form pressure.

c. Due to the potential laitance formation and the difficulty with preparation of horizontal construction joints under water, underwater concrete is usually placed in a continuous manner. The continuous concrete placement may leave inadequate time for concrete to stiffen so that the form pressure increases proportionally with the depth of fresh concrete.

d. Since the concrete is fully immersed, only its buoyant weight contributes to development of the form pressure.

e. Since the concrete is highly flowable, the kinematic movements of the massive concrete will at times cause higher intensities of form pressure than the hydrostatic pressure. The increase in form pressure depends on methods of the placement and flowability of the concrete. For example, discharge close to a wall may develop greater local pressure from kinetic energy.

The evaluation of the form pressure for design of formwork has been a subject of extensive study in the past. However, research on form pressure of underwater concrete has been limited to only a few specific projects. Pioneering research on this issue was conducted by the U.S. Army Engineer Waterways Experiment Station in connection with the innovative construction of Norfolk dry docks (Halloran and Talbot 1943) and Hunter Point dry docks (USAEWES 1947) during World War II. In comparison with the modern concrete mixture, the concrete used then was much less workable with a slump range of 100 to 150 mm (4 to 6 in.). Initial trial placement of concrete failed due to excessive segregation and voids. It was later found that placing concrete at a fast rate led to more uniform distribution of the concrete and also eliminated the friction that caused plugging of the tremie and segregation of concrete. However, a fast placement rate raised the concern about potential failure of formwork due to excessive pressure. As a result, large-scale laboratory tests and field measurements were made to investigate the form pressure from the tremie concrete. The investigation concluded that "lateral pressures at first are closely related to the equivalent liquid pressure head of the concrete, but later are reduced by the development of shear strength within the concrete due to setting" (Halloran 1943). The field measurements found that the assumptions made by the form designers had been higher than what was actually the case.

In summarizing the experience with tremie concrete construction of numerous bell piers for bridge foundations, Gerwick (1964) provided the following rule of thumb for estimating form pressures for concrete with a slump of 6 in. (15 cm):

Concrete Placement Rate	Maximum Form Pressure
5 ft/hr (1.5 m/hr)	800 lb/ft^2 (38 KPa)
4 ft/hr (1.2 m/hr)	600 lb/ft^2 (29 KPa)
2 ft/hr (0.6 m/hr)	500 lb/ft^2 (24 KPa)
1.5 ft/hr (0.5 m/hr)	300 lb/ft^2 (14 KPa)

In the last two decades, the increasing use of chemical admixtures and pozzolans has made modern concrete more flowable than ever before. Modern concrete is also likely to have greater slump retention and, consequently, experiences substantial delay in set time. As a result, the form pressures from the concrete are likely to be considerably higher than in the past. It has been postulated that direct applications of the design rules and experimental data made in the past may lead to unconservative design.

In this regard, recent experiments in Japan (Tanaka et al. 1993) provided valuable information. In the test, self-leveling concrete was continuously placed into a mock-up column at a rate of 1.5 m concrete rise per hour, and lateral pressures on the form were continuously measured. It was observed that the form pressure was the equivalent liquid head only at the beginning of the placement. As concrete rose in the box, the pressure at the bottom dropped off as a result of the stiffening of the concrete. When the concrete completely lost its slump flow at about 150 min after completion of the placement, form pressure decreased to almost nil. It should be noted that the concrete mixture had the initial set time and final set time at 20 and 32 hr, respectively.

On the basis of the tests, a calculation method was proposed to evaluate lateral form pressure for flowable concrete (Kuroda and Yamazaki 1998). Lateral pressure at any point on the form is the product of the coefficient of lateral pressure (K) and buoyancy weight of concrete as follows:

$$p = K * W * H$$
$$K = -A * t + B$$

where

p = pressure at any point
W = buoyant weight of concrete
H = height of concrete above the point
t = time from the initiation of placement

and A and B are to be determined from tests of each concrete mixture.

However, use of the above method requires elaborate laboratory testing for each concrete mixture. In practice, simple calculation methods are preferable.

In review of the past experience and experimental data, the authors believe that the form pressure drops drastically when the self-compacting concrete changes from a liquid state to a plastic state. In other words, reduction of the form pressure is associated with the slump loss of the concrete. In essence, the form pressure depends primarily on the rate of placement and the rate of slump loss of the concrete, although many other factors such as flowability of the concrete and shape of the form may also play a part. It is reasonable to assume that the concrete would not exert further pressure on formwork when its slump reaches zero. It is proposed that the design form pressure diagram be a bilinear function, as shown Figure 10. The method requires only that the slump test be taken periodically during trial batch testing. The time period required for the concrete to reach zero slump is recorded as t_0. The form pressure is calculated as follows:

$$p = W * R * t \qquad \text{when } t < t_o$$

$$p = p_{\max} = W * R * t_o \qquad \text{when } t > t_o$$

where

$p_{\max}$ = maximum form pressure
W = buoyant weight of concrete
R = placement rate
t = time lapse from initiation of the placement
t_0 = the time for concrete to reach zero slump

It should be recognized that the above formula does not represent the form pressure distribution at any particular time. Rather, it represents an envelope of maximum pressure during the entire placement process. In essence, the above formula is believed to be reasonably conservative and essentially comparable to the ACI recommendations (ACI 347R (1997b)) for concrete placed in the dry. Nevertheless, further laboratory testing and field measurements are needed to confirm the basic assumptions.

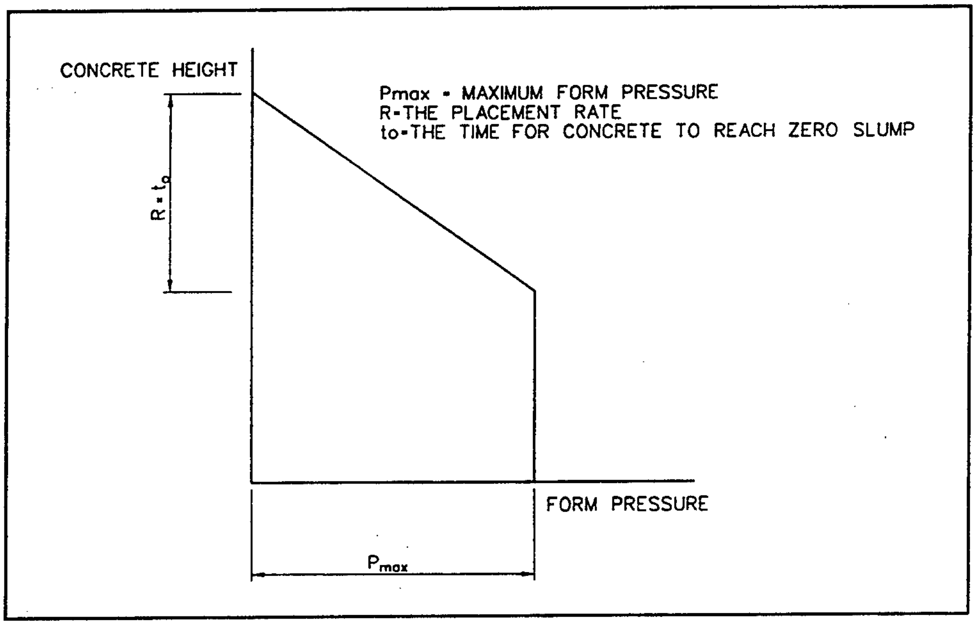

Figure 10. Form pressure diagram

Another potential major concern in underwater construction of some navigation structures is the upward pressure of fluid tremie concrete on the underside of the top slab. The uplift pressure may lift up the precast concrete form or cause misalignment of the segment. It is realized that assuming full-head hydrostatic pressure over the entire area of the slab may lead to overly conservative design. As the concrete is placed in a sequence from one side to the other side, the uplift pressure is expected to dissipate locally due to the yield stress of the concrete. Further research is recommended to quantify the local pressure and dissipation of the uplift pressure.

Strength and the other properties of hardened concrete

The strength of underwater concrete has been extensively studied in the past. The past studies concluded that fully immersed concrete has excellent curing conditions. If good placement procedures are followed, the long-term strength of underwater concrete should be higher than that of concrete placed in the dry. For example, a series of early tests conducted by the U.S. Bureau of Reclamation (Bureau of Reclamation 1975) showed that, in a period of 6 months, continuously immersed concrete developed an average compressive strength about 25 percent higher than that of comparable concrete with only 7 days moist curing. Withey's long-term tests (Withey 1931, 1941) showed that the compressive strength of continuously immersed concrete increased appreciably up to an age of 50 years. All the tests confirmed that the immersed portland cement concrete after 30 years had at least a 30 percent strength increase over the 28-day compressive strength.

The increase in strength at later age is especially pronounced in concrete containing mineral additives. Concrete containing fly ash and/or slag usually develops higher strength than portland cement concrete beyond 90 days. The common practice of using the 28-day strength criterion is based on the characteristics of portland cement concrete exposed to the air. It is not necessarily applicable to the concrete immersed under water. To account for the special characteristics of underwater concrete, the 90- or 180-day compressive strength should be used as the basis for structural design. In the strength compliance test, the test cylinders of concrete should be cured either in a fully immersed condition or in a 100-percent humidity curing environment.

Concrete strength appears to be influenced by the placement method. Coring and testing of large-scale underwater concrete placements indicated that tremie-placed concrete tends to have higher strength than pump-placed or hydrovalve-placed concrete (Netherlands Committee for Concrete Research 1973). It has been found that the concrete placed by direct pumping or the hydrovalve method is usually less cohesive and contains more voids, probably due to the method and the rate of concrete discharge from the end of the pipe.

The tensile strength of concrete develops more slowly than the compressive strength with the curing age. An approximate 10-percent increase in the tensile strength of underwater concrete is expected over that of air-dried concrete. The shear strength is expected to show an increase similar to that of the tensile strength. However, the bond strength between the precast concrete form and underwater concrete may vary to a greater extent, depending on such factors as surface preparation of the precast concrete and the underwater concrete placement technique to remove bleeding water and laitance. If full-strength bonding between precast concrete and tremie concrete is required in certain critical areas, it is recommended that additional measures be taken. Common strengthening measures include use of steel studs, surface roughening, and corrugated precast concrete forms to enhance the mechanical locking.

Algae growth (slime) should either be inhibited or cleaned off. Fortunately, the growth of algae depends on light. Since many of in-the-wet schemes proposed block off light inside the precast forms, algae growth will be minimum. However, the possibility of rapid mussel growth (e.g, zebra mussels) must not be discounted.

The elastic modulus of concrete is not influenced in the same way by the environment. In the first 3 months to 1 year, the elastic modulus of concrete increases at a higher rate than the compressive strength and remains almost constant at later ages. The elastic modulus in an immersed condition is about 15 percent greater than that of concrete in an air-dried condition.

In summary, the long-term compressive strength of underwater concrete is expected to increase at least 30 percent from its 28-day strength in 30 years. A 10-percent increase in the shear strength and a 15-percent increase in the elastic modulus of the immersed concrete is expected, compared with air-dried concrete.

A Basis for Proportioning Underwater Concrete Mixtures

The basics of proportioning underwater concrete are generally the same as those applicable to conventional concrete. In essence, underwater concrete mixtures should comply with the requirements of Engineer Manual (EM) 1110-2-2000 (Headquarters, Department of the Army 1994). The general principles of mixture proportioning should follow the recommendation in the ACI Committee 211 reports (ACI 1997a). However, underwater concreting has many peculiar characteristics due to its special site conditions, placement methods, and logistics. Underwater concrete mixtures have to be further refined to meet the special performance requirements. This section is intended to summarize some special information pertaining to underwater concrete mixture design.

In general, underwater concrete mixtures can be catagorized into two broad classes in accordance with their performance requirements: the standard mixture and the high-performance mixture. The standard mixture is applicable to the conventional construction conditions such as cofferdam seal or a typical bridge pier. The high-performance mixture refers to the self-leveling concrete and antiwashout concrete that can be placed in swift current, to fill beneath an overhanging slab, or to fill around congested reinforcing steel and embedments.

Concrete mixture proportioning is essentially a trial-and-error optimization process. The process should be guided by a set of governing variables and an understanding of how each variable affects the concrete.

As a starting point of mixture proportioning, the main efforts should be spent in optimizing a concrete mixture without aid of chemical admixtures. Only when the basic concrete mixture is optimized can chemical admixtures be effectively used to enhance the performance. Chemical admixtures should not be used to compensate for poor mixture proportions and poor materials quality.

The essential difference between underwater concrete and conventional concrete is in the workability requirements. Underwater concrete must flow laterally and compact itself under its own buoyant weight, while the conventional concrete is compacted with mechanical vibration. Based on past experience and research, the authors single out four governing variables that have the most significant effects on workability of underwater concrete:

a. The first variable is the total amount and proportions of cementitious materials in concrete. A relatively rich cementitious materials content is required for underwater concrete. Replacing part of the portland cement with fly ash or GGBF slag can remarkably change the workability of concrete. A small amount of silica fume also improves the workability. The best workability and general performance are often achieved when both fly ash and slag are used to replace about 80 percent of cement by weight. Fly ash and slag are usually proportioned approximately in a 1:3 ratio.

b. The second variable is the ratio of the water to the total fines content. The fines content is defined as the total amount of cementitious materials, limestone powder, and aggregates finer than 150 μm. The water-to-fines ratio in underwater concrete usually ranges from 0.9 to 1.0 by volume. Within this range, it is possible to adjust concrete mixes to achieve both high cohesion and high flowability.

c. The third variable is the volume ratio of coarse aggregates. It is defined as the ratio of the volume of coarse aggregates to the volume of total solids in concrete. In underwater concrete, this ratio usually ranges from 0.37 to 0.5. Within this range, lowering the ratio often improves flowability. In comparison, the ratio for the conventional concrete placed in the dry is usually 0.42 and up.

d. The fourth variable is the type and dosage of chemical admixtures used in concrete. Proper use of chemical admixtures can bring concrete to a higher level of performance. However, excessive use of chemical admixtures may cause serious construction problems.

Overdosing of water reducer and set-retarding admixtures can cause excessive delay of the setting time and, in some instances, excessive segregation and washout. However, in come cases, high dosages of these admixtures may be necessary to provide an adequate working time, and some set retardation may have to be accepted. Under most circumstances the requirement for adequate working time takes priority, provided that concrete is sufficiently cohesive and workable.

A common range of mixture proportion variables for both the standard mixture and the high-performance mixture are given in Table 1. In practice, these mixture variables can vary greatly, depending on the concrete production process and the materials selected. Flexibility must be exercised in using the table. Trial batch testing should be conducted to finalize the mixture.

Besides the workability requirements, the strength and thermal stresses are also major concerns in mass concrete. A test program for mixture proportioning commonly consists of three stages. The first stage of the program is mainly workability tests. Concrete mixtures will be adjusted to ensure the workability and in-place homogeneity within the required work window. The typical test protocol and general performance requirements for both the standard mixture and the high-performance mixture are shown in Table 2. It is recommended that the effect of concrete mixing time on concrete workability be investigated and quantified during trial batch testing.

In the second stage of the test program, the long-term physical and thermal properties of the concrete mixtures will be measured. The typical test protocol and general performance requirements of the second stage tests are shown in Table 3.

The third stage of the program is the mock-up test or field trial test. The objective of the field trial test is to verify the selected placement procedures and equipment, and to determine the important concrete performance that cannot be readily measured in the laboratory. It is recommended that concrete specifications require field trial tests or mock-up tests. The contractor should conduct the test using the same equipment, placement scheme, and workers as for the actual construction.

Table 1
Basic Mixture Proportions for Underwater Concrete

	Standard Mixture	High-Performance Mixture	Comments
Cementitious materials content (cement + slag + fly ash + silica fume)	390-450 kg/m^3 (650-750 lb/yd^3)	420-500 kg/m^3 (700-850 lb/yd^3)	Consideration should be given to replace up to 85 percent portland cement with pozzolans and GGBF slag.
Water-to-cementitious materials ratio	0.40-0.50	0.35-0.40	The ratio is the critical factor for concrete strength and durability.
Water-to-fines ratio	0.12-0.14	0.14-0.17	The ratio is one of governing factors for concrete workability.
Fine aggregate-to-total aggregate ratio	45-50 percent	45-50 percent	Relatively high percentage of fine improves fresh concrete performance.
Volume ratio of coarse aggregates	0.37-0.50	0.37-0.50	
Nominal maximum size aggregates	19.0-37.5 mm (0.75-1.5 in.)	19.0-37.5 mm (0.75-1.5 in.)	
Aggregate gradation	C-33 except that fines passing 300- and 150-μm sieve may exceed the requirement by 7 percent	C-33 except that fines passing 300- and 150-μm sieve may exceed the requirement by 7 percent	If the aggregate source lacks fines, limestone powder or equal should be used as supplement.
Antiwashout admixture (AWA)	None or a low dosage as an antibleeding admixture	Moderate to high dosage to enhance the washout resistance and the thixotropic property	AWA not only improves rheological performance, but also reduces the sensitivity to variations in the concrete mixture.
Water-reducing admixture	Use midrange or high-range water reducer to achieve the required flowability	Use high-range water reducer to achieve self-leveling performance	Overdosing water reducer may lead to excessive slump loss or delay of the set time.
Set-retarding admixture	Use proper dosage to retain the workability within the required work window	Use proper dosage to retain the workability within the required work window	The normal range of work window is between 2 and 7 hr, depending on project site conditions and placement method.
Air-entraining admixture	Use air-entraining admixture only if the concrete will subsequently be exposed to a freeze-thaw environment.	Use air-entraining admixture only if the concrete will subsequently exposed to a freeze-thaw environment.	Improper use of air entrainment may lead to erratic changes in concrete flowability, rapid slump loss, and excessive washout.

Table 2
Typical Workability Test Protocol and Requirements

Test Item	Standard Test Method	Standard Mixture Performance Requirements	High-Performance Mixture Performance Requirements
Slump tests after mixing	ASTM C 143	Slump = 180 ± 25 mm	Slump = 255 ± 25 mm
Slump flow after mixing	None	Slump flow > 255 mm	Slump flow > 405 mm
Slump tests at 30 min, 60 min, and 90 min	ASTM C 143	Slump at 60 min > 125 mm	Slump at 90 min > 125 mm
Test of the time of setting	ASTM C 403	Initial set time > 6 hr Initial set time < 14 hr Final set time < 18 hr	Initial set time > 6 hr Initial set time < 14 hr Final set time < 18 hr
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

Table 3
Test Methods for Thermal and Long-Term Properties of Concrete Mixtures

Test Item	Standard Test Method
Compressive strength at 3 days, 7 days, 14 days, 28 days, 90 days, 120 days, and 180 days	ASTM C 39
Splitting tensile strength at 3 days, 7 days, 14 days, and 28 days	ASTM C 496
Creep of concrete in compression	ASTM C 512
Adiabatic temperature rise	CRD-C 38
Coefficient of linear thermal expansion at 28 days	CRD-C 39-81
Thermal diffusivity	CRD-C 36-73
Specific heat	CRD-C 124
Elastic modulus	ASTM C 39
Autogenous shrinkage under water	CRD-C 54 modified by WES Technical Letter SL-91-9
Ultimate tensile strain capacity	CRD-C 71
Test of abrasion-erosion resistance (Optional)	CRD-C 63

3 Underwater Concrete Construction

For in-the-wet construction of the navigation structures, underwater concrete construction is a critical component of the entire project. It is technically demanding, usually on the critical path of the project schedule, and involves complex construction logistics. Therefore, its significance in the project goes far beyond the concreting operations themselves. In essence, underwater concrete can be constructed with the same degree of reliability as above-water construction. But if it is not carried out properly, with the proper concrete mixture and placement procedure, underwater concrete construction can result in a major cost and schedule overrun. This is the area where sound design and competent construction planning can achieve a meaningful reduction in risk and cost.

Review of Underwater Construction in Major Civil Works Projects

The history of underwater concrete technology is a history of innovative design and construction of major underwater civil works projects. The experience gained from these construction projects laid the foundation of modern underwater concrete practice. To give a historical perspective, several important construction projects are selectively reviewed in this section.

The early practices

Underwater placement of concrete may be traced back to Roman civilization (Netherlands Committee for Concrete Research 1973). Vitruvius's books on architecture and building construction stated that the Romans constructed stonelike solid foundations under water with mixtures of lime, stone, and a "marvallous powder" from the region of Baiae (probably pozzolan).

The earliest tremie concrete construction on record is related to the fortification of Baltimore Harbor and Florida Key West by the U.S. Army Corps of Engineers (Freeman 1934). In 1848-49, Robert E. Lee and coworkers experimented with underwater placement of concrete through a tremie which had a pyramid "frustrum" at the lower end. Concrete was lowered down through the tremie in barrel buckets and dumped directly to the bottom. Then, the concrete within the frustrum was rammed to consolidate. The concrete used was apparently not flowable, and the tremie only served as protection against washing of current.

Following the early experiments, the tremie concrete technique evolved in the later 19th century and early 20th century. In 1884, French contractor H. Heude (Heude 1885) for the first time used a tremie technique to construct a cofferdam for a railroad bridge foundation over the River Loire. A 60- by 60-mm square tube was used to deliver concrete to the bottom of the river. The tube was first filled with concrete and then lifted off the river bottom to let the concrete flow out. The tube was moved to a new location and the process was repeated again. To keep a seal at the initiation of the concrete pours, Heude used the "go-devil" method, as described below:

> A plank diaphragm can be fitted to the tube and held by cords so that it will descend as the tube is filled, thus keeping the surface of the concrete always above the water. The advantage lies in the fact that the concrete reaches the place of deposit without coming in contact with the current.

By the end of the 19th century, it had been recognized that concrete placed in water should have a different mixture proportion than that placed in dry conditions. An early book on cofferdams (Fowler 1898) contains specific recommendations on the tremie concrete mixture proportions: "tremie concrete should be made from one-third to one-half richer than would be used for similar open air work, as there will be some loss of strength."

In a presentation to the 1910 convention of the National Association of Cement Users (the predecessor of ACI), Hoff (1910) provided detailed descriptions of the first major U.S. commercial underwater concrete project using the tremie method—Detroit River Tunnel. The project was to construct a 2,549-m (8,360-ft)-long twin-tube railroad tunnel, of which 843 m (2,765 ft) was placed under the Detroit river. Over 76,469 m^3 (100,000 yd^3) of tremie concrete was used to encase the sunken tube in a dredged trench under the river. The deepest tremie placement was 23 m (74 ft) below the water surface. Hoff summarized three key points to the success of the tremie operation: (1) using flowable concrete and keeping the tremie mouth embedded in concrete at all time, (2) dividing the placement area into small compartments and tremieing each compartment individually, and (3) thorough planning of construction equipment.

Following the Detroit River project, Hoff proceeded to the construction of the New York City Subway extension across the Harlem River with essentially the same tremie technique, only further emphasis was placed on the importance of continuous concrete flow:

> ...to maintain a continuous or nearly continuous flow of concrete directly to its final position with as little movement as possible and gradually replace the water with concrete but without any mixing of them except at the contact surfaces. In meeting this

> requirement the tremie pipes were kept full of concrete, maintaining a practically constant head upon the discharge end.

By the time of construction of the San Francisco-Oakland bridge and Golden Gate bridge, tremie concrete technique had been made much more sophisticated. Specific requirements were imposed on cement types, quality and gradation of aggregates, and placement equipment and procedures. The construction quality control was highlighted in a construction inspector's report (Hands 1936) on the Bay Bridge project:

> (1) Prequalification of inspection personnel by means of reviews of appropriate literature together with occasional reports covering details of assignments especially as related to new problems and the means of solving them.
>
> (2) Prequalification of equipment and methods as well as certain labor classifications to insure adequate quality and quantities.
>
> (3) A division of aggregates into size groups, of such limits as to be readily produced by a variety of plants.
>
> (4) Requiring that each size group be furnished within 5 percent of the specified size limits.

U.S. Navy dry docks

Between 1941 and 1945, the special wartime demand for military facilities prompted major advances in tremie concrete technology. An innovative underwater construction method was used to build several Navy dry docks, including the dry docks in Philadelphia, Norfolk, and Hunter's Point (California).

In many ways, the construction method employed is similar to what is known today as in-the-wet construction. The construction typically started with dredging the site and laying down a 0.6- to 0.9-m (2- to 3-ft)-thick stone blanket. Then, the piles were driven, and steel forms or precast concrete forms were installed. Large amounts of tremie concrete were placed into the preinstalled forms to complete the floors or walls of the docks. In other words, no cofferdam was used. The tremie concrete constituted an integral part of reinforced concrete structures, rather than as a seal for a cofferdam. The success of these large-scale underwater projects attested to the quality and reliability of tremie concrete construction at the time.

Throughout these projects, a series of model tests and field measurements were conducted at various sites (Angas et al. 1944; Young 1944; Engineering News-Record 1944) to investigate the performance of tremie concrete placements. These tests and the construction experience significantly contributed to the understanding of tremie concrete behavior. Even measured against today's engineering standard, the experience from these projects is still highly valuable with regard to the tremie operation, the tremie concrete flow pattern, development of form pressure, and placement equipment.

Regarding the tremie concreting, the model test results reinstated the importance of tremie seal (Angas et al. 1944):

> The success of the tremieing operation depended upon securing a water-tight seal at the bottom of the tremie pipe so that the concrete was not subjected to washing in reaching its final position in the form. Model tests showed that failure to secure an adequate seal effectively destroyed the structural properties of the concrete.

Regarding the flow pattern of tremie concrete, the common notion was that the concrete flow is an intrusion beneath the already placed concrete. The model test for the Philadelphia dry docks construction drew a somewhat different picture (Young 1944):

> In this laboratory we have used different colored batches of concrete in a comprehensive study of the spreading action of the concrete as the pour progressed. These studies served to alter our conception of the shape tremie concrete takes after it leaves the bottom of the pipe. We thought that the concrete coming out of the tremie pipe would burrow under the surrounding concrete, but our colored batches showed us that the succeeding concrete takes the form of plumes—that is, one on top of the other, with the last concrete being on top.

Construction of the first Philadelphia dry dock started with a slow rate of placement. It was found that the tremie concrete had a very uneven upper surface and failed to fill the forms completely. Laboratory tests were conducted to determine the relation between the rate of placement and the quality of in-place tremie concrete. The study showed that faster concrete placement rate led to smoother concrete surface and a much more homogeneous distribution of the concrete. A faster rate of placement at 1.2 m (4 ft) rise per hour led to "marked improvement in progress on the project and in the quality of the tremie monoliths insofar as this could be determined by examination of the upper surfaces of the monoliths after the docks were unwatered" (Angas et al. 1944). The experience with the Norfolk dry dock showed similar results (Halloran and Talbot 1943).

This fast rate of tremie placement raised the concern about potential failure of the formwork due to excessive pressure. As a result, large-scale laboratory tests and field measurements were made during construction of Norfolk dry docks (Halloran and Talbot 1943) and Hunter's Point dry docks (USAEWES 1947). The studies showed that "lateral pressures measured in the wall forms did not exceed 500 lb/sq ft during the period of initial setting, although pressures as great as 900 lb/sq ft were measured at 5 and 6 hr after the end of the pour. (This was dependent upon the rate of placement and the time of set). These greater pressures are believed due to differential thermal expansion of the concrete mass and the steel tie rods for the forms, and occur at sufficient time after initial set to preclude any serious damage from form failure" (Halloran and Talbot 1943). Leaking under preinstalled forms was a serious problem during initial construction. It was reported that "leakage into an empty form which has not yet been poured caused a 'cold jointing' in the monolith to be poured at a later date in the supposedly empty form." Experiments showed that a canvas skirt or a roll of expanded metal proved to be the most effective measure to prevent the leakage. In addition, the rate of placement was intentionally slowed down at the beginning to ensure against excessive leakage.

Regarding tremie equipment, one of the earliest uses of valved tremie is in the construction of the first Philadelphia Navy dry dock. The valve was used to help concrete to gain initial seal. The apparatus used compressed air to dewater the tremie prior to lowering the first bucket of concrete to the bottom. The success of the apparatus is documented (Young 1944) as follows: "The efficiency of the new system is attested by the fact that not a seal has been lost up to this time, during which we have placed 130,000 cu yd of submarine concrete in 7 weeks. If a seal had been lost, it would have been a simple matter to regain it speedily without the usual danger of impairing the structure, as there would be no jetting action in making a new seal." However, despite the published report, difficulties were experienced with valved tremie due to jamming of coarse aggregate particles. In later projects, therefore, the foot valve and other complicated devices were abandoned in favor of a simple plywood and canvas disk lowered down the tremie pipe by a cable.

The construction of the Navy dry docks exemplifies the engineering excellence and ingenuity in the underwater concrete construction.

In the period of 1945-50, extensive developmental work was carried out using preplaced aggregates in underwater steel forms, which were later intruded with cement-sand mortar through embedded piping. Among the larger projects was MacKinac Strait bridge in Michigan. This process has now been abandoned in favor of tremie-placed concrete due to recurrent problems with blockage of grout flow, contamination by algae growth, and trapping of water pockets under coarse aggregate particles.

Bell-pier technique for bridge foundation construction

After World War II, the construction boom in the 1950's and 1960's prompted another innovative development in underwater concrete construction—the bell-pier method for bridge foundations using the precast concrete shells and tremie concrete. Bridges constructed with this method include Richmond-San Rafael Bridge (California, 1953-56), Columbia River Bridge at Astoria (Oregon, 1962-1966), San Mateo-Hayward Bridge (California, 1963-67). It was during this period of time that the engineering community developed a comprehensive knowledge base on in-the-wet construction of deepwater foundation with precast concrete forms.

Gerwick (1965) defined the bell-pier method as "a sophisticated type of box caisson. It enables major deep water piers to be built without cofferdams, extensive dewatering, or large open caissons." In general, bell-pier construction followed this sequence: (1) dredging the site; (2) driving temporary piles and base grids as templates for permanent piles, (3) driving permanent piles, (4) installing precast concrete bell elements underwater, and (5) placing tremie concrete inside the bells. The key element, and probably the most difficult step, of the entire construction process was the underwater placement of high-quality concrete that ties all the components together. The typical tremie concreting procedures and special problems encountered during the construction are discussed below.

After WWII, the Richmond-San Rafael bridge was the first major crossing constructed with the bell-pier method. The 6,507-m (21,343-ft)-long bridge consists of 79 major piers, including 62 piers constructed with the method. All of the tremie concrete was produced on a floating batch plant and transferred to the tremies by a crane and air-operated bucket. On the major piers, eight tremie pipes were used to continuously place up to 5,735 m^3 (7,500 yd^3) concrete at one time. The rate of concrete rise was about 0.6 m (2 ft) per hour.

Regarding the placement rate, Gerwick (1996) reported this information: "Experience on this project showed that the best tremie concrete was obtained when the pour was made at a fairly rapid and continuous rate." The concreting was conducted in a severe environment. Tidal currents up to almost 3 m/s (5.5 knots) surrounded the site. The currents create turbulence around the diaphragm forms and leach concrete through the forms. This problem was overcome by making the forms as watertight as possible and by scheduling the placements for a period of slack or low current.

During the construction, some problems with concrete flow occurred around closely spaced reinforcement, resulting in a depression behind the reinforcing cage that trapped laitance. Divers had to be sent down to clean up the laitance before the next lift was placed. In hindsight, Gerwick (1996) recommended that "increasing the clear spacing of bars to at least twice the maximum aggregate size and locating the splices above the construction joint would help to prevent this depression." Minor cracking of the precast concrete shafts and overstressing of the steel diaphragm forms also occurred during concreting. Gerwick indicated that these problems were the result of high hydrostatic pressure from concrete with extreme variations in the rate of set of cement (up to 7 hr) of the particular type used. In addition, very high and localized impact pressure from the discharge of the tremie pipe into the narrow forms was another cause of the distress.

St. Lucie Power Plant intake velocity cap

Since the 1980's, the development in underwater concrete mixtures has significantly changed the construction practice. The advanced technology brought underwater concrete construction to another level of scale and sophistication. In this regard, the underwater reconstruction of the Intake Velocity Cap at the St. Lucie Power Plant exemplifies the unique applications of antiwashout concrete (Hasan, Faerman, and Berner 1993).

The project involved reconstruction of three column-supported reinforced concrete velocity caps. The dimensions and arrangement of the caps are shown in Figure 11. The design required that the new structures have high strength and durability. The construction had to be completed during a plant outage of 58 days. Each velocity cap was constructed in three stages. First, 12 reinforced concrete columns were constructed underwater. Then, precast concrete waffle panels were prefabricated and set on top of the columns, as shown in Figure 12. Finally, rebar cages were installed, and tremie concrete was placed to tie the panels together.

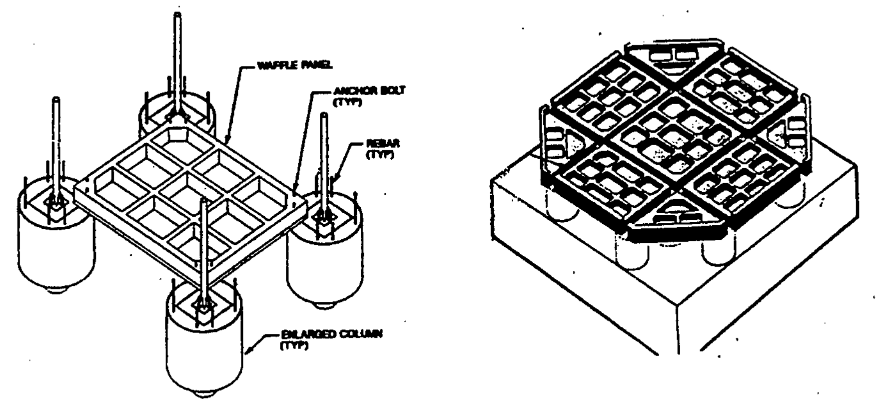

Figure 11. Configuration of the three intake velocity caps

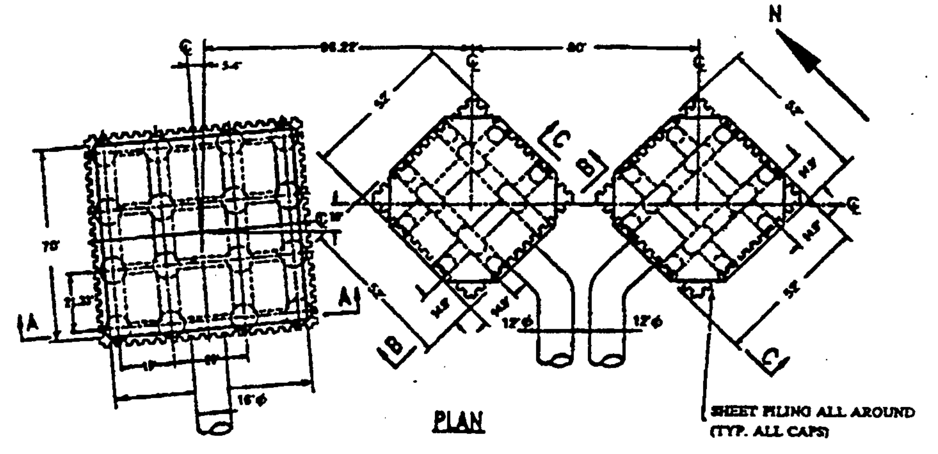

Figure 12. Typical velocity cap assembly

To meet the desired objectives, trial mixture proportions and target values for slump, placement temperature, unit weight, set time, and strength requirements were established. The specification called for a three-phase testing program leading to a final concrete placement procedure. The first phase was a laboratory trial batching of various mixtures. Only the mixture complying with the target requirements was selected. The selected mixture is self-leveling and antiwashout. The slump was over 25 cm (10 in.), slump retention over 60 min, and the 28-day strength about 62,000 kPa (9,000 psi). The second phase of the program was to verify the batching sequence and to simulate placement in a 1.5- by 1.5- by 1.5-m (5- by 5- by 5-ft) box at a finger pier in Tampa Bay, Florida. The concrete was placed at temperatures of 15.6, 21.1, and 26.7 °C (60, 70, and 80 °F), and subsequent increases in concrete temperature were measured. Finally, the selected mixture was tested under ocean conditions by a full-scale mock-up test to establish a comprehensive placement procedure. A floating batch plant was used to produce concrete onsite. The field trial setup included the pumping and tremie method. A 100-mm (4-in.)-diam steel pipe with a discharge valve was used for pumping concrete, whereas for tremie placement, a 200-mm (8-in.) tremie pipe was used. A precast test waffle panel with dimensions of 4.3 by 3.4 by 1.5 m (14 by 11 by 5 ft) was set underwater as the form. The first step was to pump 4.6 m^3 (6 yd^3) of concrete directly into four waffles of the test panel. The second stage involved tremie placement of 9.2 m^3 (12 yd^3) of concrete to fill waffles and beams. The test confirmed that the high-performance, antiwashout concrete can flow across the panels without segregation. The test showed that the concrete did not need a protective mat under the wave and currents, due to its antiwashout characteristic. The test also demonstrated that the tremie placement was superior to placement by pumping.

The construction was carried out from a work platform 370 m (1,200 ft) offshore. In addition, a 76- by 22-m (250- by 72-ft) barge was moored on a six-point anchoring system adjacent to the platform as a laydown and staging area. A floating batch plant and materials barge was moored on the other side of the platform. All equipment and materials were arranged to maximize the efficiency of the concrete production and delivery. The supporting columns were precast concrete hollow caissons filled with tremie concrete. The waffle panels serves as in situ form for the monolithic tremie placements. The panels were positioned within 250 mm (1 in.) of the design location with the guidance of large steel templates and were fixed onto the top of the column with 570-mm (2-1/4-in.)-diam anchor bolts. The most difficult task turned out to be keeping the precast panels free of sea grasses and algae. All the panels had to be cleaned with 70-MPa (10,000-psi) hydrolasers. It would take a team of three divers 3 days to get one velocity cap ready for the tremie placement. If the sea was not calm enough to start the placement on time, cleaning would have to start over again. Up to 20 tremie pipes were set up over the cap.

The tremie concrete was placed at a slump of 250 to 280 mm (10 to 11 in.). The central mixer was fitted with eight nitrogen injection ports to keep the concrete temperature within 16 to 21 °C (60 to 70 °F). The tremie placement was started at one end of the cap and proceeded to the next tremie in sequence when it was submerged at least 0.3 m (1 ft) in concrete. The advance minimized the amount of laitance entrapped in the concrete. The concrete placement was continuously monitored by a team of divers. The divers worked with the engineers on the work platform to plan where successive batches of concrete should be placed. As the concrete reached the specified depth as indicated by soundings, some tremie pipes were removed, resealed, and reinserted into the concrete in strategic locations to fill the low spots. At the final stage of the placement, divers did final inspection to verify the final profile of the tremie concrete. The project specification required one sampling for each 20 yd^3 (15 m^3) of concrete. The following data were collected from the sample: slump, unit weight, temperature, and strength test cylinders. The tests showed that concrete was of uniform consistency. The project demonstrated that highly flowable concrete can be placed in the ocean surf zone with minimal loss of materials. It should be emphasized that the entire design concept and construction methodology would not have been possible without modern high-performance concrete.

Underwater construction of bridge foundations with high-performance concrete

Modern high-performance underwater concrete has been frequently used in construction of major bridge foundations. The project experience has given us substantial insight and taught valuable lessons about underwater construction with new materials and methods. This section provides brief descriptions of the underwater concrete construction for the Akashi Kaikyo, Tsing Ma, and Second Severn bridges.

The two main tower foundations of the Akashi Kaikyo bridge, Japan, are large double-wall steel caissons filled with tremie concrete. The project required that a large volume of tremie concrete be placed up to 57 m below the water surface (Nagataki 1992). A plan view of the caisson foundation is shown in Figure 13. The steel caisson is divided into an inner core and 16 segments of outer core. While the tremie concrete in each segment of the outer core was placed at one time, the concrete in the inner circle was placed in 11 lifts. Each lift was about 3 to 4 m in thickness and 54 m in diameter. Prior to the construction, extensive tests were conducted to select the tremie concrete mixture. The concrete selected was self-leveling with a slump flow of 525 mm. The concrete mixture selected was a ternary mixture with cement:slag:fly ash proportions of 20:60:20. In addition, a significant portion of limestone powder was added to control the bleeding and improve the cohesion of the mixture.

All the tremie concrete was produced on a floating batch plant. The concrete materials required for one lift of concrete (about 9,000 m^3 (11,770 yd^3)) were collected together on two material barges that were moored to each side of the caisson. Each tremie placement was carried out continuously day and night for 3 days. Each tremie pipe covered a 100-m^2 area. The rate of placement in the inner circle was relatively slow at about 5 to 8 cm/hr. Due to the fluid characteristic of the concrete, the slow placement rate was necessary to prevent washout. The construction joints between the lifts were prepared with underwater robots and airlifting. A 3-cm-thick layer of antiwashout mortar was placed over the construction joint prior to placing another lift of tremie concrete. A total of 500,000 m^3 (653,860 yd^3) of concrete was placed in the steel caisson.

Recent experience with construction of several major bridge crossings has shown that underside leaking and erosion of tremie concrete is frequently a serious problem. The Second Severn bridge pier foundation was constructed with precast concrete box shells filled with tremie concrete. The precast concrete bottomless shells were set on pre-excavated pits in the rock. During the initial inspection, it was found that the tremie concrete tended to flow out under the edges, aggravated by the swift tidal currents. "Fences" of corrugated steel wire mesh were attached to the bottom of the wall and prevented this problem.

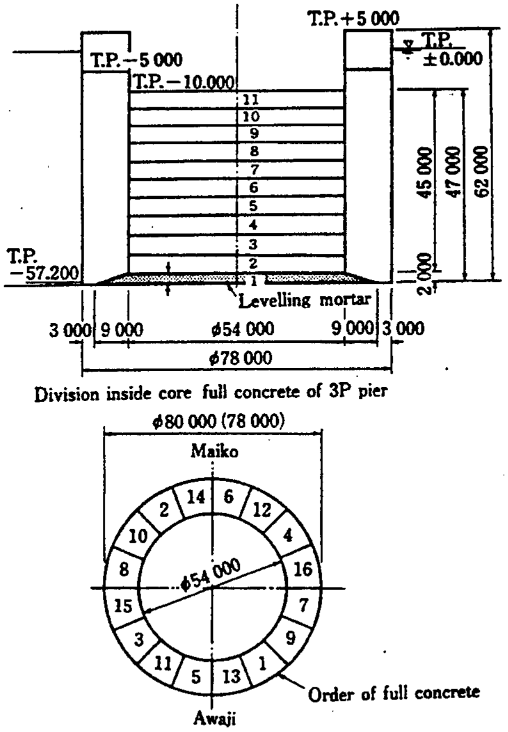

Figure 13. Akashi Kaikyo bridge tower foundation, cross sections

For the piers of Tsing Ma suspension bridge to the new Hong Kong airport, tremie concrete was placed in large precast concrete bells that had sloped overhanging roofs. The bells were seated on irregular rockbed. A stiff concrete mixture was used to minimize loss of tremie concrete under the edges. The stiff mixture did not properly fill under the roof slab, requiring supplemental grouting.

Concrete Production

The standard requirements, recommendations, and restrictions that apply to conventional concrete should also be applied to underwater concrete. In general, materials selection, batching and mixing, and transportation of concrete should conform to relevant provisions of EM 1110-2-2000. The special requirements, for underwater concrete only, are discussed below.

In-the-wet construction of locks and dams generally involves thousands of cubic meters of underwater concrete. The required quality of underwater concrete can be achieved only with a continuous and consistent placement rate. Thus, it is essential that the concrete production and delivery system be capable of producing concrete at the required placement rate. It is also essential that the necessary quantities of materials can be supplied to the batch plant at the required rate. The logistical planning should include provision for alternative or redundant supplies (onsite mixing or ready mixture concrete), provision of all the accessory items (such as barges, tugboat, and lighting), and standby key equipment (such as pumps and crane). For example, two 50-yd^3/hr (38-m^3/hr)-capacity floating batch plants are preferable to one 100-yd^3/hr (76-m^3/hr)-capacity floating batch plant.

Once the concrete production equipment is selected, the effective mixing time is critical in defining the maximum concrete productivity and the peak placement rate. It is recommended that the mixing time required to produce workable concrete be determined during trial batch tests and mock-up tests. It is noted that concrete containing AWA or silica fume requires special mixing procedures. In principle, water-reducing and set-retarding admixtures should be added to and fully mixed with other concrete ingredients before AWA and/or silica fume are finally added to the concrete. The final mixing time should be such that all the concrete ingredients are fully dispersed and the concrete reaches workable consistency. Overmixing or undermixing will lead to placement problems.

Transportation of concrete from the batch plant to the site is an important consideration in the planning. The location of the concrete batch plant has a significant impact on the construction cost, logistics, and quality control. The batch plant can be established either onshore or offshore, depending on the placement scheme and the materials delivery scheme.

Offshore concrete production facilities commonly consist of a floating batch and mixing plant, a conveyer system to transport concrete materials, materials storage and delivery barges, separate storage bins for cement and aggregates, and storage for chemical and mineral admixtures. If limestone powder is used, it should be batched separately from sand. The main advantage of offshore production is reduced time between mixing and placement. The concrete out of the floating mixer can be immediately delivered to the tremie hoppers without any loss of workability. This production method is more likely to provide for reliable control of the workability of tremie concrete. However, it may increase the logistical complexity. Once the tremie placement starts, it is essential that the floating plant continuously produces concrete at a rate that is compatible with the required concrete placement rate. It is critical to maintain an adequate supply of the concrete-making materials. For example, full production of a 76-m^3/hr (100-yd^3/hr)-capacity batch plant will require approximately 150 tons of aggregate and 40 tons of cementitious materials every hour. The high productivity requires large-materials storage barges and frequent transportation of materials from the shore. In general, it is more difficult to maintain consistent quality of the concrete materials on barges (that is, moisture and temperature of the aggregates). Frequent loading, transportation, and unloading of concrete materials by delivery barges may also seriously interfere with commercial navigation on the river. Breakdowns of floating batch plants and other equipment are likely and difficult to repair. As materials in storage on the batch plant are consumed, the barge lists. Scales must be supported so that they give accurate weights despite the change in attitude.

Alternatively, underwater concrete may be produced on land and transported to the site by transit mixers and barges. A batching and mixing plant is set up onshore, and the concrete is transported to the placement site by boats or barges. On the Great Belt Eastern bridge, ready-mix trucks were ferried on a barge. For the San Mateo-Hayward bridge across San Francisco Bay, concrete was transported in hopper buckets in boats. A retarding admixture was added to the concrete. Remixing after arrival at the site was considered, but tests showed it to be unnecessary.

Use of a commercial ready-mix plant, with delivery by ready-mix trucks to the shore and then by pumpline supported over the water, was the scheme used on the Dame Point bridge. The pumpline was supported on a piled trestle. The concrete mixture was precooled by injection of liquid nitrogen at the mixing plant. However, delays in delivery due to road traffic allowed the concrete to warm up to near ambient temperature. Since similar interruptions often occur with delivery from commercial plants, a nearshore plant should normally be required.

Another method is to dry batch concrete in a central plant and to do all the mixing at the jobsite. When concrete is transported from the batch plant to the site, the concrete will invariably suffer slump loss. The extent of the concrete slump loss is mainly dependent on the temperature and the time required for the transportation. The problem is especially pronounced when there is a delay in placement. It is essential that the concrete be checked for workability and temperature at the site, just prior to placement underwater. Good quality concrete can usually be obtained with proper agitation or remixing after being delivered to the site. An adequate amount of high-range water-reducing admixture should be available onsite for adjusting the slump. Set-retarding admixture has been found to be very effective for reducing both slump loss and temperature rise.

Due to the inherent risk in the concrete transportation, a field trial test is highly recommended. Trial placements should preferably be conducted with the same batch plant, transit mixer, and delivery and placement equipment as for the actual job.

Concrete Placement

The technical requirements for underwater concreting cover the areas of placement method and technique, placement sequence, placement equipment layout, finishing, and protection of concrete. Concrete placement planning should include the relevant subjects of detail as well as the construction logistics (the relationships among various concreting operations and their relationships with other construction operations).

The choice of a proper placement plan for a specific project has to be ultimately determined by the site condition and engineering requirements, including the required in-place concrete properties, volume and thickness of the concrete placement, water velocity during concrete placement, presence of reinforcement or obstacles, availability of equipment, technical feasibility, and cost.

Underwater concreting is currently carried out by five basic placement methods: the tremie method, the pump method, the hydrovalve method, the buckets or skip method, and the preplaced aggregates method. General descriptions of these methods are given in previous reports (Gerwick 1986; Gerwick, Inc. 1988[1]).

For the underwater construction of navigation structures, the tremie method is the only sound method for placing high-quality underwater concrete. However, some contractors will request to use the pump method because it slightly reduces the labor cost. The following sections provide a critical examination of these two methods. The other placement methods are not appropriate for high-quality underwater concrete for major structures, although they may find application in special cases.

For placement of underwater concrete, the tremie method and the pump method function in fundamentally different ways: tremie placement deposits concrete solely by its own gravity in a open system; the pump method employs surges of pump pressure to deliver concrete in a closed system. The technical difficulties and the inherent risk of failure with these two methods are substantially different.

Critical examination of the pump method

The pump method is defined as pumping concrete directly into its final position, involving both horizontal and vertical delivery of concrete in a closed system of discharge pipes. Pumping concrete has the advantage of operational efficiency with potential savings of time and labor. In recent years, the pump method has become increasingly popular for above-water structures due to the advancements of pumping equipment and techniques. The advancements have led to increasingly high pump outputs and pressures. Concrete has been pumped up to 600 m high in one stage at a delivery rate of 24.2 m^3/hr. Unfortunately, these advanced pumping technologies do not address the inherent problems associated with pumping concrete down into water. Pumping underwater concrete still faces the same technical difficulties and risk of failure as operations over 50 years ago.

In terms of proper concrete mixtures for placement methods, underwater concrete may be divided into two categories: concrete containing NMSA greater than 9.5 mm (3/8 in.) and concrete containing NMSA smaller than 9.5 mm. In general, NMSA in mass underwater concrete ranges from 25.0 to 37.5 mm (1 to 1-1/2 in.). Pumping the mass concrete directly down to structures on the riverbed or seafloor has several technical problems that will increase the risk of construction failure or poor quality concrete:

a. In tremie placement by gravity feed, the concrete flow rate can be controlled by the rate at which concrete is fed into the tremie. On the

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[1] Ben C. Gerwick, Inc. (1988). "Review of technology for underwater repair of abrasion resistance concrete," prepared for U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

other hand, the pump system fully fills the pumpline with concrete. For placement in deep water, the weight of concrete in the pumpline is much greater than the hydrostatic head from the water and concrete outside the pipe. Thus, the concrete exits the pipe at an uncontrollably high speed, causing significant disturbance of already placed concrete and segregation of the concrete being poured.

b. A pump system is closed to the atmosphere. When concrete is pumped down to deep water, concrete may fall through and exit a pumpline at a rate faster than the pump output. Thus, a vacuum will be created in the line. The vacuum pressure so created will suck away the cement paste from aggregates, causing segregation and plugging of the line.

c. Pressure surges from the pump can cause disruption of the concrete flow and plugging of the line.

d. A concrete mixture optimized for pumping may not be the optimum concrete mixture for underwater applications.

e. Pumping into a confined space can potentially result in excessive pressures.

f. If the end of the pumpline is not adequately buried, excessive pump pressure surge can kick the pumpline out of the in-place concrete, causing mixing of the concrete with water.

In the past, pumping underwater concrete has led to numerous incidents and poor-quality concrete. In general, pumping concrete through deep water down to river bed or seafloor should be prohibited. In some cases, pumping concrete in shallow water (less than about 9 m or 30 ft) is feasible. For example, pumping has been successfully used in the repair of stilling basins in relatively shallow water. But the pump method is still riskier than tremie placement.

Grout and flowable concrete containing NMSA less than 9.5 mm (3/8 in.) can be successfully placed under water by pumping. A pumpline for injecting grout has a much smaller diameter than one used for concrete. The pipe with a diameter less than 90 mm (3-1/2 in.) has a high ratio of skin friction to the volume of grout in the pipe. The skin friction between the pipe and grout prevents free falling of the grout. In this case, the formation of a vacuum in the pumpline is prevented by the resistance to flow and maintaining a positive pressure from the pump.

If a pumpline has a diameter greater than 90 mm (3-1/2 in.), the skin friction is relatively small and the grout will fall at a high speed under its own weight. In this case, it is recommended that an air vent be installed over the top bend of the pumpline. Thus, the pump system is open to the atmosphere, the grout flow is controlled by the hydrostatic equilibrium, and a vacuum will not develop in the pipe.

If a flexible hose is extended to the end of the pumpline, the pump pressure at stopping and restarting of the pump can easily kick the flexible hose out of the already deposited grout, resulting in loss of seal. Therefore, a steel pipe should be used at the end of the pumpline, connected to a flexible hose by a gasketed and bolted joint.

In summary, pumping concrete directly under deep water (>9 m or 30 ft in water depth) is a technically flawed procedure. Although pumping concrete in shadow water is feasible, it still involves significant risks and potentially poor concrete quality. For massive underwater concrete construction of navigation structures, the pump method should be prohibited. However, the pump method is an excellent way to deliver concrete horizontally to a tremie hopper. It is also an excellent way of placing grout or flowable sand underwater.

Tremie system

Over more than a century, the tremie concrete technology has evolved through a trial-and-error process and has now become the standard method to place high-quality concrete under water. The tremie system consists of a rigid pipe suspended either vertically or slightly inclined through the water and a hopper fixed on top of the pipe to receive concrete. The tremie method can be defined as a way of placing underwater concrete through a rigid pipe by means of gravity flow. The concrete flow mechanism in a typical tremie arrangement is illustrated in Figure 14. The concrete flow occurs only when the weight of concrete inside the tremie overcomes (1) the resistance of concrete outside the tip of the tremie, (2) the friction between the concrete and the tremie wall, and (3) the hydrostatic pressure of water or slurry. There is always a point at which the gravity force inside the tremie is in equilibrium with the resistance to flow. At this point, the height of concrete inside the tremie is referred to as the hydrostatic balance point. Any concrete added above the hydrostatic balance point will cause concrete to flow. The more concrete added above the balance point, the faster the concrete flow rate.

For a given concrete mixture, the tremie placement rate can be theoretically evaluated on the basis of three geometrical parameters: (1) the concrete height inside the tremie H; (2) the embedment depth of the tremie tip in concrete, h; and (3) the water or slurry depth above the tremie concrete, D. The theoretical balance point can be estimated as follows:

$$H' = \frac{W_c * h + W_w * D}{W_c}$$

where

H' = concrete height at the hydrostatic balance point

W_c and W_w = unit weight of concrete and water, respectively

The above equation is based upon experience, showing that the friction between concrete and the internal tremie wall and the cohesion of already placed concrete are negligibly small. In reality, the flow resistance from the friction and concrete cohesion will require a small additional hydrostatic head of tremie concrete in order to initiate concrete flow. In the past, the flow resistance was often calculated by comparing the actual measurements of the hydrostatic balance point with the theoretical value from the above equation. The measurements indicate that the flow resistance may vary greatly from site to site. As a rule of thumb, the extra concrete head required to overcome the flow resistance due to the cohesion is within the range of 0.1 to 1.0 times the tremie embedment depth in concrete (*h*), depending on the concrete mixture. The friction inside the tremie is about 1 to 5 percent of the concrete weight inside the tremie, depending on the size of tremie pipe. The larger the tremie pipe, the less the skin friction. If the flow resistance F_R is included, the hydrostatic balance point can be estimated as follows:

$$H = \frac{W_c * h + W_w * D + F_R}{W_c}$$

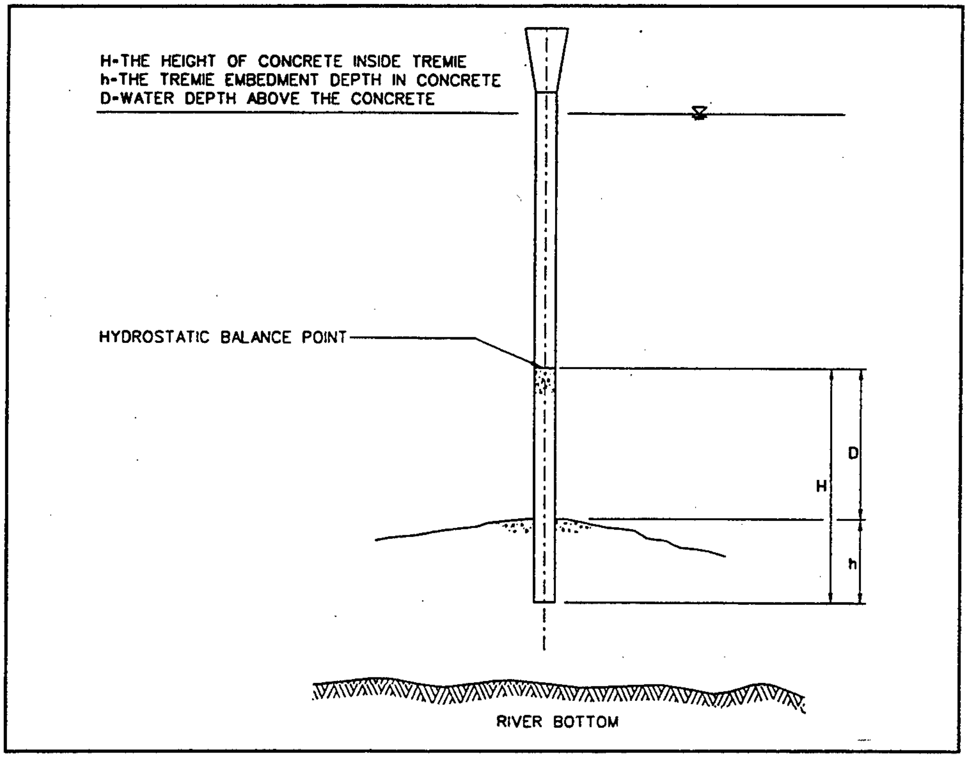


Figure 14. Hydrostatic balance point in a tremie system

The concrete inside the tremie always tends to adjust toward the hydrostatic balance point. The tremie system is a self-adjusting system that balances the concrete outflow with the concrete inflow fed into the tremie. In practice, it is not necessary to determine the precise location of the balance point after the seal is established. It is recommended that the balance point be measured periodically against the sounding outside the tremie and the embedment depth of the tremie pipe. A sudden change of the observed balance point may indicate a high flow resistance or plugging of tremie or loss of the seal.

From the above analysis, it is apparent that the hydrostatic balance point changes with the embedment depth of the tremie pipe. The concrete flow can be increased or decreased by simply raising or lowering the tremie pipe. In practice, however, it is not recommended that the concrete flow be controlled by means of frequent vertical movement of the tremie. Rather, the flow should be adjusted by the rate of concrete delivery into the tremie. Constantly moving the tremie up and down not only disrupts a smooth and continuous concrete flow, but also runs the risk of losing the seal. Lifting the tremie is necessary when the tremie embedment in concrete is too deep to achieve the desirable placement rate. All vertical movements of the tremie pipe shall be carefully controlled with a stable lift rig such as an air hoist. Once the tremie is adjusted to a desirable elevation, it should be supported on a stable platform to prevent further movements in both the horizontal and vertical directions.

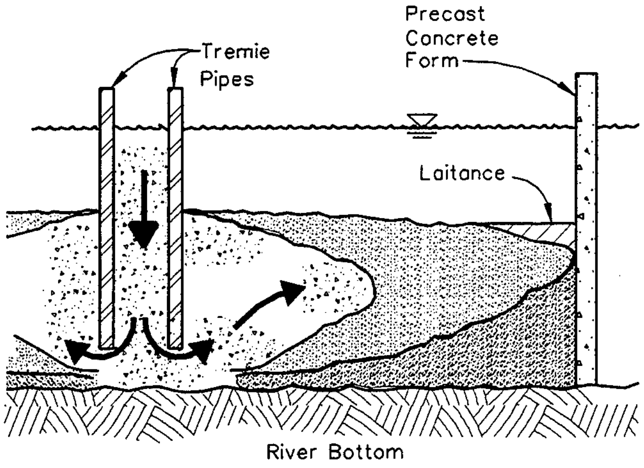
Tremie concrete, with or without the antiwashout admixture, should always be discharged into and beneath the already placed concrete. Specifications should require that the tip of tremie be always embedded in fresh concrete by at least 0.6 m (2 ft). This requirement not only helps to prevent a loss of the seal, but also improves the concrete flow pattern.

The importance of concrete flow pattern on the quality of tremie concrete was recognized in the early part of this century. It was generally believed that concrete discharged below the already placed concrete would flow beneath the concrete-water interface. Thus, only the first concrete pour would have direct contact with water.

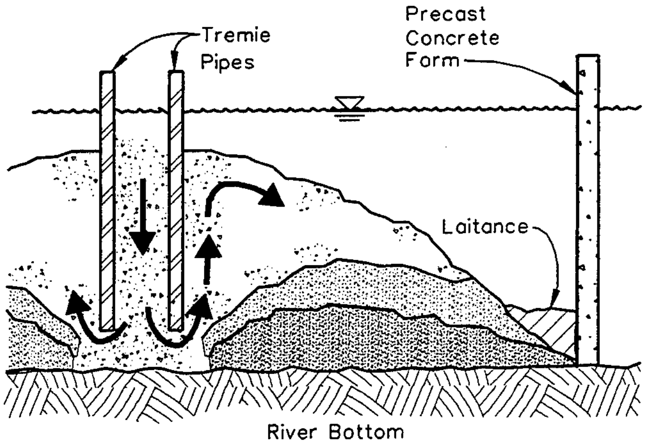
Further investigations on this issue indicate that this common notion about the tremie flow may not always be correct. During construction of the Philadelphia Navy dry dock in 1943, large-scale mock-up tremie pours with different dyes were made to determine the flow pattern (Halloran and Talbot 1943). Gerwick, Holland, and Komendant (1981) conducted large-scale tests to further verify the tremie concrete flow. These tests showed that concrete flows out of tremie in two distinctive patterns. The first flow pattern is the so-called "bulged pattern," as shown in Figure 15a, where the newly placed concrete pushes the existing concrete sideways from the tremie. The second pattern is the "layered pattern," shown in Figure 15b, where the newly placed concrete flows upward around the tremie and then flows over the top of the existing concrete. The bulged flow pattern tends to develop a smooth, flat surface and is associated with uniformly distributed, good-quality concrete. The layered pattern often develops a very steep and rugged surface with large quantities of laitance.

The concrete flow pattern is dependent upon the consistency of the concrete mixture and the placement rate. In addition, the flow pattern is also affected by the thickness of the concrete placement and the tremie embedment depth in concrete.

The previous studies have shown that highly flowable and cohesive concrete mixtures usually flow in the bulged pattern, while less flowable concrete mixtures flow in the layered pattern. In terms of the rheology, a low apparent viscosity of a concrete mixture gives the most favorable flow pattern.



a. Bulging flow pattern



b. Layered flow pattern

Figure 15. Flow patterns of tremie concrete (after Gerwick, Holland, and Komendant 1981)

Before chemical admixtures were widely used in concrete construction, underwater concrete mixtures generally had stiffer consistencies than the concretes used today. Consequently, concrete placed at a slow rate often had very uneven, steep surfaces and a nonhomogeneous distribution of concrete mass. In practice, it was found that rapid placement of concrete resulted in marked improvement in the tremie concrete quality. The technique of rapid placement takes advantage of the dynamic energy of flowing concrete to overcome the lack of concrete flowability. Up to the 1980's, a concrete placement rate of 0.6 to 1.2 m (2 to 4 ft) concrete rise per hour was often recommended. However, this may not be practicable for large placements.

With a highly flowable concrete mixture, the kinetic energy of the fast-flowing concrete is not always required for placement of good-quality concrete. Nevertheless, a smooth and continuous tremie placement is still essential for good-quality concrete. In general, a placement rate of 0.2 to 0.6 m/hr (0.75 to 2 ft/hr) or 38 to 76 m^3/hr (50 to 100 yd^3/hr) is often appropriate for modern concrete mixtures, depending on the size of the tremie placement and spacing of tremie pipes.

The concrete flow pattern is also dependent upon the tremie embedment depth in concrete. It is noted that all of the previous large-scale mock-up tests on the flow pattern (Gerwick, Holland, and Komendant 1981; Halloran and Talbot 1943) involved relatively shallow placements (tremie thickness < 1.2 m or 4 ft). So far, the effects of tremie embedment depth on the concrete flow have not yet been investigated in laboratory tests. However, past experience shows that deeper tremie embedment in concrete often leads to a flatter concrete surface and much less laitance. It is likely that deep tremie embedment causes intrusion of tremie concrete beneath the already placed concrete, as shown in Figure 16. In essence, moderately deep tremie embedment is preferable for concrete placement. However, the tremie embedment should not risk locking the tremie in set concrete. For every project, it is recommended that an estimate be made of the proper tremie embedment depth with respect to the time of set, concrete temperature, and the rate of concrete rise.

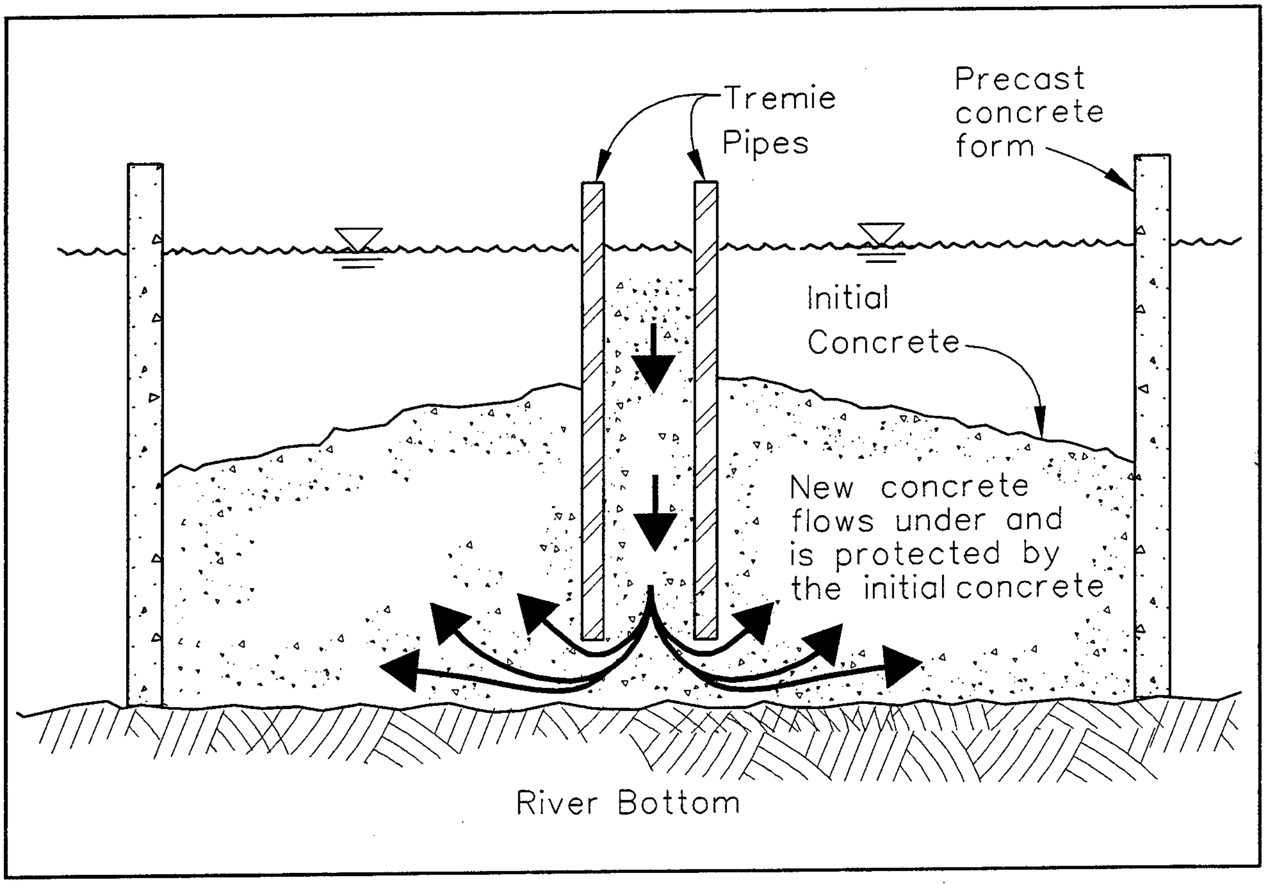


Figure 16. Tremie concrete flow in deep pour

A smooth and continuous flow of tremie concrete is essential to ensure good-quality in-place concrete. To this end, the diameter of tremie pipe should be approximately 6 to 8 times the maximum size aggregates in concrete. The inside wall of the tremie pipe should be kept smooth to avoid disruption to the tremie concrete flow.

When the tremie size is relatively small (152 mm (6 in.) or less), it has been found that air is frequently entrapped in the concrete and pushed through the tremie into the concrete mass. In practice, it is not rare to see large bubbles coming out of the surface of water around the tremie pipe. Some of the entrapped air bubbles are squeezed into the concrete mass, leaving large air pockets in concrete. Two simple techniques are used to avoid this problem. The first technique is to use an inclined tremie, i.e., to position the tremie at a slight angle to the vertical (say, 10 deg). As the concrete falls through, it will slide along the lower side of the tremie, allowing the air gap to form along the high side of the tremie. Alternatively, large tremie pipes can be used and the placement rate controlled so that there is always a continuous gap in the tremie for air to escape. In general, specifications should require that the contractor take positive measures to avoid the air trapping.

Measurements taken during tremie placement indicate that the concrete falls through the upper portion of a tremie pipe at a relatively high speed. There has been a concern that free-falling concrete is susceptible to serious segregation. It had been suggested that the tremie pipe be filled with concrete up to the hopper throughout the tremie placement. This suggested procedure is not only unnecessary but also impractical. Field investigation and measurements (Construction Methods 1942; STS Consultants, Ltd. 1994) show the tremie concrete has little segregation after free falling 15 to 30 m (50 to 100 ft). This is because the underwater concrete mixtures are inherently more cohesive and segregation-resistant than concrete mixtures placed in the dry. Furthermore, the concrete remixes after its fall. The remixing of cohesive and flowable concrete generally eliminates the segregation problem. For starting a placement, an initial grout bed should be placed as described in the following section, to allow initial remixing.

Under some circumstances, the quality of in-place tremie concrete can be substantially influenced by the velocity of flowing water passing the placement area, because significant water flow over the fresh concrete surface increases the tendency of washing out or diluting the cement paste. The maximum allowable water velocity in which good-quality concrete may be reliably placed is largely dependent upon the size of concrete placement and the concrete mixture. If concrete is placed in a thin layer, such as that used in underwater repair of thin scour holes in stilling basins, the water velocity should be limited to about 0.5 m/s (1.5 ft/s) during concrete placement. For mass tremie concrete placement, the allowable water velocity may be increased to 0.6 m/s (2 ft/s) for conventional tremie concrete mixtures, and 1.8 m/s (6 ft/s) for high-performance concrete mixtures containing antiwashout admixture. For in-the-wet construction of navigation structures, however, underwater concrete is mostly placed within the precast concrete formwork without much influence of flowing water in the river. Wherever fresh underwater concrete is exposed to flowing water, the above limitations on water velocity should be imposed.

Initiation of tremie placement

Initiation of the concrete placement is one of the most critical steps in the entire process. An improper startup often causes excessive laitance and severe segregation of the concrete. The key is to establish a good concrete seal at the tremie tip with little disturbance. It is preferable to place about 0.4 m^3 (0.5 yd^3) grout at the start of concrete placement. The grout should contain the same mixture proportions of the underwater concrete with coarse aggregates removed. The objective of the grout is twofold: it coats the inside of placement pipe, and it facilitates remixing of concrete.

There are two basic techniques to start the placement: the dry method and the wet method. The dry method entails installation of an end cap at the tip of placement pipe, such as the device shown in Figure 17. Thus, the end of the placement pipe is sealed from the entry of water when the pipe is lowered into water. Once the pipe is set upon the riverbed, concrete is placed into the dry pipe until the pipe is full. Then, the placement pipe is lifted up off the bottom by 15 cm (6 in.) to let the concrete flow out. For concrete placement in deep water, the dry method may have buoyancy problem, i.e., it is difficult to place an empty tremie with a closed end to the bottom because of the large buoyancy force. In such cases, the tremie can be weighted to overcome the buoyancy. Another technique is to partially fill the tremie with concrete prior to lowering it into water. The concrete inside the tremie compensates the buoyancy.

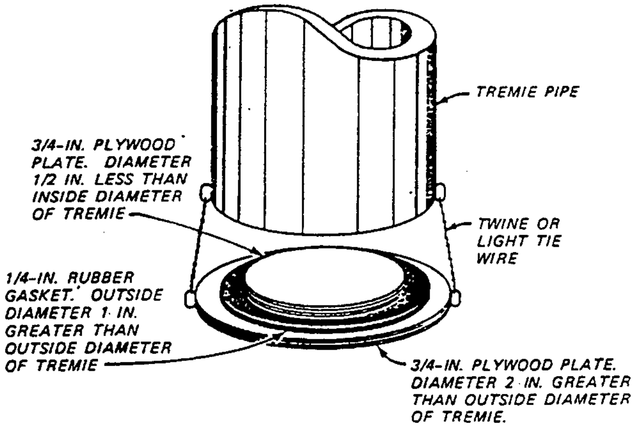


Figure 17. Tremie pipe with end cap

In the wet method, the placement pipe is lowered into water with the end open. Then, a plug is pushed through the placement pipe and concrete is slowly added on the top to force down the plug. The plug separates the concrete from water until the plug is pushed out of the placement pipe. The plug is commonly referred to as a "go-devil" or a "pig." A pipeline pig (solid with rubber squeegees) is one of the proper plugs to use. Use of an inflated ball as a go-devil must be prohibited, since the ball will collapse under about 8 m (25 ft) of hydrostatic pressure.

The wet method is often used for deep-water placement (over 30 m). However, there is a serious concern with the wet method: concrete usually pushes the pig out of the pipe at a high speed. The rapid ejection of water in front of the plug causes violent disturbances in water, resulting in erosion and scour of the soil or already placed concrete at the tip of the pipe. To avoid the excessive disturbance to any already placed concrete, the concrete specifications usually prohibit using the pig method to restart concrete placement. In the past, however, a wire line had been connected to the plug to control the lowering speed of the pig.

In comparing the two techniques, the dry method is a relatively more reliable way to establish the initial seal under almost all circumstances, while the wet method usually cannot be used to restart the placement.

Tremie layout

Concrete placement schemes cover a wide range of activities, including the tremie layout, the placement sequence, and the placement rate. In the planning stage, consideration must be given to the synergy of all the important variables. Failure to recognize the intricate relations among these variables can result in costly consequences.

When tremie placement involves a large area, the layout of the tremie pipes and sequence of the concrete placement are important considerations. The layout and spacing of tremie pipes generally depend on the allowable concrete flow distance and the placement sequence.

The allowable concrete flow distance is the distance that concrete may flow without any significant degradation of concrete properties. Specifications usually limit the spacing of tremie pipes so as to limit the maximum allowable flow distance of tremie concrete. From the historical perspective, many concrete specifications limited the concrete flow distance to 4.6 to 6 m (15 to 20 ft). For example, EM 1110-2-2000 requires that "spacing of tremie pipes should not exceed 15 ft." Although the specified limit is justified for conventional concrete, it is important to recognize that the allowable flow distance is also highly dependent on the rheology of the concrete. Modern concrete mixtures containing proper cementitious materials and chemical admixtures are inherently more flowable and cohesive than conventional concrete. Field observations indicate that properly proportioned underwater mixtures can flow much farther without excessive segregation, laitance, and other adverse effects (Gerwick, Holland, and Komendant 1981; Brunner 1975[1]). For example, tremie concrete for the cofferdam seal of the Uniontown dam flowed over 9 m (30 ft). In the construction of the I-205 Columbia bridge

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[1] G. A. Brunner. (1975). "Tremie concrete placement at the Uniontown Dam, Kentucky," U.S. Army Engineer District, Louisville, KY.

foundation, the tremie concrete flowed over 21 m (70 ft). In both cases, cores were taken at the extreme end of the tremie flow. The tremie concrete was shown to have excellent quality. Based upon recent experience, the authors conclude that specification of a 9- to 14-m (30- to 45-ft) allowable flow distance is well justified for modern underwater concrete mixtures.

Other factors affecting the allowable flow distance are the rate of placement and the thickness of the tremie placement. When the placement rate is high, the flow distance can be increased. When the tremie placement is deep, the spacing of the tremie pipes can usually be increased.

Tremie placement sequence

Planning a tremie placement sequence must be based upon the size and geometry of the placement area, the available concrete production and delivery capabilities, and the concrete mixture properties.

There are two basic schemes to sequence a tremie placement. The first scheme is to feed concrete into several tremie pipes at about the same time. Thus, the concrete rises everywhere at approximately the same rate. In this case, the maximum concrete flow distance is approximately one half the tremie spacing. This placement scheme is suitable for tremie placement in small areas. For relatively large concrete placement, however, this scheme demands very high, and sometimes impractical, concrete production capacity. Furthermore, cold joints can potentially form between two adjacent tremie pours as laitance accumulates at the boundaries. A practical method is to divide a large area into several smaller areas, as shown in Figure 18. Walls of steel sheet piles and of precast concrete have both been used. Within each confined area, the simultaneous placement scheme can be applied.

The second placement scheme is the advancing slope method. In this scheme, the placement starts at one location and progressively proceeds to cover the entire area. Only after the concrete at the tremie location has risen to the required elevation and an adjacent tremie has immersed in concrete by at least 0.3 m (1 ft) will the tremie placement proceed to the adjacent tremie. The tremie concrete flows out with an advancing slope, as shown in Figure 19. The surface slope of tremie concrete usually ranges from 1:5 to 1:40, depending on the concrete flowability and the placement rate. Thus, the tremie placement advances from one end of the placement area to the other end, following an advancing slope of the tremie concrete.

The main advantage of this method is that it imposes less demand on the concrete production capability than the first scheme. In addition, the scheme facilitates the removal of laitance. As the placement progresses from one side to another, most of the laitance is pushed to the front edge of the advancing slope and eventually collects at one end of the form. Then, the top of the hardened concrete can be jetted off, and the suspended laitance is removed by air lifting or eduction. This method eliminates the potential cold joints between adjacent tremie pours.

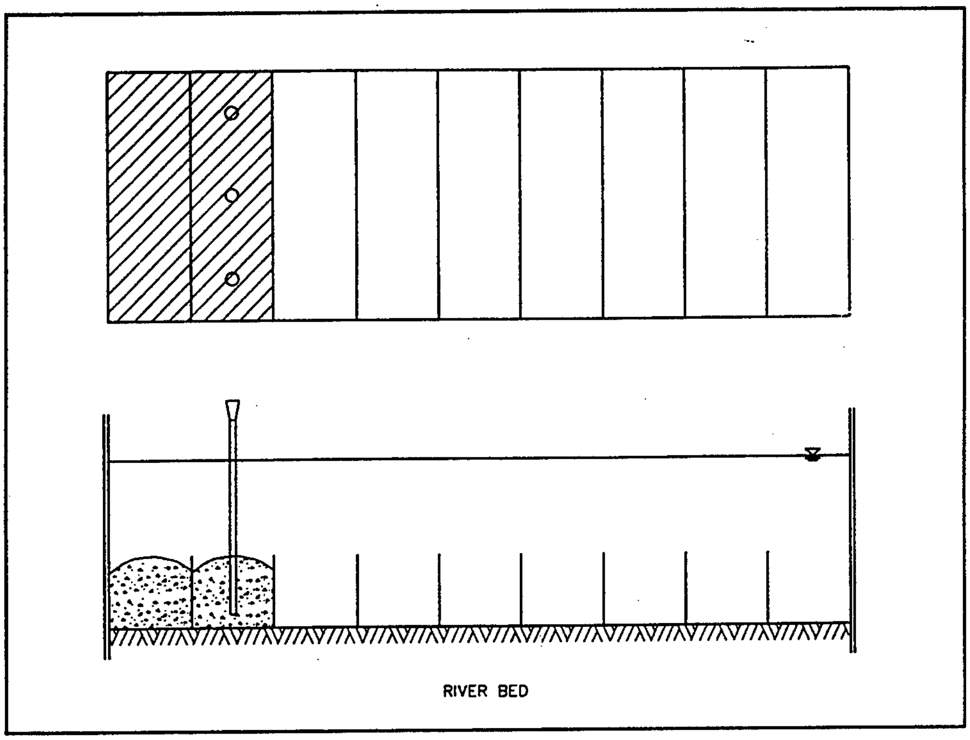

Figure 18. Simultaneous placement scheme

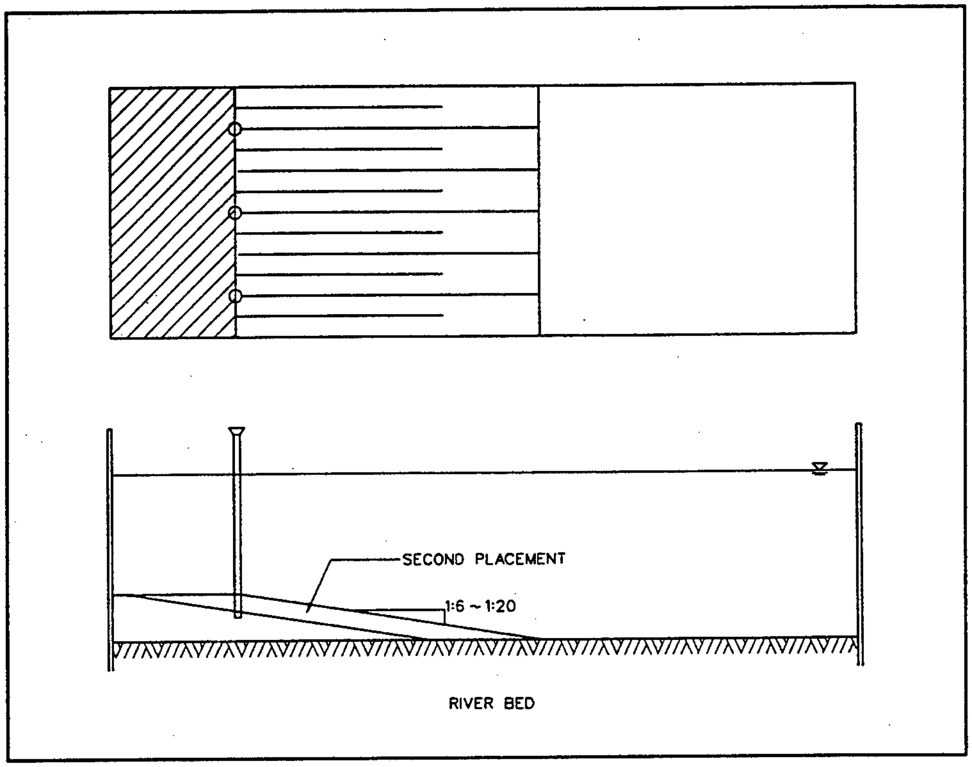

Figure 19. Advancing slope method

In some large-scale concrete placements, a combination of the simultaneous placement and the advancing slope scheme is most appropriate. Figure 20 shows that concrete is simultaneously fed into a row of tremie pipes that proceed with an advancing slope. The objective of this approach is to achieve optimum balance between the required placement rate and the concrete production capability.

Tremie placement through reinforcement

For in-the-wet construction of navigation structures, steel reinforcement is often required in the tremie concrete. Reinforcing steel can be preinstalled in the precast concrete forms. Alternatively, reinforcement can be set as a prefabricated cage. The tremie concrete placed into the reinforced form is often required to pass through the reinforcing cage without segregation or entrapping water. To satisfy this requirement, attention should be given to the layout and detailing of the reinforcement as well as the underwater concrete mixture proportions.

The arrangement of reinforcing bars should be simple, with adequate space between them. The space between rebars should be at least three times the maximum aggregate size. To facilitate the underwater concrete placement, large rebars are preferred to a large number of small bars. Bundled rebars are preferred to closely spaced single bars. Mechanical couplers are preferable to lap splices. Flowing concrete can impart a significant force on the reinforcement. It is desirable to make the reinforcement into cages that are securely fixed to the precast concrete form at multiple points.

If the tremie pipe is embedded too deeply in the concrete so that the concrete around the reinforcement has taken initial set, or if the reinforcement cage is too close to permit flow, the steel cage can be raised out of position. Steel cages have been lifted several feet by incorrect control of the placement.

Finishing and protection of tremie concrete

Tremie seals for braced cofferdams normally do not require special finishing procedures. The laitance on top of the seal placement is removed in the dry. In-the-wet construction of navigation structures often requires complete filling of the precast concrete shells with tremie concrete. A particular area requiring attention is the bond between the tremie concrete and the underside of the top slab (shown in Figure 2). Unless special measures are taken to remove the bleed water and laitance of the tremie concrete, the bond strength will be weak or air gaps may form beneath the slab. It is important to incorporate vent holes or standpipes in the design of precast shells. The underside of the overhanging slab can preferably be sloped to guide the bleed water to the vent.

Another special concern is the temporary high form pressure on the overhanging roof slab or walls. It may be necessary to provide internal support to resist the uplift. It is usually effective to extend dowels from the precast slab down into tremie concrete. The previously set tremie concrete develops anchorage for the dowels.

Recent construction experience with several major bridge foundations showed that there is a serious danger of erosion of fresh concrete by river current. Before the tremie concrete gains adequate strength, the current can erode a portion of the exposed concrete. This problem is especially pronounced with modern underwater concrete mixtures due to the prolonged delay of the set time or slow gain of the early strength. Therefore, it is recommended that positive measures be taken to protect the concrete exposed to current. Sealing the gap between the bottom of precast concrete segments and an existing riverbed can be accomplished in several ways. In the past, sandbags have been placed by divers to seal the gap. Steel skirts and protective mats are often used in offshore construction. A recent technique is to attach pleated curtains of canvas around precast concrete segments. Steel chains are sewn onto one side of the curtains as counterweights. The curtains are initially held up by fiber lines. Once the precast segments are installed, the lines are cut loose and the curtains drop to seal the gap. A more reliable technique is to use inflatable fabric bags. The bags are attached to the bottom of precast segments around the edges. Once the segments are in position, grout is pumped into the bag to inflate the bags. This method has recently been successfully used in several large projects, such as the foundation construction of the Confederation bridge in Canada.

When the tremie placement is finished, the tremie pipe will be approximately half full of concrete. If the pipe is then raised up, that concrete will progressively fall out. The concrete will consequently form a hardened mass on top of the slab unless it is promptly removed before it hardens. An alternative is to flood the tremie pipe with water and bail the concrete out of the tremie before lifting up the tremie pipe. Another alternate is to use a valve to close the tip of the tremie before lifting the pipe. In the past, however, valves have often been jammed by coarse aggregates. Further investigations into a reliable valve for tremie placement is recommended.

Underwater concrete has an excellent curing environment. Normally, no special postplacement operation is required. However, heat of hydration in mass concrete can potentially cause serious cracking. Since the thermal stresses are typically three-dimensional, it is best to design reinforcement for 3-D cracking. Although cracks may form during cooling as the heat of hydration dissipates, the cracks will be kept small and the steel will tend to close the crack once the concrete mass reaches ambient temperature. The thermal stresses can be minimized by proper mixture design, proper construction procedures, and proper form design.

Table 4 summarizes the parameters of concern and limitations of tremie operations.

Table 4
General Rules and Limitations of Tremie Operations

Parameters	Range	Comments
Concrete placement rate	To produce either a concrete surface rise of 0.2 to 0.6 m/hr (0.75 to 2 ft/hr) or a volume of 38 to 76 m^3/hr (50 to 100 yd^3/hr)	The optimum placement rate depends on the concrete mixture, the size of the tremie placement, and spacing of tremie pipes. In essence, a smooth and continuous tremie placement is important for good-quality concrete.
Tremie pipe size	8 times the nominal maximum size of aggregates	Adequate size of tremie pipe is essential in preventing plugging.
Tremie pipe spacing	3 - 11 m (10 - 35 ft)	Tremie pipe spacing depends on the concrete mixture and placement schemes. For modern concrete mixtures, allowable lateral flow distance is in the range of 9- to 14-m (30- to 45-ft).
Minimum embedment depth of tremie pipe in fresh concrete	0.6 m (2 ft)	The requirement for minimum tremie embedment is essential to preventing loss of seal and poor-quality concrete.
Minimum size of the hopper provided on top of the tremie pipe	2 m^3 (3 yd^3)	The hopper should have adequate size to facilitate transfer of concrete to the tremie pipe.
Maximum water velocity for which massive tremie concrete may be reliably placed	0.6 m/s (2 ft/s) water velocity for conventional tremie concrete mixtures, 1.8 m/s (6 ft/s) water velocity for high-performance concrete containing anti-washout admixtures	Water velocity should be limited if the fresh concrete is exposed to flow water. The allowable water velocity also depends on the size of concrete placement. The limitation should be more strict if concrete is placed in a thin layer.
Minimum spacing between reinforcing bars	3 times the nominal maximum size of aggregate	Adequate spacing between reinforcing bars is essential in ensuring smooth and continuous flow of underwater concrete.

Construction Inspection and Quality Control

Because of the poor visibility and difficult accessibility of underwater work, there is uncertainty with the quality and integrity of underwater concrete. Strict enforcement of engineering requirements and quality control is required for underwater concreting. In principle, onsite monitoring and quality control of underwater concrete placement should be mainly carried out above water. Under most circumstances, the effectiveness of divers' inspection is very limited due to the poor visibility. Divers walking on the concrete surface will create turbulance and laitance. Nevertheless, periodic inspection by divers should be made for such conditions as the seal of the precast form to the riverbed.

Five critical items should be continuously monitored throughout concrete placement: rate of concrete placement, depth of concrete at various locations, volume of concrete produced versus volume of in-place concrete measured by sounding, concrete delivery system (leakage, plug, or spillover), and embedment depth of the tremie.

Specific recommendations for quality control include the following:

a. The workers should have been properly trained and supervised full time by an experienced foreman or engineer who is familiar with the requirements for good workmanship.

b. Contractor should conduct frequent testing of concrete from batch to batch and within a batch. Important tests include slump, slump flow, unit weight, temperature, and concrete compressive strength of concrete cylinders. Commonly adopted test protocols for these tests are as follows:

  (1) Slump and slump flow test: every 23 m^3 (30 yd^3)

  (2) Temperature and unit weight: every 230 m^3 (300 yd^3)

  (3) Cylinders for strength tests: every 765 m^3 (1,000 yd^3)

c. After the concrete hardens, cores should be taken to verify the quality of the in-place concrete. Locations of the corings should be determined by the project engineer after examining the concrete placement log. Cores are often taken at locations where incidents have taken place during concrete placement, such as where a cold joint is formed due to a substantial delay of concrete placement, or possible loss of tremie seal during construction. During early stages of construction, coring is sometimes performed in order to verify the Contractor's placement procedure and workmanship. If all the tests consistently prove a high quality of in-place concrete, it may not be necessary to take additional core at later stages.

d. Continuous soundings should be taken at predetermined and well-marked locations over the entire placement areas. All sounding data should be recorded on data sheets and submitted to the project engineer at the end of each shift. A typical sounding device is a plate connected to a weighted line marked for easy reading. Alternatively, sonar depth finders can be used to constantly monitor the depth of concrete at specific locations. Underwater inspection or monitoring by divers without independent soundings is not recommended.

e. The concrete placement rate and sequence should be carefully monitored and controlled. The concrete level within the tremie should be frequently checked and compared with the sounding data. The concrete placement should ensure continuous flow of concrete.

f. The volume of concrete produced and fed into the tremie should be compared with the volume of concrete theoretically required to complete the placement as determined by soundings. If the in-place concrete volume measured by sounding is less than that produced and fed into the tremie, it is an underrun of concrete. If the in-place concrete volume is more than that fed into the tremie, it is an overrun of concrete. In general, underrun indicates a possibility of loss of concrete, possibly leaking through a skirt or cutoff wall. Overrun is indicative of serious segregation of the concrete. The segregation may be caused by a leaking joint in the tremie or loss of the tremie seal. Overrun or underrun of 3 percent or less is typical. Over 5 percent deviation should be investigated.

g. All concreting operations should be carefully monitored, including any restart and completion of concrete placement. The tremie pipe should be clearly marked to indicate the depth of the tremie tip.

h. Periodic checking of concrete delivery and placement equipment. Before using a tremie pipe, all the joints should be checked for possible leakage.

i. Adequate contingency plans should be provided in the contractor's quality assurance program. If the sounding data indicate an undesirable distribution of tremie concrete, the foreman will determine the need to adjust the placement rate or relocate the tremie according to the contingency plan.

For in-the-wet construction of navigation structures, many precast concrete shells have top slabs due to the requirement for accurate surface profile and abrasion resistance of the structures. Typical concrete shell segments are shown in Figure 1. The top slab of the segments usually takes the shape of the sill and ogee of the dam with numerous access holes. These access holes must be carefully designed in order to serve three purposes: (a) placement of concrete inside the shell, (b) venting of water and laitance, and (c) facilitating the sounding of concrete elevation during tremie placement.

The total quantity of underwater concrete required should be determined prior to placement. If the precast concrete shells are open on the bottom, a survey may be needed. During concrete placement, soundings of concrete elevation at various locations are periodically taken, say at every hour. The volume of in situ concrete can be estimated on the basis of the sounding survey. Concurrently, the quantity of concrete actually placed should be monitored to control the rate of placement. The volume of in situ concrete should be compared with that of concrete placed. Any major discrepancy between the two volumes may be an indication of operation blunder. If the discrepancy is more than 5 percent, an investigation should be made immediately to determine the source and cause.

It is also recommended that the effect of fluctuation in the surface moisture on the aggregates, as projected at the production batch plant, be quantified through trial batch tests. As a rule of thumb, a 1-percent change in surface moisture of the sand will result in variations of the slump by approximately 38 mm (1.5 in.). This problem is especially pronounced in underwater concrete, because the placeability of the concrete could have abrupt variations from batch to batch even with the calibration of moisture meters. Fortunately, however, proper use of AWA and high-range water-reducer can substantially reduce the sensitivity of concrete to moisture variation. The construction specifications should require uniform and stable moisture content of the sand with an acceptable tolerance to onsite variations.

Basis for Guidelines of Underwater Concrete Specification

Concrete specification should cover at least eight key elements that contribute to the success of underwater concreting:

a. Performance requirements of the concrete mixture.

b. Quality of the concrete mixture components.

c. Handling, storage, and testing of concrete mixture components.

d. Batching, mixing, and transportation of the concrete.

e. Equipment.

f. Concrete placement procedures.

g. Curing and protection of fresh concrete.

h. Quality control.

In general, specification for underwater concrete should conform to the requirements of EM 1110-2-2000 (Headquarters, Department of the Army 1994). Only special items pertaining to large-scale underwater concrete construction are discussed in this section.

The following sections provide the key specification items pertaining to massive underwater concrete construction of navigation structures. General specification items are omitted. Readers are referred to standard specification guidelines such as EM 1110-2-2000 for general information.

Typical performance requirements of concrete mixtures are given below. (A range of suggested target values is shown in parentheses.)

a. Slump (180 to 280 mm or 7 to 11 in.).

b. Slump flow (310 to 710 mm or 12 to 28 in.).

c. Slump retention (20 percent slump loss in 60 min).

d. Bleeding (<0.1 to 2 percent).

e. Antiwashout property (<6 to 12 percent per CRD-C 61-89A).

f. Time of the set (>4 hr, <18 hr).

g. Adiabatic temperature rise (21.1 °C (<70 °F)).

h. Strength (greater than the design strength of concrete).

i. Bond strength between underwater concrete and precast concrete form (greater than tensile strength of underwater concrete).

j. Creep.

k. Abrasion resistance, if concrete will be permanently exposed to river currents.

Prior to concrete construction, a comprehensive plan of concrete production, placement, and quality control shall be developed by the contractor and approved by the engineer. The plan shall include descriptions and supporting calculations pertaining to the following items:

a. Concrete mixture proportions (if requested), and the test data showing their compliance with the specification.

b. Concrete delivery system and placement plan with detailed placement schedules and the system capacities. The validity of the systems shall be supported by the calculation of concrete placement rate and concrete delivery capacity. The systems shall be shown to meet the specified placement rate.

c. Equipment for production, transportation, and placement of concrete.

d. Plan and details of placing, positioning, and supporting reinforcement, if any.

e. The methods and equipment for sounding underwater concrete.

f. A contingency plan to deal with foreseeable incidents and breakdown, such as accidental discharge of concrete in water and blockage of the tremie pipe.

For placing concrete containing aggregates greater than 9.5 mm (3/8 in.), only the tremie method shall be used. The tremie method is defined as placement of underwater concrete through a tremie pipe by means of gravity flow.

The tremie shall be of heavy-gauge steel pipe with an inside diameter equal to or greater than eight times the nominal maximum size of aggregates. The tremie pipe shall be marked to allow determination of depth to the tremie mouth.

The tremie shall be a straight pipe of uniform diameter and smooth internal wall surface. Under no circumstance shall the tremie be sharply bent to accommodate concrete placement. All splices shall be flush on the inside.

Joints between tremie pipe sections shall be gasketed and bolted so as to be watertight through the tremie placement.

A hopper or funnel with a size of at least 2 m^3 (3 yd^3) capacity shall be provided on top of the tremie to facilitate transfer of concrete.

An adequate supply of extra end plates and gaskets shall be provided to allow resealing of the tremie, if necessary.

The tremie and hopper shall be supported on a stable frame or platform to keep a vertical position and to prevent horizontal movement. A power hoist shall be provided to raise the tremie pipe in a controlled manner.

A crane or other lift equipment shall be available at the site for complete removal of tremie for the purpose of resealing or relocation.

The method selected for transporting concrete shall ensure delivery without segregation, excessive delay, or excessive temperature change. Pumpline for horizontal delivery should be insulated and, in hot climates, painted with reflective paint. Similarly, conveyer belts should be covered and insulated and/or painted.

After the introduction of mixing water to concrete, no retempering of the concrete mixture shall be permitted without the engineer's approval.

Tremie placement shall be a continuous operation uninterrupted until completion, if possible.

The placement rate shall be controlled by the rate of concrete delivered to the tremie hopper. Vertical movement of the tremie shall be carefully controlled to prevent loss of seal.

Throughout tremie placement, the tip of the tremie shall remain embedded in the fresh concrete at least 0.6 m (2 ft) at all times. At no time shall concrete be allowed to fall through the water or slurry.

The spacing of tremie pipes and sequence of the placement shall meet the specification requirement of the maximum allowable horizontal distance of concrete flow.

The starting point of the tremie placement shall be at the lowest point in elevation within the confines of the placement.

During the placement, the tremie shall be relocated in accordance with the placement plan and on the basis of the concrete flow as indicated by soundings.

For massive concrete placement, the tremie shall not be moved horizontally. To relocate, the tremie shall be lifted from the water, resealed, relocated, and restarted.

If the tremie loses the seal due to any reason, placement shall be halted immediately and the tremie shall be removed, resealed, and restarted.

The wet method, i.e., the "pig" or "go-devils" method, shall not be used to restart a concrete placement. The tremie or pumpline shall be resealed in the dry and reinserted into the fresh concrete to restart the placement. Restarting the tremie placement shall follow the standard procedure as specified below:

a. Lift the tremie pipe out of water and tie on an end plate with gasket.

b. Position the pipe at the placement location. Then, lower the pipe to seat the tip through the fresh concrete to rest on the bottom.

c. Start placement with 0.4 m^3 (0.5 yd^3) grout and fill the tremie up to 40 percent of water depth.

d. Lift the tremie off the bottom by 150 mm (6 in.) and continue the placement.

At completion of the concrete placement, exposed laitance shall be green-cut after concrete has set.

4 Conclusions

For in-the-wet construction of navigation structures, underwater concrete construction is a critical component of the entire project. It is technically demanding, is usually on the critical path of the project schedule, and involves complex construction logistics. This is the area where sound design and competent construction planning can achieve a meaningful reduction in risk and cost.

Past experience shows that underwater concrete construction can be accomplished with the same degree of reliability as above-water construction. However, if it is not carried out properly, with the proper concrete mixture and placement procedure, underwater construction can result in a major overrun in construction cost and schedule.

The performance requirements of underwater concrete for in-the-wet construction of navigation structures have been investigated. The essential difference between underwater concrete and conventional concrete is in the workability requirements. Underwater concrete must flow laterally and compact itself under its own buoyant weight, while conventional concrete is compacted with mechanical vibration. In accordance with the requirements for concrete workability, underwater concrete mixtures can be categorized into two broad classes: the standard concrete mixture and the high-performance mixture.

This study concludes that five primary mechanisms affect the rheological behavior of concrete:

a. The free water content of the concrete.

b. Dispersion characteristics of the solid particles in the concrete.

c. Particle packing as determined by particle size distribution.

d. The amount and rate of the early hydration of C_3A.

e. The beginning of the acceleration of alite hydration.

The effects of concrete mixture variables on concrete workability were investigated. Four governing variables were identified as having the most significant effects on workability of underwater concrete:

a. Total amount and proportions of cementitious materials in concrete. The best workability and general performance are often achieved when both fly ash and slag are used to replace about 80 percent of the cement by weight.

b. Ratio of water to total fines content. The water-to-fines ratio in underwater concrete usually ranges from 0.12 to 0.17.

c. Volume ratio of coarse aggregates. For underwater concrete, this ratio usually ranges from 0.37 to 0.5.

d. Type and dosage of chemical admixtures used in the concrete.

It is emphasized that chemical admixtures should not be used to compensate for poor mixture proportions, poor materials quality, or poor construction execution. Only when the concrete proportions are optimized can chemical admixtures effectively improve the performance of concrete.

A test protocol for trial batch testing of underwater concrete is proposed. At present, there is no standard test method to determine the degree of concrete resistance to segregation under various placement conditions. Conformance with this important criterion depends on experience and observation.

For underwater construction of major civil works projects, it is insufficient to depend only on laboratory tests to verify the concrete workability. Field trial placement testing or mock-up testing should be conducted to verify the construction procedures and equipment, and to determine the important concrete properties that cannot be readily measured in the laboratory. The concrete placement method and equipment used in the testing should be the same as, or close to, those planned for the construction.

High thermal stress due to cement hydration is one of the most critical problems with massive underwater concrete construction. It is most effective to combine several techniques in a synergistic manner to control the thermal problem. The most effective techniques, with regard to both mixture proportions and construction procedures, are identified.

Laitance, bleeding, and segregation are especially detrimental to in-the-wet construction of navigation structures because the precast forms often contain a top "roof" slab. Effective techniques for minimizing laitance, bleeding, and segregation are identified.

Form pressure due to the hydrostatic pressure of underwater concrete frequently dictates, at least in part, the design of the precast form. It is concluded that design considerations for time-dependent reduction of the form pressure can be fully justified for underwater concrete, provided that the concrete placement is adequately controlled and properties of the concrete are understood. However, the rheological behavior of modern underwater concrete is significantly different from that of conventional tremie concrete. Direct applications of the design rules and experimental data made in the past may lead to unconservative design. This study proposes a new design approach that takes into account the time-dependent reduction of form pressure.

Fully immersed concrete has excellent curing conditions. If good placement procedures are followed, the long-term strength of underwater concrete should be higher than that of concrete placed in the dry.

The rate of concrete placement is a critical parameter to the quality of in-place concrete, the form pressure, and the construction planning in general. It is essential that the concrete production and delivery system be capable of producing concrete at the required placement rate. It is also essential that the necessary quantities of materials can be supplied to the batch plant at the required rate. The logistical planning should include provision for alternative or redundant supplies, provision of all the accessory items, and standby key equipment.

It is recommended that the mixing procedure and the mixing time required to produce workable concrete be determined during trial testing. In general, the mixing water should be fully mixed with the other components in concrete before water-reducing admixtures are added to the concrete. Only after the water-reducing admixtures are fully mixed should silica fume and/or AWA be added to the concrete.

The location of the concrete batch plant has a significant impact on the construction cost, logistics, and quality control. The main advantage of the offshore production is reliable control of concrete quality and the cost of operation. This production method is more likely to produce high-quality concrete, although it may increase the logistical complexity. On the other hand, while overwater transportation of concrete batched and mixed onshore can be cost effective under certain circumstances, it is critical to check and control the workability of the concrete at the site of placement.

The methods of concrete placement are investigated for in-the-wet construction of navigation structures. The investigation concludes that directly pumping concrete containing nominal maximum size aggregates greater than 10 mm (3/8 in.) through deep water is a technically flawed procedure. It involves significant risks and potentially poor concrete quality. For massive underwater concrete construction of navigation structures, the pump method should be prohibited. However, the pump method is an excellent way to deliver concrete horizontally to tremie hopper. It is also an excellent way of placing grout or flowable concrete containing NMSA less than 9.5 mm (3/8 in.).

At present, the tremie placement method is the standard way of placing high-quality concrete under water. The other placement methods are not able to reliably place high-quality underwater concrete for major structures, although they may find application in special cases.

During concrete placement, moderately deep embedment of the tremie pipe in fresh concrete improves the in-place concrete quality and reduces laitance. The optimum depth of tremie pipe embedment is that which raises the hydrostatic balance point as high as possible without affecting the desirable placement rate and without the risk of locking the tremie pipe in set concrete.

Tremie concrete placement may be initiated with either the dry method or the wet method. The dry method is the more reliable way to establish the initial seal under all circumstances. The wet method cannot be used to restart concrete placement.

Field observations indicate that properly proportioned tremie mixtures can flow much farther than commonly allowed in specifications without detrimental consequence. The study concludes that specification of a 9- to 14-m (30- to 45-ft) allowable flow distance is well justified for the modern concrete mixtures in massive concrete placement.

The placement sequence may follow the simultaneous placement method or the advancing slope method, or a combination of the two. It is essential that the placement sequence selected take into account the concrete mixture properties, rate and thickness of the concrete placement, presence of reinforcement or obstacles, availability of equipment, technical feasibility, and cost.

Due to the generally poor visibility and difficult accessibility of underwater work, engineering requirements and quality control of underwater concrete construction should be stricter than for above-water construction. In principle, onsite monitoring and quality control of underwater concrete placement should be carried out above water. The study identified five critical items that need to be continuously monitored during concrete placement:

a. Concrete mixture properties, especially slump and slump flow.

b. Rate of concrete placement.

c. Depth of concrete at various locations.

d. Volume of concrete produced versus volume of in-place concrete measured by sounding.

e. Embedment depth of the tremie pipes in fresh concrete.

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14. ABSTRACT

Major recent developments by the U.S. Army Corps of Engineers in the underwater construction of locks and dams include the "in-the-wet" or "offsite prefabricated" construction method. This method uses precast concrete modules as the in situ form into which concrete is placed directly underwater without use of a cofferdam. The underwater concrete is designed to work in composite with the precast concrete.

In-depth studies have shown that in-the-wet construction will lead to substantial savings in cost and construction time, in addition to minimizing the effect on river traffic during construction and substantially reducing or eliminating the impact on navigation during rehabilitation.

Many outstanding examples exist of high-quality concrete placed underwater. However, a significant number of failures have occurred which have resulted in excessive cost overruns and delays. Due in large part to improper concrete mixtures and improper placement techniques, these failures might have been prevented if state-of-the-art underwater concrete technology had been more widely disseminated among engineers and contractors.

This report focuses on the basic performance requirements of underwater concrete materials, with emphasis on practical construction issues for in-the-wet construction of navigation structures. Latter portions of the report address underwater concrete construction procedures. A general checklist for underwater concrete specifications is provided.

15. SUBJECT TERMS

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Navigation structures
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Tremie concrete
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