15

Specialized Construction Applications

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15.1 Introduction

Specialized construction applications are considered to be those that contain materials that are not routinely used in conventional structural or mass concrete (ACI 116R, 1990), those that are not proportioned using procedures given in the American Concrete Institute Standard Practice 211.1 (ACI 211.1, 1991), or those that are placed with equipment or by methods that require additional attention from the contractor to ensure the required quality is achieved. The techniques of mixing, batching, transporting, consolidating, protecting, and placing concrete have drastically changed during the past few decades. The reasons for these drastic changes include the following:

- Owners demanded that cost escalation of new construction must be kept under control.
- These demands required the development of accelerated construction techniques and new materials.
- Governmental agencies initiated regulations that required better protection of the environment.
- Construction had to be accomplished with fewer workers; consequently, new techniques being developed had to use innovative equipment and materials.

Some of the more successful specialized construction techniques, primarily relating to the use of hydraulic-cement concrete, that are covered in this chapter include:

- Preplaced-aggregate concrete
- Underwater concreting
- Conveying concrete by pumping
- Vacuum processing
- Cement mortar and plastering
- Self-consolidating concrete (SCC)
- Mass concrete
- Roller-compacted concrete (RCC)

Research has resulted in many new types of equipment, materials, admixtures, and improvements in older types, thereby permitting concrete construction to be accomplished more quickly and, consequently, more economically, with better control and superior quality. The use of admixtures, both mineral and chemical, has greatly expanded the utilization of concrete in new construction techniques, has extended the life of freshly mixed concrete for as long as the user desires, and has allowed concrete to be dropped through water without segregating or separating. Admixtures have allowed concrete to be used in corrosive environments without corrosion of the reinforcing steel and to be used in freezing and thawing environments without the previously experienced rapid deterioration. They have also allowed concrete to attain much greater compressive strength with higher moduli of elasticity for use in high-rise concrete structures. These vastly improved capabilities have been accomplished to keep hydraulic-cement concrete competitive as a primary construction material. This competitiveness has to be maintained for concrete to remain the most cost-effective construction material in the world. Without the progress of concrete technology, the industry will flounder and more exotic construction materials will be developed as alternatives.

15.2 Preplaced-Aggregate Concrete

15.2.1 General

Preplaced-aggregate concrete (PA) (ACI 116R, 1990) is concrete produced by placing coarse aggregate in a form and later injecting a hydraulic cement, sand, and fly-ash grout, usually with chemical admixtures, to fill the voids. Smaller-size coarse aggregate (less than 1/2 in.) is not used in the mixture to facilitate grout injection (ASTM C 926, 2006). Much of the information presented on preplaced-aggregate concrete has been taken from the U.S. Army Corps of Engineers' *Standard Practice for Concrete for Civil Works Structures* (U.S. Army Corps of Engineers, 1994).

One of the primary advantages claimed for PA concrete is that it can easily be placed in locations where conventional concrete would be extremely difficult to place. The primary use of PA concrete is in the repair of existing concrete structures. PA concrete may be particularly suitable for underwater construction, for placements in areas with closely spaced reinforcing steel and cavities where overhead contact is necessary, and in areas where low-volume change of the hardened concrete is desired. PA differs from conventional concrete in that it contains a higher percentage of coarse aggregate, as the coarse aggregate is placed directly into the forms, with coarse aggregate having point-to-point contact rather than being contained in a flowable plastic mixture.

Hardened PA concrete properties are greatly dependent on the properties of the coarse aggregate. Drying shrinkage of PA concrete may be less than 50% that of conventional concrete, which partially accounts for the excellent bond between PA concrete and existing roughened concrete. The compressive strength of PA concrete is dependent on the quality, proportioning, and handling of materials but is generally comparable to that achieved with conventional concrete. The frost resistance of PA concrete is also comparable to conventional air-entrained concrete, assuming that the grout mixture has air content, as determined by ASTM C 231 (2004), of approximately 9%.

Preplaced-aggregate concrete may be particularly applicable to underwater repair of old structures and new underwater construction where dewatering may be difficult, expensive, or impractical. Bridge piers and abutments are typical of applications for underwater PA concrete construction or repair. ACI 304R (1989) provides an excellent discussion of PA concrete.

15.2.2 Applications

Preplaced-aggregate concrete has been used successfully on various types of projects, including those in the following construction categories:

- Underwater construction of and/or repair of bridge piers
- Resurfacing of lock chambers and guide walls
- Massive fills in permanent sheet-piling piers and cofferdams
- Construction of atomic-reactor shields
- Resurfacing of dam spillways

Preplaced-aggregate concrete is not used frequently, perhaps due to concern on the part of the construction industry that the technology exceeds the industry's normal capabilities; however, successful PA projects can be accomplished by any construction entity that has a knowledgeable concrete technologist on staff.

15.2.3 Materials and Proportioning

Intrusion grout mixtures should be proportioned in accordance with ASTM C 938 (2002) to obtain the specified consistency, air content, and compressive strength. The grout mixture should also be proportioned such that the maximum water/cement ratio complies with the same ratio that conventional concrete would be required to have for the same environmental exposure and placing requirements. Compressive-strength specimens should be made in accordance with ASTM C 943 (2002). Compressive-strength testing of the grout alone should not be used to estimate the PA concrete strength because it does not reveal the weakening effect of bleeding; however, such testing may provide useful information on the potential suitability of grout mixtures.

The ratio of cementitious materials to fine aggregate will usually range from about 1 for structural preplaced-aggregate concrete to 0.67 for massive concrete sections. A grout fluidifier meeting the requirements of ASTM C 937 (2002) is commonly used in the intrusion grout mixtures to offset bleeding, to reduce the water/cement ratio while still providing a given consistency, and to retard stiffening so handling times can be extended. Grout fluidifiers typically contain a water-reducing additive or admixture, a suspending agent, aluminum powder, and a chemical buffer to ensure timed reaction of the aluminum powder with the alkalis in the hydraulic cement.

Products proposed for use as fluidifiers that have no prior record of successful use in PA concrete can normally be accepted based on successful field use. ASTM C 937 (2002) requires that intrusion grout, made as prescribed for acceptance testing of fluidifiers, have an expansion within certain specified limits that may be dependent on the alkali content of the cement used in the test. Experience has shown, however, that because of differences in mixing time and other factors, expansion of the field-mixed grout ordinarily will range from 3 to 5%. If, under field conditions, expansion of less than 2% or more than 6% occurs, adjustments to the fluidifier should be made to bring the expansion to within these limits. The fluidifier should be tested under field conditions with job materials and equipment as soon as practicable so sufficient time is available to make adjustments to the fluidifier, if necessary. If the aggregates are potentially reactive, the total alkali content of the hydraulic cement plus fluidifier added to increase expansion should not exceed 0.60%, calculated as equivalent sodium oxide by mass of cement. The grout submitted for use may exhibit excess bleeding if the ratio of its cementitious material to fine aggregates is different from that of the grout mixture used to evaluate the fluidifier. Expansion of the grout should exceed bleeding, as desired, at the expected in-place temperature. Grouts should be placed in an environment where the temperature will rise above 40°F, as expansion caused by the fluidifier ceases at temperatures below 40°F.

This condition is normally readily obtainable when preplaced-aggregate concrete is placed in massive sections or placements are enclosed by timber forms. When an air-entraining admixture is used in the PA concrete, adjustments in the grout mixture proportions may be necessary to compensate for the significant strength reduction caused by the combined effects of entrained air and the hydrogen generated by the aluminum powder in the fluidifier; however, these adjustments must not reduce the air content of the mixture to a level that compromises its frost resistance. The largest practical nominal maximum size aggregate (NMSA) should be used to increase the economy of the PA concrete. A 1.5-in. NMSA will typically be used in most PA concrete, although provisions are made for the use of 3-in. NMSA when it is considered appropriate. It is not expected that many situations will arise where the use of aggregate larger than 2 in. will be practical and economical. Pozzolan is usually specified to increase flowability of the grout.

15.2.4 Preplacing Aggregate

Because excessive breakage and objectionable segregation are to be avoided, it is necessary to preplace the coarse aggregate in the placement with extreme care. The difficulties are magnified as the nominal maximum size of the aggregate increases, particularly when two or more sizes are blended; therefore, proposed methods of placing aggregate should be carefully established to ensure that satisfactory results will be attained. Coarse aggregate must be prewashed, screened, and saturated immediately prior to placement to remove dust and dirt and to eliminate coatings and undersized particles. Washing aggregate in forms should never be permitted because fines may accumulate at the bottom.

15.2.5 Contaminated Water

Contaminated water is a matter of concern when PA concrete is placed underwater. Contaminants present in the water may coat the aggregate and adversely affect setting of the cement or bonding of the mortar to the coarse aggregate. If contaminants in the water are suspected, the water should be tested before construction begins. If contaminants are present in such quantity or of such character that the harmful effects cannot be eliminated or controlled, or if the construction schedule imposes a long delay between aggregate placement and grout injection, then PA concrete should not be used.

15.2.6 Preparation of Underwater Foundation

The cleanup of foundations in underwater construction when the foundation material is glacial till or similar material is always difficult. The difficulty develops when, as a result of prior operations, an appreciable quantity of loose, fine material is left on the foundation or in heavy suspension just above the foundation. The fine material is displaced upward into the aggregate as it is being placed. The dispersed fine material coats the aggregate or settles and becomes concentrated in void spaces in the aggregate just above the foundation, thus precluding proper intrusion and bond. Care must therefore be exercised to ensure that as much loose, fine material is removed as possible before placement of the aggregate.

15.2.7 Pumping

Pumping of grout should be as continuous as practical; however, minor stoppages are permissible and ordinarily will not present any difficulties when proper precautions are taken to avoid plugging of grout lines. The rate of grout rise within the aggregate should be controlled to eliminate cascading of grout and to avoid form pressures greater than those for which the forms were designed. For a particular application, the grout injection rate will depend on form configuration, aggregate grading, and grout fluidity.

15.2.8 Joint Construction

A cold joint is formed in PA concrete when pumping is stopped for longer than the time it takes for the grout to harden. When delays in grouting occur, the insert pipes should be pulled to just above the grout surface before the grout stiffens and then rodded clear. When pumping is ready to resume, the pipes should be worked back to near contact with the hardened grout surface, and then pumping should be resumed slowly for a few minutes. Construction joints are formed similarly by stopping grout rise approximately 12 in. below the aggregate surface. Care must be taken to prevent dirt and debris from collecting on the aggregate surface or filtering down to the grout surface.

15.2.9 Grouting Procedure

The two patterns for grout injection are the horizontal layer and the advancing slope. Regardless of the system used, grouting should start from the lowest point in the form.

- *Horizontal layer.* In this method, grout is injected through an insert pipe that raises the grout until it flows from the next insert hole, 3 to 4 ft above the point of injection. Grout is then injected into the next horizontally adjacent hole, 4 or 5 ft away, and the procedure is repeated sequentially around the member until a layer of coarse aggregate is grouted. Successive layers of aggregate are grouted until all aggregate in the form has been grouted.
- *Advancing slope.* The horizontal-layer method is not practical for construction of slabs having large horizontal dimensions. In such situations, it becomes necessary to use an advancing-slope method of injecting grout. In this method, intrusion is begun at one end of the form and pumping is continued until the grout emerges on the top of the aggregate for the full width of the form and assumes a slope that is advanced and maintained by pumping grout through successive rows of intrusion pipes until the entire mass is grouted. In advancing the slope, the pumping pattern is begun first in the row of holes nearest the toe of the slope and continued row by row up the slope (opposite to the direction of advance of slope) to the final row of pipes. This process is repeated, moving ahead one row of pipes at a time as the intrusion is completed.
- *Grout insert pipes and sounding devices.* The number, location, and arrangement of grout insert pipes will depend on the size and shape of the work being constructed. For most work, grout insert pipes will consist of pipes arranged vertically and at various inclinations to suit the configurations of the work. Grout pipes are generally either 3/4, 1, or 1-1/2 in. Normally, either a 3/4- or 1-in. diameter would be necessary for structural concrete having a maximum size aggregate of 1-1/2 in. or less. If the preplaced aggregate has a maximum size larger than 1-1/2 in., then the grout insert pipes should have a diameter of 1-1/2 in.

Intrusion points should be spaced about 6 ft apart; however, spacing wider than 6 ft may be permissible under some circumstances, and spacing closer than 6 ft will be necessary in some situations. Normally, one sounding device should be provided for every four intrusion points, but fewer sounding devices may be permissible under some circumstances. There should always be enough sounding devices, and these should be so arranged that the level of the grout at all locations can be accurately determined at all times during construction. Accurate knowledge of the grout level is essential to accomplish the following tasks:

- Check the rate of intrusion.
- Avoid getting the grout too close to the level of the top of the aggregate when placement of the aggregate and intrusion are progressing simultaneously.
- Avoid damage to the work that would occur if a plugged intrusion line was washed out while the end of the line was within the grout zone.

Sounding devices usually consist of wells (slotted pipes) through which the level of the grout maybe readily and accurately determined. If sounding devices other than wells are considered, conclusive demonstrations should be performed to verify that such devices will readily and accurately indicate the level of the grout at all times.

15.2.10 Finishing Unformed Surfaces

If a screeded or troweled finish is required, the grout should be brought up to flood the aggregate surface, and any diluted grout should be removed. A thin layer of pea gravel or 3/8- to 1/2-in. crushed stone should then be worked into the surface by raking and tamping. After the surface has stiffened sufficiently, it may be finished as required. A finished surface may also be obtained on PA concrete by adding a bonded layer of conventional concrete of the prescribed thickness to the surface. The surface should be adequately prepared prior to applying the topping.

15.3 Underwater Concrete

15.3.1 General

(See ASTM C 150, 2007; ASTM C 231, 2004; ASTM C 943-02, 2002.) Until recently, underwater concreting was defined as tremie concrete only, but now, due to research in the use of admixtures, new procedures have been developed so freshly mixed concrete can now be placed by dropping it through water without the use of a tremie. Although this system is discussed here, it is recommended that, unless absolutely necessary, the concrete should be deposited through a tremie or possibly a pump line.

Placement of concrete underwater requires conveying freshly mixed concrete from the surface of a liquid environment to a location underneath that surface in such a way that the concrete is not damaged by segregation or separation. During administration of the U.S. Army Corps of Engineers' Repair, Evaluation, Maintenance and Rehabilitation (REMR) research program (Scanlon et al., 1983), it was discovered that the cost of dewatering an underwater area to be repaired increased the cost of the repair by 100% when compared to making the same repair in dry conditions.

Generally, many organizations avoid placing concrete underwater, as the probability of major problems occurring is excessive. Also, many owners desire to actually see the concrete that has been placed so they have a better understanding of the appearance and quality. Underwater concreting normally cannot be observed due to the water. Underwater concreting can be a very successful operation, but it is absolutely necessary for the contractor to pay close attention to details.

At times it is physically or economically impracticable to expose a foundation prior to concrete placement. At such times, suitable underwater placing procedures such as pumping or use of tremies or special concrete buckets should be employed. Research has provided techniques for placing freshly mixed concrete through water without the use of a pump line, tremie, or bucket, and innovative antiwashout chemical admixtures have been developed that permit freshly mixed concrete to be dropped through water without segregation or separation (see Figure 15.1). Although these are proprietary admixtures, practically all of the chemical admixture companies provide versions to the industry.

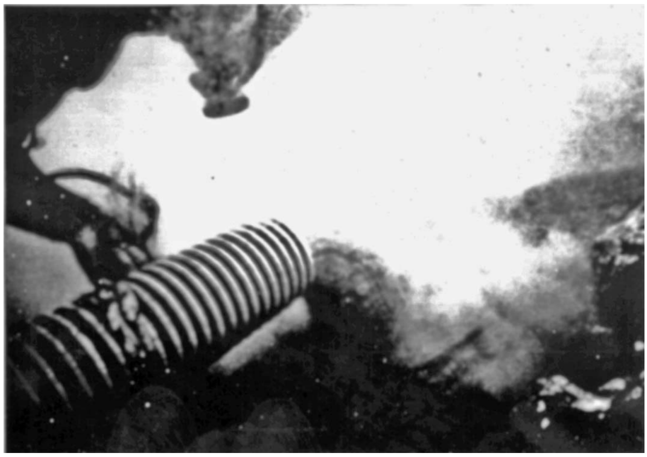

FIGURE 15.1 Clearness of underwater concreting.

15.3.2 Structures Conducive to Underwater Placement

Underwater concreting is appropriate for all types of structures: massive sections, walls, slabs, foundations, piers, caissons, stilling basins, cofferdams, conduits, and many others. It is obvious that underwater concreting is most advantageous for relatively large structures such as bridge piers, cofferdams, thick walls, and large foundations. In this chapter, we discuss the use of tremies, buckets, pumps, aqua valves, and, of course, antiwashout admixtures.

15.3.3 Available Methods

Use of the tremie is currently the most often utilized technique for placing concrete under water. A tremie is defined by the American Concrete Institute in ACI 116R (1990) as a pipe or tube through which concrete is deposited under water, having at its upper end a hopper for filling and a bail for moving the assemblage, as shown in Figure 15.2. Underwater bucket placing consists of lowering a special bucket

FIGURE 15.2 Tremie concreting operation.

containing freshly mixed concrete to the bottom of the foundation and opening the bucket slowly to permit the concrete to flow out gently without causing turbulence or mixing with the water. One of the most troublesome problems associated with using a tremie is controlling the head pressure on concrete in the tremie pipe so the pipe does not empty itself too quickly and allow water to enter the pipe from the bottom. Fortunately, a concrete pump can be used to overcome this problem. A concrete pump permits the pump line to remain full at all times, and the end of the pump line can remain very deep in the fresh concrete, preventing the intrusion of water into the pump line. We will now discuss underwater placement techniques in greater detail.

15.3.4 Bucket Placement

The buckets used for underwater placement of freshly mixed concrete should have drop-bottom or roller-gate openings. The gates should be able to be opened from above water. If air is used to open the bucket, the air should discharge through a line to the surface to prevent water disturbance. The top of the bucket must be covered to prevent water from washing the surface of the freshly mixed concrete. One way is to cover the top with canvas or plastic sheets; the covering should be as watertight as possible. Special buckets designed for the underwater placement of concrete have sloping tops that minimize the water surge. The first bucket of concrete should be slowly lowered to the bottom of the foundation and allowed to rest on the bottom. The gates should be opened slowly to permit the concrete to flow out gently, without causing turbulence or mixing with the water. Additional buckets should land on the previously placed concrete and slightly penetrate the surface so opening the gates and releasing the fresh concrete will result in even less turbulence. The operation is continued until all of the concrete has been placed. An example of concrete placed underwater with buckets is the foundation for the San Francisco–Oakland Bay Bridge, which has a 240-ft-deep foundation.

15.3.5 Tremie

The tremie process is the underwater placing technique used most frequently by contractors. Figure 15.2 depicts a conveyor being used to feed concrete to the tremie hopper for distribution down the tremie pipe in a massive placement. The tremie consists of a vertical pipe through which concrete is placed. The concrete flows from the bottom of the tremie pipe. After the original placement, the end of the tremie pipe is kept submerged in the fresh concrete at all times. The first concrete placed is the concrete that will most likely end up on top of the placement in small-diameter placements. It has been observed that, in a 36-in. caisson, the first cubic yard of grout placed ends up on top of the placement and then is allowed to overflow the top of the caisson until the caisson is filled with concrete. This assures the contractor that there will be no voids in the placement, and when the tremie pipe is removed slowly a good job is almost guaranteed. The discharge end of the pipe should always remain buried in the freshly placed concrete after the initial placement. A tremie pipe should be made of heavy-gauge steel to withstand all stresses induced by the handling operation. The pipes should have a diameter large enough to ensure that aggregate bridging will not occur. Normally, pipes should be between 8 and 12 in. in diameter for concrete containing up to 2 in. NMSA. Pipe sections in increments of 10 ft should be used; for deep placements, the tremie should be fabricated in sections with joints that permit the upper sections to be removed as the placement progresses; otherwise, the hopper will become too elevated for efficient discharge from a ready-mix truck. The joints between sections of pipe must be watertight and capable of being disconnected rapidly so no major interruptions occur during placement of the concrete.

15.3.6 Basic Tremie Methods

The two basic methods of initiating concrete placement when using the tremie method underwater are the **wet-pipe** and **dry-pipe** methods. The wet-pipe method refers to initiating placement with the open-ended tremie pipe on the bottom and with the pipe filled with water. To keep the concrete being delivered from being washed out by the water in the pipe, a plug or go-devil is placed at the upper level of the water in the pipe before the concrete is discharged into the tremie. When the concrete is discharged into the tremie, the plug or go-devil is between the water and the fresh concrete, preventing the fresh concrete from being washed out.

The weight of the concrete (approximately 140 lb/ft^3) pushes the water, which weighs approximately 64 lb/ft^3, down the tremie pipe. When the concrete, which has never been in contact with the water, arrives at the bottom, it pushes the plug or go-devil out of the pipe, and the concrete is deposited on the bottom of the placement. Many go-devils are designed so they are lighter than water and float to the top to be used at a later time. When the fresh concrete begins to flow from the end of the tremie, the end of the pipe should stay submerged in the concrete. Continuing to deposit fresh concrete into the tremie hopper causes the concrete to continue flowing through the pipe. The end of the tremie pipe should be kept at a depth in the freshly deposited concrete that permits the concrete to flow at a slow speed through the pipe.

If the concrete flows out of the pipe so the concrete load in the pipe is less than the water load outside the pipe, and if the pipe is not adequately embedded in the freshly placed concrete, then water may refill the pipe. This will not happen if the end of the tremie pipe is adequately embedded in the freshly placed concrete. If the crane operator holding the tremie and hopper feels that the fresh concrete is being completely discharged onto the bottom, the operator should immediately drop the pipe so it will be more deeply embedded. This may prevent the water from getting into the empty pipe. If water does not get into the empty pipe, concrete placement can continue, but if water does get into the pipe it will be necessary to restart the placement by reinserting the plug or go-devil as during initiation of the placement. An ideal tremie placement is one where the initial concrete placed is the concrete that ends up on top. This will only occur when the placement area is relatively small (say, 4 ft^2). The dry-pipe method requires a tremie pipe that is watertight, including the sectional pipe joints. In this method, a pressure-seal plate is attached to the bottom of the tremie pipe in such a way that the water pressure makes the end completely watertight and the interior of the pipe is completely empty and free of any water. Such a method requires that the walls of the pipe be heavy enough to overcome the buoyancy of the water; otherwise, it would be impossible to lower the tremie pipe to the bottom of the placement.

When the end of the tremie pipe with a pressure-seal plate is placed on the bottom, freshly mixed concrete can be introduced into the pipe. After the pipe is sufficiently filled with concrete, the pipe can be slowly raised, which releases the pressure-seal plate due to the weight of the concrete. After the initial discharge of fresh concrete on the bottom, the placement continues exactly as in the wet-pipe method. One drawback to the dry-pipe method is that the pressure-seal plate has to be left in the placement; however, it can be retrieved if a rope or cable is attached in such a way that the cable is on the outside of the tremie pipe. Another technical drawback is that, should the tremie seal be lost (water gets into the pipe), a plug or go-devil would be required to reinitiate the start of the placement.

15.3.7 Mixtures for Underwater Placements

Concrete must be proportioned for very workable concrete if it is to be placed underwater. The slump should be controlled at approximately 7 in. Normally, the hydraulic-cement content should be around seven bags per cubic yard. The maximum size aggregate should be 1-1/2 to 2 in., and the fine aggregate (fine) content should be around 45% of the total aggregate content. The concrete should be air entrained at about 6 to 7%. Any application that improves the workability of concrete should be considered. This includes pozzolans, natural aggregates in lieu of crushed stone, and use of chemical admixtures to extend the setting time and permit additional water reduction.

15.3.8 Use of Antiwashout Admixtures

(See ACI 304.1, 1995; ACI 524R, 1992; ASTM C 937, 2002; ASTM C 938, 2002; Neeley, 1988.) Many of the companies dealing with the manufacture of concrete construction materials have developed admixtures for use in concrete that permit the concrete to be placed underwater without the use of a tremie.

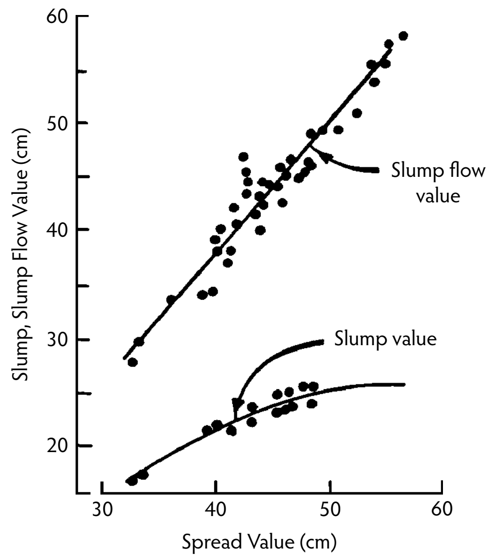

FIGURE 15.3 Relationship of slump, slump-flow value, and spread value.

These materials are referred to as *antiwashout admixtures*. Japan has been a leader in this new concrete technology, although it is believed that Japan obtained its knowledge from a product that was originally used in Germany. Figure 15.1 depicts the clearness with which concrete containing an antiwashout admixture can be discharged under water. Other terms for this type of concrete are *nondispersible concrete* and *colloidal underwater concrete*. The admixture that provides the clearness of this special concrete is known as a nondispersible underwater concrete admixture, but in the United States it is referred to as an antiwashout admixture. This innovative admixture was developed in West Germany around 1981. The admixture is intended to prevent washout of cementitious material and dispersion of aggregate during underwater placement of concrete. The admixture serves to increase the viscosity and the water retention of the concrete matrix. The antiwashout admixtures currently being marketed in Japan use cellulose or acrylic as the primary ingredient. Admixtures containing acrylic use a polyacrylamide polymer as the primary ingredient. Admixtures containing cellulose use a nonionic water-soluble cellulose ether, which has a hydroxide ion (OH) base and is almost like water. Hydroxyethylcellulose (HEC), hydroxyethylmethylcellulose (HEMC), and hydroxypropylmethylcellulose (HPMC) are among the various admixtures used. When dissolved, their viscosities differ considerably according to polymerization, molecular weight, and type of substituent. They dissolve in water rapidly when placed in a high-pH environment such as concrete. They are also not susceptible to chemical changes within concrete-like reactions, gelation, or decomposition.

15.3.9 Characteristics of Antiwashout Underwater Concrete

Antiwashout underwater concretes have slightly different properties than ordinary hydraulic cement concrete because of the effect of the admixture. Fresh antiwashout concrete can be characterized by the following properties.

15.3.9.1 Flowability

Because of the increased viscosity of antiwashout underwater concrete, the slump transformation takes place over several minutes. The slump is ultimately 8 to 10 in. To have a better understanding of the flowability of this type of concrete, a slump-flow value or a spread value determined by the German Standard DIN 1048 is more suitable than a slump value. The relationship of these values is demonstrated in Figure 15.3. Table 15.1 provides criteria for the relationship between flowability and conditions of execution.

TABLE 15.1 Criteria of Relationship Between Flowability and Conditions of Execution

Slump Flow Value (cm)	Softness	Conditions for Applications	Conditions for Execution
40	Hard consistency	When it is desired to keep the flow small, such as the execution of a slanted path	Concrete pump pressure transmission boundary
45	Medium consistency	General case	Less than 50-m concrete pump pressure transmission distance
50	Medium soft consistency	When excellent filling capability is needed	Concrete pump pressure transmission distance of 50–200 m
55	Soft consistency (plastic concrete) Supersoft consistency	When excellent flowability is especially needed, such as in reinforced concrete members of dense fiber and filler for narrow and deep supersoft consistency holes	

15.3.9.2 Air Content

Mortar and concrete mixed with cellulose ether have greatly increased air content; therefore, such antiwashout admixtures contain an air-detraining admixture to reduce the air content of the concrete to between 3 and 5%. From a petrographic standpoint, the bubble-spacing factor of concrete containing the antiwashout admixture is about the same as concrete without the admixture, but the freezing and thawing resistance tends to be somewhat low.

15.3.9.3 Bleeding

Concrete containing the antiwashout admixture retains more of the mixing water. Because the normal amount of admixture used is more than double the amount required to prevent bleeding, very little, if any, bleeding occurs in antiwashout underwater concrete. This lack of bleeding is responsible for the small reduction in quality of the concrete and increases the need for reinforcing steel.

15.3.9.4 Setting Time

The use of antiwashout cellulose admixtures affects the setting time of underwater concrete. When a cellulose antiwashout admixture is used, the setting time (ASTM C 191, 2007) is greatly extended; therefore, the antiwashout admixture contains an accelerating admixture. The most common accelerating admixture amounts are adjusted to result in a final setting time of from 5 to 12 hours. Antiwashout admixtures containing acrylic have no effect on the setting time. When an air-entraining, water-reducing admixture is added to the antiwashout admixture, the setting time is slightly extended, but the increase in setting time for the normal admixture amounts is less than 5 hours. Specialty admixtures can extend the setting time for underwater antiwashout concrete by 30 hours or more.

15.3.9.5 Underwater Dispersion Resistance

The dispersion resistance of concrete during an underwater placement operation is evaluated by such tests as the cementitious materials outflow rate, the change of water permeation rate, the turbidity of the water, the change of pH value, and the change of composition. The rate of dispersion is decreased as the quantity of antiwashout admixture in the underwater concrete is increased.

15.3.10 Characteristics of the Hardened Concrete

15.3.10.1 Compressive Strength

The relationship between the compressive strength of concrete containing no antiwashout admixture and concretes containing various amounts of cellulose antiwashout admixture is shown in Figure 15.4. Generally, the compressive strength of a test specimen fabricated in air is lowered by an increase in the

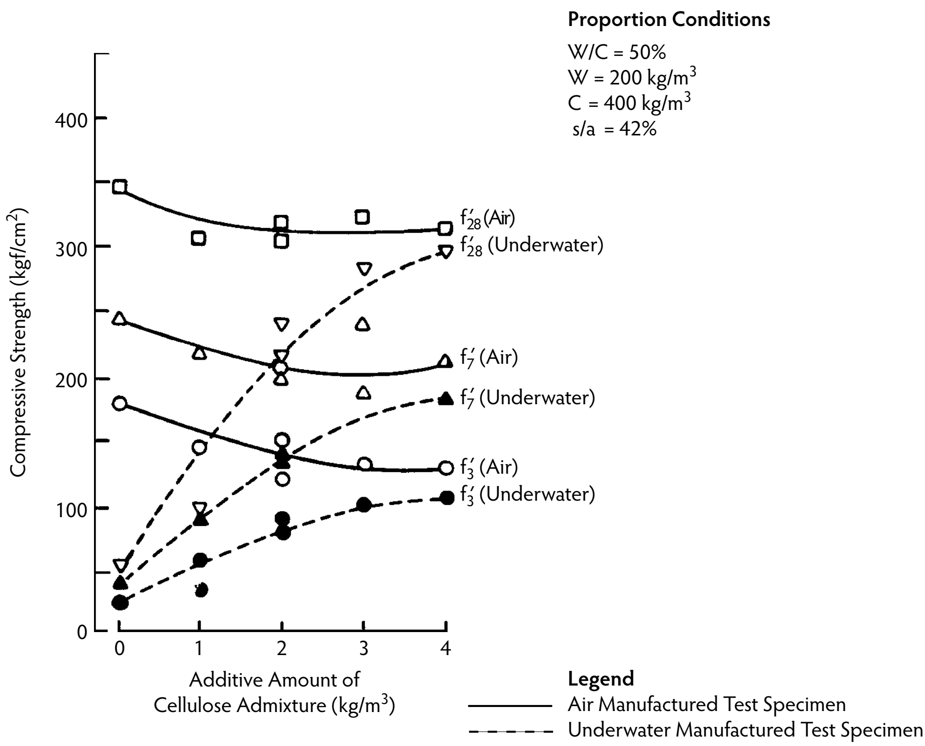

FIGURE 15.4 Relationship of quantity of cellulose admixture and concrete compressive strength.

quantity of admixture, but in some instances the compressive strength has increased slightly. Test specimens fabricated underwater are made by placing concrete into water that is 12 to 20 in. deep. The compressive strength of such specimens increases with an increase in the quantity of antiwashout admixture used; consequently, the compression strength ratio of test specimens made underwater increases compared to those made in air as the quantity of admixture increases. The amount of admixture to be used is determined by the flowability required, depth of the underwater placement, horizontal flow distance, desired water cementitious materials ratio, and, of course, the quantity of cementitious materials to be used. In general, the compressive strength ratio referenced above can be expected to range from 0.8 to 0.9.

15.3.10.2 Miscellaneous Strength and Other Characteristics

The ratio of tensile strength and flexural strength to compressive strength of an underwater fabricated test specimen is identical to that of specimens fabricated in ordinary dry concrete. The modulus of elasticity is the same or slightly less than that of ordinary concrete. The unit volume of water in antiwashout underwater concrete is much greater than that of ordinary concrete. Because water retention is so high, drying shrinkage is large at 20 to 35%. Also, creep in air appears to be somewhat greater than in ordinary concrete.

15.3.11 Characteristics of the Horizontal Flow Time of Nondispersible Underwater Concrete

Qualitative changes in antiwashout underwater concrete can be made by adding a water-reducing admixture, which causes the concrete to flow longer distances. Underwater concrete with water-reducing admixtures has been shown to have a slump flow of 50 to 60 cm, a cement content of 364 to 430 kg/m^3, and a water/cement ratio of 0.48 to 0.60. The final flow gradient was 1/125 to 1/500. Even though the

TABLE 15.2 Combinations of Antiwashout and Water-Reducing Admixtures

Antiwashout Admixtures	Water-Reducing Admixtures
Cellulose	Melamine sulfonate (triazine)
Acrylic	Naphthalene sulfonate Melamine sulfonate (triazine) Acrylic Polycarbonic acid

concrete surface was virtually horizontal, qualitative changes were recognizable when the flow distance exceeded 10 m. The area near the edge of the concrete may suffer a drop in unit weight and modulus of elasticity as well as in compressive strength because the quantity of aggregate declines. The greatest flow distance is best determined by fully considering proportions and placement conditions.

15.3.12 Principal Considerations

Because antiwashout underwater concrete has a high viscosity, the mixer load is increased by 25 to 50%, so the capability of the mixer and the quantity of materials mixed must be considered. Use of a water-reducing admixture causes a decline in dispersion resistance and some extension of the time of setting. In some instances, a specific flowability cannot be obtained by combining the water-reducing admixture and the antiwashout admixture; therefore, the types of water-reducing admixture and their recommended dosages must be considered. Table 15.2 illustrates the various combinations of types of antiwashout admixtures and water-reducing admixtures ordinarily used. Because the dispersion resistance is high, blockage will occur in pump lines only if problems are encountered within the pressure transmission tube during the pumping pressure period. Qualitative changes in the concrete should not occur before or after the pressure is transmitted. Due to high viscosity, however, pressure transmission resistance is 2 to 4 times that of ordinary concrete. It has been reported that the pressure transmission capacity of the squeeze-type pumps is inferior to that of the piston-type pumps, an aspect that must be considered.

15.3.13 Summary

Antiwashout underwater concrete is being considered for use in many underwater structures and other large-scale projects. Under current conditions, several problems remain, such as: (1) differences in performance of the more than ten kinds of admixtures currently being marketed, (2) differences in mixing methods and placement methods used by various contractors, and (3) inappropriateness of the antiwashout concrete for use in above-water structures due to its drying shrinkage and poor resistance to freezing and thawing. It is recommended, therefore, that the engineer and contractor fully understand the quality of the antiwashout underwater concrete and the procedures involved in the placement of this relatively new and innovative material.

15.4 Vacuum Processing

15.4.1 General

The ACI report 116R (1990) defines vacuum concrete as concrete from which excess water and entrapped air are extracted by a vacuum process before hardening occurs. This process is administered by applying a vacuum to formed or unformed surfaces of ordinary concrete immediately or very soon after the concrete is placed. Additional compaction of the concrete is the primary result of vacuum processing. As the water and entrapped air are removed, the mortar is subjected to consolidation; the concrete becomes denser because approximately 40% of the water close to the surface has been removed. Entrapped air is also removed, resulting in a concrete surface that is more resistant to freezing and thawing, especially if the concrete originally contained entrained air of at least 9% of the paste fraction. The air, being noncontinuous, is removed from the surface and not from the interior. The depth of water extracted and the amount of water removed depend on the coarseness of the mixture, mixture proportions, and the number of surfaces to which the vacuum is applied. The depth of water extraction can, under good conditions, extend to 12 in., and the amount of water extracted a few inches below the surface can be equal to one third of the mixing water. Removal of an average of 20% of the water down to a depth of 6 in. from the surface is common. The best results from vacuum processing occur when (1) the mixture contains a minimum amount of fines, (2) the vacuum can be applied promptly while the concrete is still plastic, and (3) the concrete near the vacuum panel can be vibrated during the first few minutes of the vacuum treatment. Vacuum procedures result in concrete with higher strength and greater durability. The Bureau of Reclamation (1992) found that vacuum processing increased the 3-day strength of one concrete from 800 psi to 1800 psi. Although vacuum processing improves the surface of hardened concretes, the improved appearance is normally not adequate justification for use of the process. Vacuum processing improves durability, but this should not be used as justification not to use air entrainment. Vacuum treatment has been used to increase the resistance of concrete surfaces to high-velocity liquid flow, but its use should not justify reduced efforts to perfect alignment of flow lines.

15.4.2 Concrete Mixtures

It is not absolutely necessary that special concrete mixtures be used when vacuum processing of the concrete surface is planned. This is not to say that slight changes in the normal mixtures should not be considered. The best results are obtained when the fines are at a minimum; in other words, vacuum processing seems to work best when the mixture is relatively lean and contains a minimum amount of fine aggregate (sand) that is on the coarse side of the grading. Sticky mixtures with an excess of fines do not respond well to vacuum treatment. The treatment is also more effective at low ambient temperatures. One of the primary goals of concrete construction is to place concrete in a uniform fashion so the finished results will be uniform. The vacuum should be applied soon after placing the concrete while the concrete is still plastic. The concrete should be highly workable, and during the first few minutes of the vacuuming process the concrete should be slightly vibrated, permitting the small channels left by the water removal to close, thus improving the watertightness.

15.4.3 Early Equipment

During early use of the vacuum process, the vacuum was applied to the concrete surface by vacuum hoses attached to special vacuum mats or form panels. The mats for unformed surfaces were usually reinforced plywood faced with two layers of screen wire covered by muslin. For unformed curved surfaces, such as the buckets of dams, flexible steel that could adapt to the curved surface was used in lieu of plywood. Sometimes, a fiberglass cloth without screen backing was used for the lining of steel forms for concrete pipe. The equipment was very cumbersome and required much preparation time. In addition, it was expensive and complicated. As a result, use of the equipment was not very inviting, and very little use was made of the process.

15.4.4 New Equipment

Vacuum equipment has since been simplified, and its use, especially in Europe, has greatly increased. The vacuum process is now being used more frequently in the United States. The panels have been replaced by vacuum pads that are flexible, light, and easy to handle (see Figure 15.5). This newer system greatly improves the handling, and the system is much more efficient and cost effective.

FIGURE 15.5 Distribution of vacuum pads on newly placed concrete slab.

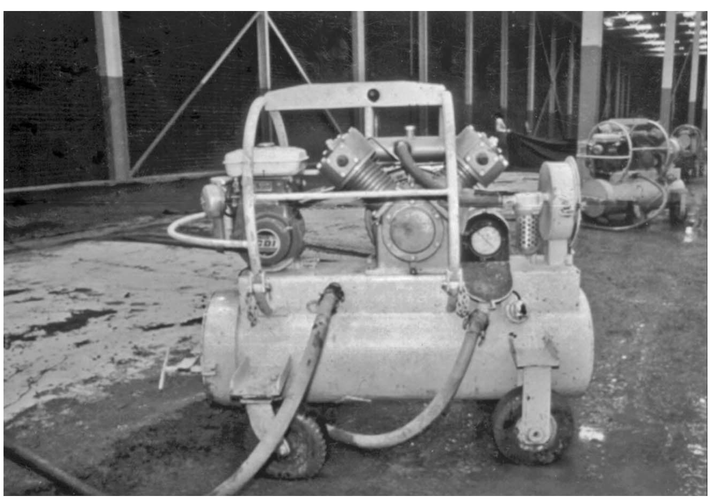

FIGURE 15.6 Vacuum pump used in vacuum processing.

15.4.5 Procedure

After the concrete slab is vibrated, the surface is immediately covered with a base filter pad and a suction mat connected to a vacuum pump. The pump (see Figure 15.6) creates a vacuum under the pad. The vacuum causes the atmospheric pressure to compress the concrete, and the water is extracted. The base pad is designed to distribute the vacuum under the entire surface evenly and permit water to pass through. The vacuum is applied for approximately 4 minutes for each inch of slab thickness. After the pads and mats are removed, the surface is normally firm enough to walk on, and finishing is then performed with specially designed, low-amplitude, high-frequency disk floats. Following finishing, the slabs are preferably cured with water, but practically any method that prevents the concrete from additional drying can be used. Because internal water has been removed from the concrete, it is best to ensure that adequate water is available for hydration of the cement; consequently, water curing is best.

15.4.6 Conclusions

For attaining a highly impervious concrete floor, vacuum processing is a viable method, but, just as for all processing methods, options such as using low water/cement ratios and adequately air-entrained concrete and incorporating proper curing and protection techniques must be considered during construction. Do not depend 100% on vacuum processing to provide the high-quality, low-permeability, smooth floor that is desired; quality concrete materials must be used, and proven mixing, transporting, placing, finishing, curing, and protection procedures also have to be followed.

15.5 Portland Cement Plaster Construction

15.5.1 General

Portland cement plaster construction, commonly referred to as *stucco*, has been around for many years, but it has normally been considered an art rather than a science. The knowledge necessary to apply Portland cement plaster was previously acquired by learning from others and not from technical literature. ACI Report 524R, *Guide to Portland Cement Plastering*, was developed in 1992. Before then, little information was available to engineers who wished to include this subject in project specifications; consequently, the U.S. Army Corps of Engineers initiated worldwide studies to identify the problems associated with defective concretes and Portland cement plaster construction.

15.5.2 Most Frequently Found Problems

During visits to the various sites around the world, numerous installations were inspected where the design and the workmanship for stucco were excellent. The recurring problems that were found can be separated into three categories:

- Questionable design
- Incomplete specifications or specifications lacking in detail
- Inadequate inspection and poor workmanship

The following general procedures must be fully considered when contemplating a Portland cement plaster construction project:

- Quality plaster is essential to any successful installation. The plaster must develop adequate tensile strength to resist imposed stress and have sufficient resiliency to accommodate expansion and contraction. Consistency in the batching operation is as important to the development of quality plaster as the ingredients and quantities.
- The most important ingredient is the aggregate. Aggregate should conform to specifications. The physical properties of aggregate that have the most pronounced effect on plaster are grading, shape and denseness of the particles, and particle surface characteristics (roughness and porosity).
- Curing procedures play a vital role in reducing shrinkage cracking by permitting the plaster to dry slowly and uniformly. Fog curing requires the application of a fine mist at intervals related to job conditions. The purpose of curing is to maintain enough water within the plaster to keep the interior relative humidity above 80% during the specified curing period.
- It is acceptable to place a second coat of plaster as soon as the first coat is strong enough to withstand the pressure of the second application. When plaster is applied to a solid backing such as block, concrete, or wire lath backed with rigid sheathing, both base coats can be applied in one day and the finish coat on the following day. Or, successive coats can be applied on consecutive days.

15.5.3 Technical Aspects of Portland Cement Plaster

The desirable properties of fresh Portland cement plaster can be summarized by the following properties:

- *The ability to stick to the particular substrate*—The primary concerns in this area relate to the influence of the aggregate, the water/cement ratio, and the absorptive characteristics of the substrate or base.
- *The ability of the fresh plaster to stick to itself*—The plaster should not sag, slough, or separate (delaminate).
- *The ability to be placed, shaped, floated, and tooled*—The plaster should already have the first two properties; plaster without these abilities is generally incorrectly proportioned or possibly incorrectly mixed.

Hardened Portland cement plaster should have excellent durability against weathering, should be highly impermeable, and should be resistant to temperature changes. Such plaster should also be highly resistant to the action of freezing and thawing. Plaster should be air entrained for better freeze–thaw resistance and better impermeability, which provides protection from acid rain and aggressive chemicals. Hardened Portland cement plaster should also be proportioned for high tensile strength. Properly proportioned plasters that have been properly cured should have acceptable tensile strength.

15.5.4 Portland Cement Plaster Materials

The cement used in Portland cement plaster may be practically any type or class of cementitious materials conforming to the various ASTM Standards, such as:

- Portland cement (ASTM C 150, 2007)
- Blended cements (ASTM C 595, 2007)
- Masonry cement (ASTM C 91, 2007)
- Plastic cement (ASTM C 926, 2006)

Should the aggregates be potentially reactive, low-alkali cements should be used, and air-entraining cements should be used, when possible. Lime conforming to the requirements of Type S, ASTM C 206 (2003) or ASTM C 207 (2006) should be used along with an air-entraining admixture when possible. Lime is necessary only when regular cement is used.

The aggregates should be either natural or manufactured fine aggregate (sand) complying with the requirements of ASTM C 897 (2005). Lightweight aggregates such as perlite or vermiculite may be used but should not be used in base courses when conventional-weight aggregate plaster is to be applied as a finish coat. Perlite or vermiculite aggregates have low resistance to freezing and thawing. Sand should be washed clean; should be free of organic matter, clay, and loam; and should be well graded.

The water used should be as good as water used in hydraulic-cement concrete. Drinking water is normally all right to use. The water should comply with the requirements of ASTM C 191 (2007) for setting time and ASTM C 109 (2007) for strength. Calcium chloride should not be used in Portland cement plaster because of the embedded metals. Should chemical admixtures be considered for use, be sure they do not contain chlorides and they are not corrosive. Accelerating admixtures that do not contain chlorides or other corrosive materials are available and could be used.

15.5.5 Proportioning

As stated earlier, Portland cement plastering (stucco) is thought of as an art and not a science. The industry does not seem to want to join the 21st century, as materials are still proportioned by shovel. Measurement of sand is accomplished by counting the number of shovels of sand per bag of cement and seven No. 2 shovels are equated to one cubic foot of sand. The quantity of water is determined by the appearance of the plaster in the mixer. Some project specifications require the use of a cone for measuring the slump; the cone is 6 in. high by 4 in. in diameter at the bottom and 2 in. in diameter at the top. Many specifications permit a slump of 1-1/2 to 3 in. for either hand- or gun-applied plaster. Plasticizers are also normally required, and again the quantity is determined by the appearance. When plastic or masonry cements are used, the addition of plasticizers is not necessary. When Portland or blended cements are used, it may be necessary to add plasticizer to up to 20% by weight of the cementitious material. Avoid sloppy and overwatered mixtures, as they tend to cause segregation and separation of materials. Proportioning Portland cement plaster drastically affects the final quality and serviceability of the hardened plaster. Proportions of the ingredients should be in accordance with project specifications, local building codes, and ASTM C 926 (2006).

15.5.6 Mixing

Experience dictates that a particular sequence for mixing should be followed: The water should be added first, followed by 50% of the sand, the cement and any admixtures, and finally the remaining 50% of the sand. Normal mixing time is approximately 3 to 10 minutes. Excessive mixing should be avoided because it could be detrimental to the quality of the plaster.

15.5.7 Bases for Plaster

Metal plaster bases come in three types. One type is woven-wire plaster base, which is fabricated galvanized steel wire that is reverse twisted into a hexagonal mesh pattern and normally comes in rolls or sheets. Expanded-metal diamond mesh lath is fabricated from coils of steel that are slit and then expanded to form a diamond pattern (chicken wire). The third type is welded-wire lath, which is fabricated from at least 15-gauge copper-bearing, cold-drawn galvanized steel wire.

15.5.8 Weather Barrier Backing

Several materials are being used as weather barrier backing, including waterproof paper or felt meeting the requirements of Federal Specifications UU-B-790, Type II, Class D. The paper should be free of holes and breaks and should weigh at least 14 lb per 108-ft^2 roll. A large number of accessories are required to obtain a proper plaster job. Accessories establish plaster grounds and transfer stresses in critical areas of plaster elements. Portland cement plaster should not be considered to be part of the load-bearing members; the plastering project should be designed so the plaster is not placed under stress. To construct a successful plaster project, all locations—corners and joints (expansion and contraction)—must contain the correct accessories to prevent the plaster from experiencing the normal stress that would occur at these locations. Special accessories are made for corners; they may be expanded flange corner beads, welded or woven wire, vinyl bead, or expanded-metal corner lath. The corner reinforcement must be designed so plaster can be applied without hollow areas. Inside corner joints must have accessories designed to provide stress relief at internal angles. Casing beads, often called *plaster stops*, should be installed wherever plaster terminates or joins a dissimilar material. Plaster screeds are used to establish the thickness of the plaster or to create decorative motifs. Ventilating screeds contain perforated webs that permit air to pass freely from the outside. Additional screeds include drip screeds that are installed on outside plaster ceilings to prevent the water that runs down the face of the structure from penetrating the plaster soffits and the ceiling. Weep screeds are normally installed at the foundation plate line and function as a plaster stop, permitting trapped moisture to escape from the space between the backing paper and the plaster.

15.5.9 Sample Panels

Sample panels or mock-ups should always be constructed, especially on large jobs where all the plastering will not be performed by one crew of plasterers. These panels or mock-ups should include examples of all joints, windows, doors, corners, and, in general, all conditions to which the plaster will be exposed.

Sample panels should be constructed until the results describe the desired quality and appearance expected of the structure. The panels should be kept close to the project so workers and supervisors can verify that the previously approved results are being obtained.

15.5.10 Surface Preparation

Concrete surfaces to which plaster will be applied should be straight, true to line, and plane. Concrete surfaces should be cleaned or roughened to increase the likelihood of a good chemical and mechanical bond. The concrete surface should be cleaned with a cleaning agent to remove most surface contaminates. Other methods of cleaning might include the use of wire brushes, hammers or chisels, water blasting, or light sandblasting.

15.5.11 Application of Plaster

Prior to beginning to apply plaster, the substrate must be prepared as described above. It is also necessary to verify that the lath and backup paper have been installed along with the necessary accessories. After the required substrate treatment has been verified, proper application procedures must be followed. The project specifications will normally require or allow the plaster to be applied by hand or by machine. When hand application is permitted, the plasterer applies the plaster to the surface using a trowel. The plasterer determines the amount of water required to obtain the desired consistency of the plaster. Plaster pumps are sometimes required for plaster application. In this case, batches of plaster are prepared in a mixer, and the individual performing the mixing operation is responsible for batching the correct quantities of cement, sand, and water. The quantity of water is determined by the mixer operator. The plaster is placed in a hopper and pumped onto the surface through a hose and nozzle. The nozzle operator controls the spray pattern by adjusting the air jet, air pressure, and nozzle orifice.

15.5.12 Types of Application

Portland cement plaster is normally applied in either two or three coats. The three coats are referred to as the *scratch coat*, *brown coat*, and *finish coat*. The scratch coat should be thick enough to result in a good bond to the substrate; on substrates containing metal laths, this coat should fully cover the lath. The scratch coat should be scored horizontally so mechanical bonding is improved. When the specification requires a delay between application of the scratch coat and the brown coat, it is necessary to cure the scratch coat by moist curing. If no delay is required, then the brown coat should be applied as soon as possible to secure a good bond. The brown coat should be applied when the scratch coat is rigid enough to receive the brown coat without cracking. The brown coat normally contains more sand than the scratch coat. The required thicknesses are established either in the local specifications or by construction codes. In some cases, the brown coat is the finish coat. Where a finish coat is specifically required, it is normally proportioned to provide a particular texture, color, or appearance. Prior to applying the finish coat, the brown coat must be moist cured for at least 2 days. Finish coats can be applied and finished in numerous aesthetically pleasing patterns. Smooth troweled surfaces are not recommended because of their tendency to crack. Finish coats must not be burnished; burnishing will almost always induce cracking. Moist curing is an absolute necessity.

15.6 Self-Consolidating Concrete (SCC)

15.6.1 Introduction

Self-compacting concrete (SCC) or self-consolidating concrete, as it is referred to by ASTM Subcommittee C09.47, can be defined as concrete that does not require compaction or vibration. Because of its high viscosity, SCC can flow freely without segregation. SCC is able to flow under its own self-weight into corners of formwork and through closely spaced reinforcement with little or no vibration or compaction.

This leads to lower energy cost, lower stress on the formwork, reduced labor costs, and elimination of potential human error in the consolidation of the concrete. The concrete becomes more consistent, as the cementitious paste and aggregates are equally dispersed. As a result, both SCC mechanical properties and durability are improved over normal or conventional concrete, and it has enjoyed increased popularity in Europe and Japan (Okamura, 1997); however, the use of SCC in the United State remains limited. Part of the reason is because of the limited knowledge and experience regarding its use, as well as its high initial cost. Nevertheless, the Federal Highway Administration (FHWA) is leading an effort to promote the use of SCC in transportation structures in the United States, and SCC has been used by several state departments of transportation, such as those in New York, New Jersey, and Virginia.

The proper use of SCC requires: (1) good understanding and knowledge of the new generation of superplasticizers and chemical admixtures, (2) control of the constituent materials and water content of the concrete, (3) familiarity with and understanding of the acceptance of fresh and hardened concrete, (4) documentation of properties and durability, (5) use and implementation of proper casting methods, (6) control of pressure on the formwork, and (7) contingency plans for repair of defects and for interrupted casting (Suksawang et al., 2005).

15.6.2 Mix Design

Fresh concrete can easily attain high flowability by simply increasing the water-to-binder (w/b) ratio; however, increasing the w/b ratio alone could lead to concrete segregation and less durability. Thus, to successfully develop SCC, mineral and chemical admixtures, such as pozzolans, limestone filler, superplasticizer, and viscosity-modifying admixtures (VMAs), must be added to the mix design to prevent segregation and enhance the durability of SCC. In addition, the absolute volume of coarse aggregates also must be limited to reduce interparticle friction and allow the SCC to flow under its self-weight without segregation (Okamura, 1997). Also, a reduction in the volume of coarse aggregate would have to be balanced by an increase in the volume of cement paste, which would result in higher material costs and an increase in the capillary pores. One solution to decreasing the paste volume is to use a VMA that reduces interparticle friction and increases flowability, so the volume of coarse aggregates could be increased. Despite this solution, concrete producers and owners still have questions regarding the use of VMAs because little information on its long-term effects and the effects of various chemical admixtures on SCC is available. An alternative solution is to use pozzolans, such as fly ash or dust powder, to replace the cement content (Persson, 2001; Zhu and Bartos, 2003). The pozzolanic materials not only reduce the cement content but also fill the capillary pores, thus making the concrete denser and increasing its durability. Moreover, some pozzolans, such as fly ash and slag, can also increase the flowability of concrete, which reduces the amount of superplasticizers required and lowers production costs. However, any decrease in the volume of coarse aggregate and any increase in the volume of cementitious paste will greatly affect the mechanical properties of SCC. Also, most of these mix designs are based on Japanese and European experiences. SCC mix designs using raw materials in the United State are limited. The cementitious materials typically consist of ordinary Portland cement (OPC), silica fume (SF), fly ash, and slag. Fine and coarse aggregates consist of river sand and crushed aggregates. The size and type of coarse aggregates influence concrete consolidation and distribution. In addition, several admixtures such as high-range, water-reducing agents and air-entraining agents (AEAs) are also used in SCC mix designs. Viscosity-modifying admixtures can also be used to increase flowability without segregation, which allows the volume of coarse aggregates to be increased.

15.6.3 Testing Methods and Specifications

For SCC to become a standard concrete mixture, acceptance tests on fresh and hardened SCC to evaluate its physical and mechanical properties must be established to ensure a level of comfort for the contractors, designers, and owners (Persson, 2001). As mentioned earlier, SCC does not require compaction; therefore, the rheological characteristics of SCC are very important, as its consolidation depends on its rheological performance. In ordinary concrete, adequate slump in conjunction with good consolidation practice will

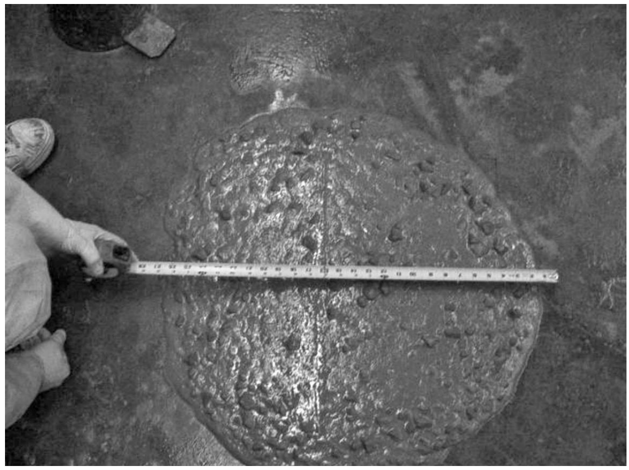

FIGURE 15.7 Self-consolidating concrete (SCC) spread test.

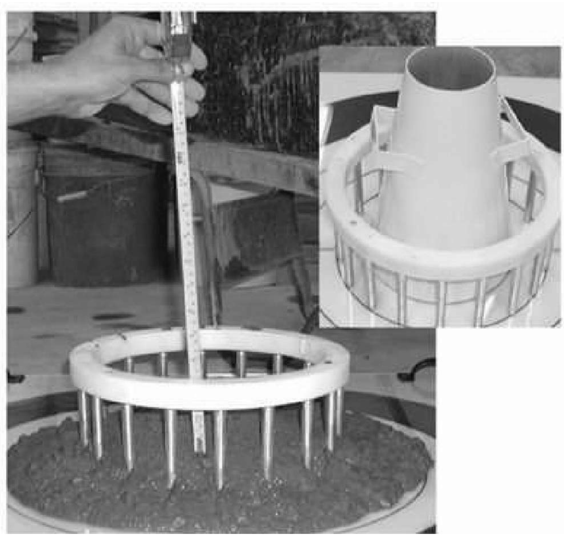

FIGURE 15.8 J-ring test for SCC.

yield a dense concrete structure with few air voids. The external forces due to vibration compensate for the variations in plastic concrete, so the rheology of concrete can be ignored; hence, only the slump test is performed for testing fresh ordinary concrete. In SCC, however, the rheological characteristic cannot be ignored, because the concrete must meet certain rheological requirements. The plastic concrete is generally described as a Bingham fluid, where the concrete behavior is characterized by its shear yield stress and plastic viscosity. For SCC, the shear yield stress has to be lower than ordinary concrete for the concrete to self-compact (Khayat, 1999). The rheology of concrete could be measured using a concrete rheometer, which measures the shear yield stress and viscosity of concrete. The problem with doing so is that the device is very expensive, and the test is impractical to perform at a job site, so other practical fresh concrete testing methods similar to the slump test of ordinary concrete have been developed. These tests include: (1) the spread test, (2) the L-shaped or U-shaped box, (3) the V-funnel (4) the J-ring, and (5) sieve stability. Figure 15.7, Figure 15.8, and Figure 15.9 illustrate the various tests for fresh SCC (Suksawang et al., 2005, 2006). It must be noted, however, that these tests do not measure the rheology of concrete but instead are used to simulate actual environment and field conditions. Furthermore, not

FIGURE 15.9 L-box test for SCC.

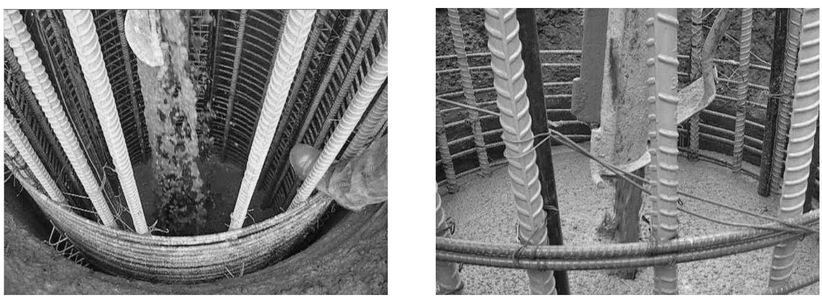

FIGURE 15.10 SCC in drilled shafts.

enough data are available to correlate these tests with the rheology of concrete, especially for mix designs that use raw materials available in the United States. Hardened SCC is subjected to the same tests used for normal concrete, such as compressive strength, elastic modulus, shrinkage, freeze–thaw, rapid chloride permeability, and scaling, among others.

15.6.4 Applications

Because of its ability to flow easily in highly congested areas, SCC is now being considered for structural members with high volumes of steel reinforcement. In addition, SCC is become more attractive because it offers accelerated construction schedules, reduced noise levels, and smooth surface finishes. The first SCC application in Japan was in buildings in 1990. Since then, it has been used in bridge towers, bridge girders, bridge decks, box culverts, anchorages, and immersed tunnels. Lightweight SCC was also used in bridge girders (Okamura and Ouchi, 2003). In the United States, SCC has been used in nonstructural elements such as noise walls and parapets. The New York State Department of Transportation is already using SCC in bridge decks, and the New Jersey Department of Transportation is using SCC in drilled shafts. Figure 15.10 shows SCC pours in drilled shafts. Durability issues in SCC and its mechanical properties compared to those of normal concrete are being evaluated by many researchers; however, these studies are still limited and do not address all of the durability issues for highway structures. In addition, current prediction equations for the mechanical properties of normal or conventional concrete still must be validated for their applicability and accuracy in predicting properties of SCC mixes.

15.7 Mass Concrete

15.7.1 Introduction

Mass concrete is defined in ACI Committee 116 (1990) as "any concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking." Mass concrete according to the Portland Cement Association (PCA,

1987) can be any placement of normal concrete that has minimum dimension equal to or greater than 3 ft. Many structural elements require the use of large amounts of concrete, such as abutments, shear walls, tanks, mat foundations, large-diameter drilled shafts, footings, transfer girders, and dams. The biggest concerns with mass concrete are the maximum temperatures generated and the maximum temperature differentials. Several factors influence temperature changes, including the size of the component, the amount of reinforcement, the ambient temperature, the initial temperature of the concrete at time of placement, and the curing program. To minimize the effects of high thermal loads in mass concrete, engineers use various methods to apply mass concrete. These methods include refining concrete mix proportions, protecting exposed surfaces and formwork from extreme environmental factors, using aggregates with desirable thermal properties, precooling the concrete constituent materials prior to mixing, using internal pipes to cool the concrete itself after placement, and placing the concrete in several lifts or pours.

15.7.2 Methods of Controlling Temperatures

Some mix designs for mass concrete include supplementary cementitious materials in the mix, including slag cement or fly ash. The Slag Cement Association offers some guidance on specifying slag cement for mass concrete. The American Coal Ash Association also offers information on the benefits and specification of fly ash. Many state departments of transportation specify 35°F (19°C) as the maximum differential temperature between the core and the surface and 135°F (57°C) as the maximum concrete temperature (Gajda and Alsamsam, 2006). This is difficult to achieve unless other measures are used to control the heat of hydration. Many argue that this limit is arbitrary and should not be put in the specifications; rather, the maximum differential temperature should be calculated using ACI guidelines given in ACI 207.2R (Anon., 2001). Using less cement content and adding fly ash or ground granulated blast-furnace slag to replace some of the cement or using aggregates with low coefficient of thermal expansion can help reduce the rise in temperature and the temperature differential in mass concrete. In addition to controlling the mix design, other temperature control methods include precooling the concrete mix using shading and sprinkling of the aggregates, using cold water in the mix, and post-cooling of concrete using cooling pipes (Gajda and Alsamsam, 2006). Placing concrete in several lifts has also been used, but precautions should be taken to avoid cold joints. Slag and fly ash should be used with caution, but slag and fly ash can be useful for small mass concrete pours with temperature control.

Modeled temperatures in a 10-ft slab with 600 lb/yd^3 of cementitious materials made up of 65% Type II cement and 35% fly ash Type F are shown in Figure 15.11. The figure shows the variations in temperature vs. time for different locations in the slab as well as variations in the differential temperatures in the concrete with time (Gajda and Alsamsam, 2006). Figure 15.12 shows the temperature change with time for the massive footing shown in Figure 15.13. For this massive concrete pour, an optimal mix design was used along with cooling pipes to cool the concrete after the pour (Gajda, 2003).

15.8 Roller-Compacted Concrete

15.8.1 Introduction

Roller-compacted concrete (RCC) is a type of concrete that exhibits zero slump and requires no vibration or forms; paving machines and compaction rollers compact the concrete after placement. Newer generations of paving machines, however, can achieve compaction of RCC during placement without the need for any additional compaction (see http://www.cement.org/pavements/pv_rcc_pcc.asp). Applications of this type of concrete include pavements, dams, and industrial sites with large areas, such as maintenance yards, military fields, container and truck distribution areas, and precast yards. RCC is an attractive material because of its easy preparation and placement, speed of construction, reduced labor requirements, and high strength. With its low water/cement ratio and high density, RCC has high strength and good durability; however, it requires special equipment for placement and lacks a smooth surface finish. The material was developed in the mid-1970s by Canadian builders for the logging industry. Today, RCC is a competitive material that is widely used in many projects all over the world.

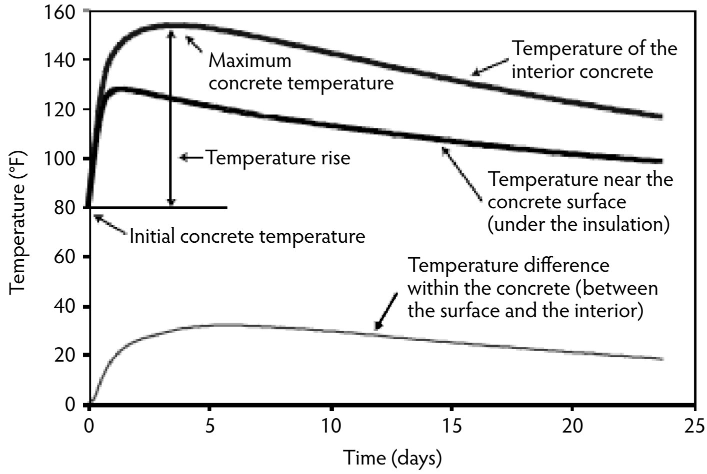

FIGURE 5.11 Modeled temperatures for 10-ft slab with 600 lb of cement materials per cubic yard (65% Type II OPC and 35% fly ash). (From Gajda, J. and Alsamsam, E., *Engineering Mass Concrete Structures*, Seminar Development Series, Portland Cement Association, Skokie, IL, 2006.)

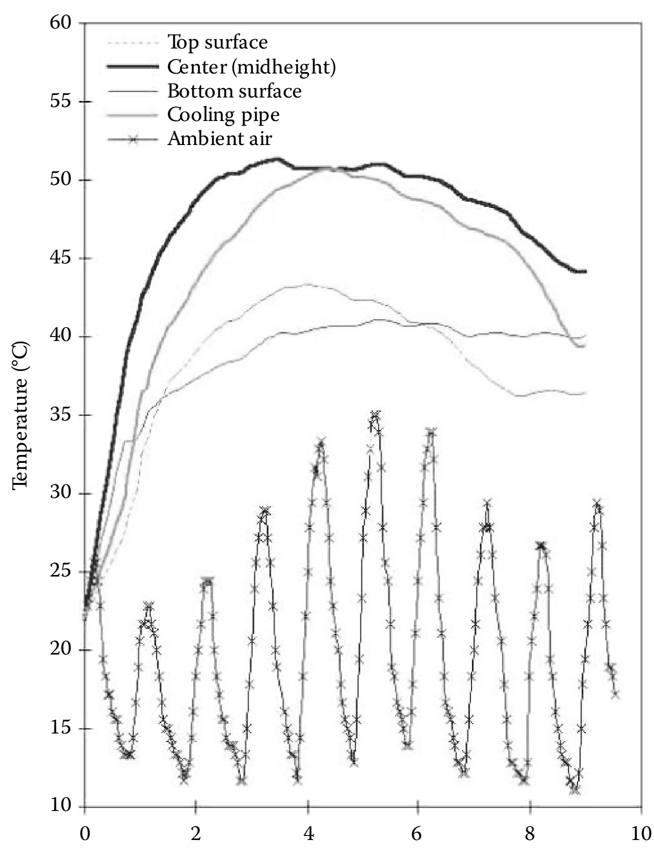

FIGURE 15.12 Measurement of concrete temperature in footing. (From Gajda, J., *Concrete Technol. Today*, 24(3), 34–37, 2003.)

FIGURE 15.13 Overview of footing and pier prior to footing placement. (From Gajda, J., *Concrete Technol. Today*, 24(3), 34–37, 2003.)

15.8.2 Mix Design, Placement, and Curing

Mix design for RCC uses a low water-to-binder ratio, making it a dry mix with zero slump. The aggregates are a blend of various sizes chosen to achieve a well-graded aggregate mix. Typical maximum coarse aggregate size is 3/4 in. Aggregate sizes larger then 3/4 in. could result in segregation and less density. Gravel aggregates or crushed stone are typically used for coarse aggregates, and natural sand or river sand is used for fine aggregates (PCA, 2000). RCC is placed in various thicknesses and various widths. Thicknesses can be as thin as 5 in. and as thick as 12 in for slabs; the width depends on the paving machine used. Placement can also be achieved by spreading the RCC mix and then applying compaction; however, care must be taken to ensure that the spread is continuous and the compaction process is uniform. Precaution should be taken when placing RCC in hot weather—when the temperature increases, the mix tends to lose more moisture. Contractors should maintain the required moisture of the mix by either increasing the moisture content in the mix or delaying the moisture loss by using admixtures or cooling methods. Like regular concrete, RCC should be cured. Improper curing could lead to severe dryness and incomplete hydration of cement, resulting in weaker RCC and cracking. Curing is typically applied for 7 days after placement. Plastic sheets and wet burlap can be used similar to regular concrete (PCA, 2000).

15.8.3 Testing Methods for RCC

The moisture content and densities of RCC are important properties that must be verified for acceptance. ASTM Subcommittee C09.45 is in charge of developing standard test procedures for measuring RCC properties. ASTM Subcommittee C09.45 developed ASTM Standard C 1170 (2006), a test method for determining the consistency of concrete using a vibrating table and a surcharge and determining the density of the consolidated concrete specimen. They also developed ASTM Standard C 1040 (2005), a standard test method for in-place density of unhardened and hardened concrete, including roller-compacted concrete, by nuclear methods using gamma radiation.

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References

ACI 116R. 1990. *Cement and Concrete Terminology*. American Concrete Institute, Farmington Hills, MI.

ACI 211.1. 1991. *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*. American Concrete Institute, Farmington Hills, MI.

ACI 304.1. 1989. *Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications*. American Concrete Institute, Farmington Hills, MI.

ACI 304R. 1989. *Guide for Measuring, Mixing, Transporting, and Placing Concrete*. American Concrete Institute, Farmington Hills, MI.

ACI 524R. 1992. *Guide to Portland Cement Plastering*. American Concrete Institute, Farmington Hills, MI.

Anon. 2001. Are temperature requirements in mass concrete specifications reasonable? *Concrete Construct. Mag.*, October, pp. 68–70.

ASTM C 91. 2005. *Specifications for Masonry Cement*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 109. 2007. *Test Method for Compressive Strength of Hydraulic Cement Mortars Using 2-in Cube Specimens*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 150. 2007. *Specifications for Portland Cement*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C191. 1992. *Test Method for Time of Setting of Portland Cement by Vicat Needle*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 206. 2003. *Specification for Finishing Hydraulic Lime*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 207. 2006. *Specifications for Hydraulic Lime for Masonry Purposes*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 231. 2004. *Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 595. 2007. *Specifications for Blended Hydraulic Cement*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 897. 2005. *Aggregate for Job-Mixed Portland Cement-Based Plasters*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 926. 2006. *Specifications for Application of Portland Cement-Based Plaster*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 937. 2002. *Specifications for Grout Fluidifiers for Preplaced-Aggregate Concrete*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 938. 2002. *Practice for Proportioning Grout Mixtures for Preplaced-Aggregate Concrete*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 943-02. 2002. *Practice for Making Test Cylinders and Prisms for Determining Strength and Density of Preplaced-Aggregate Concrete in the Laboratory*. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 1040. 2005. *Standard Test Methods for In-Place Density of Unhardened and Hardened Concrete, Including Roller-Compacted Concrete, by Nuclear Methods*, Vol. 04.02. American Society for Testing and Materials, Philadelphia, PA.

ASTM C 1170. 2006. *Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table*, Vol. 04.02. American Society for Testing and Materials, Philadelphia, PA.

Bureau of Reclamation. 1992. *Concrete Manual: A Manual for the Control of Concrete Construction*, 9th ed. U.S. Department of the Interior, Washington, D.C.

Gajda, J., Save time and money on concrete construction. *Concrete Technol. Today*, 24(3), 34–37.

Gajda, J. and Alsamsam, E. 2006. *Engineering Mass Concrete Structures*, Seminar Development Series, Portland Cement Association, Skokie, IL.

Gerwick, B.C. 1988. *Review of the State of the Art for Underwater Repair Using Abrasion-Resistant Concrete*, Technical Report REMR-CS-19, prepared for U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. University of California, Berkeley.

Kawai, T. 1988. Special underwater concrete admixtures. *Concrete J.*, 26(3), 45–49.

Khayat, K. 1999. Workability, testing and performance of self-consolidating concrete. *ACI Materials Journal*, 96(3), 346–353.

Khayat, K. and Hester, W. 1991. *Underwater Repair of Concrete Slab*, Technical Report REMR-CS-13X. University of California, Berkeley.

Neeley, B.D. 1988. *Evaluation of Concrete Mixtures for Use in Underwater Repairs*, Technical Report REMR-CS-18. U.S. Army Waterways Experiment Station, Vicksburg, MS.

Neeley, B.D. 1989. *Antiwashout Admixtures for Use in Underwater Concrete Placement*, Video Report REMR-CS-3. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Neeley, B.D. and Saucier, K.L. 1990. *Laboratory Evaluation of Concrete Mixtures and Techniques for Underwater Repairs*, Technical Report REMR-CS-34. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Okamura, H. 1997. Self-compacting high-performance concrete. *Concrete Int.*, 19(7), 50–54.

Okamura, H. and Ouchi, M. 2003. Self-compacting high-performance concrete. *J. Advanced Concrete Technol. Jpn. Concrete Inst.*, 1(1), 5–15.

PCA. 1987. *Concrete for Massive Structures*. Portland Cement Association, Skokie, IL.

PCA. 2000. *Guide for Developing RCC Specifications and Commentary: Roller-Compacted Concrete for Embankment Armoring and Spillway Projects*. Portland Cement Association, Skokie, IL.

Persson, B. 2001. A comparison between mechanical properties of self-compacting concrete and the corresponding properties of normal concrete. *Cement Concrete Res.*, 31, 193–198.

Rail, R.D. and Haynes, H.H. 1991. *Underwater Stilling Basin Repair Techniques Using Precast or Prefabricated Elements*, Technical Report REMR-CS-118. Naval Civil Engineering Laboratory, Port Hueneme, CA, and Haynes and Associates, Oakland, CA.

Ribar, J.W. and Scanlon, J.M. 1984. *How to Avoid Deficiencies in Portland Cement Plaster Construction*, Technical Report SL-84-10. U.S. Army Corps of Engineers. Washington, D.C.

Scanlon, J.M., McDonald, J.E., McAnear, C.L., Hart, E.D., Whalin, R.W., Williamson G.R., and Mahloch, J.L. 1983. *REMR Research Program Development Report*, prepared for Chief of Engineers, U.S. Army, Washington, D.C.

Suksawang, N., Nassif, H., and Najm, H. 2005. Durability of self-consolidating concrete (SCC) with pozzolanic materials. In *Proceedings of the SCC Second North American Conference and Fourth RILEM International Conference*, October 20–November 2, Chicago, IL.

Suksawang, N., Nassif, H., and Najm, H. 2006. Evaluation of mechanical properties of self-consolidating, normal, and high-performance concrete. *Transport. Res. Record, J. Transport. Res. Board*, No. 1979, Transportation Research Board of the National Academies, Washington, D.C., pp. 36–45.

U.S. Army Corps of Engineers. 1994. *Standard Practice for Concrete for Civil Works Structures*, EM 1110-2-2000. U.S. Government Printing Office, Washington, D.C.

Waddell, J.J. and Dobrowolski, J.A. 1993. Preplaced-aggregate concrete. In *Concrete Construction Handbook*, 3rd ed., Dobrowolski, J.A. and Waddell, J.J., Eds., pp. 38.1–38.7. McGraw-Hill, New York.

Zhu, W. and Bartos, P. (2003) Permeation properties of self-compacting concrete. *Cement Concrete Res.*, 33(6), 921–926.

(a)

(b)

(a) Repair of deteriorated beam underside. (Photograph courtesy of Portland Cement Association, Skokie, IL.)
(b) Repair of deteriorated bridge element. (Photograph courtesy of Randall W. Poston.)