Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications

Reported by ACI Committee 304

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ACI Committee 304 expresses its appreciation to John C. King for his work as the principal author of this document. Beginning in 1947, he evaluated data, prepared specifications, and guided the conversion of repair procedures into those more suitable for new construction with preplaced aggregate concrete.

This guide explains the preplaced aggregate (PA) method for concrete construction, describes special properties, and gives materials requirements where they differ from those used in normal concrete. A brief history of the development of the procedure is covered. Short descriptions of several typical applications are included.

Keywords: fluidizing; grout; heavyweight concrete; inserts; preplaced aggregate concrete; underwater construction.

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ACI 304.1R-92 (Repproved 2005) supersedes ACI 304.1R-69.

CHAPTER 1—INTRODUCTION

This report on preplaced aggregate (PA) concrete for structural and mass concrete applications describes practices as developed over many years by engineers and contractors in the successful use of the method; defines the reasons for material requirements that are different from those usually specified for normal concrete; and provides information on equipment, forms, aggregate handling, and grouting procedures. A brief history of the development of the method is given. Photographs with short descriptions for a few major applications are used to illustrate techniques.

PA concrete, the finished product, is defined in ACI 116R as "Concrete produced by placing coarse aggregate in a form and later injecting a portland cement-sand grout, usually with admixtures, to fill the voids." Other terms describing the method, used both in America and internationally, include grouted aggregate concrete, injected aggregate concrete, two-stage concrete, Prepakt, Col-Crete, Naturbeton, and Arbeton. PA concrete is particularly useful for underwater construction, placement in areas with closely spaced reinforcement and in cavities where overhead contact is necessary, repairs to concrete and masonry where the replacement is to participate in stress distribution, heavyweight (high-density) concrete, high-lift monolithic sections and, in general, where concrete of low volume change is required.

1.1—History

Lee Turzillo and Louis S. Wertz conceived the PA method of producing concrete circa 1937 during rehabilitation work in a Santa Fe railroad tunnel near Martinez, Calif. When grouting voids in the concrete at crown areas, the grouting crew began filling larger spaces with coarse aggregate before grouting to reduce the consumption of grout. The next logical step was to form over the areas where concrete was to be replaced, place a graded aggregate into the forms, and grout the aggregate. The resulting "concrete" showed such promise that Professor Raymond E. Davis was engaged to develop grout mixtures and basic procedures to make the method viable. In the course of this work, Davis also determined most of the unique properties of PA concrete, which are cited elsewhere in this guide. A series of patents on the method (trade-named Prepakt) and admixtures, mainly grout fluidifier, were applied for and granted in about 1940. All patents have expired, with the possible exception of some on admixture refinements.

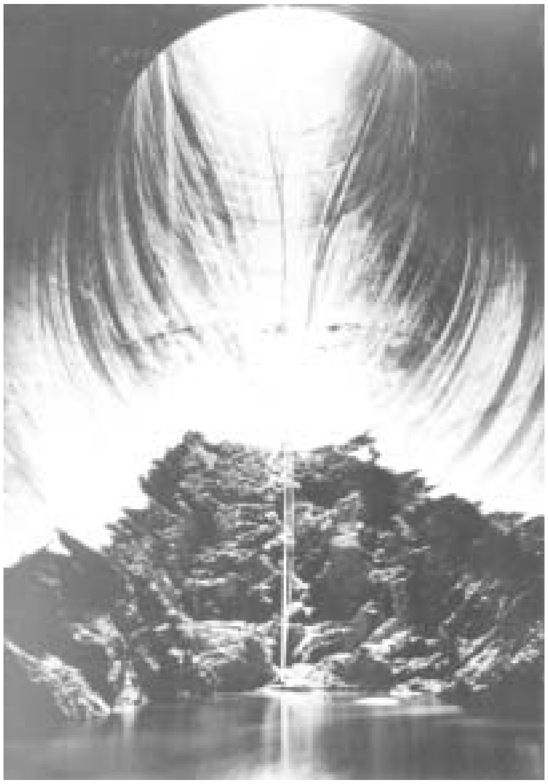

Fig. 1.1—Eroded area in spillway tunnel at Hoover Dam, 500 ft (152 m) below crest, before repair with PA concrete.

Initially, in view of the lack of any performance history, the use of PA concrete was limited to the repair of bridges and tunnel linings to extend their usefulness. After extensive laboratory testing, the Bureau of Reclamation backfilled a large eroded area in the spillway at Hoover Dam.[1,2] The replacement was 112 ft (34 m) long by 33 ft (10 m) wide and up to 36 ft (11 m) deep, as shown in Fig. 1.1. The next major project was the addition to the upstream face to Barker Dam[3] at Nederland, Colo., in 1946. This resurfacing of the 170 ft (52 m) high dam involved anchoring precast concrete slabs some 6 ft (1.8 m) in front of the dam, as shown in Fig. 1.2, and backfilling the space with coarse aggregate during the winter when the reservoir was empty. The aggregate was grouted in late spring in a 10-day continuous pumping operation with the reservoir full. This work proved the method usable for construction. In 1951, the U. S. Army Corps of Engineers began to permit its use for the embedment of turbine scroll cases, as illustrated in Fig. 1.3, and other structures. During 1954 and 1955, approximately 500,000 yd^3 (380,000 m^3) of PA concrete were used in construction of the 34 piers of the Mackinac Bridge.[4] In 1950, construction companies in Japan bought rights to the method and built several bridge piers. During the 1970s, the Honshu-Shikoku Bridge Authority engaged in extensive research culminating in the construction of a large bridge complex. The Snowy Mountains Authority, Australia, used PA concrete for embedding turbine scroll cases and draft tubes in its hydroelectric power projects. The method also found wide use in placing biological shields around nuclear reactors and x-ray equipment. B. A. Lamberton and H. L. Davis were largely responsible for the development of heavyweight (high-density) PA concrete.

1.2—General considerations

The design of structures using PA concrete should follow the same requirements as conventionally placed concrete. The designer may take advantage of certain favorable physical properties and placement procedures summarized in the following sections.

1.3—Special properties

PA concrete differs from conventional concrete in that it contains a higher percentage of coarse aggregate because coarse aggregate is deposited directly into the forms with point-to-point contact rather than being contained in a flowable plastic mixture. Therefore, the properties of PA concrete are more dependent on the coarse aggregate. The modulus of elasticity has been found to be slightly higher and the drying shrinkage less than half that of conventional concrete.[5-7]

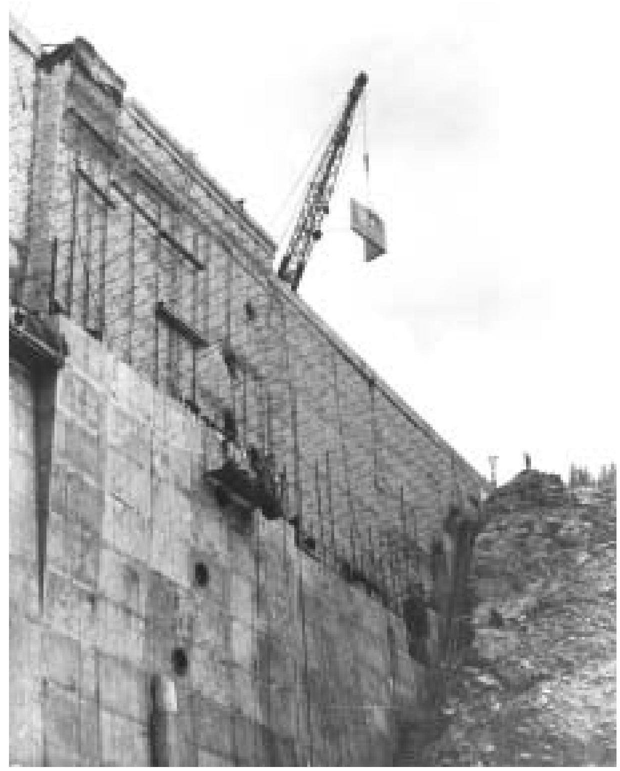

Fig. 1.2—Barker Dam, Colorado, during refacing in 1946. Coarse aggregate placed behind precast concrete slab forms for the entire upstream face of the dam (170 ft [52 m] high by 1300 ft [400 m] long at crest). Grout was placed in one continuous, 10-day pumping operation after the reservoir had been refilled to load the dam and cool the aggregate. Behind the form concrete, the new face has no joints of any kind.

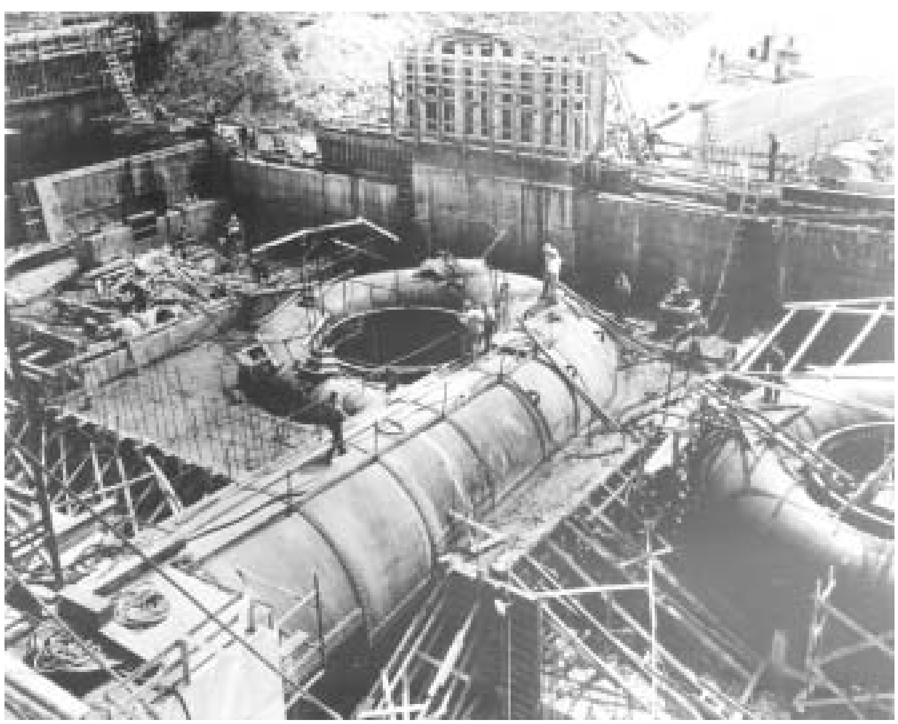

Fig. 1.3—Turbine scroll case at Bull Shoals Dam powerhouse at completion of the first (10 ft [3 m]) lift of PA concrete. A second lift completed the embedment.

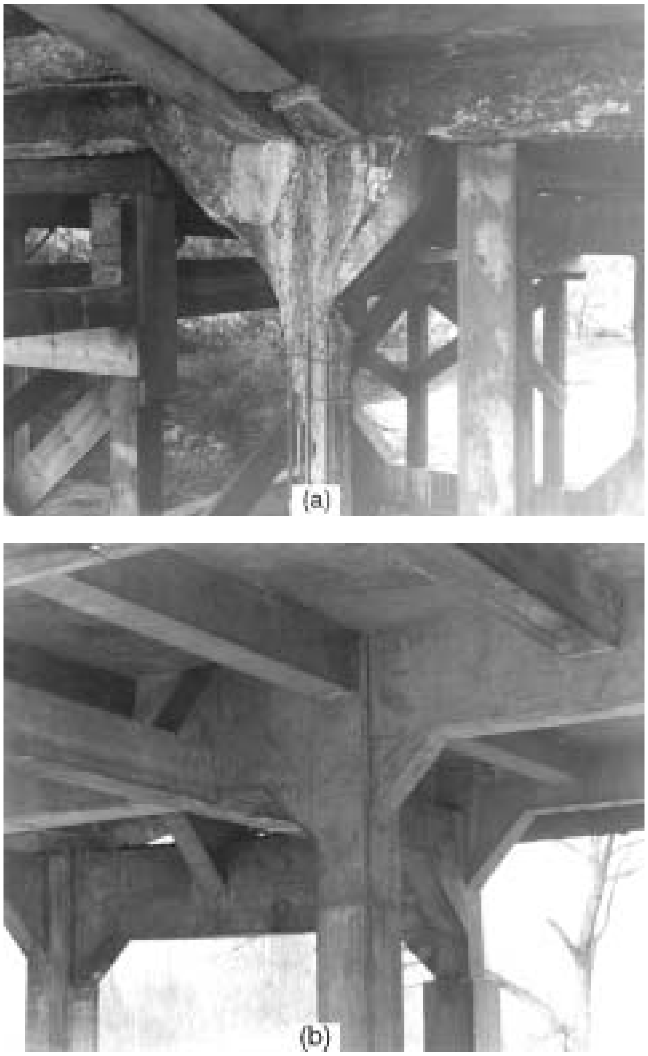

Fig. 1.4—Viaduct column and beams: (a) before repair; and (b) 26 years after repair with PA concrete.

1.4—Strength

The strength of PA concrete depends on the quality, proportioning, and handling of the materials as discussed throughout this report. Compressive strengths up to 6000 lb/in.^{2} (41 MPa) at 28 or 90 days, depending on water-cementitious material ratio (*w/cm*), are readily attainable. Strengths of 9000 lb/in.^{2} (62 MPa) at 90 days and 13,000 lb/in.^{2} (90 MPa) at 1 year have been reported.[3,8] It would appear that strength could be increased through the use of high-range water-reducing admixtures (HRWRAs), silica fume, and/or other admixtures, but neither research nor performance data are available.

1.5—Bond

The bond of PA concrete added to existing roughened concrete is excellent.[7] There are two reasons for this: 1) the grout used to consolidate the PA penetrates surface irregularities and pores to establish initial bond, and 2) the low drying shrinkage of PA concrete, where drying can occur, minimizes stress at the interface. Unpublished test data on beams in which PA concrete was placed against conventional concrete showed a modulus of rupture of over 80% of that of a monolithic beam of the older concrete, and numerous cores taken from one concrete bonded to another and tested in bending nearly always break on one side of the interface or the other, but not at the bonded surface.

1.6—Durability

PA concrete was produced for many years without air entrainment other than that contributed by the lignin and the grout fluidifier. Nevertheless, PA concrete used for repairs, which are normally exposed to severe weathering, has shown excellent durability. A typical example is illustrated in Fig. 1.4, which shows the condition of a column in the West 6th Street Viaduct, Erie, Pa., before repair and of the same column 26 years after repair. Another example is noted in Reference 9. In this instance, the PA concrete refacing of a lock wall on the Monongahela River above Pittsburgh, Pa., from far below low pool level to the top of the lock walls, was found to be in visibly sound condition at 35 years. A series of tests conducted at the U.S. Army Corps of Engineers Waterways Experiment Station laboratory[10] on PA concrete, however, shows that air entrainment is necessary to provide durability comparable to that of air-entrained conventional concrete. Currently, Corps of Engineers Specification for PA Concrete[11] require that PA concrete contains 9 ± 1% air entrainment measured in accordance with ASTM C 33 15 minutes after completion of mixing of the grout.

1.7—Heat of hydration control

Where heat of hydration must be considered, the PA concrete method makes it feasible to cool the aggregate the forms. Then, by intruding chilled grout, in-place initial temperatures as low as 40 to 45 °F (4 to 7 °C) are readily obtainable. Temperature control procedures are given in this report in Chapter 5.

1.8—Closely spaced reinforcement

The PA procedure is particularly applicable where reinforcement is too closely spaced to permit the use of vibrators, which would be necessary even when HRWRAs are used with conventional concrete. Because the coarse aggregate is inert, it may be placed as forms are erected around the reinforcement while access is still possible. When the preceding is in place, the member may be grouted into a monolithic unit of PA concrete.

1.9—Heavyweight (high-density) concrete

By preplacing heavyweight coarse aggregate, the hazard of segregation can be avoided. An example is shown in Fig. 1.5. Heavyweight fine aggregate can also be used in the grout. Work and materials in this field are described by Tirpak,[12] Davis,[6] and Narrow.[13] See also ACI 304.3R.

1.10—Monolithic placements

The only limits to height of a monolithic placement are the strength of forms required to contain the PA and the need to mix and pump grout continuously from start to finish of the grouting operation.

Fig. 1.5—Hand placing high-density aggregate (barite) for biological shield at Materials Testing Reactor, Arco, Idaho.

1.11—Exposed aggregate surfaces

With PA concrete, the forms are filled with coarse aggregate. The percentage of coarse aggregate in the resulting concrete is significantly greater than the roughly 70% coarse aggregate in conventionally placed concrete. If the surface grout is green cut or sandblasted after removal of the forms, approximately 25% more aggregate will be exposed. This procedure has been used to provide an attractive architectural finish.

CHAPTER 2—MATERIALS AND PROPORTIONING

2.1—Coarse aggregate

Coarse aggregate should be clean crushed stone or natural gravel, free of surface dust and fines, and should conform to the requirements of ASTM C 33, except that grading limits should be those shown in Table 2.1. A screening and washing operation is shown in Fig. 2.1. For economy and minimal temperature rise, the void content of the aggregate should be as low as possible. In general, minimum void content is attained when the coarse aggregate is graded from the smallest allowable particle size to the largest, consistent with the usual limitations established for thickness of section and spacing of reinforcement. In mass concrete, the only limitation on the maximum size of coarse aggregate is that which can be handled economically. The minimum size of coarse aggregate determines the void dimensions through which the grout must pass. Hence, minimum coarse aggregate size and maximum fine aggregate size are related. Grading 1 or 2 from Table 2.1 is normally used in the Americas and the Orient. In general, not more than 10% should pass the 3/4 in. (19.0 mm) sieve with 0 to 2% passing a 1/2 in. (12.5 mm) sieve (Grading 2). Where there is a large amount of closely spaced reinforcement, or where the placement is in relatively shallow patches, the minimum may include up to 10% passing the 1/2 in. (12.5 mm) sieve with not more than 2% smaller than 3/8 in. (9.5 mm) (Grading 1). These gradings may not always be readily available; special processing may be required.

Void content will range between approximately 35% for aggregate well graded between 3/4 in. (19.0 mm) and 6 to 8 in. (150 to 200 mm), to high as 50% for uniformly sized aggregate. Void contents as low as 25% have been attained experimentally by deliberate gap grading, in which half of the aggregate was 1/2 to 1-1/2 in. (12.5 to 37.5 mm) and half was 8 to 10 in. (200 to 250 mm).

In some European countries, it is common practice to use coarse aggregate having a minimum size of 1-1/2 in. (37.5 mm) or larger to employ fine aggregate more closely approaching

Fig. 2.1—Rotary screen is used to wash coarse aggregate and remove undersize particles.

Table 2.1—Grading limits coarse and fine aggregates for preplaced aggregate concrete

Sieve size	Percent passing: Grading 1 For 1/2 in. (12.5 mm) *minimum* size coarse aggregate	Grading 2 For 3/4 in. (19.0 mm) *minimum* size coarse aggregate	Grading 3 For 1-1/2 in. (37.5 mm) *minimum* size coarse aggregate
	Coarse aggregate		
1-1/2 in. (37.5 mm)	95 to 100	—	0.5
1 in. (25.0 mm)	40 to 80	*	—
3/4 in. (19.0 mm)	25 to 40	0 to 10	—
1/2 in. (12.5 mm)	0 to 10	0 to 2	—
3/8 in. (9.5 mm)	0 to 2	0 to 1	—
	Fine aggregate		
No. 4 (4.75 mm)	—		100
No. 8 (2.36 mm)	100		90 to 100
No. 16 (1.18 mm)	95 to 100		80 to 90
No. 30 (600 microns)	55 to 80		55 to 70
No. 50 (300 microns)	30 to 55		25 to 50
No. 100 (150 microns)	10 to 30		5 to 30
No. 200 (75 microns)	0 to 10		0 to 10
Fineness modulus	1.30 to 2.10		1.60 to 2.45

*Grade for minimum void content in fractions above 3/4 in. (19.0 mm).

that used with conventional concrete. There are also occasions where labor is so inexpensive that hand selection and placement is feasible. For these situations, Grading 3, Table 2.1 is acceptable.

2.2—Fine aggregate

Either manufactured or natural sand may be used. The sand should be hard, dense, durable, uncoated rock particles. It should conform to ASTM C 33, except the grading should be as shown in Table 2.1. Fine aggregate that does not fall within these grading limits is usable, provided results fall within the requirements of Section 2.8.1.

2.3—Cement

Grout can be made with any of the non-air-entraining types of cement that comply with ASTM C 150 or ASTM C 595. The use of air-entrained cement combined with a gas-forming fluidifier can result in excessive quantities of entrained air, resulting in reduced strength. Where air entrainment is required for added resistance to freezing and thawing, air-entraining admixture should be added separately. Dosage should be determined by laboratory tests and verified by actual tests to determine air content of the grout in the field. Data on the use of blended hydraulic cement are not available.

2.4—Pozzolan

Both fly ash and natural pozzolans conforming to ASTM C 618, Class F or N, may be used. Class F fly ash has been used in the great majority of installations because it improves the pumpability of the fluid grout and extends grout handling time. It provides the same properties to PA concrete as conventional concrete.[14] Class C fly ash and blast-furnace slag have been employed to a limited extent, but data on grout mixture proportions, properties, and in-place experience are lacking. There are no known data on the application of silica fume in grout for PA concrete.

2.5—Admixtures

2.5.1 *Grout fluidifier*—A grout fluidifier meeting the requirements of ASTM C 937 is commonly incorporated in the grout mixture to offset the effect of bleed water that normally tends to collect on the underside of coarse aggregate particles. It also reduces the *w/cm* to provide a given fluidity, and retards stiffening to provide added handling time in the mixing-pumping cyde and in the penetration of the voids in the coarse aggregate mass. A grout fluidifier is customarily a preblended material obtained commercially. It normally consists of a water-reducing admixture, a suspending agent, aluminum powder, and a chemical buffer to ensure a properly timed reaction of the aluminum powder with the alkalies in portland cement. Reaction of the aluminum powder generates hydrogen gas, which causes expansion of the grout while fluid, and leaves minute bubbles in the hardened grout. The aluminum powder is consumed in the reaction, leaving little or no residual metallic aluminum. Normal dosage of grout fluidifier is 1% by weight of the total cementitious material (cement or cement plus pozzolan) in the grout mixture.

In the laboratory, 1% fluidifier should produce expansion, as indicated in ASTM C 937, ranging from as much as 7 to 14% with cements containing 0.8% or more Na_2O equivalent, to as little as 3 to 5% with cements having 0.3% or less Na_2O equivalent. The grade and type of aluminum powder in the fluidifier should be selected to produce approximately all of the expansion within 4 hours. Expansion of field-mixed grouts that do not have the same fine aggregate-cementitious material ratios as those specified for qualifying the fluidifier may produce excess bleeding. The amount of bleeding should not be permitted to exceed the amount of expansion. Bleeding and expansion should be determined in accordance with ASTM C 940, using job materials.

The expansion of grout caused by the grout fluidifier ceases at temperatures below 40 °F (4 °C). In massive sections or placements enclosed by timber forms, the heat liberated by the hydrating cement normally raises the internal temperature sufficiently for the grout fluidifier to perform properly. Grout should be placed in an environment where the temperature will rise above 40 °F (4 °C).

2.5.2 *Air-entraining admixtures*—Air-entraining admixtures should meet the requirements of ASTM C 260 to provide resistance to freezing and thawing.[10] The user must remember, however, that the total air in the hardened grout will be the sum of that contributed by the air-entraining admixture and by the hydrogen generated by the aluminum powder in the grout fluidifier. If the total is sufficient to affect strength adversely, mixture proportions may have to be adjusted, but the air content should be adequate to ensure durability.

2.5.3 *Calcium chloride*—Calcium chloride must meet the requirements of ASTM D 98 and has been used occasionally to promote early strength development. When used in excess of 1%, however, this admixture depresses the expansive action of grout fluidifier. Pretesting of the grout for expansion, bleeding, and rate of hardening (ASTM C 953) and testing of the grout in PA concrete at job placement temperatures is advisable.

Where reinforcement is present, the limitations on amounts of calcium chloride and other materials that promote corrosion of steel shall be limited, as advised in ACI 201.2R and ACI 318.

2.5.4 *Chemical admixtures*—Chemical admixtures (ASTM C 494) may be considered for special situations. A Type D water-reducing and retarding admixture (calcium lignosulfonate) has been used successfully, for example, with a factory-blended “non-shrink” grout to increase fluid stiffening time from 15 minutes to nearly 60 minutes. Thorough pretesting of materials to be used in the work is advisable.

2.5.5 *High-range water-reducing admixtures*—HRWRAs, ASTM C 494 Types F and G, appear to be potentially useful, but no data are available on their use in grout for PA concrete.

2.6—Prepackaged grout products

Prepackaged “non-shrink” grouts of the type used under machine base plates may be used, provided:

1. They can be mixed to the consistency and perform as called for in Section 2.8;

2. The grout remains at suitable consistency for a sufficient period of time to permit proper intrusion into the preplaced aggregate; and

3. The maximum size of fine aggregate in the preblended material meets the requirements of Table 2.1.

Some machine base grouts tend to stiffen rapidly. Others are amenable to retardation. Because little data are available on the compatibility of retarders with the ingredients in premixed grouts, premixed grouts not formulated for PA concrete should be used with caution.

2.7—Resinous grout

Two-component epoxy resin grout may be used where high early strength is needed, and where, if cast against concrete, bond strength equal to the strength of the concrete is desired. The optimum formula should be one having a low exothermal potential, low viscosity, and a pot life of at least 30 minutes. Epoxies produce large amounts of heat as they harden. To prevent steam generation, the preplaced aggregate must be completely dry. Other thermal effects may be alleviated to a greater or lesser extent by limiting thickness, as in surface patches, to approximately 2 in. (50 mm) or by installing piping in massive sections through which water can be circulated to remove heat as it is generated. Cooling the aggregate in place with a compressed or liquid gas, such as nitrogen, may also be helpful.

2.8—Grout mixture proportioning

Grout mixture proportions should be determined in accordance with ASTM C 938 and specified by weight. All weighing and measuring equipment should be calibrated for accuracy and operated within tolerances allowable for conventional practice (ACI 304R).

A partial exception to complete weight proportioning has become accepted trade practice for small and geographically isolated projects. When the size and location of the work preclude the use of on-site weigh-batching equipment, volumetric batching has been used. On such projects, mixture proportions are rounded off to whole bags of cement and pozzolan, cubic feet of sand (damp and loose) measured in cubic foot boxes, and gallons of water. A typical mixture for a small routine bridge pier repair job, for example, would be 2:1:3, signifying a mixture containing 2 sacks at 94 lb (43 kg) of cement, 1 bag (70 lb [32 kg]) of fly ash (pozzolan), and 3 ft^3 (0.085 m^3) of damp sand. An initial mixture is made using 5 gal. (0.019 m^3) of water per sack of cementitious material. The mixture is checked by flow cone, and the water in later batches is adjusted to obtain the desired flow consistency, usually 22 ± 2 seconds. As the work continues, the flow cone is used to monitor the mixture and control the *w/cm*, which may vary with changing moisture content of the sand. Where bag weights differ from those commonly used in the U.S., a similar procedure is followed, after making appropriate adjustments to accommodate whole bags of cementing materials.

2.8.1 *Proportioning requirements*—Materials should be proportioned in accordance with ASTM C 938 to produce a grout of required consistency, as indicated elsewhere in this report, which will provide specified strength after injection into PA concrete cylinders (ASTM C 943). For optimal results, bleeding should be less than 0.5%, but, in any event, expansion should exceed bleeding at the in-place temperatures. Testing of the grout alone in cubes or cylinders for prediction of strength in PA concrete is not recommended because such testing does not reveal the weakening effect of bleeding. Such testing, however, may provide useful information on the potential of grout mixtures.

2.8.2 *Fine aggregate*—Compressive strength, pumpability,[5,15] and void penetrability requirements limit the amount of fine aggregate (sand) that can be used in the grout. For PA concrete for use in beams, columns, and thin sections, the ratio of cementitious material to sand will usually be in the ratio of 1:1 by weight (Grading 1). For massive placements where the minimum nominal size of coarse aggregate is 3/4 in. (19.0 mm), the cement-sand ratio may be increased to 1:1.5. With Grading 3 aggregates and appropriate equipment for pumping the grout, the ratio of cementitious material to sand may be increased to approximately 1:3.

2.8.3 *Cementitious material*—The proportion of pozzolan to portland cement is usually in the range of 20 to 30% by weight. The richer mixtures provide strengths of PA concrete comparable to those obtained with conventional concrete of the same proportions of cementitious material. The leaner mixtures usually provide strengths in 60 to 90 days equal to those obtained at 28 days for conventional concrete[14] with the same proportions of cementitious materials. Pozzolan-to-portland cement ratios have been used that are as high as 40% for lean mass concrete and low heat of hydration, and as low as 10% for extra-high-strength concrete. Occasionally, the pozzolan has been omitted entirely.

2.8.4 *Consistency of grout*—The flow cone, shown in Fig. 2.2, is used to determine grout consistency when using fine aggregate with 100% passing the No. 8 (2.36 mm) sieve, such as Grading 1 or 2 (Table 2.1). The method of test is given in ASTM C 939. This test consists of pouring 1725 mL of grout into a funnel having 1/2 in. (12.7 mm) discharge tube and observing the time of efflux of the grout. The time of efflux for water is 8.0 ± 0.2 seconds. For most work, such as walls and structural repairs, grout with a time of efflux of 22 ± 2 seconds is usually satisfactory. For massive sections and underwater work where the top size of coarse aggregate is larger, it is practical to use consistencies with a time of efflux ranging from 18 to 26 seconds. Where special care was taken in the execution of the work (Chapter 4) and higher strengths were required, grout with times of efflux as high as 35 to 40 seconds have been used.

When Grading 3 fine aggregate is used, the flow cone should be replaced by the flow table or some other device to determine a suitable consistency at which the grout will flow adequately through the voids in the coarse aggregate. If the flow table as described in ASTM C 230 is used, a flow of approximately 150%, measured after five drops in three seconds, should be suitable to produce a grout that will flow through the voids in the PA.

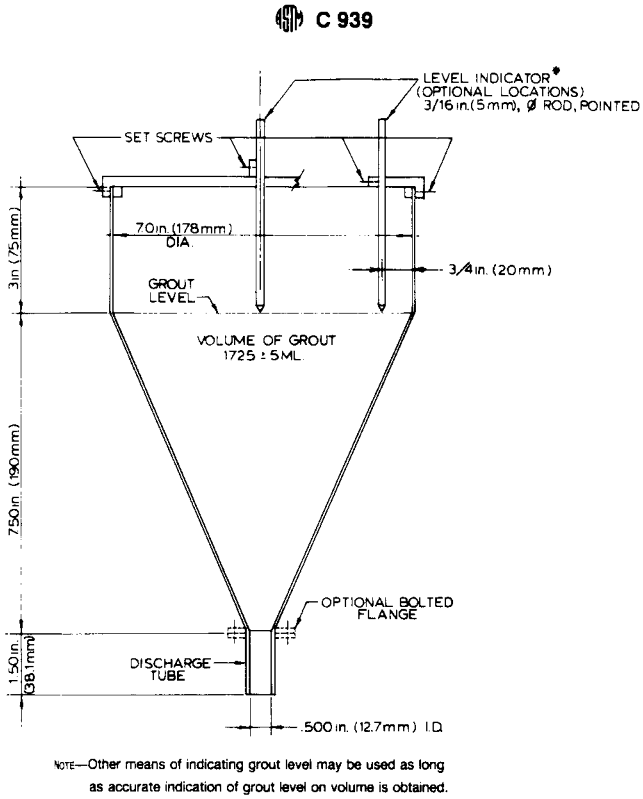

Fig. 2.2—Cross section of flow cone (as given in ASTM C 939).

Fig. 3.1—Double-tub grout mixer and progressive cavity pump, compressed air driven.

Fig. 3.2—Double-tub mixer and Simplex pump in operation. Inspector, left, holds flow cone for checking fluidity of grout.

CHAPTER 3—EQUIPMENT

3.1—Aggregate handling

Coarse aggregate may be handled and placed by any type of equipment that will not cause the aggregate to degrade or segregate excessively as it is moved and deposited. Means that have been used successfully in various situations are described in Section 4.5.

3.2—Grout mixers and pumps

3.2.1 *Tiers*—Vertical-shaft paddle-type, double-tub mixers are commonly used for preparing grout on small jobs. Mixer tubs range in capacity from 6 to 12 ft^3 (0.2 to 0.4 m^3) or more, and operate at 60 to 120 rpm. One tub serves as a mixer while the other acts as an agitator to feed the grout pump until its load is consumed. Although both mixers can be driven from a common shaft using gasoline, electricity, or compressed air as the power source, individual air motors for each tub are preferable because this type of power offers simple, separate speed control for each mixer. Commercially available double-tub mixers are shown in Fig. 3.1 and 3.2. These combinations have a rated maximum grout output of 2.7 ft^3/min (0.077 m^3/min). For large-volume grout output, horizontal-shaft mixers discharging by gravity into a third agitating mixer have been found suitable. One such plant is shown in Fig. 3.3. In this instance, cement, fly ash, and fine aggregate were batched at the project's concrete plant and fed to the hoppers over the mixers. Mixer power requirements range from 1/4 to l/2 hp per ft^3 (0.03 m^3) of capacity.

The pan or turbine-type concrete mixers are well suited for mixing grout, although maintenance of a sufficiently tight seal at the discharge gate can cause problems. Conventional revolving-drum concrete mixers are also usable if the mixing is sufficiently prolonged to ensure thorough mixing. The so-called colloidal, or shear, mixer provides extremely high-speed first stage mixing of cement and water in a close-tolerance centrifugal pump followed by mixing of the cement slurry with sand with an open impeller pump. This type of mixer provides a relatively bleed-free mixture, but because of the high-energy input, mixing time should be very short to avoid heating up the grout.

Ready mixed concrete plants are another source of grout, especially where large quantities are needed, provided that transit time to the work site is less than 30 minutes for a grout mixture that has an acceptable pot life of over 2 hours. Upon arrival, the grout is discharged into an agitator and the transit-mix truck released to return for another batch.

Mixed grout should be passed through a screen before it enters the pump(s). This removes lumps and other objectionable material, which can cause pumping difficulty and line blockage and interfere with proper grout flow in the voids in the preplaced aggregate. Screen openings should be approximately 1/4 to 3/8 in. (6 to 10 mm). A screen is normally laid over the pump hopper. Retained lumps are raked off frequently. In Fig. 3.3, mixed grout is fed to the agitator through a rotary screen, which automatically drops tramp (oversized) material over the end of the agitator. Power-driven shaker screens have also been used.

3.2.2 *Pumps*—Grout pumps should be of the positive displacement type such as piston, progressive cavity, or diaphragm. Centrifugal pumps have been found unsatisfactory except for rapid, low-pressure discharge, as from a high-speed "colloidal" mixer. The pump outlet should be equipped with a bypass connecting the discharge with the pump hopper or agitator to permit continuous, or at least frequent, pump operation during interruptions in grouting. By throttling the bypass, it is also possible to exercise a measure of control on the quantity of grout going to the work. A pressure gauge on the grout line in full view of the pump operator is necessary to indicate grouting resistance and possible line blockage.

3.3—Grouting systems

The most reliable grout delivery system consists of a single line from the grout pump directly to an insert (grout) pipe extending into the preplaced aggregate. To provide for continuous grout flow while a connection is changed from one insert to another, a wye fitting may be used in the immediate vicinity of the inserts. The wye should be provided with valves at the inlet and at the two outlets. Grout should be injected through only one leg of the wye at a time. Manifold systems, intended to supply two or more inserts simultaneously, are not advisable because flow of grout within the coarse aggregate will vary appreciably from insert to insert, resulting in uncertain grout distribution and plugged inserts.

It is a good practice to keep the length of the delivery line from the grout pump to the insert area as short as practicable. The line should be of sufficient diameter to maintain grout velocity in the range of 2 to 4 ft/s (0.6 to 1.2 m/s). Velocities that are too low may result in segregation or stiffening of grout, and in line blockage. Velocities that are too high will raise pumping pressure unnecessarily, increase wear, and waste energy.

High-pressure grout hose, having a capacity of 400 lb/in.^{2} (2.8 MPa) or higher, is commonly used for transmission lines from the pump to the point of use. For small work, a 1 in. (25 mm) inside diameter line is sometimes used, but 1-1/4 or 1-1/2 in. (30 or 40 mm) diameter lines are preferred for distances up to 500 ft (150 m). For longer distances, up to approximately 1000 ft (300 m), a 2 in. (50 mm) diameter line is preferred. Relay agitator-pump combinations are required for longer distances. It is essential that all pipe and hose connections be completely watertight because any loss of water from grout will cause thickening and probably blockage at the point of leakage. Quick-disconnect couplings are preferred to facilitate rapid pipe clean-out. Pipes should be cleaned out at 1 to 4 hour intervals, depending on the temperature and continuity of the operation.

All valves in the system should be of the type that provide for straight-through, undisturbed flow when open. It is also desirable that they be quick to open and easily disassembled for cleaning. Plug or ball valves, stem-lubricated when over 1 in. (25 mm) diameter, are preferred. Gate valves have been used in emergencies, but their service life is short because grout soon fills and hardens in the lower portion of the gate slot. Globe valves are not recommended in grout lines.

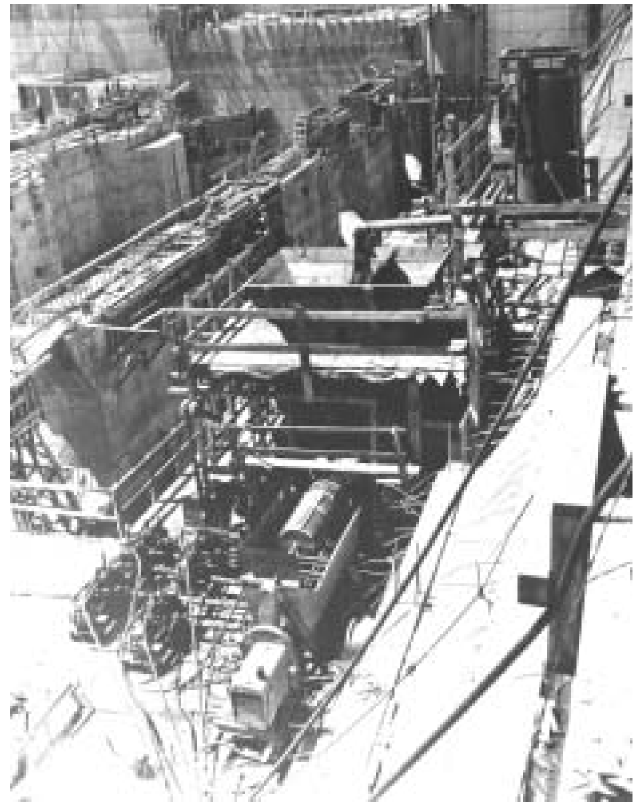

Fig. 3.3—Mixing and pumping plant at Bull Shoals Dam. Grout materials were dry-batched into 4 yd^3 (3 m^3) concrete buckets at the conventional concrete plant for transfer to this mixing plant located at the rear of the powerhouse substructure. Water batcher is above and to the right. Note rotary ground screen and agitator (in lower foreground) from which the battery of four pumps draws the grout.

CHAPTER 4—CONSTRUCTION PROCEDURE

4.1—General considerations

Steps to be taken, in the order of execution, for placing PA concrete is as follows:

1. Prepare existing surfaces against which the PA concrete is to be placed.
2. Place reinforcement and install grout (insert) pipes as required.
3. Erect forms.
4. Place coarse aggregate. This step may be coincident with the preceding Steps 2 and 3. Where reinforcement is closely spaced, or placing conditions are difficult for other reasons, or where high lifts of joint-free in-place concrete are desired, it may be advantageous to place the aggregate while access is available.
5. Mix and pump grout into the voids of the preplaced aggregate.
6. Finish and cure as required.

4.2—Preparation of concrete surfaces

Existing concrete surfaces to which PA concrete is to establish good bond should be thoroughly cleaned and all deteriorated

Fig. 4.1—After damaged concrete has been removed, coarse aggregate is placed as timber forms are erected.

Fig. 4.2—Concrete preparation of an arch rib before removal of deteriorated concrete, McArthur Bridge, Detroit, Mich.

Fig. 4.3—Concrete of an arch rib ready for erection of forms and placement of coarse aggregate, McArthur Bridge, Detroit, Mich.

or honeycombed concrete removed. Figure 4.1 shows a properly prepared surface after removal of honeycomb from a newly placed column in a turbine stand. Note that coarse aggregate is being placed as the forms are erected.

To repair surface defects, the concrete should be removed to reach sound concrete. In addition, a space not less than four times the maximum-size aggregate should be provided behind any existing reinforcing steel or where new reinforcement is to be added. Figures 4.2 and 4.3 show concrete removed from an arch rib of the McArthur Bridge in Detroit, meeting all three of these conditions.

4.3—Grout inserts, sounding wells, and vent pipes

4.3.1 *Grout insert pipes*—For the usual structural concrete, pipes used for injecting grout into the PA are normally 3/4 to 1-1/4 in. (20 to 30 mm) diameter, Schedule 40 pipe. For mass concrete, up to 1-1/2 in. (40 mm) diameter, Schedule 40 pipe is used. The grout insert pipes should extend vertically to within 6 in. (150 mm) of the bottom of the preplaced aggregate or they may extend horizontally through the formwork at different elevations. Occasionally, they are set at an angle to permit injection of grout around embedded items or into restricted areas. Insert pipes should be withdrawn during injection in such a way that the end remains at all times a minimum of 1 ft (0.3 m) below the grout surface. Where inserts are required for use in depths of aggregate exceeding approximately 50 ft (15 m), flush-coupled Schedule 120 pipe or flush-coupled casing is recommended. For very deep placements, such as caissons in deep water, additional pipe inserts may be required. For example, a 1 in. (25 mm) pipe may be placed within a 2 in. (50 mm) pipe to grout elevations 100 to 50 ft (30 to 15 m) and 50 to 0 ft (15 to 0 m), respectively. A pipe extending to a depth of 100 ft (30 m) or more in PA may be difficult to withdraw because of the friction. To alleviate this on the Mackinac Straits Bridge piers, a 1 in. (25 mm) pipe was placed to the full depth, and then a larger pipe was slipped over it to approximately half the depth.

The spacing of insert pipes will range from 4 to 12 ft (1.2 to 3.7 m) with 5 or 6 ft (1.5 or 1.8 m) spacing commonly used. As a conservative guide for the layout of insert pipes, it can be assumed that the grout surface will take a 1:4 slope in dry locations and 1:6 under water. On work being served by several pumps, inserts should be tagged with a number or other code to identify the insert being served by each pump.

Insert pipes are normally located and supported to permit withdrawal during grout injection and extraction from the aggregate after injection is complete. Straight pipes are preferable because they may be cleaned by rodding if they become obstructed. If it is necessary to place nonremovable grout pipes, such as those curved beneath an embedment, extra pipes should be placed in the event that some become obstructed. These pipes may also serve as vent pipes (Section 4.3.3).

The grouting of surface repairs and thin walls up to approximately 18 in. (450 mm) thick may also be accomplished through pipe nipples screwed into holes in the forms or into flanges attached to the forms over the holes. Spacing of these injection points will vary from as little as 2 to 3 ft (0.5 to 0.9 m) for sections as thin as 4 in. (100 mm) to 3 to 4 ft (0.9 to 1.2 m) for thicker sections.

4.3.2 *Sounding wells*—When grout is to be injected through vertical insert pipes, sounding wells are installed to provide a means to locate the grout surface. The ratio of sounding wells to insert pipes normally ranges from 1:4 up to 1:10. Sounding wells usually consist of 2 in. (50 mm) thin-wall steel pipe provided with milled (not burned) 1/2 in. (13 mm) open slots 6 in. (150 mm) long with 12 in. (300 mm) between slots at frequent intervals. Partially rolled, unwelded steel tubing providing a continuous slot has also been used successfully.

4.3.3 *Vent pipes*—Vent pipes should reach into areas that are likely to trap air and water as the grout rises in the coarse aggregate. These may be placed before or concurrently with the reinforcement.

4.4—Forms

Forms should be designed and erected in accordance with ACI 347, keeping in mind that the pressure exerted by the grout is the static head of the grout, which weighs approximately 130 lb/ft^3 (2080 kg/m^3). Grout pumping pressure is not a factor, provided that forms are open at the top, because grout moves through the in-place coarse aggregate so freely that pressure in grout pipes is dissipated within a few pipe diameters of the end of the insert.

For most projects, it has been found conservative to use standard form design tables and assume 10 lb/in.^{2} (0.07 MPa) minimum static grout pressure, approximately equivalent to a 10 ft (3 m) head of grout. For deep, massive placements, such as bridge piers, additional allowance is made for lateral load from the superimposed, ungrouted coarse aggregate. When placing heavyweight concrete, the constant 150 lb/ft^3 (2400 kg/m^3) in the formulas in ACI 347 should be replaced with the actual anticipated unit weight of the PA concrete.

Form workmanship must be of high quality to prevent leakage. Grout can stop water seepage but cannot be depended on to stop flow through openings wider than 1/16 in. (1.5 mm). Joints between form panels that do not match perfectly are usually sealed on the inside with self-adhesive tape. Anchor bolts and other penetrations may be tightly fitted through the sheathing or sealed with a ring of mortar applied inside. Where forms lap over concrete or other surfaces, sealing has been affected by placing a strip of compressible plastic or triple-folded cloth, or a strip of mortar in the joint. The use of mastics that do not harden has been found inadvisable because they tend to blow out as the grout rises behind the forms.

Forms constructed of tongue and groove boards are shown in Fig. 4.1. Plywood cut to fit at the job site is frequently employed on small jobs and wherever tailoring is necessary. Preassembled steel angle and plywood systems have been used successfully on large projects. Precast forms of air-entrained concrete with prepositioned steel anchor dowels tied or welded to the slab reinforcement have been used successfully for refacing large concrete dams.[7] Steel forms, either permanent or temporary, have been used on projects involving nuclear shields.

For underwater pier construction, including the encasement of existing pier bases, steel sheet piling is most frequently used. For deep-water piers where placement of coarse aggregate may be by the intermittent boatload while grout mixing and pumping is continuous, care should be taken to provide adequate internal anchorage for the sheet piling. The reason for this is that after a day or more of pumping, fresh grout is being injected into aggregate well above hardened concrete lower down in the structure. Without sufficient anchorage, the static pressure of the fresh grout may cause deflection of the sheeting. This will permit grout to flow down between the piling and hardened concrete, resulting in further deflection and, possibly, bulging or breaching of the forms.

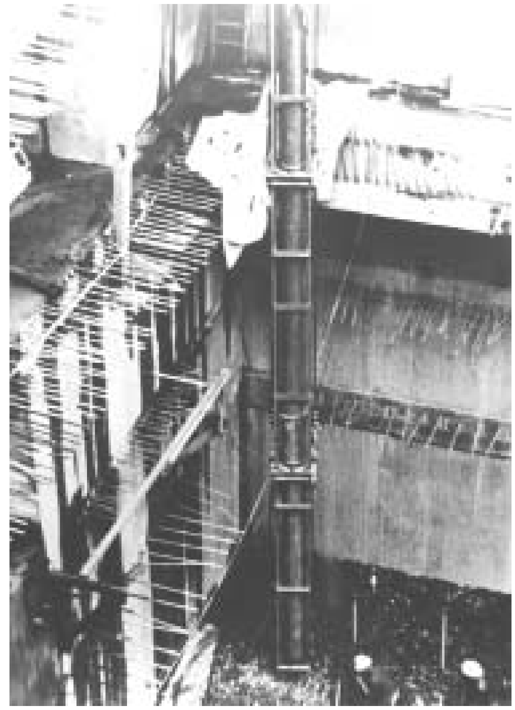

Fig. 4.4—Flow of coarse aggregate through tremie pipe for embedment of draft tubes was controlled by keeping lower end slightly below surface of stone already deposited. Cables attached to the pipe controlled placing. Washed aggregate was delivered by 10-ton dump trucks into a hopper attached to a pipe at an accessible deck level 50 ft (15 m) above deposition level, Tumu III Pumped Storage Hydro Plant, Snowy Mountains Project, Australia.

4.5—Coarse aggregate placement

4.5.1 *Preparation for placement*—Coarse aggregate should be washed and screened to remove dust and dirt, and to eliminate coatings and undersized particles immediately before placement. Washing in the forms should never be attempted because fines will accumulate at the bottom. No amount of flushing will remove such fines which, if present, will produce honeycombed concrete, an unbonded joint, or a poor bottom surface;[15] refer to ACI 309.2R. If more than one size of aggregate is being used, the sizes may be batched and mixed before final washing and screening, or they may be discharged at proportional rates onto vibrating decks or revolving wash screens.

4.5.2 *Aggregate placement*—Coarse aggregate is commonly conveyed to the forms in concrete buckets, dump trucks, and/or conveyors. Where the drop is over 5 ft (1.5 m), tremies or other means should be used to minimize segregation and breakage. A steel pipe having a diameter at least four times the maximum aggregate size has been used for lowering aggregate from 50 ft (15 m), as shown in Fig. 4.4, to 1000 ft (300 m) at the Kemano penstock.[16] In Fig. 4.4,

Fig. 4.5—Most of the coarse aggregate for 500,000 yd^3 (380,000 m^3) of PA concrete in 34 piers of the Mackinac Bridge was placed from self-unloading boats at approximately 2000 ton/h (1800 Mg/h). Water as much as 200 ft (60 m) deep in the forms cushioned the fall and chilled the stone to 40 to 45 °F (4 to 7 °C). Grout was mixed and pumped from semi-automatic plant on left.

Fig. 4.6—Coarse aggregate being deposited by clamshell from barge for Mackinac Bridge pier located in shallow water. Short sleeves welded to the caisson shells supported grout pipes with upper ends protected.

with the bottom end on the floor, the pipe was filled with aggregate, then maintained full as it was slowly raised. Keeping the lower end slightly into the mound of discharged material controlled the rate of aggregate flow. Ropes attached affected horizontal movement of the pipe to the pipe. Where it is impractical to withdraw the pipe, as at Kemano, sections may be burned off as needed to permit the aggregate to flow. Aggregate has also been blown into place. Aggregate for tunnel liners has been blown into place with

Fig. 4.7—Space over an equipment hatch in a nuclear containment structure. Cable ducts are shown at left. Additional reinforcement will be added.

large volumes of air in a pipe 6 in. (150 mm) or larger. A turbine blower provided air at approximately 3 psi (0.02 MPa).

Where coarse aggregate is being placed through water, as in bridge piers, it may be dropped directly into the water from self-unloading ships or clamshell buckets, as shown in Fig. 4.5 and 4.6, or from bottom dumps barges. The terminal velocity of aggregate falling through water is low enough to avoid particle breakage, and segregation from differential falling rates is negligible for the size ranges used.

There is little to be gained from attempts to consolidate the coarse aggregate in place by rodding or vibration. Rodding and compressed air lances, however, are frequently used to place aggregate in congested reinforcement and in overhead repair areas (Fig. 4.7). Lances are typically 1/2 in. (13 mm) pipes attached to air lines, as illustrated in Fig. 4.8. Expanded metal lath can be used to retain aggregate some 3 in. (75 mm) from the face; the remaining space is filled with aggregate as the forms are erected. Around closely spaced piping, reinforcement, and penetrations, as in some nuclear shielding situations,[12,13] hand placement of coarse aggregate may be required (Fig. 1.5).

4.6—Contamination

In underwater construction where organic contamination is known or suspected to exist, the water should be sampled and tested to determine the rate of sludge buildup on immersed aggregate and its possible influence on the quality of the concrete. Normally, where unexpected pollution is present, the aggregate may be safely grouted within a day or two after placement. 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, the PA concrete process should not be used. In clean water, coarse aggregate has been allowed to remain in place for approximately 6 months before the grouting operation without apparent adverse results.[17]

4.7—Grout injection

4.7.1 *Mixing procedure*—The standard batching order of grout materials into the mixer is water, grout fluidifier cementitious materials, and fine aggregate as stated in the "Standard Practice for Concrete," Department of the Army.[3] The fluidifier should be added with the water to help achieve good distribution of the grout ingredients. If additional retardation is desired, as in some hot weather situations, the fluidifier may be added after the cementitious materials have been mixing for a few minutes.

4.7.2 *Preparation*—At the time the coarse aggregate is grouted, it and any existing concrete surfaces should be in a saturated condition. If the placement is not under water, it is a good practice to ensure saturation of the aggregate, as well as to check the forms for excessive leakage, by filling the forms with water. Injection should be through the insert pipes so that the water rises gently through the aggregate. If the aggregate or concrete is internally dry, it is advisable to maintain the ponding for at least 12 hours. After saturation, the water may be drained by pumping from inserts of through-holes near the bottom of the forms. If the aggregate was saturated and surface wet at time of placement and only the upper 12 in. (300 mm) or so have dried out, this area may be dampened by application of a gentle fog spray. Before starting to mix and pump grout, it is advisable to disconnect grout hoses from inserts or from inlet points and flush the grout lines with water. Grout pumped through a dry hose or pipe will often clog as mixture water is absorbed from the grout by a dry surface. Excess water should be cleared from the pumps and lines to the extent feasible.

At the start of grouting, with the grout lines disconnected at the insert ends, grout should be pumped and wasted until grout exiting the line is the same uniform consistency as that being discharged from the mixer. Connection may then be made to the insert and injection into the preplaced aggregate started. The rate of pumping should be slow for the first few minutes to allow buildup of a mound of grout at the discharge point in the aggregate.

Fig. 4.8—Using air lance to place aggregate at rear of cavity and behind cable ducts.

4.7.3 *Grouting procedure*—There are essentially two basic patterns for grout injection: the horizontal layer and the advancing slope. With both systems, grouting should start from the lowest point in the form.

In the horizontal layer method, grout is injected through an insert pipe to raise the grout until it flows from the next insert hole 3 to 4 ft (0.9 to 1.2 m) above the point of injection. Grout is then introduced into the next horizontally adjacent hole, 4 to 5 ft (1.2 to 1.5 m) away, and the procedure repeated sequentially until a layer of coarse aggregate is grouted. This procedure is repeated in successive layers of aggregate until all of the aggregate in the form has been grouted. After each injection, the insert is withdrawn until the lower end of the insert is a minimum of 1 ft (0.3 m) below the grout surface. When injecting through ports in the forms or through horizontal inserts, grouting should be continuous through the injection point until grout flows from the second higher injection point above. For the next lift of grout, injection should be into the next injection point above that just completed, that is, well below the actual grout surface.

When the layer procedure is not practical, as in the construction of a thick slab having plan dimensions relatively large compared to depth, the advancing slope method of grout injection is used. In this procedure, intrusion is started at one end of the form and pumping continued through the first row of inserts until grout appears at the surface or is at least 1 ft (0.3 m) deep at the next row of inserts. Pumping successive rows of inserts until the entire layer has been grouted advances the slope. The natural slope of 22-second (flow one) grout in 3/4 in. (19.0 mm) nominal *minimum* size coarse aggregate will be approximately 1:10 in a submerged slab and may be as steep as 1:5 in a dry slab, The grout displaces water cleanly. Figure 4.9 shows a glass-faced form filled with 1/2 in. (13 mm) nominal *minimum* size aggregate.

When the grout contains pozzolan, the stiffening time of the grout will usually be long enough to allow insert pipes to stand full between injections for one to several hours, depending on mixture proportions and temperatures. It has

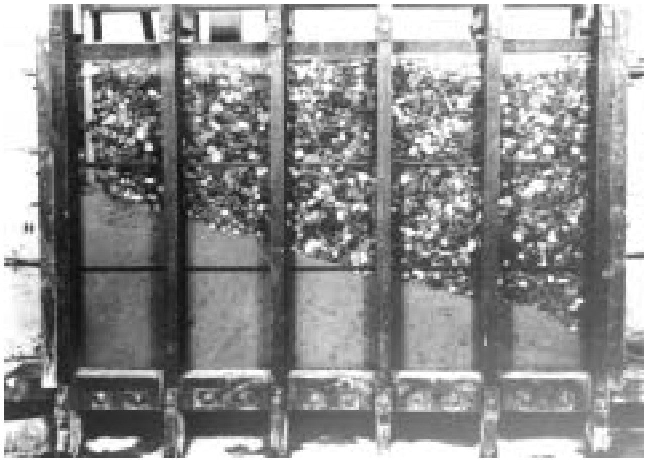

Fig. 4.9—Grout displaces water cleanly in glass-faced form and takes natural slope of approximately 1:5 in 1/2 in. (12.5 mm) minimum size aggregate.

been found desirable to rod out pipes that have been idle for some time before restarting grout injection. Insert pipes should not be cleaned by flushing water through them, especially when the lower end of the pipe is below the grout surface, because this will cause severe segregation of sand and an increased *w*/*cm* in the vicinity of the end of the pipe.

It is important that the rate of grout rise within the aggregate be controlled to eliminate cascading of grout and to avoid form pressures greater than those for which the forms were designed. Normally, a rate of grout rise of 2 ft/min (0.6 m/min) or less will ensure against cascading. As noted in Section 4.4, pressure from grout is that of the fluid head of grout above the point under consideration. An arbitrary rule used by some field engineers is that at 70 °F (21 °C), grout in PA stiffens sufficiently in 4 hours to resist superimposed pressures of up to 5 lb/in.^{2} (0.03 MPa), which is approximately equivalent to 5 ft (1.5 m) of fluid grout.

Normal injection rates through a given insert vary from less than 1 ft^3/min (0.03 m^3/min) to over 4 ft^3/min (0.11 m^3/min). For a particular application, the injection rate will depend on form configuration, aggregate grading, and grout fluidity. When grouting around embedded items, particularly under large, flat surfaces or under recessed areas, it is essential that provisions be made for venting entrapped air and water. Grouting should be continued until good-quality grout is returned from the vent pipes, thereby indicating completeness of grout injection. Low-frequency, high-amplitude external vibration of forms at or just below the grout surface will permit grout to cover aggregate-to-form contacts, thereby providing an excellent, smooth surface appearance. Excessive form vibration will encourage bleeding, and usually causes sand-streaking from the upward movement of bleedwater. Internal vibration serves no useful purpose and should be avoided except for short bursts to level the grout between inserts for topping out purposes.

4.7.4 *Grout surface determination*—The grout surface within a mass of PA may be located by observing seepage of milky-appearing water or grout from cracks, joints, small drilled holes, or injection points in forms.

Where the aggregate is being grouted through vertical insert pipes, sounding wells (described in Section 4.3.2) are used. The sounding line is usually equipped with a 1 in. (25 mm) diameter float so weighted as to sink through water yet float on the grout. An electronic system, replacing the sounding line and registering grout locations continuously on graphs at the pumping plant, was devised for the Honshu-Shikoku bridge piers in Japan. Details for this system are not available.

4.8—Joint construction

Cold joints are formed within the mass of PA when pumping is stopped for longer than the time it takes the grout to harden. When delays occur, the insert pipes should be pulled just above the grout surface before the grout stiffens, and then rodded clear. To resume pumping, the pipes should be worked back to near contact with the hardened grout surface and then the pumping resumed slowly for a few minutes to create a mound of grout around the end of the pipe. Because the coarse aggregate pieces cross this joint, bond and shear strengths in most cases will be unaffected. If the grout bleeds excessively, however, some laitance may collect on the grout surface portion of the joint and weaken tensile bond.

Construction joints may be formed in the same manner by stopping the grout rise approximately 12 in. (300 mm) below the aggregate surface. Dirt and debris should be prevented from collecting on the exposed aggregate surface or filtering down to the grout surface.

If bringing the grout up to the surface of the coarse aggregate makes construction joints, the surface should be green-cut (that is, water- or sandblasted after the grout has set but not appreciably hardened) to provide a clean, rough surface for the grout in the next lift.

4.9—Finishing

The grout injection rate is usually slowed down when topping out to avoid lifting or dislodging the surface aggregate.[5] Coarse aggregate at or near the surface that tends to float on the upward-moving grout may be restrained by a wire screen held in place with a few light beams or weights. The screen is removed before finishing.

When a screened or trowelled finish is required, grout should be brought up to flood the aggregate surface. Diluted grout should be removed. A thin layer of pea gravel or 3/8 to 1/2 in. (9.5 to 12.5 mm) crushed aggregate is then worked into the surface by raking and tamping. When the surface has stiffened sufficiently, it may be screened, floated, and/or trowelled as required. Occasionally, a PA concrete surface has been left 3 to 6 in. (75 to 150 mm) below grade and later topped off with conventional concrete.

4.10—Curing

PA concrete should be cured in the same manner as conventional concrete, that is, in accordance with ACI 308.1. Where the cementitious material includes pozzolan, impermeability and strength will be improved if curing time is extended.

CHAPTER 5—TEMPERATURE CONTROL

Temperature rise in PA concrete resulting from the heat of hydration, and the peak temperature attained by the concrete in place may be limited by one or more of the procedures described in the following sections. Information on temperature control measures can also be found in ACI 207.4R.

5.1—Grout mixture proportioning

As with conventional concrete, heat of hydration is related to the type and amount of portland cement and other cementitious materials in the mixture. The temperature rise depends on the amount and rate of heat released. The amount of heat can obviously be minimized by using a moderate or low heat-of-hydration cement and a mixture as lean as possible consistent with design requirements. If early strengths are not required, as in many massive structures where 90-day strength results are acceptable, high proportions of fly ash or pozzolan may be considered. The slower rate of strength gain results in slower heat release and additional time for heat dissipation.

5.2—Chilling coarse aggregate in place

Chilling occurs whenever the aggregate is deposited in cold water, as in bridge piers and other marine installations. For structures above water, circulating chilled water, introduced at the bottom of the forms and drawn off at the top, until the desired aggregate temperature is obtained, may cool the in-place aggregate. Spreading crushed or shaved ice on top, as shown in Fig. 5.1, may also cool in-place aggregate. This procedure, which allows cold air to settle through the voids in the aggregate mass and cold water to trickle down from the melting ice, has been found effective but time-consuming.[18] Cooling the aggregate with liquid nitrogen has been reported to be successful, but no details of such use are available.

5.3—Chilling aggregate before placement

Because of the time delay between aggregate placement and grout injection, cooling of the aggregate before placement in the forms is not recommended.

5.4—Chilling the grout

Cold mixing water may be used to reduce the temperature of grout, but this method is relatively ineffective unless the dry materials have also been cooled by low temperature storage.

An effective procedure, especially during warm weather, is the substitution of shaved ice for a portion of the mixing water. It takes 1 BTU to raise 1 lb of water 1 °F (1 Cal/g/°C), while 143 BTU are absorbed by 1 lb of ice (80 Cal/g) in melting. Using shaved ice, grout temperatures of 40 °F (4 °C) have been obtained. Precaution should be exercised when using ice to ensure that mixing continues until all ice particles are melted before the grout is pumped. This is important when minimum grout temperatures are being sought and especially so if crushed ice is substituted for shaved ice. Trial mixtures to determine the amount of ice substitution and the extension of mixing time, if any, are advisable. Chilling may also increase the fluidity of the grout sufficiently to permit some reduction in total mixing water.

Fig. 5.1—Cooling of in-place coarse aggregate with shaved ice prior to grouting.

5.5—Cold weather placement

The precautions and limiting conditions stated in ACI 306R should be observed. There are a few additional precautions peculiar to PA concrete. For the grout fluidifier to expand properly, the temperature of the grout should not fall below 40 °F (4 °C). If the coarse aggregate or concrete substrate is cold but not below 32 °F (0 °C), the grout may be heated by using warmed ingredients. Grout temperatures above 50 °F (10 °C) in monolithic PA concrete, or 60 °F (16 °C) in patches where cold base concrete will act as a heat sink, may be used to provide a suitable in-place temperature without causing an undue rise in temperature from the heat of hydration. Occasionally, where repair work had to proceed in severely cold weather, entire piers or structures have been enclosed and heated to ensure that base concrete temperatures were above the freezing point. This practice also protects the new PA concrete after placement.

CHAPTER 6—QUALITY ASSURANCE AND CONTROL

6.1—Quality assurance

To assure quality work:

1. Determine that the contractor has had experience in making PA concrete. If not, he or she should demonstrate capability by making two or three small test sections or blocks. The laboratory should practice their procedures at the same time;

2. Check materials reports for acceptability as is done for conventional concrete;

3. Check mixing and pumping equipment. Outlet gates should be watertight to prevent leakage of batch water during the batching process. It is advisable to ensure that both mixers and pumps are in good working condition before starting the first batch. Where cold joints must be avoided, standby equipment in proven working condition should be provided at the work site, ready for hook-up within 15 to 30 minutes. Although a skilled operator can usually tell

when pumping pressures are rising, a pressure gage at the pump outlet is recommended; and

4. See that quality control is being exercised during the course of the work.

6.2—Quality control

Quality control of both materials and workmanship should be exercised in accordance with appropriate ACI and ASTM standards.

6.2.1 *Before placement*—Selection of materials meeting specification requirements should be done in advance of the start of placement. It is advisable to prepare and test grout mixtures for consistency, bleeding, and expansion. When time permits, strength tests of cubes (ASTM C 942) may be made for a preliminary indication of performance. It should be noted, however, that the strength of grout determined from testing cubes might bear little relationship to the strength of PA concrete made with the same grout. The reason for this is that cube or cylinder testing does not reveal the weakening effect of excessive bleeding of the grout within the preplaced aggregate, nor does it account for the restraining effect on the expansion of the gas bubbles. The next step is the preparation of PA concrete cylinders (ASTM C 943). Usually six test specimens are made for testing, three each at 7 and 28 days of age. For work where materials savings are a factor or where the leanest practicable mixture is desired to minimize temperature rise, a series of mixtures may be prepared and tested simultaneously.

6.2.2 *During placement*—Particular attention should be given to the items in Sections 6.2.2.1 through 6.2.2.4.

6.2.2.1 *Coarse aggregates*—This material should be checked frequently as it is being placed in the forms to ensure that it is free of undersize particles and coatings. The use of dirty aggregate to which grout cannot bond will result in weakened concrete.

6.2.2.2 *Fine aggregate*—Fine aggregate that is not graded as specified in Table 2.1 may cause excessive bleeding that will, in turn, reduce strength. Oversize particles can cause problems with the valving systems of most piston pumps as well as clog the void spaces to be filled in the preplaced aggregate. Occasional pieces of tramp material will be retained on the grout screen, but excessive quantities lead to wasted material.

The free moisture content of the fine aggregate should be determined before the start and during the work and adjustments made to the amount of batching water required to satisfy the specified *w/cm*.

6.2.2.3 *Grout mixture control*—The accuracy of job-site batching of grout materials is most easily checked by use of the flow cone described in ASTM C 939. Flow cone measurements should be made on successive batches of grout from each mixer until fluidity is consistent within allowable limits, usually ±2 seconds. Thereafter, random flow testing at five to 10 batch intervals is generally considered adequate. Consistency adjustments, when necessary, are made in two steps: first, by varying the amount of mixture water within allowable *w/cm*, then by adjusting the cementitious materials.

6.2.2.4 *Strength tests*—Strengths should be determined from PA concrete cylinders made at the work site, preferably in the vicinity of the grout mixing and pumping plant, using grout diverted from the pump(s). The procedure is similar to that description in ASTM C 943 (a laboratory practice), except for the following: 1) casting temperatures are those at the work site, and 2) the cylinders are protected and left undisturbed where cast for at least 24 hours (or longer where strength gain is retarded by low temperatures or the pozzolan content of the grout) before stripping. After stripping, the cylinders are carefully transported to a laboratory for completion of curing and testing, or protected and cured in place if the effects of job-curing conditions are to be measured. On occasion, grout has been withdrawn from the mixer or agitator, as it is being fed to the pumps and taken in containers to a field laboratory for the preparation of cylinders. In such cases, the grout should be pumped into the cylinders within about 15 minutes of the time when it is withdrawn.

If cores are desired for strength testing, they should be taken and tested in accordance with ASTM C 42. It has been shown that properly made PA cylinders bear a close relationship to cores taken from the PA concrete in place, as indicated in Fig. 7.11 of ACI 304R.

CHAPTER 7—CONCLUSION

7.1—Economics

Whether PA concrete construction costs more or less than concrete that is conventionally mixed and placed depends on each situation; however, some general comments can be made. For PA concrete, some 60% of the material—the coarse aggregate—is placed directly in the forms. Only 40%—the cementitious material, fine aggregate, admixtures, and water—goes through a mixing and pumping procedure. Therefore, PA concrete has or may have a cost advantage where coarse aggregate is readily placeable in the forms. Favorable situations include open-water structures accessible to self-unloading craft, clamshell unloading from barges, or bottom-dump barges. The same applies to land-based structures into which the aggregate may be deposited by bulk handling equipment.

Because coarse aggregate grading is not critical, except for the minimum particle size, it is occasionally feasible to process aggregate as it is being excavated, and place it in the forms immediately. Then the grout can be mixed and pumped from a convenient location. In deep mines in South Africa, for example, forms for lining pump chambers were filled with hand-selected rock from a nearby heading. Grout was mixed at the top of a nearby shaft, dropped 2500 to 3000 ft (760 to 910 m) through a l-1/2 in. (40 mm) pipe into an agitator, and then pumped varying distances to the forms. This method was an economical solution that did not interfere with the elevators that were needed for normal mine operations. In bridge pier encasements, it is often difficult, expensive, or both, to dewater or maintain a dewatered condition within the form or cofferdam when dewatering is required for inspection and preparation. Inward water leakage during concrete placement, whether from the bottom or through the forms, will damage the concrete. When the PA concrete method is employed, the forms may be flooded on completion of the preparatory work and filled with coarse aggregate. Then, when the grout is pumped, any water leakage that does occur will be outward.

For column, beam, and surface repairs, the PA concrete method is commonly more expensive than conventionally or pneumatically placed concrete because forms must be tighter and because PA concrete placement requires two operations. It is up to the engineer and the owner to decide whether the bond, durability, or other properties of the PA concrete in place are worth the added cost.

With respect to heavyweight concrete for nuclear biological shielding, Oak Ridge National Laboratory[12] has stated that wherever there is adequate space for placing low-slump concrete, conventionally mixed and placed concrete should generally be used, but where embedded items require higher slump which may result in segregation, the PA method should be considered. Refer to ACI 304.3R for cost comparisons.

In the case of large monolithic placements, the economics will depend largely on the location of the work with respect to the supply of concrete and on design considerations. Where large, thick slabs are required and an adequate supply of conventional concrete is available, standard placement will normally be used. If concrete is not available, the PA method may be less costly than constructing a plant for concrete on site. Moreover, if the slab is heavily reinforced top and bottom, positioning the reinforcing bars on the coarse aggregate as it is placed may be more economical than supporting the bars above the ground. Vertical placements of PA concrete, such as those at Barker Dam (mentioned previously in this report), may also be relatively economical and the only practical method for accomplishing the work.

There are placement situations where factors other than cost may dictate the PA construction method. One such situation was where the steel reinforcing bars were so closely spaced that vibrators could not be inserted or withdrawn. This precluded the use of high-slump concrete. PA concrete or nonshrink grout were the only alternatives. In addition, the nonshrink grout posed a heat-of-hydration problem that was unacceptable, so PA concrete was selected as the method used.

7.2—Closure

The PA method of placing concrete has been used in a wide variety of applications over the past 68 years. In some places, the method was by far the most economical. In others, favorable properties were the principal reasons for its use.

CHAPTER 8—REFERENCES

8.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

116R Cement and Concrete Terminology
201.2R Guide to Durable Concrete
207.4R Cooling and Insulating Systems for Mass Concrete
304R Guide for Measuring, Mixing, Transporting, and Placing Concrete
304.3R Heavyweight Concrete: Measuring, Mixing, Transporting, and Placing
306R Cold Weather Concreting
308.1 Standard Specification for Curing Concrete
309.2R Identification and Control of Visible Effects of Consolidation on Formed Concrete Surfaces
318 Building Code Requirements for Structural Concrete
347 Guide to Formwork for Concrete

ASTM International

C 33 Standard Specification for Concrete Aggregates
C 42 Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 150 Standard Specification for Portland Cement
C 230 Standard Specification for Flow Table for Use in Tests of Hydraulic Cement
C 260 Standard Specification for Air-Entraining Admixtures for Concrete
C 494 Standard Specification for Chemical Admixtures for Concrete
C 595 Standard Specification for Blended Hydraulic Cements
C 618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
C 937 Standard Specification for Grout Fluidifier for Pre-placed-Aggregate Concrete
C 938 Standard Practice for Proportioning Grout Mixtures for Preplaced-Aggregate Concrete
C 939 Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method)
C 940 Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory
C 942 Standard Test Method for Compressive Strength of Grouts for Preplaced-Aggregate Concrete in the Laboratory
C 943 Standard Practice for Making Test Cylinders and Prisms for Determining Strength and Density of Pre-placed-Aggregate Concrete in the Laboratory
C 953 Standard Test Method for Time of Setting of Grouts for Preplaced-Aggregate Concrete in the Laboratory
D 98 Standard Specification for Calcium Chloride

These publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, Mich. 48333-9094

ASTM International
100 Barr Harbor Dr.
West Conshohocken, Pa. 19428-2959

8.2—Cited references

1. *Concrete Manual*, Eighth Edition, U. S. Bureau of Reclamation, Denver, Colo., 1981.

2. Keener, K. B., "Erosion Causes Invert Break in Boulder Dam Spillway Tunnel," *Engineering News-Record*, Nov. 18, 1943.

3. "Standard Practice for Concrete (EM 11 10-2-2000)," Department of the Army, Office of Chief of Engineers, Washington, D.C., Nov. 1971.

4. Davis, R. E., Jr., and Haltenhoff, C. E., "Mackinac Bridge Pier Construction," ACI JOURNAL, *Proceedings* V. 53, No. 6, Dec. 1956, pp. 581-595.

5. "Investigation of the Suitability of Prepakt for Mass and Rein-forced Concrete Structures," *Technical Memorandum* No. 6-330, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Aug. 1954.

6. Davis, H. E., "High-Density Concrete for Shielding Atomic Energy Plants," ACI JOURNAL, *Proceedings* V. 54, No. 11, May 1958, pp. 965-977.

7. Davis, R. E., "Prepakt Method of Concrete Repair," ACI JOURNAL, *Proceedings* V. 57, No. 2, Aug. 1960, pp. 155-172.

8. Klein, A. M., and Crockett, J. H. A., "Design and Construction of a Fully Vibration-Controlled Forging Hammer Foundation," ACI JOURNAL, *Proceedings* V. 49, No. 29, Jan. 1953, pp. 421-444.

9. "Evaluation and Repair of Concrete Structures," EM 11 lO-2-2002, Office, Chief of Engineers, U.S. Army, Washington D.C., July 1986.

10. Tynes, W. O., and McDonald, J. E., "Investigation of Resistance of Preplaced-Aggregate Concrete to Freezing and Thawing," *Miscellaneous Paper* C-68-6, U.S. Army Waterways Experiment Station, Vicksburg, Miss., 1968.

11. Civil Works Construction Guide Specification CW-03362, "Preplaced Aggregate Concrete," Department of the Army Corps of Engineers' Office of the Chief of Engineers, July 1983.

12. Tirpak, E. G., "ORNL-1739, Report on Design and Placement Techniques of Barite Concrete for Reactor Biological Shields," U.S. Atomic Energy Commission, Technical Information Service, Oak Ridge, May 1954.

13. Narrow, L., "Barite Aggregate and Grout Instrusion Method Used in Shield for Materials Testing Reactor," *Civil Engineering*, May 1954.

14. Tuthill, L. H., "Mineral Admixtures," *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, STP-169B, ASTM International, West Conshohocken, Pa., 1978, Chapter 46.

15. King, J. C., "Special Concretes and Mortars," *Handbook of Heavy Construction*, 2nd Edition, McGraw-Hill Book Co., New York, 1971, pp. 22-1 to 22-30.

16. Davis, R. E., Jr.; Johnson, G. D.; and Wendell, G. E., "Kemano Penstock Tunnel Liner Backfilled with Prepacked Concrete," ACI JOURNAL, *Proceedings* V. 52, No. 3, Nov. 1955, pp. 287-308.

17. Ciccolella, LCDR J. A., and Gault, R. D., "Sweets Point Light Established," *Engineer's Digest*, U.S. Coast Guard, Jan.-Feb. 1949.

18. "Shrinkage Control for Massive Beams, Crushed Ice Melts through Preplaced Aggregate," *Engineering News-Record*, Dec. 1955.