Guide for Measuring, Mixing, Transporting, and Placing Concrete

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This guide presents information on the handling, measuring, and batching of all the materials used in making normalweight, lightweight structural, and heavyweight concrete. It covers both weight and volumetric measuring; mixing in central mixture plants and truck mixers; and concrete placement using buckets, buggies, pumps, and conveyors. Underwater concrete placement and preplaced aggregate concrete are also covered in this guide, as well as procedures for achieving good quality concrete in completed structures.

Keywords: batching; conveying; heavyweight concretes; lightweight concretes; materials handling; mixing; placing; preplaced aggregate concrete; pumped concrete; tremie concrete; volumetric measuring; continuous mixing.

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CHAPTER 1—INTRODUCTION

1.1—Scope

This guide outlines procedures for achieving good results in measuring and mixing ingredients for concrete, transporting it to the site, and placing it. The first six chapters are general and apply to all types of projects and concrete. The following four chapters deal with preplaced-aggregate concrete, underwater placing, pumping, and conveying on belts. The concluding three chapters deal with heavyweight, radiation-shielding concrete, lightweight concrete, and volumetric-measuring and continuous-mixing concrete equipment.

1.2—Objective

When preparing this guide, ACI Committee 304 followed this philosophy:

- Progress in improvement of concrete construction is better served by the presentation of high standards rather than common practices;
- In many, if not most, cases, practices resulting in the production and placement of high-quality concrete can be performed as economically as those resulting in poor concrete. Many of the practices recommended in this document improve concrete uniformity as well as quality, yielding a smoother operation and higher production rates, both of which offset potential additional cost; and
- Anyone planning to use this guide should have a basic knowledge of the general practices involved in concrete work. If more specific information on measuring, mixing, transporting, and placing concrete is desired, the reader should refer to the list of references given at the end of this document, and particularly to the work of the U.S. Bureau of Reclamation (1981), the U.S. Department of Commerce (1966), the Corps of Engineers (1994a), ASTM C 94, ACI 311.1R, and ACI 318. To portray more clearly certain principles involved in achieving maximum uniformity, homogeneity, and quality of concrete in place, figures that illustrate good and poor practices are also included in this guide.

1.3—Other considerations

All who are involved with concrete work should know the importance of maintaining the unit water content as low as possible and still consistent with placing requirements (Mielenz 1994; Lovern 1966). If the water-cementitious materials ratio (*w*/*cm*) is kept constant, an increase in unit water content increases the potential for drying-shrinkage cracking, and with this cracking, the concrete can lose a portion of its durability and other favorable characteristics, such as monolithic properties and low permeability. Indiscriminate addition of water that increases the *w*/*cm* adversely affects both strength and durability.

The more a form is filled with the right combination of solids and the less it is filled with water, the better the resulting concrete will be. Use only as much cement as is required to achieve adequate strength, durability, placeability, workability, and other specified properties. Minimizing the cement content is particularly important in massive sections subject to restraint, as the temperature rise associated with the hydration of cement can result in cracking because of the change in volume (ACI 207.1R and 207.2R). Use only as much water and fine aggregate as is required to achieve suitable workability for proper placement and consolidation by means of vibration.

CHAPTER 2—CONTROL, HANDLING, AND STORAGE OF MATERIALS

2.1—General considerations

Coarse and fine aggregates, cement, pozzolans, and chemical admixtures should be properly stored, batched, and handled to maintain the quality of the resulting concrete.

2.2—Aggregates

Fine and coarse aggregates should be of good quality, uncontaminated, and uniform in grading and moisture content. Unless this is accomplished through appropriate specifications (ASTM C 33) and effective selection, preparation, and handling of aggregates (Fig. 2.1), the production of uniform concrete will be difficult (Mielenz 1994; ACI 221R).

2.2.1 *Coarse aggregate*—The coarse aggregate should be controlled to minimize segregation and undersized material. The following sections deal with prevention of segregation and control of undersized material.

2.2.1.1 *Sizes*—A practical method of minimizing coarse aggregate segregation is to separate the material into several size fractions and batch these fractions separately. As the range of sizes in each fraction is decreased and the number of size separations is increased, segregation is further reduced. Effective control of segregation and undersized materials is most easily accomplished when the ratio of maximum-to-minimum size in each fraction is held to not more than four for aggregates smaller than 1 in. (25 mm) and to two for larger sizes. Examples of some appropriate aggregate fraction groupings follow:

Example 1

Sieve designations
No. 8 to 3/8 in. (2.36 to 9.5 mm)
No. 4 to 1 in. (4.75 to 25.0 mm)
3/4 to 1-1/2 in. (19.0 to 37.5 mm)

Example 2

Sieve designations
No. 4 to 3/4 in. (4.75 to 19.0 mm)
3/4 to 1-1/2 in. (19.0 to 37.5 mm)
1-1/2 to 3 in. (37.5 to 75 mm)
3 to 6 in. (75 to 150 mm)

2.2.1.2 *Control of undersized material*—Undersized material for a given aggregate fraction is defined as material that will pass a sieve having an opening 5/6 of the nominal minimum size of each aggregate fraction (U.S. Bureau of Reclamation 1981). In Example 2 in Section 2.2.1.1, it would be material passing the following sieves: No. 5 (4.0 mm), 5/8 in. (16.0 mm), 1-1/4 in. (31.5 mm), and 2-1/2 in. (63 mm). For effective control of gradation, handling operations that do not increase the undersized materials in aggregates significantly before their use in concrete are essential (Fig. 2.1 and 2.2). The gradation of aggregate as it enters the concrete mixer should be uniform and within specification limits. Sieve analyses of coarse aggregate should be made with sufficient frequency to ensure that grading requirements are met. When two or more aggregate sizes are used, changes may be necessary in the proportions of the sizes to maintain the overall grading of the combined aggregate. When specification limits for grading cannot be met consistently, special handling methods should be instituted. Materials tend to segregate during transportation, so reblending may be necessary. Rescreening the coarse aggregate as it is charged to the bins at the batch plant to remove undersized materials will effectively eliminate undesirable fines when usual storage and handling methods are not satisfactory. Undersized materials in the smaller coarse aggregate fractions can be consistently reduced to as low as 2% by rescreening (Fig. 2.2). Although rescreening is effective in removing undersized particles, it will not regrade segregated aggregates.

2.2.2 *Fine aggregate (sand)*—Fine aggregate should be controlled to minimize variations in gradation, giving special attention to keeping finer fractions uniform and exercising care to avoid excessive removal of fines during processing.

If the ratio of fine-to-coarse aggregate is adjusted in accordance with ACI 211.1 recommendations for mixture proportioning, a wide range of fine aggregate gradings can be used (Tynes 1962). Variations in grading during production of concrete should be minimized, however, and the ASTM C 33 requirement that the fineness modulus of the fine aggregate be maintained within 0.20 of the design value should be met.

Give special attention to the amount and nature of material finer than the No. 200 screen (75 μm sieve). As stated in ASTM C 33, if this material is dust of fracture, essentially free of clay or shale, greater percentages of materials finer than the No. 200 screen (75 μm sieve) are permissible. If the reverse is true, however, permissible quantities should be significantly reduced. The California sand equivalent test is sometimes used to determine quantitatively the type, amount, and activity of this fine material (Mielenz 1994; ASTM D 2419). Excessive quantities of material finer than the No. 200 screen (75 μm sieve) increase the mixing-water requirement, rate of slump loss, and drying shrinkage, and therefore decrease strength.

Avoid blending two sizes of fine aggregate by placing alternate amounts in bins or stockpiles or when loading cars or trucks. Satisfactory results are achieved when different size fractions are blended as they flow into a stream from regulating gates or feeders. A more reliable method of control for a wide range of plant and job conditions, however, is to separate storage, handling, and batching of the coarse and fine fractions.

2.2.3 *Storage*—Stockpiling of coarse aggregate should be kept to a minimum because fines tend to settle and accumulate. When stockpiling is necessary, however, use of correct methods minimizes problems with fines, segregation, aggregate breakage, excessive variation in gradation, and contamination. Stockpiles should be built up in horizontal or gently sloping layers, not by end-dumping. Trucks, loaders, and dozers, or other equipment should not be operated on the stockpiles because, in addition to breaking the aggregate, they frequently track dirt onto the piles (Fig. 2.1).

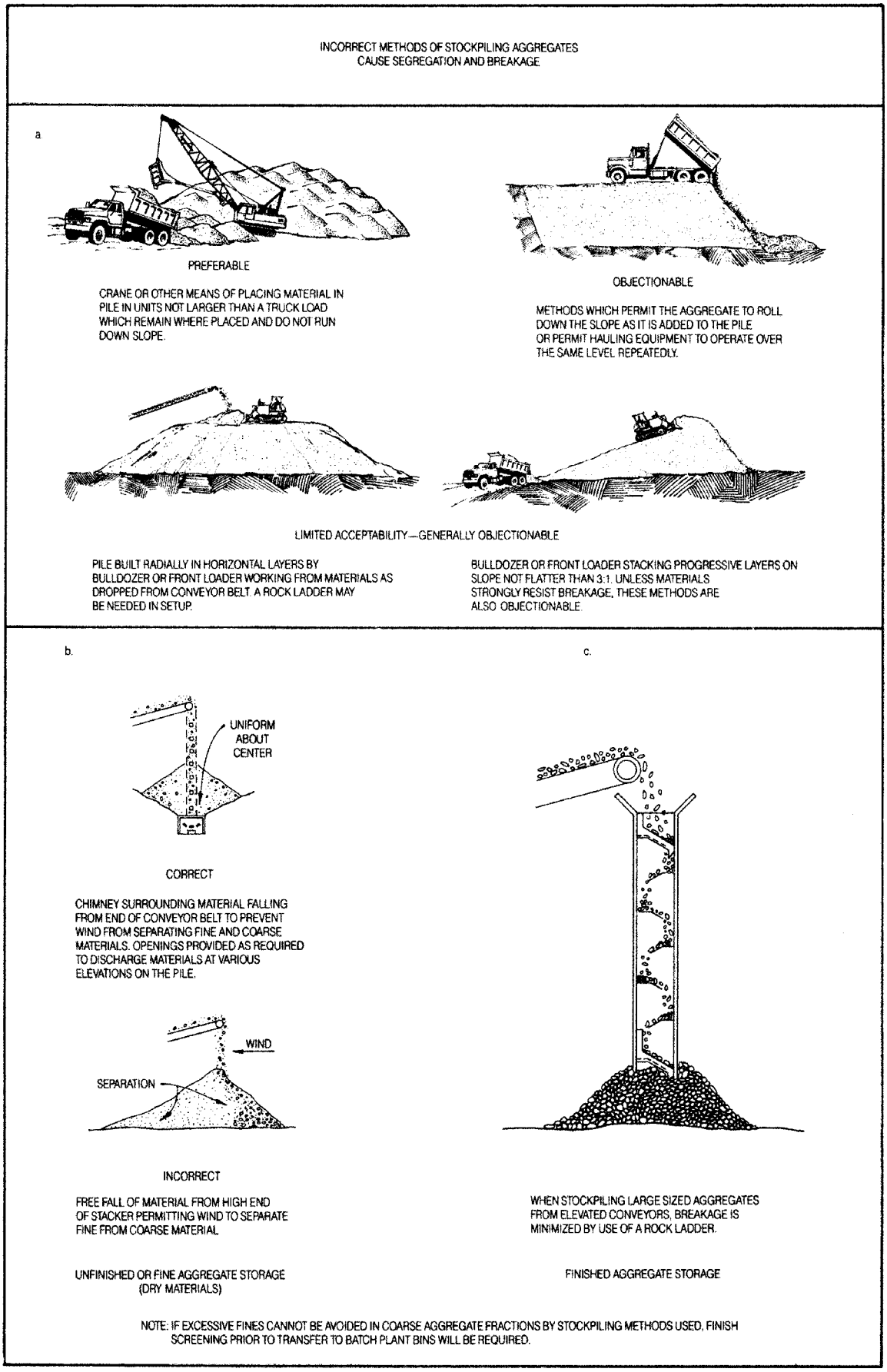

Fig. 2.1—Correct and incorrect methods of handling and storing aggregates.

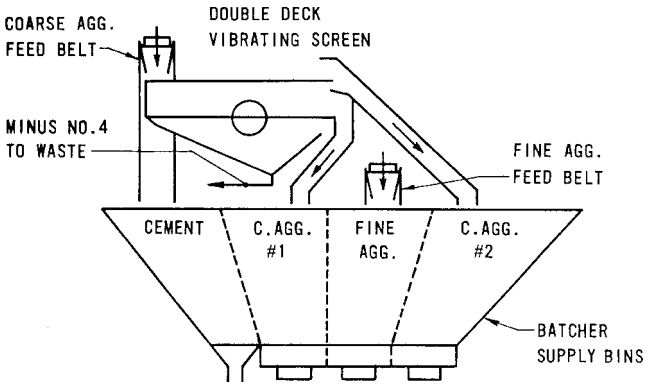

Fig. 2.2—Batching plant rescreen arrangement.

Provide a hard base with good drainage to prevent contamination from underlying material. Prevent overlap of the different sizes by suitable walls or ample spacing between piles. Protect dry, fine aggregate from being separated by the wind by using tarps or windbreaks. Do not contaminate stockpiles by swinging aggregate-filled buckets or clam-shovels over the other piles of aggregate sizes. In addition, fine aggregate that is transported over wet, unimproved haul roads can become contaminated with clay lumps. The source of this contamination is usually accumulation of mud between the tires and on mud flaps that is dislodged during dumping of the transporting unit. Bottom-dump trailers are particularly susceptible to causing contamination when they drive through discharged piles. Clay lumps or clay balls can usually be removed from the fine aggregate by placing a scalping screen over the batch plant bin.

Keep storage bins as full as practical to minimize breakage and changes in grading as materials are withdrawn. Deposit materials into the bins vertically and directly over the bin outlet (Fig. 3.1b). Pay particular attention to the storage of special concrete aggregates, including lightweight, high-density, and architectural-finish aggregates. Contamination of these materials has compounding effects on other properties of the concrete in which they are to be used (Chapters 11 and 12).

2.2.4 *Moisture control*—Ensure, as practically as possible, a uniform and stable moisture content in the aggregate as batched. The use of aggregates with varying amounts of free water is one of the most frequent causes for loss of control of concrete consistency (slump). In some cases, wetting the coarse aggregate in the stockpiles or on the delivery belts may be necessary to compensate for high absorption or to provide cooling. When this is done, the coarse aggregates should be dewatered to prevent transfer of excessive free water to the bins.

Provide adequate time for drainage of free water from fine aggregate before transferring it to the batch plant bins. The storage time required depends primarily on the grading and particle shape of the aggregate. Experience has shown that a free-moisture content of as high as 6%, and occasionally as high as 8%, can be stable in fine aggregate. Tighter controls, however, may be required for certain jobs. The use of moisture meters to indicate variations in the moisture of the fine aggregate as batched, and the use of moisture compensators for rapid batch weight adjustments, can minimize the influence of moisture variations in the fine aggregate (Van Alstine 1955, Lovern 1966).

2.2.5 *Samples for test*—Samples representing the various aggregate sizes batched should be obtained as closely as possible to the point of their introduction into the concrete. The difficulty in obtaining representative samples increases with the size of the aggregate. Therefore, sampling devices require careful design to ensure meaningful test results. Methods of sampling aggregates are outlined in detail in ASTM D 75.

Maintaining a running average of the results of the five to 10 previous gradation tests, dropping the results of the oldest and adding the most recent to the total on which the average is calculated, is good practice. This average gradation can then be used for both quality control and for proportioning purposes.

2.3—Cement

All cement should be stored in weathertight, properly ventilated structures to prevent absorption of moisture. Storage facilities for bulk cement should include separate compartments for each type of cement used. The interior of a cement silo should be smooth, with a minimum bottom slope of 50 degrees from the horizontal for a circular silo and 55 to 60 degrees for a rectangular silo. Silos should be equipped with nonclogging air-diffuser flow pads through which small quantities of dry, oil-free, low-pressure air can be introduced intermittently at approximately 3 to 5 psi (20 to 35 kPa) to loosen cement that has settled tightly in the silos. Storage silos should be drawn down frequently, preferably once per month, to prevent cement caking.

Each bin compartment from which cement is batched should include a separate gate, screw conveyor, air slide, rotary feeder, or other conveyance that effectively allows both constant flow and precise cutoff to obtain accurate batching of cement.

Make sure cement is transferred to the correct silo by closely monitoring procedures and equipment. Fugitive dust should be controlled during loading and transferring.

Bags of cement should be stacked on pallets or similar platforms to permit proper circulation of air. For a storage period of less than 60 days, stack the bags no higher than 14 layers, and for longer periods, no higher than seven layers. As an additional precaution the oldest cement should be used first.

2.4—Ground slag and pozzolans

Fly ash, ground slag, or other pozzolans should be handled, conveyed, and stored in the same manner as cement. The bins, however, should be completely separate from cement bins without common walls that could allow the material to leak into the cement bin. Ensure that none of these materials is loaded into a cement bin on delivery.

2.5—Admixtures

Most chemical admixtures are delivered in liquid form and should be protected against freezing. If liquid admixtures are frozen, they should be properly reblended before they are used in concrete. Manufacturers' recommendations should be followed.

Long-term storage of liquid admixtures in vented tanks should be avoided. Evaporation of the liquid could adversely affect the performance of the admixture (ACI 212.3R).

Table 3.1.2—Typical batching tolerances

Ingredient	Batch weights greater than 30% of scale capacity		Batch weights less than 30% of scale capacity	
	Individual batching	Cumulative batching	Individual batching	Cumulative batching
Cement and other cementitious materials	±1% of required mass or ±0.3% of scale capacity, whichever is greater		Not less than required weight or 4% more than required weight	
Water (by volume or weight), %	±1	Not recommended	±1	Not recommended
Aggregates, %	±2	±1	±2	±0.3% of scale capacity or ±3% of required cumulative weight, whichever is less
Admixtures (by volume or weight), %	±3	Not recommended	±3	Not recommended

2.6—Water and ice

Water for concrete production can be supplied from city or municipal systems, wells, truck wash-out systems, or from any other source determined to be suitable. If questionable, the quality of the water should be tested for conformance with the requirements given in ASTM C 94. Concrete made with recycled wash water can show variations in strength, setting time, and response to air-entraining and chemical admixtures. Recycled wash water may be required to meet chemical requirements of ASTM C 94. Compensation may be necessary for the solids in recycled water to maintain yield and total water content in the concrete.

The water batcher and the water pipes should be leak-free.

If ice is used, the ice facilities, including the equipment for batching and transporting to the mixer, should be properly insulated to prevent the ice from melting before it is in the mixer.

2.7—Fiber reinforcement

Synthetic fiber reinforcement is available in one cubic yard (one cubic meter) or multicubic yard (cubic meter) increments from most manufacturers. These prepackaged units should be readily accessible so they can be added directly to the mixer during the batching process.

Steel fibers are packaged in various sizes; the most common are 50 or 100 lb (23 or 45 kg) increments. Appropriate equipment should be used to disperse the fibers into the mixer to minimize the potential for the development of fiber balls. Steel fibers should be stored so that they are not exposed to moisture or other foreign matter. For more information on working with steel fibers, see ACI 544.3R.

CHAPTER 3—MEASUREMENT AND BATCHING

3.1—General requirements

3.1.1 *Objectives*—An important objective in producing concrete is to achieve uniformity and homogeneity, as indicated by physical properties such as unit weight, slump, air content, strength, and air-free unit weight of mortar in individual batches and successive batches of the same mixture proportions (U.S. Department of Reclamation 1981, U.S. Department of Commerce 1966, Bozarth 1967, ASTM C 94, Corps of Engineers 1994b). During measurement operations, aggregates should be handled so that the desired grading is maintained, and all materials should be measured within the tolerances acceptable for desired reproducibility of the selected concrete mixture. Another important objective of successful batching is the proper sequencing and blending of the ingredients (U.S. Department of Commerce 1966, Bozarth 1967). Visual observation of each material being batched is helpful in achieving this objective.

3.1.2 *Tolerances*—Most engineering organizations, both public and private, issue specifications containing detailed requirements for manual, semiautomatic, partially automatic, and automatic batching equipment for concrete (U.S. Bureau of Reclamation 1981, Corps of Engineers 1994b, ASTM C 94, AASHTO 1993). Batching equipment currently marketed will operate within the usual specified batch-weight tolerances when the equipment is maintained in good mechanical condition. The "Concrete Plant Standards of the Concrete Plant Manufacturers Bureau" (Concrete Plant Manufacturers Bureau 1996a) and the "Recommended Guide Specifications for Batching Equipment and Control Systems in Concrete Batch Plants" (Concrete Plant Manufacturers Bureau 1996b) are frequently used for specifying batching and scale accuracy. Batching tolerances commonly used are given in Table 3.1.2.

Other commonly used requirements include: beam or scale divisions of 0.1% of total capacity and batching interlock of 0.3% of total capacity at zero balance (Concrete Plant Manufacturers Bureau 1996a); quantity of admixture weighed never to be so small that 0.4% of full scale capacity exceeds 3% of the required weight; isolation of batching equipment from plant vibration; protection of automatic controls from dust and weather; and frequent checking and cleaning of scale and beam pivot points. With good inspection and plant operation, batching equipment can be expected to perform consistently within the required tolerances.

3.2—Bins and weigh batchers

Batch plant bins and components should be of adequate size to accommodate the productive capacity of the plant. Compartments in bins should separate the various concrete materials, and the shape and arrangement of aggregate bins should be conducive to the prevention of aggregate segregation and breakage. The aggregate bins should be designed so that material cannot hang up in the bins or spill from one compartment to another.

Weigh batchers should be charged with easily operated clamshell or undercut radial-type bin gates. Gates used to charge semiautomatic and fully automatic batchers should be power-operated and equipped with a suitable dribble control to allow the desired weighing accuracy. Weigh batchers should be accessible for obtaining representative samples, and they should be arranged to obtain the proper sequencing and blending of aggregates during charging of the mixer.

Illustrations showing proper and improper design and arrangement of batch plant bins and weigh batchers are given in Fig. 3.1.

3.3—Plant type

Factors affecting the choice of the batching systems are: 1) size of job; 2) required production rate; and 3) required

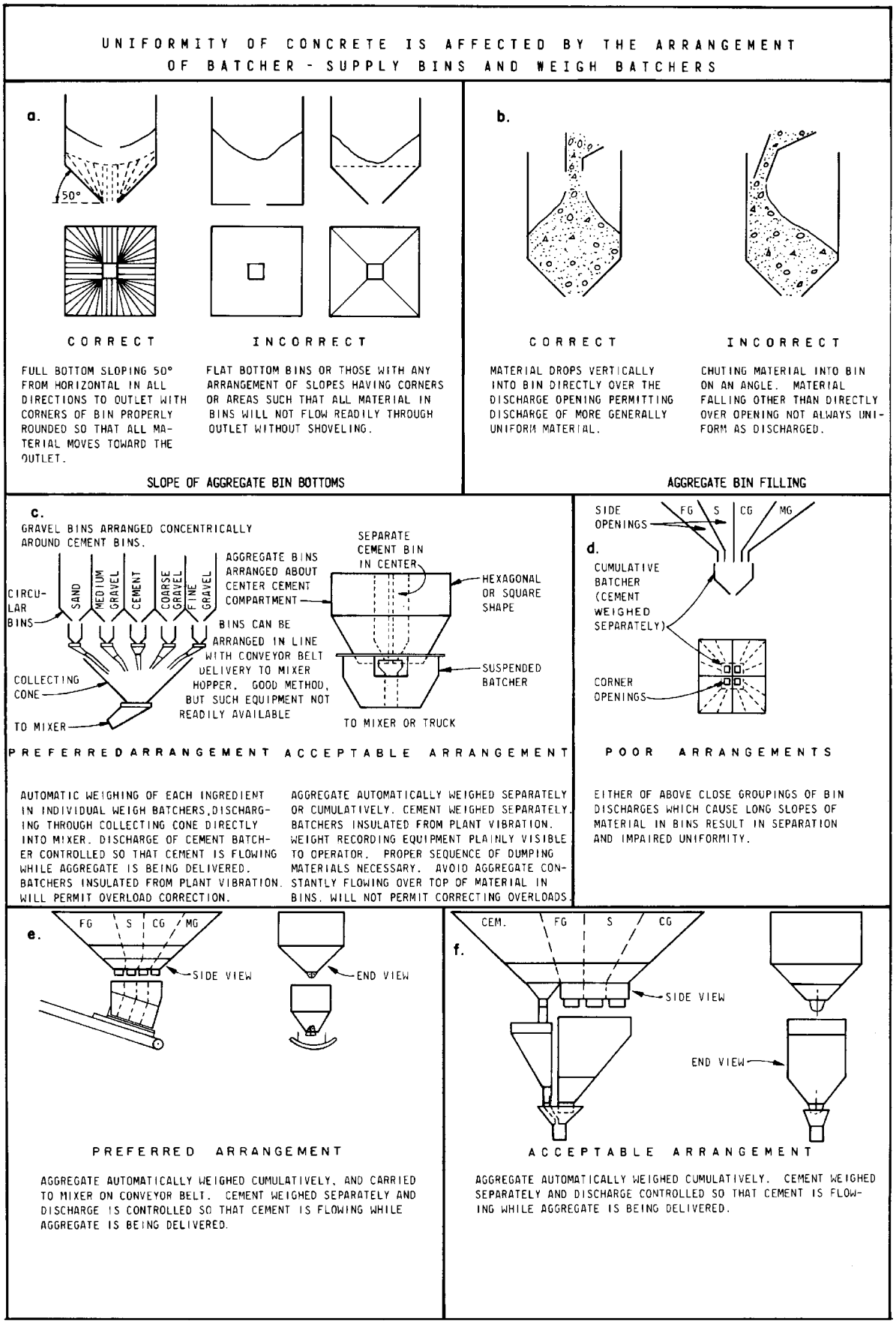

Fig. 3.1—Correct and incorrect methods of batching.

standards of batching performance. The production capacity of a batch plant is determined by a combination of the materials handling system, bin size, batcher size, and mixer size and number.

Available weigh batch equipment falls into four general categories: manual; partially automatic; semiautomatic; and fully automatic (Concrete Plant Manufacturers Bureau 1996a).

3.3.1 *Manual weigh batching*—As the name implies, all operations of weighing and batching of the concrete ingredients are controlled manually. Manual plants are acceptable for small jobs having low batching-rate requirements. As the job size increases, automation of batching operations is rapidly justified. Attempts to increase the capacity of manual plants by rapid batching can result in excessive weighing inaccuracies.

3.3.2 *Partially automatic weigh batching*—A partially automatic system consists of a combination of batching controls where at least one of the controls for weighing either cement or aggregates is either semiautomatic or automatic as described as follows. Weighing of the remaining materials is manually controlled and interlocking of the batching system to any degree is optional. This system can also lack accuracy when rapid batching is required.

3.3.3 *Semiautomatic weigh batching*—In this system, aggregate-bin gates for charging are opened by manually operated buttons or switches. Gates are closed automatically when the designated weight of material has been delivered. With satisfactory plant maintenance, the batching accuracy should meet the tolerances given in Section 3.1.2. The system should contain interlocks that prevent batcher charging and discharging from occurring simultaneously. In other words, when the batcher is being charged, it cannot be discharged, and when it is being discharged, it cannot be charged. Visual confirmation of the scale reading for each material being weighed is essential.

3.3.4 *Automatic weigh batching*—Automatic weigh batching of all materials is activated by a single starter switch. Interlocks, however, interrupt the batching cycle when the scale does not return to 0.3% of zero balance or when preset weighing tolerances detailed in Section 3.1.2 are exceeded.

3.3.4.1 *Cumulative automatic weigh batching*—Interlocked sequential controls are required for this type of batching. Weighing will not begin, and it will be automatically interrupted when preset tolerances in any of the successive weighings exceed values such as those given in Section 3.1.2. The charging cycle will not begin when the batcher discharge gate is open, and the batcher discharge cycle will not begin when batcher charging gates are open or when any of the indicated material weights is not within applicable tolerances. Presetting of desired batch weights is completed by such devices as punched cards, digital switches, or rotating dials and computers. Setting of weights, starting the batch cycle, and discharging the batch are all manually controlled. Mixture and batch-size selectors, aggregate moisture meters, manually controlled fine aggregate moisture compensators, and graphic or digital devices for recording the batch weight of each material are required for good plant control (Van Alstine 1955; Lovern 1966). This type of batching system provides greater accuracy for high-speed production than either the manual or semiautomatic systems.

A digital recorder can have a single measuring device for each scale or a series of measuring devices can record on the same tape or ticket. This type of recorder should reproduce the reading of the scale within 0.1% of the scale capacity or one increment of any volumetric batching device. A digital batch-documentation recorder should record information on each material in the mixture along with the concrete mixture identification, size of batch, and production facility identification. Required information can be preprinted, written, or stamped on the document. The recorder should identify the load by a batch-count number or a ticket serial number. The recorder, if interlocked to an automatic batching system, should show a single indication of all batching systems meeting zero or empty balance interlocks. All recorders should produce two or more tickets containing the information stated previously and also leave space for the identification of the job or project, location of placement, sand moisture content, delivery vehicle, driver's signature, purchaser's representative's signature, and the amount of water added at the project site.

3.3.4.2 *Individual automatic weigh batching*—This system provides separate scales and batchers for each aggregate size and for every other material batched. The weighing cycle is started by a single start switch, and individual batchers are charged simultaneously. Interlocks for interrupting weighing and discharge cycles when tolerances are exceeded, mixture selectors, aggregate moisture meters and compensators, and recorders differ only slightly from those described for cumulative automatic batching systems.

3.3.5 *Volumetric batching*—When aggregates or cementitious materials are batched by volume, it is normally a continuous operation coupled with continuous mixing. Volumetric batching and continuous mixing are covered in Chapter 13.

3.4—Cementitious materials

3.4.1 *Batching*—For high-volume production requiring rapid and accurate batching, bulk cementitious materials should be weighed with automatic, rather than semiautomatic or manual, equipment. All equipment should provide access for inspection and permit sampling at any time. The bins and weigh batchers should be equipped with aeration devices, vibrators, or both to aid in the smooth and complete discharge of the batch. Return to zero and weighing tolerance interlocks described in Section 3.1.2 should be used. Cement should be batched separately and kept separate from all ingredients before discharging. When both cement and pozzolan or slag are to be batched, separate silos should be used. They can be batched cumulatively, however, if the cement is weighed first.

3.4.2 *Discharging*—Effective precautions should be taken to prevent loss of cementitious materials during mixer charging. At multiple-stop plants where materials are charged separately, losses can be minimized by discharging the cementitious materials through a rubber drop chute. At one-stop plants, cement and pozzolan can be successfully charged along with the aggregate through rubber telescopic dropchutes. For plant mixers, a pipe should be used to discharge the cementitious materials to a point near the center of the mixer after the water and aggregates have started to enter the mixer. Proper and consistent sequencing and blending of the various ingredients into the mixer during the charging operation will contribute significantly toward the maintenance of batch-to-batch uniformity and, perhaps, reduced mixing time when confirmed by mixer performance

tests (U.S. Department of Commerce 1966, Gaynor and Mullarky 1975, ASTM C 94).

3.5—Water and ice measurement

3.5.1 *Batching equipment*—On large jobs and in central batching and mixing plants where high-volume production is required, accurate water and ice measurement can only be obtained by the use of automatic weigh batchers or meters. Equipment and methods used should, under all operating conditions, be capable of routine measurement within the 1% tolerance specified in Section 3.1.2. Tanks or vertical cylinders with a center-siphon discharge can be permitted as an auxiliary part of the weighing, but should not be used as the direct means of measuring water. For accurate measurement, a digital gallon (liter) meter should be used. All equipment for water measurement should be designed for easy calibration so that accuracy can be quickly verified. Ice-batching equipment should be insulated to avoid melting the ice.

3.5.2 *Aggregate moisture determination and compensation*—Measurement of the correct total mixing water depends on knowing the quantity and variation of moisture in the aggregate (particularly in the fine aggregate) as it is batched. Aggregate that is not saturated surface dry will absorb mixture water from the concrete. Fine aggregate moisture meters are frequently used in plants and when properly maintained do satisfactorily indicate changes in fine aggregate moisture content. Use of moisture meters in fine sizes of coarse aggregate is also recommended if these materials vary in moisture content. Moisture meters should be calibrated to oven-dried samples for optimum consistency of readings. Moisture meters should be recalibrated monthly or whenever the slump of the concrete produced is inconsistent.

Moisture-compensating equipment can also be used that can reproportion water and fine aggregate weights for a change in aggregate moisture content, with a single setting adjustment. Compensators are usually used on the fine aggregate, but occasionally are also used on the small coarse aggregate size fractions. The moisture setting on the compensators is made manually with calibration dials, buttons, or levers. The use of moisture compensators is recommended when used in conjunction with calibrated moisture meters or regularly performed conventional moisture-control tests. Under these conditions, compensators can be useful tools for maintaining satisfactory control of the fine aggregate and the mixing water content.

Most computer-controlled batching systems now have software that interlocks moisture meters or compensating equipment with the measuring of fine aggregate and water. Readings are taken automatically and incorporated into the batching of these ingredients. Some systems work with an individual reading, whereas others can continuously record moisture as the fine aggregate is batched. Regardless of the system used, the software should impose user-defined upper and lower moisture limits and alert the operator when moisture values are outside those limits. Proper maintenance and calibration of equipment is essential to satisfactory performance and consistent production of concrete.

3.5.3 *Total mixing water*—In addition to the accurate weighing of added water, uniformity in the measurement of total mixing water involves control of such additional water sources as mixer wash water, ice, and free moisture in aggregates. One specified tolerance (ASTM C 94) for accuracy in measurement of total mixing water from all sources is ± 3%.

The operating mechanism in the water measuring devices should be such that leakage (dribbling or water trail) will not occur when the valve is closed. Water tanks on truck mixers or other portable mixers should be constructed so that the indicating device will register, within the specified accuracy, the quantity of water discharged, regardless of the inclination of the mixer.

3.6—Measurement of admixtures

Batching tolerances (Section 3.1.2) and charging and discharge interlocks described previously for other mixture ingredients should also be provided for admixtures. Batching and dispensing equipment should be readily capable of calibration. When timer-activated dispensers are used for large-volume admixtures such as calcium chloride, a container with a sight tube calibrated to show admixture quantity (usually referred to as a “calibration tube”) should be used to allow visual confirmation of the volume being batched. In practice, calibration tubes are usually installed for all liquid admixtures.

Refer to ACI 212.3R for additional information on recommended practices in the use and dispensing of admixtures in concrete.

3.7—Measurement of materials for small jobs

If the concrete volume on a job is small, establishing and maintaining a batch plant and mixer at the construction site may not be practical. In such cases, using ready-mixed concrete or mobile volumetric batching and continuous mixing equipment may be preferable. If neither is available, precautions should be taken to properly measure and batch concrete materials mixed on the job site. Bags of cementitious materials should be protected from moisture and fractional bags should not be used unless they are weighed. The water-measuring device should be accurate and dependable, and the mixer capacity should not be exceeded.

3.8—Other considerations

In addition to accurate measurement of materials, correct operating procedures should also be used if concrete uniformity is to be maintained. Ensure that the batched materials are properly sequenced and blended so that they are charged uniformly into the mixture (U.S. Department of Commerce 1966; Bozarth 1967). Arrange the batching plant control room, if possible, with the plant operator’s station located in a position where the operator can closely and clearly see the scales and measuring devices during batching of the concrete, as well as the charging, mixing, and discharging of the mixtures without leaving the operating console. Some common batching deficiencies to be avoided are: overlapping of batches; loss of materials; loss or hanging up of a portion of one batch, or its inclusion with another.

CHAPTER 4—MIXING AND TRANSPORTING

4.1—General requirements

Thorough mixing is essential for the production of uniform, quality concrete. Therefore, equipment and methods should be capable of effectively mixing concrete materials containing the largest specified aggregate to produce uniform mixtures of the lowest slump practical for the work. Recommendations on maximum aggregate size and slump to be used for various types of construction are given in ACI 211.1 for concretes made with ASTM C 150 and C 595M cements, and in ACI

223R for concretes made with ASTM C 845 expansive hydraulic cements. Sufficient mixing, transporting, and placing capacity should be provided so that unfinished concrete lifts can be maintained plastic and free of cold joints.

4.2—Mixing equipment

Mixers can be stationary parts of central mixture plants or of portable plants. Mixers can also be truck mounted. Satisfactorily designed mixers have a blade or fin arrangement and drum shape that ensure an end-to-end exchange of materials parallel to the axis of rotation or a rolling, folding, and spreading movement of the batch over itself as it is being mixed. For additional descriptions of some of the various mixer types, refer to the publications of the Concrete Plant Manufacturers Bureau (1996c) and of the Truck Mixer Manufacturers Bureau (1996).

The more common types of mixing equipment are:

4.2.1 *Tilting drum mixer*—This is a revolving drum mixer that discharges by tilting the axis of the drum. In the mixing mode, the drum axis can be either horizontal or at an angle.

4.2.2 *Nontilting drum mixer*—This is a revolving drum mixer that charges, mixes, and discharges with the axis of the drum horizontal.

4.2.3 *Vertical shaft mixer*—This is often called a turbine or pan-type mixer. Mixing is accomplished with rotating blades or paddles mounted on a vertical shaft in either a stationary pan or one rotating in the opposite direction to the blades. The batch can be easily observed and rapidly adjusted, if necessary. Rapid mixing and low overall profile are other significant advantages. This type of mixer does an excellent job of mixing relatively dry concretes and is often used for laboratory mixing and by manufacturers of concrete products.

4.2.4 *Pugmill mixers*—These mixers are defined in ACI 116R as "a mixer having a stationary cylindrical mixing compartment, with the axis of the cylinder horizontal, and one or more rotating horizontal shafts to which mixing blades or paddles are attached." Although this is an accurate definition, there are many types, styles, and configurations. Pugmills can have single or double shafts. They can have a curved blade configuration or a paddle configuration that is vertical to the shaft. In either case, they are designed to fold and move the concrete from one end of the pugmill to the other.

These mixers are suitable for harsh, stiff concrete mixtures. They have primarily been used in the production of concrete block units, cement-treated bases, and roller compacted concrete. Newer versions of these mixers are used in the production of normal- and high-strength concrete, with slumps of up to 8 in. (200 mm).

4.2.5 *Truck mixers*—There are two types of revolving drum truck mixers currently in use—rear discharge and front discharge. The rear-discharge, inclined-axis mixer predominates. In both, fins attached to the drum mix concrete in the mixing mode and also discharge the concrete when drum rotation is reversed.

4.2.6 *Continuous mixing equipment*—Two types of continuous mixing equipment are available. In the first type, all materials come together at the base of the mixing trough. Mixing is accomplished by a spiral blade rotated at a relatively high speed inside the enclosed trough, which is inclined at 15 to 25 degrees from the horizontal. These can be mobile, mounted either on a truck chassis or a trailer, or stationary. The second type is a continuous-feed pugmill mixer generally used for roller-compacted concrete and cement-treated base. Aggregates, cement, and fly ash are measured by weight or volume and fed into the charging end of the pugmill by variable-speed belts. Water is metered either from an attached tank or an outside source. Mixing is accomplished by paddles attached to one or two rotating horizontal shafts. The mixture is lifted and folded as it is moved from the charging end to the discharging end of the pugmill, where the completed mixture is discharged onto an elevated conveyor belt for easy loading into trucks. These types of continuous-feed mixers can be used for normal concretes as well. These would be considered semimobile plants as they are mounted on wheels and can be broken down for transport. Refer to Chapter 13 for additional information on continuous mixing equipment.

4.2.7 *Separate paste mixing*—Experimental work has shown that the mixing of cement and water into a paste before combining these materials with aggregates can increase the compressive strength of the resulting concrete (Mass 1989). The paste is generally mixed in a high-speed, shear-type mixer at a *w*/*cm* of 0.30 to 0.45 by mass. The premixed paste is then blended with aggregates and any remaining batch water, and final mixing is completed in conventional concrete mixing equipment.

4.3—Central-mixed concrete

Central-mixed concrete is mixed completely in a stationary mixer and then transferred to another piece of equipment for delivery. This transporting equipment can be a ready-mixed truck operating as an agitator, or an open-top truck body with or without an agitator. The tendency of concrete to segregate limits the distance it can be hauled in transporters not equipped with an agitator. If a truck mixer or a truck body with an agitator is used for central-mixed concrete, ASTM C 94 limits the volume of concrete charged into the truck to 80% of the drum or truck volume.

Sometimes the central mixer will partially mix the concrete with the final mixing and transporting being done in a revolving-drum truck mixer. This process is often called "shrink mixing" as it reduces the volume of the as-charged mixture. When using shrink mixing, ASTM C 94 limits the volume of concrete charged into the truck to 63% of the drum volume.

4.4—Truck-mixed concrete

Truck mixing is a process by which previously proportioned concrete materials from a batch plant are charged into a ready-mixed truck for mixing and delivery to the construction project. To achieve thorough mixing, total absolute volume of all ingredients batched in a revolving drum truck mixer should not exceed 63% of the drum volume (Truck Mixer Manufacturers Bureau 1996; ASTM C 94).

4.5—Charging and mixing

The method and sequence of charging mixers is of great importance in determining whether the concrete will be properly mixed. For central plant mixers, obtaining a preblending or ribboning effect by charging cement and aggregates simultaneously as the stream of materials flow into the mixer is essential (U.S. Department of Commerce 1966; Bozarth 1967; Gaynor and Mullarky 1975).

In truck mixers, all loading procedures should be designed to avoid packing of the material, particularly sand and cement,

in the head of the drum during charging. The probability of packing is decreased by placing approximately 10% of the coarse aggregate and water in the mixer drum before the sand and cement.

Generally, approximately 1/4 to 1/3 of the water should be added to the discharge end of the drum after all other ingredients have been charged. Water-charging pipes should be of proper design and of sufficient size so that water enters at a point well inside the mixer and charging is complete within the first 25% of the mixing time (Gaynor and Mullarky 1975). Refer to Section 4.5.3.1 for additional discussion of mixing water.

The effectiveness of chemical admixtures will vary depending upon when they are added during the mixing sequence. Follow the recommendations of the admixture supplier regarding when to add a particular product. Once the appropriate time in the sequence is determined, chemical admixtures should be charged to the mixer at the same point in the mixing sequence for every batch. Liquid admixtures should be charged with the water or on damp sand, and powdered admixtures should be ribboned into the mixer with other dry ingredients. When more than one admixture is used, each should be batched separately unless premixing is allowed by the manufacturer.

Synthetic fiber reinforcement can be added any time during the mixing process as long as at least 5 min of mixing occurs after the addition of the synthetic fibers.

4.5.1 *Central mixing*—Procedures for charging central mixers are less restrictive than those necessary for truck mixers because a revolving-drum central mixer is not charged as full as a truck mixer and the blades and mixing action are quite different. In a truck mixer, there is little folding action compared with that in a stationary mixer. Batch size, however, should not exceed the manufacturer's rated capacity as marked on the mixer name plate.

The mixing time required should be based on the ability of the mixer to produce uniform concrete throughout the batch and from batch to batch. Manufacturers' recommendations and other typical recommendations, such as 1 min for 1 yd^3 (3/4 m^3) plus 1/4 min for each additional cubic yard (cubic meter) of capacity can be used as satisfactory guides for establishing initial mixing time. Final mixing times, however, should be based on the results of mixer performance tests made at frequent intervals throughout the duration of the job (U.S. Bureau of Reclamation 1981; U.S. Department of Commerce 1966; ASTM C 94; CRD-C 55). The mixing time should be measured from the time all ingredients are in the mixer. Batch timers with audible indicators used in combination with interlocks that prevent under- or over-mixing of the batch and discharge before completion of a preset mixing time are provided on automatic plants and are recommended on manual plants. The mixer should be designed for starting and stopping under full-load conditions.

4.5.2 *Truck mixing*—Generally, 70 to 100 revolutions at mixing speed are specified for truck mixing. ASTM C 94 limits the total number of revolutions to a maximum of 300. This limits the grinding of soft aggregates, loss of slump, wear on the mixer, and other undesirable effects that can occur in hot weather. Final mixing can be done at the producer's yard, or, more commonly, at the project site.

If additional time elapses after mixing and before discharge, the drum speed is reduced to the agitation speed or stopped. Then, before discharging, the mixer should be operated at mixing speed for approximately 30 revolutions to enhance uniformity.

Mixer charging, mixing, and agitating speeds vary with each truck and mixer-drum manufacturer. ASTM C 94 requires that these speeds and the mixing and agitating capacity of each drum be shown on a plate attached to the unit.

Maximum transportation time can be extended by several different procedures. These procedures are often called dry batching and evolved to accommodate long hauls and unavoidable delays in placing by attempting to postpone the mixing of cement with water. When cement and damp aggregate come in contact with each other, however, free moisture on the aggregate results in some cement hydration. Therefore, materials cannot be held in this manner indefinitely.

In one method, the dry materials are batched into the ready-mixed truck and transported to the job site where all of the mixing water is added. Water should be added under pressure, preferably at both the front and rear of the drum with it revolving at mixing speed, and then mixing is completed with the usual 70 to 100 revolutions. The total volume of concrete that can be transported in truck mixers by this method is the same as for regular truck mixing, approximately 63% of the drum volume (Truck Mixer Manufacturers Bureau 1996, ASTM C 94).

Another approach to accommodate long hauls is to use extended-set admixtures. The concrete is mixed and treated with the admixture before leaving the plant. The admixture dosage is typically selected to wear off shortly after the concrete arrives at the placement site, allowing the concrete to set normally. In some instances, an accelerator is added to activate the concrete once it arrives at the placement site. Concrete has been transported over 200 miles (320 km) using this technique.

4.5.3 *Water*

4.5.3.1 *Mixing water*—The water required for proper concrete consistency (slump) is affected by variables such as amount and rate of mixing, length of haul, time of unloading, and ambient temperature conditions. In cool weather, or for short hauls and prompt delivery, problems such as loss or variation in slump, excessive mixing water requirements, and discharging, handling, and placing problems rarely occur. The reverse is true, however, when rate of delivery is slow or irregular, haul distances are long, and weather is warm. Loss of workability during warm weather can be minimized by expediting delivery and placement and by controlling the concrete temperature. Good communication between the batching plant and the placement site is essential for coordination of delivery. It may be necessary to use a retarder to prolong the time the concrete will respond to vibration after it is placed. When feasible, all mixing water should be added at the central or batch plant. In hot weather, however, it is better to withhold some of the mixing water until the mixer arrives at the job. With the remaining water added, an additional 30 revolutions at mixing speed is required to adequately incorporate the additional water into the mixture. When loss of slump or workability cannot be offset by these measures, the procedures described in Section 4.5.2. should be considered.

4.5.3.2 *Addition of water on the job*—The maximum specified or approved *w*/*cm* should never be exceeded.

If all the water allowed by the specification or approved mixture proportions has not been added at the start of mixing, it may be permissible, depending upon project specifica-

tions, to add the remaining allowable water at the point of delivery. Once part of a batch has been unloaded, however, it becomes impractical to determine what *w*/*cm* is produced by additional water.

The production of concrete of excessive slump or adding water in excess of the proportioned *w*/*cm* to compensate for slump loss resulting from delays in delivery or placement should be prohibited. Persistent requests for the addition of water should be investigated.

Where permitted, a high-range water-reducing admixture (superplasticizer) can be added to the concrete to increase slump while maintaining a low *w*/*cm* (Cement and Concrete Association 1976; Prestressed Concrete Institute 1981). Addition of the admixture can be made by the concrete supplier or the contractor by a variety of techniques. When this admixture is used, vibration for consolidation is reduced. In walls and sloping formed concrete, however, some vibration is necessary to remove air trapped in the form. Use of this admixture can also increase form pressure.

4.5.3.3 *Wash water*—Most producers find it necessary to rinse off the rear fins of the mixer between loads and wash and discharge the entire mixer only at the end of the day. Hot weather and unusual mixture proportions can require washing and discharge of wash water after every load. Rinse water should not remain in the mixer unless it can be accurately compensated for in the succeeding batch. Rinse water can be removed from the mixer by reversing the drum for 5 to 10 revolutions at medium speed. Pollution-control regulations make it increasingly difficult to wash out after every load and have created an interest in systems to reclaim and reuse both wash water and returned concrete aggregates.

ASTM C 94 describes the reuse of wash water based on prescribed tests. Particular attention is necessary when admixtures are being used because the required dosages can change dramatically. When wash water is used, admixtures should be batched into a limited quantity of clean water or onto damp sand.

Wash water can also be treated using extended-set admixtures. In this case, a limited amount of wash water is added to a drum after all solid materials are discharged. Typically 50 gal. (200 L) instead of the normal 500 gal. (2000 L) are used. The admixture is added to the drum and the drum is rotated to ensure that all surfaces are coated. This treated wash water can be left in the truck overnight or over a weekend. The next morning or after the weekend, concrete can be batched using the treated wash water as part of the mixing water. Given the small amount of the admixture used for this application, use of an activating admixture is not usually required.

4.6—Mixture temperature

Batch-to-batch uniformity of concrete from a mixer, particularly with regard to slump, water requirement, and air content, also depends on the uniformity of the concrete temperature. Controlling the maximum and minimum concrete temperatures throughout all seasons of the year is important.

Concrete can be cooled using ice, chilled mixing water, chilled aggregates, or liquid nitrogen. In-place concrete temperatures as low as 40 F (4 C) are not unusual.

Liquid nitrogen at a temperature of –320 F (–196 C) can be used to chill mixture water, aggregates, or concrete (Anon. 1977). Liquid nitrogen has been injected directly into central mixers, truck mixers, or both to achieve required concrete temperatures (Anon. 1988). Concrete can be warmed by using heated water, aggregates, or both. Recommendations for control of concrete temperatures are discussed in detail in ACI 305R and 306R.

4.7—Discharging

Mixers should be capable of discharging concrete of the lowest slump suitable for the structure being constructed, without segregation (separation of coarse aggregate from the mortar). Before discharge of concrete transported in truck mixers, the drum should again be rotated at mixing speed for about 30 revolutions to reblend possible stagnant spots near the discharge end into the batch.

4.8—Mixer performance

The performance of mixers is usually determined by a series of uniformity tests made on samples taken from two or three locations within the concrete batch after it has been mixed for a given time period (U.S. Bureau of Reclamation 1981, ASTM C 94 and CRD-C 55). Mixer performance requirements are based on allowable differences in test results of samples from any two locations or a comparison of individual locations with the average of all locations. The procedures published by Gaynor and Mullarky (1975) are an excellent reference.

Among the many tests used to check mixer performance, the following are the most common: air content; slump; unit weight of air-free mortar; coarse aggregate content; and compressive strength.

Another important aspect of mixer performance is batch-to-batch uniformity of the concrete, which is also affected by the uniformity of materials and their measurement as well as by the efficiency of the mixer. Visual observation of the concrete during mixing and discharge from the mixer is an important aid in maintaining a uniform mixture, particularly with a uniform consistency. Some consistency-recording meters, such as those operating from the amperage draw on the electric motor drives for revolving-drum mixers, have also proven to be useful. The most positive control method for maintaining batch-to-batch uniformity, however, is a regularly scheduled program of tests of the fresh concrete, including unit weight, air content, slump, and temperature. All plants should have facilities and equipment for conveniently obtaining representative samples of concrete for routine control tests in accordance with ASTM C 172. Although strength tests provide an excellent measure of the efficiency of the quality control procedures that are employed, the strength-test results are available too late to be of practical use in controlling day-to-day production.

4.9—Maintenance

Mixers should be properly maintained to prevent mortar and dry material leakage. Inner mixer surfaces should be kept clean and worn blades should be replaced. Mixers not meeting the performance tests referenced in Section 4.8 should be taken out of service until necessary maintenance and repair corrects their deficient performance.

4.10—General considerations for transporting concrete

4.10.1 *General*—Concrete can be transported by a variety of methods and equipment, such as pipeline, hose, conveyor belts, truck mixers, open-top truck bodies with and without

agitators, or buckets hauled by truck or railroad car. The method of transportation should efficiently deliver the concrete to the point of placement without losing mortar or significantly altering the concrete's desired properties associated with *w*/*cm*, slump, air content, and homogeneity. Various conditions should be considered when selecting a method of transportation, such as: mixture ingredients and proportions; type and accessibility of placement; required delivery capacity; location of batch plant; and weather conditions. These conditions can dictate the type of transportation best suited for economically obtaining quality in-place concrete.

4.10.2 *Revolving drum*—In this method, the truck mixer (Section 4.2.5) serves as an agitating transportation unit. The drum is rotated at charging speed during loading and is reduced to agitating speed or stopped after loading is complete. The elapsed time before discharging the concrete can be the same as for truck mixing and the volume carried can be increased to 80% of the drum capacity (ASTM C 94).

4.10.3 *Truck body with and without an agitator*—Units used in this form of transportation usually consist of an open-top body mounted on a truck, although bottom-dump trucks have been used successfully. The metal body should have smooth, streamlined contact surfaces and is usually designed for discharge of the concrete at the rear when the body is tilted. A discharge gate and vibrators mounted on the body should be provided at the point of discharge for control of flow. An agitator, if the truck body is equipped with one, aids in the discharge and ribbon-blends the concrete as it is unloaded. Water should never be added to concrete in the truck body because no mixing is performed by the agitator.

Use of protective covers for truck bodies during periods of inclement weather, proper cleaning of all contact surfaces, and smooth haul roads contribute significantly to the quality and operational efficiency of this form of transportation. The maximum delivery time specified is usually 30 to 45 min, although weather conditions can require shorter or permit longer times.

Trucks that have to operate on muddy haul roads should not be allowed to discharge directly on the grade or drive through the discharged pile of concrete.

4.10.4 *Concrete buckets on trucks or railroad cars*—This is a common method of transporting concrete from the batch plant to a location close to the placement area of a mass concrete placement. A crane then lifts the bucket to the final point of placement. Occasionally, transfer cars operating on railroad tracks are used to transport the concrete from the batch plant to buckets operating from cableways. Discharge of the concrete from the transfer cars into the bucket, which can be from the bottom or by some form of tilting, should be closely controlled to prevent segregation. Delivery time for bucket transportation is the same as for other nonagitating units—usually 30 to 45 min.

4.10.5 *Other methods*—Transporting of concrete by pumping methods and by belt conveyors are discussed in Chapters 9 and 10, respectively. Helicopter deliveries have been used in difficult-to-reach areas where other transporting equipment could not be used. This system usually employs one of the methods described previously to transport the concrete to the helicopter, which then lifts the concrete in a lightweight bucket to the placement area.

4.11—Returned concrete

Disposal of returned concrete is becoming more and more difficult for some producers. Two approaches for alleviating this problem are currently being used:

4.11.1 *Admixtures*—Extended-set admixtures were developed to address the need to hold returned concrete overnight. These admixtures are also used to hold concrete during the day for reuse on the same day.

The appropriate dosage of admixture is determined by the mixture characteristics, the quantity of concrete to be stabilized or held, and the length of time that the concrete is to be held. Depending on the length of time that the concrete is held, an accelerating admixture may be required. The stabilized concrete is usually blended with freshly batched concrete before being sold.

Various methods have been developed by concrete producers to handle and determine the volume of returned concrete. In some cases, all returned concrete is transferred at the end of a day to a single mixer for treatment and holding. Other producers have elected to handle the concrete on a truck-by-truck basis.

4.11.2 *Mechanical methods*—Equipment has been developed to process plastic, unused concrete returned to a plant. This equipment typically involves washing the concrete to separate it into two or more components. Some or all of the components are then reused in concrete production. The components can include coarse and fine aggregate, combined aggregate, and a slurry of cement and water, sometimes called gray water.

Although the processed components can often be reused in new concrete, a concrete producer should take care to ensure that these materials will not adversely affect the new concrete. Variations in aggregate grading can occur due to degradation of the previously used aggregate during mixing or reclaiming. Use of the slurry can affect strength and setting time. Conduct appropriate testing to verify that the concrete meets project requirements.

CHAPTER 5—PLACING CONCRETE

5.1—General considerations

This chapter presents guidelines for transferring concrete from the transporting equipment to its final position in the structure.

Placement of concrete is accomplished with buckets, hoppers, manual or motor-propelled buggies, chutes and drop pipes, conveyor belts, pumps, tremies, and paving equipment. Figure 5.1 and 5.2 show a number of handling and placing methods discussed in this chapter and give examples of both satisfactory and unsatisfactory construction procedures.

Placement of concrete by the preplaced aggregate method and by pumps and conveyors is discussed in Chapters 7, 9, and 10, respectively. In addition, placing methods specific to underwater, heavyweight, and lightweight concreting are noted in Chapters 8, 11, and 12, respectively. Another effective placement technique for both mortar and concrete is the shotcrete process. Thin layers are applied pneumatically to areas where forming is inconvenient or impractical, access or location provides difficulties, or normal casting techniques cannot be employed (ACI 506R).

Placing of concrete by the roller-compacted method is not covered in this guide. Refer to ACI 207.5R.

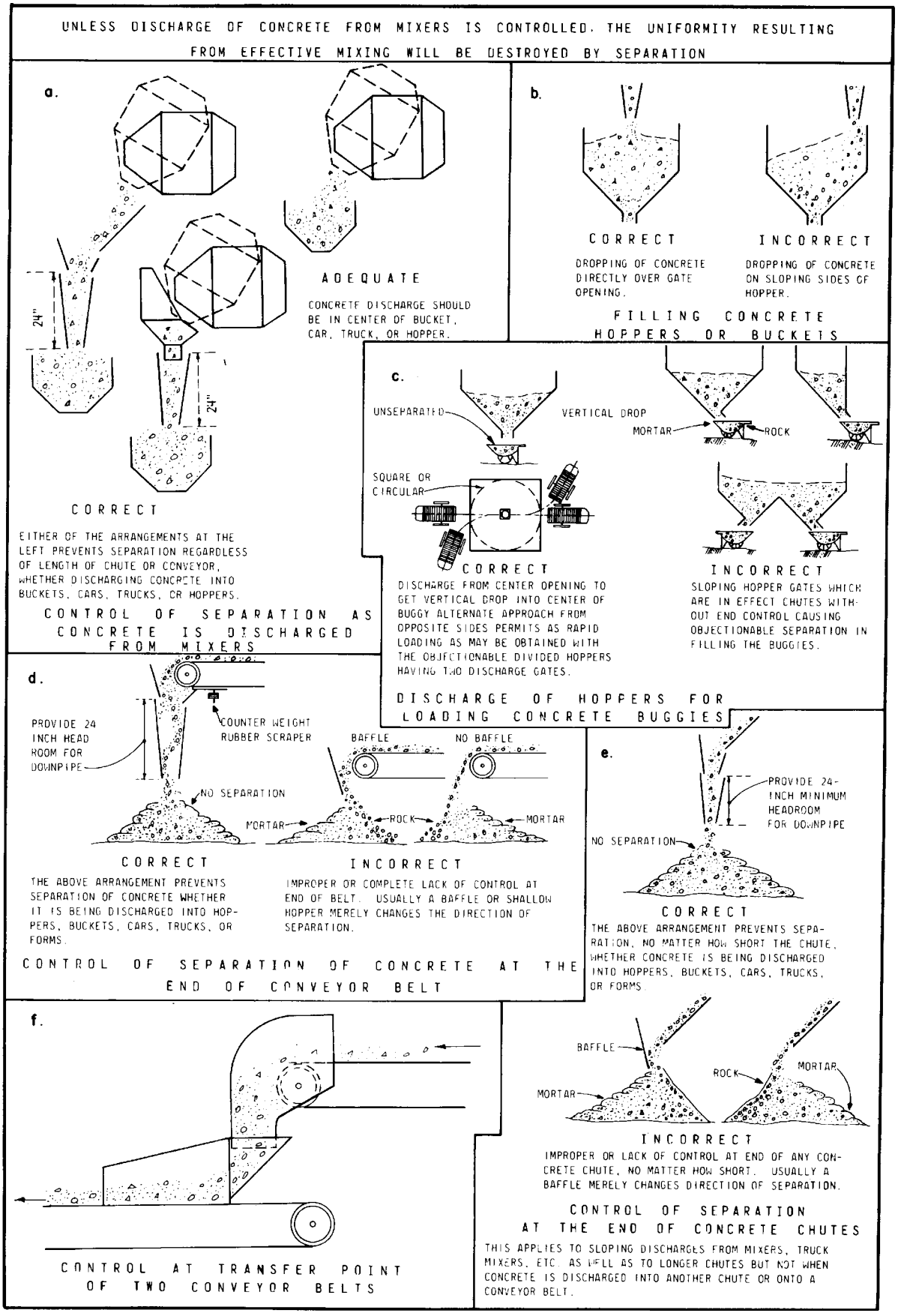

Fig. 5.1—Correct and incorrect methods of handling concrete.

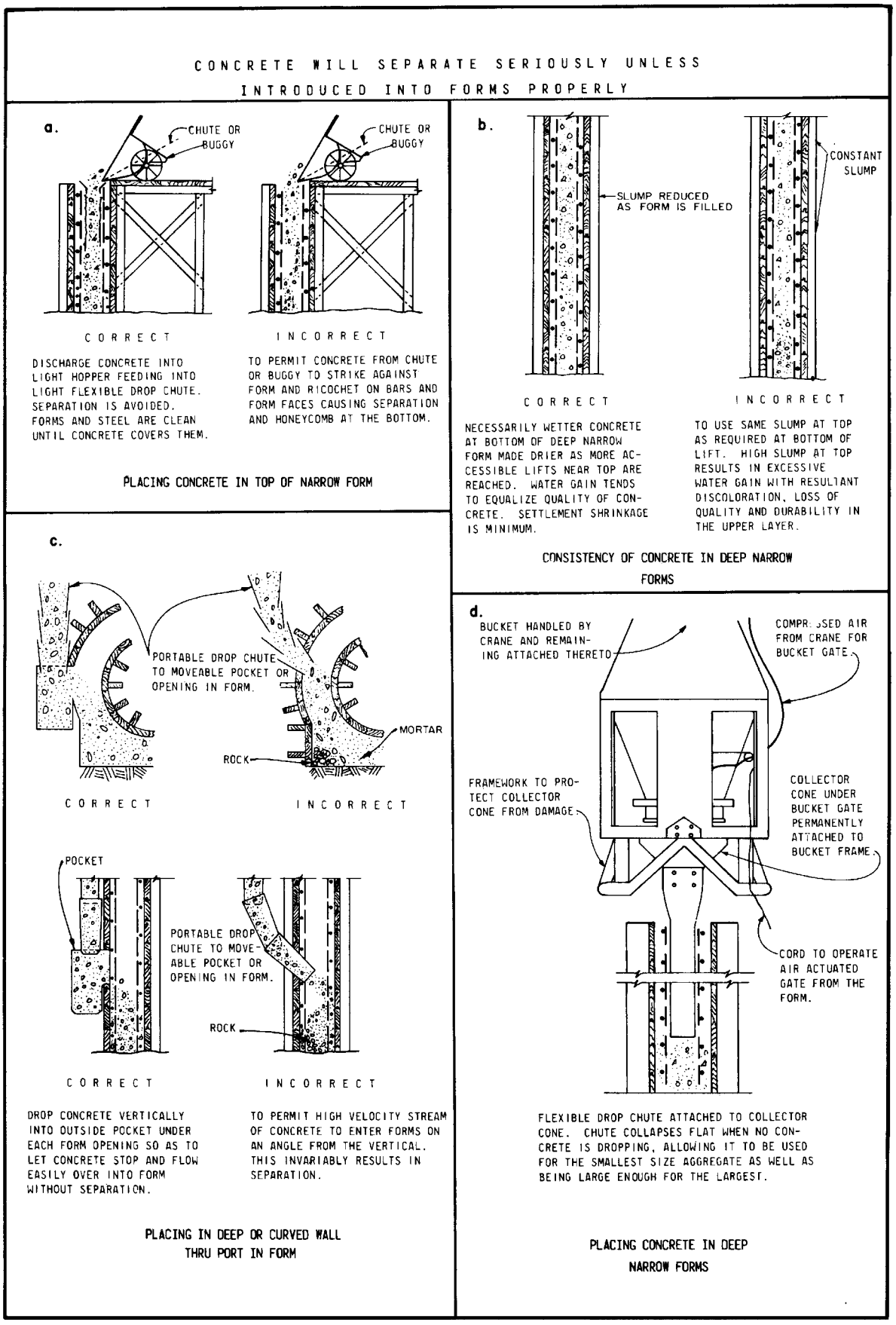

Fig. 5.2(a) to (d)—Correct and incorrect methods of placing concrete.

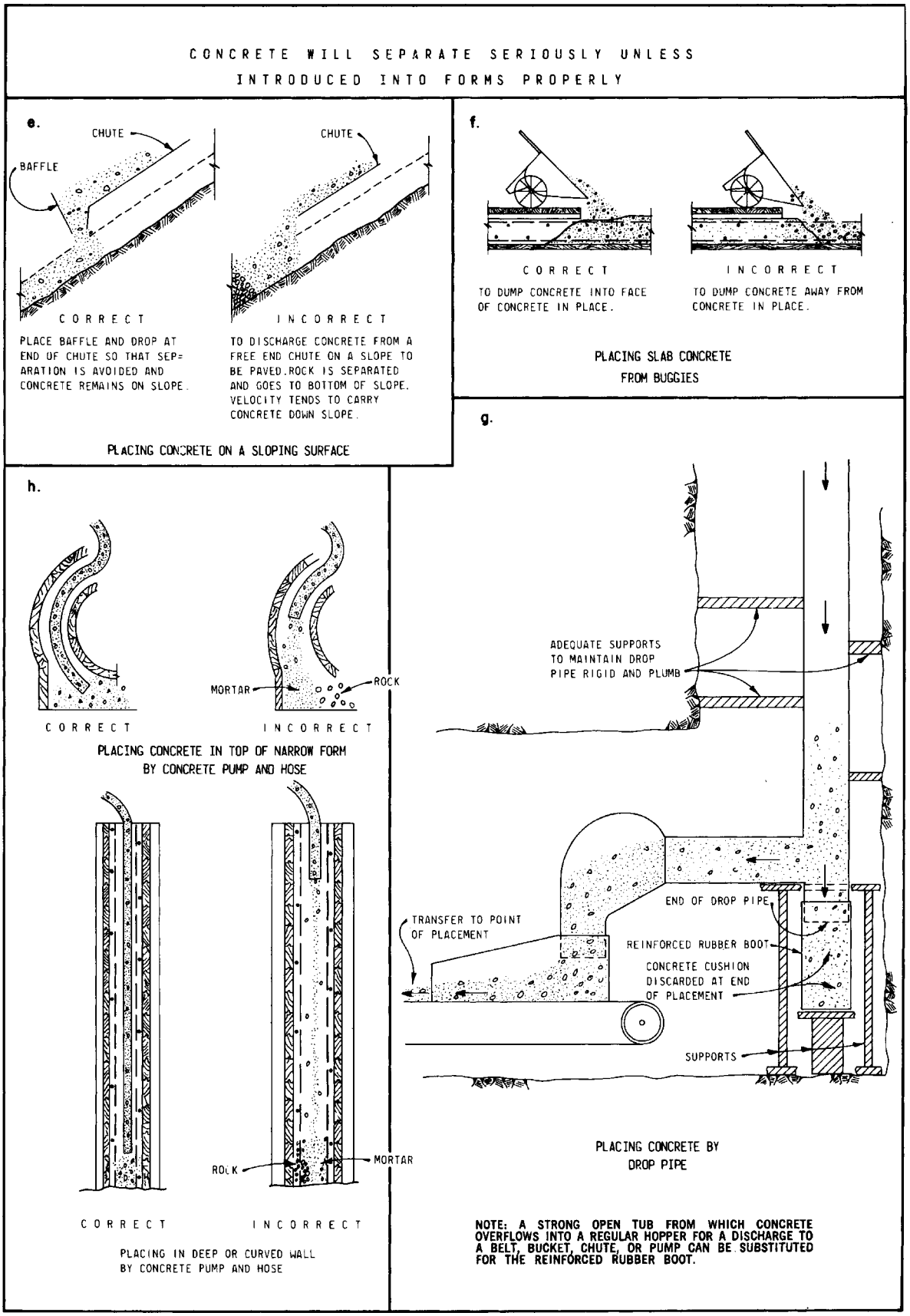

Fig. 5.2 (e) to (h)—Correct and incorrect methods of placing concrete.

5.2—Planning

A basic requirement in all concrete handling is that both quality and uniformity of the concrete, in terms of *w*/*cm*, slump, air content, and homogeneity, have to be preserved. The selection of handling equipment should be based on its capability to efficiently handle concrete of proportions most advantageous for being readily consolidated in place with vibrators. Equipment requiring adjustment of mixture proportions beyond ranges recommended by ACI 211.1 should not be used.

Advance planning should ensure an adequate and consistent supply of concrete. Sufficient placement capacity should be provided so that the concrete can be kept plastic and free of cold joints while it is being placed. All placement equipment should be clean and in proper repair. The placement equipment should be arranged to deliver the concrete to its final position without significant segregation. The equipment should be adequately and properly arranged so that placing can proceed without undue delays and manpower should be sufficient to ensure the proper placing, consolidating, and finishing of the concrete. If the concrete is to be placed at night, the lighting system should be sufficient to illuminate the inside of the forms and to provide a safe work area.

Concrete placement should not commence when there is a chance of freezing temperatures occurring, unless adequate facilities for cold-weather protection have been provided (ACI 306R). Curing measures should be ready for use at the proper time (ACI 308). Where practical, it is advantageous to have radio or telephone communications between the site of major placements and the batching and mixing plant to better control delivery schedules and prevent excessive delays and waste of concrete.

The concrete should be delivered to the site at a uniform rate compatible with the manpower and equipment being used in the placing and finishing processes. If an interruption in the concreting process is a potential problem, consideration should be given to the provision of backup equipment.

A final detailed inspection of the foundation, construction joints, forms, water stops, reinforcement, and any other embedments in the placement should be made immediately before the concrete is placed. A method of documenting the inspection should be developed and approved by all parties before the start of work. All of these features should be carefully examined to make sure they are in accordance with the drawings, specifications, and good practice.

5.3—Reinforcement and embedded items

At the time of concrete placement, reinforcing steel and embedded items should be clean and free from mud, oil, and other materials that can adversely affect the steel's bonding capacity. Most reinforcing steel is covered with either mill scale or rust and such coatings are considered acceptable provided that loose rust and mill scale are removed and that the minimum dimensions of the steel are not less than those required in ACI 318.

Care should be taken to ensure that all reinforcing steel is of the proper size and length and that it is placed in the correct position and spliced in accordance with the plans. Adequate concrete cover of the reinforcing steel has to be maintained.

Mortar coating on embedded items within a lift to be completed within a few hours need not be removed, but loose dried mortar on embedded items projecting into future lifts should be removed prior to placing those lifts.

The method of holding a waterstop in the forms should ensure that it cannot bend to form cavities during concreting.

Bars and embedded items should be held securely in the proper position by suitable supports and ties to prevent displacement during concreting. Concrete blocks are sometimes used for support of the steel. Metal bar chairs with or without plastic protected ends or plastic bar chairs are more commonly used. Whatever system is used, there should be assurance that the supports will be adequate to carry expected loads before and during placement and will not stain exposed concrete surfaces, displace excessive quantities of concrete, or allow bars to move from their proper positions (Concrete Reinforcing Steel Institute 1982).

In some cases when reinforced concrete is being placed, it is useful to have a competent person in attendance to adjust and correct the position of any reinforcement that may be displaced. Structural engineers should identify critical areas where such additional supervision would be advantageous.

5.4—Placing

5.4.1 *Precautions*—Arrange equipment so that the concrete has an unrestricted vertical drop to the point of placement or into the container receiving it. The stream of concrete should not be separated by falling freely over rods, spacers, reinforcement, or other embedded materials. If forms are sufficiently open and clear so that the concrete is not disturbed in a vertical fall into place, direct discharge without the use of hoppers, trunks or chutes is favorable. Concrete should be deposited at or near its final position because it tends to segregate when it has to be flowed laterally into place.

If a project involves monolithic placement of a deep beam, wall, or column with a slab or soffit above, delay placing the slab or soffit concrete until the deep concrete settles. The time allotted for this settling depends on the temperature and setting characteristics of the concrete placed, but is usually about 1 h. Concreting should begin again soon enough to integrate the new layer thoroughly with the old by vibration.

5.4.2 *Equipment*—When choosing placement equipment, consider the ability of the equipment to place the concrete in the correct location economically without compromising its quality.

Equipment selection is influenced by the method of concrete production. Certain types of equipment, such as buckets, hoppers, and buggies will suit batch production; whereas other equipment, such as belt conveyors and pumps, are more appropriate for continuous production.

5.4.2.1 *Buckets and hoppers*—The use of properly designed bottom-dump buckets permits placement of concrete at the lowest practical slump consistent with consolidation by vibration. The bucket should be self-cleaning upon discharge, and concrete flow should start when the discharge gate is opened. Discharge gates should have a clear opening equal to at least five times the maximum aggregate size being used. Side slopes should be at least 60 degrees from the horizontal.

Control the bucket and its gate opening to ensure a steady stream of concrete is discharged against previously placed concrete where possible. Stacking concrete by discharging the bucket too close to the lift surface or discharging buckets while traveling, commonly causes segregation.

To prevent contamination, do not shovel spilled concrete back into buckets or hoppers for subsequent use or swing buckets directly over freshly finished concrete.

To expedite the placement schedule, the use of two or more buckets per crane is recommended.

5.4.2.2 *Manual or motor-propelled buggies*—Buggies should run on smooth, rigid runways independently supported, and set well above reinforcing steel. Concrete being transferred by buggies tends to segregate during motion; therefore, the planking on which the buggies travel should be butted rather than lapped to maintain the smoothest possible surface and subsequently reduce separation of concrete materials in transit.

The recommended maximum horizontal delivery distance to transfer concrete by manual buggies is 200 ft (60 m), and for power buggies, 1000 ft (300 m). Manual buggies range in capacity from 6 to 8 ft^3 (0.2 to 0.3 m^3) with placing capacities averaging from 3 to 5 yd^3 (3 to 5 m^3) per h. Power buggies are available in sizes from 9 to 12 ft^3 (0.3 to 0.4 m^3) with placing capacities ranging from 15 to 20 yd^3 (14 to 18 m^3) per h, depending on the distance traveled.

5.4.2.3 *Chutes and drop chutes*—Chutes are frequently used for transferring concrete from higher to lower elevations. They should have rounded corners, be constructed of steel or be steel-lined, and should have sufficient capacity to avoid overflow. The slope should be constant and steep enough to permit concrete of the required slump to flow continuously down the chute without segregation.

Drop chutes are circular pipes used for transferring concrete vertically from higher to lower elevations. The pipe should have a diameter of at least eight times the maximum aggregate size at the top 6 to 8 ft (2 to 3 m) of the chute, but can be tapered to approximately six times the maximum aggregate size below. It should be plumb, secure, and positioned so that the concrete will drop vertically. The committee is aware of instances in which concrete has been dropped several thousand feet in this manner without adverse effects.

The flow of the concrete at the end of a chute should be controlled to prevent segregation. Plastic or rubber drop chutes or tremies can be used and shortened by cutting them rather than raising them as placement progresses. When using plastic drop chutes, ensure that the chutes do not fold over or kink.

5.4.2.4 *Paving equipment*—The use of large mixers, high-capacity spreaders, and slipform pavers has made it possible to place large volumes of concrete pavement at a rapid rate. Most of the same principles of quality control are required for successful paving as for other forms of concrete placement. The rapid rate at which concrete pavement is placed necessitates routine inspection procedures to detect any deviations from acceptable quality that should be corrected.

Some of the more frequent problems that can detrimentally affect the quality of the concrete in paving are also common in other types of placement, namely, poor batch-to-batch mixing uniformity, variation in slump and air content, and nonuniform distribution of the paste through the aggregates.

Placing concrete with paving equipment is covered in ACI 325.9R.

5.4.2.5 *Slipforming*—This method entails placing concrete in prefabricated forms that are slipped to the next point of placement as soon as the concrete has gained enough dimensional stability and rigidity to retain its design shape.

Careful, consistent concrete control with suitable mixture adjustments for changing ambient temperatures is required.

5.5—Consolidation

Internal vibration is the most effective method of consolidating plastic concrete for most applications. The effectiveness of an internal vibrator depends mainly on the head diameter, frequency, and amplitude of the vibrators. Detailed recommendations for equipment and procedures for consolidation are given in ACI 309R.

Vibrators should not be used to move concrete laterally. They should be inserted and withdrawn vertically, so that they quickly penetrate the layer and are withdrawn slowly to remove entrapped air. Vibrate at close intervals using a systematic pattern to ensure that all concrete is adequately consolidated (Fig. 5.3).

As long as a running vibrator will sink into the concrete by means of its own weight, it is not too late for the concrete to benefit from revibration, which improves compressive and bond strengths. There is no evidence of detrimental effects either to embedded reinforcement or concrete in partially cured lifts that are revibrated by consolidation efforts on fresh concrete above.

In difficult and obstructed placements, supplemental form vibration can be used. In these circumstances, avoid excessive operation of the vibrators, which can cause the paste to weaken at the formed surface.

On vertical surfaces where air-void holes need to be reduced, use additional vibration. Extra vibration, spading, or mechanical manipulation of concrete, however, are not always reliable methods for removing air-void holes from surfaces molded under sloping forms. Conduct trial placements to determine what works best with a particular concrete mixture.

The use of experienced and competent vibrator operators working with well-maintained vibrators and a sufficient supply of standby units is essential to successful consolidation of fresh concrete.

5.6—Mass concreting

The equipment and method used for placing mass concrete should minimize separation of coarse aggregate from the concrete. Although scattered pieces of coarse aggregate are not objectionable, clusters and pockets of coarse aggregate are and should be scattered before placing concrete over them. Segregated aggregate will not be eliminated by subsequent placing and consolidation operations.

Concrete should be placed in horizontal layers not exceeding 2 ft (610 mm) in depth and inclined layers and cold joints should be avoided. For monolithic construction, each concrete layer should be placed while the underlying layer is still responsive to vibration, and layers should be sufficiently shallow to permit the two layers to be integrated by proper vibration.

The step method of placement should be used in massive structures where large areas are involved to minimize the occurrence of cold joints. In this method, the lift is built up in a series of horizontal, stepped layers 12 to 18 in. (300 to 450 mm) thick. Concrete placement on each layer extends for the full width of the block, and the placement operations progress from one end of the lift toward the other, exposing only small areas of concrete at a time. As the placement progresses, part

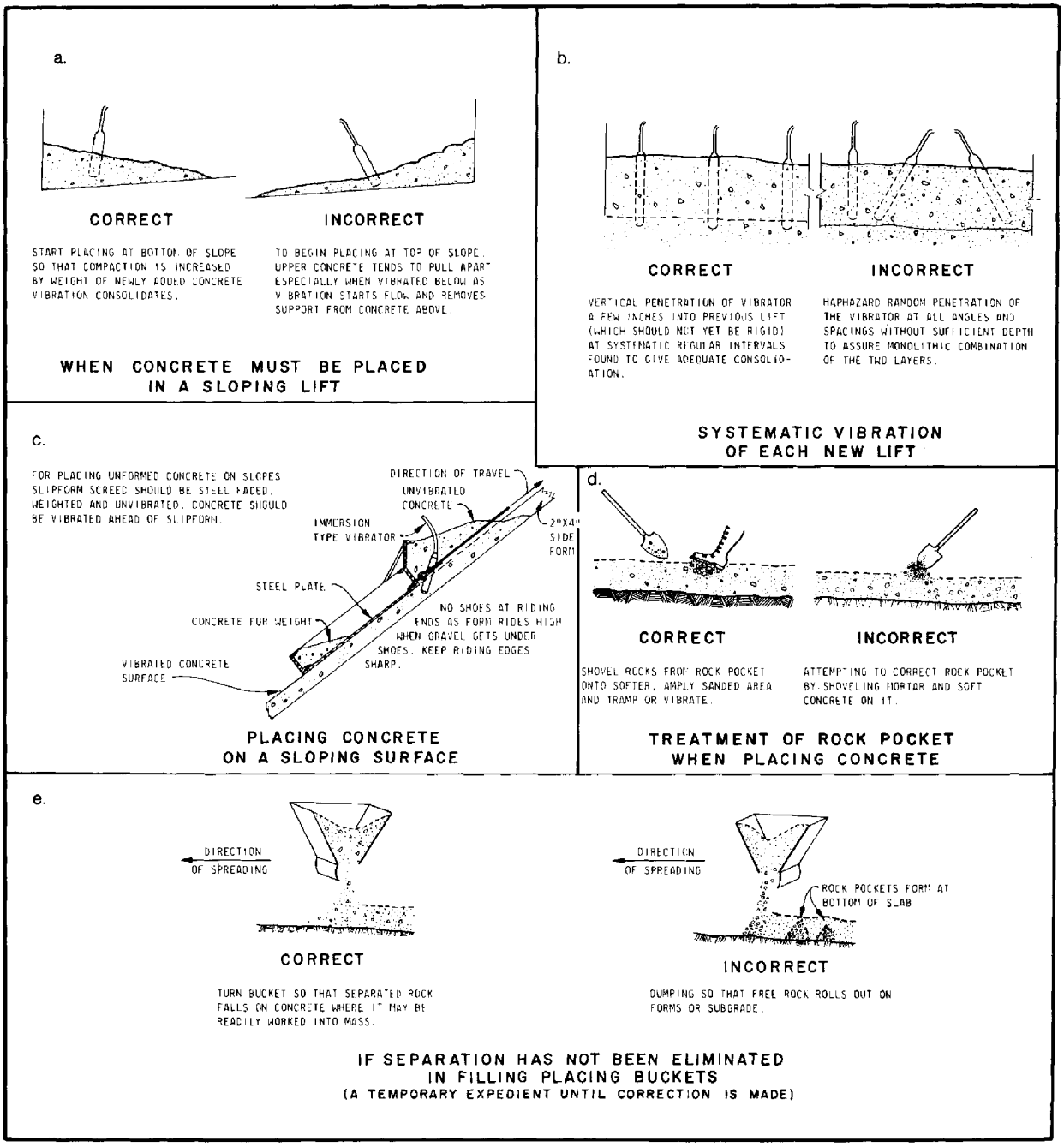

Fig. 5.3—Correct and incorrect methods of consolidation.

of the lift will be completed while concreting continues on the remainder.

For a more complete discussion of mass concrete and the necessary thermal considerations, see ACI 207.1R.

CHAPTER 6—FORMS, JOINT PREPARATION, AND FINISHING

6.1—Forms

Forms are the molds into which concrete is placed and falsework is the structural support and the necessary bracing required for temporary support during construction. Formwork is the total system of support for freshly placed concrete, including forms and falsework. Formwork design should be established before erection, and shop drawings containing construction details, sequence of concrete placing, and loading values used in the design should be approved before construction begins. Shop drawings should be available on site during formwork erection and when placing the concrete.

Design and construction of concrete forms should comply with ACI 347R. The design and construction of concrete formwork should be reviewed to minimize costs without sacrificing either safety or quality. Because workmanship in concrete construction is frequently judged by the appearance of the concrete after removal of the forms, proper perfor-

mance of formwork while bearing the plastic concrete weight and live construction loading is of vital importance.

Forms should be built with sufficient strength and rigidity to carry the mass and fluid pressure of the actual concrete as well as all materials, equipment, or runways that are to be placed upon them. Fluid pressure on forms should be correlated to the capacity and type of placement equipment, planned rate of placing concrete, slump, temperature, and stiffening characteristics of the concrete.

Form-panel joints, corners, connections, and seams should be mortar-tight. Consolidation will liquefy the mortar in concrete, allowing it to leak from any openings in the formwork, leaving voids, sand streaks, or rock pockets. When forms are set for succeeding lifts, avoid bulges and offsets at horizontal joints by resetting forms with only 1 in. (25 mm) of sheathing overlapping the concrete below the line made by the grade strip from the previous lift and securely tying and bolting the forms close to the joint. The form ties used should result in the minimum practical hole size and their design should permit removal without spalling surrounding concrete. Leakage of mortar around ties should be prevented, and filling of cone holes or other holes left by form ties should be done in a manner that results in a secure, sound, nonshrinking, and inconspicuous patch (ACI 311.1R). Before concreting, forms should be protected from deterioration, weather, and shrinkage by proper oiling or by effective wetting. Form surfaces should be clean and of uniform texture. When reuse is permitted, they should be carefully cleaned, oiled, and reconditioned if necessary.

Steel forms should be thoroughly cleaned and promptly oiled to prevent rust staining. If peeling of concrete is encountered when using steel forms, leaving the cleaned, oiled forms in the sun for a day, vigorously rubbing the affected areas with liquid paraffin, or applying a thin coating of lacquer will usually remedy the problem. Sometimes peeling is the result of abrasion of certain form areas from impact during placement. Abrasion can be reduced by temporarily protecting form areas subject to abrasion with plywood or metal sheets.

Form faces should be treated with a releasing agent to prevent concrete from sticking to the forms and thereby aid in stripping. The releasing agent can also act as a sealer or protective coating for the forms to prevent absorption of water from the concrete into the formwork. Form coatings should be carefully chosen for compatibility with the contact surfaces of the forms being used and with subsequent coatings to be applied to the concrete surfaces. Form coatings that are satisfactory on wood are not always suitable for steel forms; for example, steel forms would require a coating that acts primarily as a releasing agent, whereas plywood requires a coating that also seals the forms against moisture penetration.

Ample access should be provided within the forms for proper cleanup, placement, consolidation, and inspection of the concrete.

For the sake of appearance, proper attention should be paid to the mark made by a construction joint on exposed formed surfaces of concrete. Irregular construction joints should not be permitted. A straight line, preferably horizontal, should be obtained by filling forms to a grade strip. Rustication strips, either a v-shaped or a beveled rectangular strip, can be used as a grade strip and to form a groove at the construction joint when appropriate.

6.2—Joint preparation

Construction joints occur wherever concreting is stopped or delayed so that fresh concrete subsequently placed against hardened concrete cannot be integrated into the previous placement by vibrating. Horizontal construction joints will occur at the levels between lifts, whereas vertical joints occur where the structure is of such length that it is not feasible to place the entire length in one continuous operation. In general, the preparation of a vertical construction joint for acceptable performance and appearance is the same as for horizontal joints.

The surfaces of all construction joints should be cleaned and properly prepared to ensure adequate bond with concrete placed on or adjacent to them and to obtain required watertightness (U.S. Bureau of Reclamation 1981; Tynes 1959, 1963). Several methods of cleanup are available depending on the size of the area to be cleaned, age of the concrete, skill of workers, and availability of equipment. Creating a satisfactory joint when high-quality concrete has been properly placed is not difficult. When large quantities of bleed water and fines rise to the construction-joint surface, concrete at the surface is so inferior that adequate cleanup becomes difficult. Under normal circumstances, it is necessary only to remove laitance and expose the sand and sound surface mortar by sandblasting or high-pressure water jetting.

Sandblasting is performed to prepare the surface of the construction joint after the concrete has hardened and preferably just before forms are erected for the next placement (U.S. Bureau of Reclamation 1981; Tynes 1959, 1963). Wet sandblasting is usually preferred due to the objectionable dust associated with the dry process. Wet sandblasting produces excellent results on horizontal joint surfaces, particularly on those placed with 2 in. (50 mm) or less slump concrete using internal vibrators.

Another method for cleaning construction joints entails the use of a water jet under a minimum pressure of 6000 psi (40 MPa). As with the sandblasting method, cleanup is delayed until the concrete is sufficiently hard so that only the surface skin of mortar is removed and no undercutting of coarse aggregate particles occurs.

Cloudy pools of water will leave a film on the joint surface when they dry and should be removed by thorough washing after the main cleanup operation is completed. Cleaned joint surfaces should be continuously moist-cured until the next concrete placement or until the specified curing time has elapsed. Before placing new concrete at the joint, the surface should be restored to the clean condition that exists immediately after initial cleanup. If the surface has been properly cured, little final cleaning will be necessary prior to placement.

Hand tools such as wire brushes, wire brooms, hand picks, or bush hammers can be used to remove dirt, laitance, and soft mortar, but are only practical for small areas.

Retarding admixtures can be used, if allowed by the project specifications, to treat concrete surfaces after the finishing operations and before the concrete has set. Manufacturer's instructions for application and coverage rate should be followed. Subsequent removal of the unhardened surface mortar is completed with other cleanup methods such as water jets, air-water jets, or hand tools. Concrete surfaces treated with retarding admixtures should be cleaned as soon as practical after initial set; a longer delay results in less of the retarded surface layer being removed.

The clean concrete joint surface should be saturated, surface dry at the time new concrete is placed on it. Surface moisture weakens the joint by increasing the *w*/*cm* of the newly placed concrete. Ensure that the first layer of concrete on the construction joint is adequately consolidated to achieve good bond with the previously hardened concrete.

6.3—Finishing unformed surfaces

To obtain a durable surface on unformed concrete, proper procedures should be carefully followed. The concrete used should be of the lowest practical slump that can be properly consolidated, preferably by means of internal vibration. Following consolidation, the operations of screeding, floating, and first troweling should be performed in such a manner that the concrete will be worked and manipulated as little as possible to produce the desired result.

Overmanipulation of the concrete brings excessive fines and water to the surface, which lessens the quality of the finished surface, causing checking, crazing, and dusting. For the same reason, each step in the finishing operation, from the first floating to the final floating or troweling, should be delayed as long as possible while still working toward the desired grade and surface smoothness. Free water is not as likely to appear and accumulate between finishing operations if proper mixture proportions and consistency are used. If free water does accumulate, however, it should be removed by blotting with mats, draining, or pulling off with a loop of hose so that the surface loses its water sheen before the next finishing operation is performed. Under no circumstances should any finishing tool be used in an area before accumulated water has been removed, nor should neat cement or mixtures of sand and cement be worked into the surface to dry such areas.

Satisfactory results can be achieved from a correctly designed mortar topping placed on, and worked into, base concrete before the base concrete sets. The mortar consistency, consolidation, and finishing should be as described previously. A concrete of correct proportions, consistency, and texture placed and finished monolithically with the base concrete, however, is preferable to a mortar topping. See ACI 302.1R for a detailed discussion and recommendations on concrete floor and slab finishing.

Several special floor finishes, such as terrazzo, that are installed over cured concrete surfaces require special techniques and are not covered in this guide.

CHAPTER 7—PREPLACED-AGGREGATE CONCRETE

7.1—General considerations

In this method of construction, forms are first filled with clean, coarse aggregate. The voids in this coarse aggregate are then filled with structural quality grout to produce preplaced-aggregate (PA) concrete. This type of concrete is particularly useful where concrete is to be placed under water, where structures are heavily reinforced for seismic or other reasons, where structural concrete or masonry is to be repaired, or where concrete of low volume change is required (U.S. Bureau of Reclamation 1981; Davis and Haltenhoff 1956; Davis et al. 1955; Anon. 1954; King 1971; Davis 1958; Corps of Engineers 1994a).

PA concrete differs from conventionally placed concrete in that it contains a higher percentage of coarse aggregate; consequently, the properties of the coarse aggregate have a greater effect on the properties of the concrete. For example, the modulus of elasticity is slightly higher than that of conventional concrete. Also, because of point-to-point contact of the coarse aggregate, drying shrinkage is approximately 1/2 the magnitude of that in conventionally placed concrete (Davis 1958, Davis 1960). Structural design for PA concrete, however, is the same as for conventionally placed concrete (U.S. Bureau of Reclamation 1981, Corps of Engineers 1994a).

Structural formwork for PA concrete is usually more expensive than that required for conventionally placed concrete because greater care is needed to prevent grout leaks. In underwater construction, higher placing rates at lower cost have been achieved by this method than by conventional placement methods.

Because PA concrete construction is specialized in nature, the work should be undertaken by qualified personnel experienced in this method of construction. Detailed information on all aspects of PA concrete is given in ACI 304.1R.

7.2—Materials

7.2.1 *Cement*—Grout can be made with any one of the nonair-entraining types of cement that complies with ASTM C 150 or ASTM C 595M. Use of air-entrained cements combined with gas-forming fluidifiers could result in excessive quantities of entrained air in the grout, resulting in reduced strengths. When air entrainment is required to a higher extent than that provided by the gas-forming fluidifier, air-entraining agent should be added separately.

7.2.2 *Coarse aggregate*—Coarse aggregate should be washed, free of surface dust and fines, and in conformance with the requirements of ASTM C 33, except as to grading.

The void content of the aggregate should be as low as possible and is usually attained when the coarse aggregate is graded uniformly from the smallest allowable particle size to the largest (King 1971).

Grading 1 or 2 (Table 7.1) is recommended for general use. Where reinforcement is crowded or the placement is in relatively shallow patches, Grading 1 should be used. Where special circumstances dictate the use of coarser sand, Grading 3 is acceptable.

7.2.3 *Fine aggregate*—Sand should conform to ASTM C 33, except that grading should be as shown in Table 7.1. Fine aggregate that does not fall within these grading limits is usable provided results fall within the requirements of Section 7.3.

7.2.4 *Pozzolan*—Pozzolans conforming to ASTM C 618, Class N or F, can be used in PA concrete. Class F has been used in the great majority of installations as it improves pumpability of the fluid grout and extends grout handling time. Class C fly ash and blast-furnace slag have been used to a limited extent, but extensive data on grout mixture proportions and properties are not currently available.

7.2.5 *Admixtures*

7.2.5.1 *Grout fluidifier*—This admixture is commonly used to offset the effects of bleeding, reduce the *w*/*cm* for a given fluidity, and retard stiffening. The usual dosage of grout fluidifier is 1% by weight of the total cementitious material in the grout mixture.

7.2.5.2 *Calcium chloride*—A small quantity of calcium chloride may be desirable to promote early strength development. Calcium chloride in excess of 1% by weight of cementitious materials, however, will diminish the expansive action of the aluminum powder, if present, in the

Table 7.1—Gradation limits for coarse and fine aggregates for preplaced-aggregate concrete

Percentage passing			
Coarse aggregate			
Sieve size	Grading 1	Grading 2	Grading 3
	For 1/2 in. (1.25 mm) minimum size coarse aggregate	For 3/4 in. (19 mm) minimum size coarse aggregate	For 1-1/2 in. (38 mm) minimum size coarse aggregate
1-1/2 in. (37.5 mm)	95 to 100	—	0 to 5
1 in. (25.0 mm)	40 to 80	—	—
3/4 in. (19.0 mm)	20 to 45	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 (sand)			
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

grout fluidifier because the acceleration will reduce the time available for expansion to take place. Pretesting for expansion, bleeding, rate of curing, and strength in PA concrete cylinders is recommended (refer to ASTM C 953).

7.3—Grout proportioning

7.3.1 *Cementitious materials*—Usually, the proportion of portland cement-to-pozzolan is in the range of 2.5:1 to 3.5:1 by mass. Ratios as low as 1.3:1 (equal bulk volumes) for lean mass concrete and as high as 12:1 for high-strength concrete have been used. The *w*/*cm* usually ranges from 0.42 to 0.50.

7.3.2 *Fine aggregate*—Compressive strength, pumpability (Anon. 1954; King 1971), and void-penetration requirements control the amount of fine aggregate that can be used in the grout. For structural grade PA concrete, the ratio of cementitious material-to-fine aggregate will usually be 1:1 by mass. For massive placements where the minimum size of coarse aggregate is 3/4 in. (19 mm), the ratio may be increased to 1:1.5. With Grading 3 (Table 7.1), the ratio may be further increased to approximately 1:3.

7.3.3 *Proportioning requirements*—Materials should be proportioned in accordance with ASTM C 938 to produce a grout of required consistency that will provide the specified strength of PA concrete. For best results, bleeding should be less than the total measured expansion. Strength, bleeding, and expansion should be tested according to ASTM C 943.

7.3.4 *Consistency of grout*—For most work, such as walls and structural repairs, a 22 ± 2 s flow (ASTM C 939) is usually satisfactory. For massive sections and underwater work, the flow can be as low as 20 ± 2 s or as high as 24 ± 2 s.

Where special care can be taken in the execution of work and higher strengths are required, flows as high as 35 to 40 s can be used.

7.4—Temperature control

For mass concrete placements, temperature rise in PA concrete can be limited by one or more of the following procedures: chilling coarse aggregate before placement; chilling coarse aggregate in place; chilling the grout with chilled mixing water; and reducing the cement content to the minimum for obtaining the desired properties. Refer to ACI 207.2R and ACI 224R for more detail.

7.5—Forms

Forming materials for PA concrete are similar to those for conventionally placed concrete. The forms, however, should be tight enough to prevent grout leakage and resist high lateral pressures (refer to ACI 347R). After the forms are erected, shored, properly braced, and set to line and grade, all small openings should be caulked. All joints between adjacent panels should be sealed on the inside of the form with tape. Specifications may require that a layer of water 1 to 2 ft (0.3 to 0.6 m) deep be maintained above the rising grout surface to ensure saturation of the coarse aggregate particles. In these cases, the forms should be essentially watertight.

7.6—Grout pipe systems

7.6.1 *Delivery pipes*—The most reliable grout delivery system consists of a single line. To provide for continuous grout flow, a y-shaped fitting can be incorporated. The grout should be injected through only one leg of the y at a time.

The delivery line should be of sufficient diameter to allow grout velocity at the planned operating rate to range between 2 and 4 ft/s (0.6 and 1.2 m/s).

High-pressure grout hose, 400 psi (3 MPa) or higher, is commonly used for delivery lines. A hose diameter of 1-1/4 or 1-1/2 in. (30 or 40 mm) is preferred for distances up to 500 ft (150 m). For longer distances, up to approximately 1000 ft (300 m), 2 in. (50 mm) diameter is preferred.

7.6.2 *Grout insertion pipes*—Insertion pipes are used to inject the grout into the aggregate mass and are normally schedule 40 pipe, 3/4 to 1-1/4 in. (20 to 30 mm) diameter for normal structural concrete and up to 1-1/2 in. (40 mm) for mass concrete. The grout insertion pipes should extend vertically to within 6 in. (150 mm) of the bottom of the aggregate mass, or they can extend horizontally through the formwork at different elevations. When insert pipes are required in depths of aggregate exceeding approximately 50 ft (15 m), flush-coupled schedule 120 pipe or flush-coupled casing is recommended. For deep placements, such as

caissons in deep water, telescoping-insertion pipes can be required.

7.6.3 *Vent pipes*—Vent pipes should be used where water or air can be entrapped by the rising grout surface, such as beneath a blockout or under some embedments. Grout is usually injected through insert pipes until it returns through these vent pipes.

7.7—Coarse aggregate placement

7.7.1 *Preparation for placement*—Coarse aggregate should be washed and screened immediately before placing in forms. Coarse aggregate should not be flushed with water after placement in the forms (Anon. 1954; King 1971). This will cause fines to accumulate in the lower strata of aggregate. When it is necessary to flood the coarse aggregate to obtain saturation or precooling (King 1971), the water should be injected through the insert pipes so that the water rises gently through the coarse aggregate.

For underwater placement, all loose, fine material should be removed from the foundation area before placement of aggregate to prevent subsequent coating of the aggregate or filling of voids with stirred-up sediment. Where the concrete will bear on piles, it is only necessary to remove soft material a sufficient depth below pipe encasement depth to provide for a filter cloth on the mud. Additionally, a layer of aggregate is carefully dropped on top of the cloth to stabilize it and form a base for the bulk of the coarse aggregate to follow.

7.7.2 *Aggregate placement*—For structural concrete work, aggregate is commonly delivered to the forms in concrete buckets and placed through a flexible elephant trunk to prevent segregation and breakage of the aggregate. A pipe having a diameter of at least four times the maximum aggregate size has been used for lowering aggregate preplaced under water to depths ranging from 50 to 1000 ft (15 to 300 m) (Davis, Johnson, and Wendell 1955). The pipe is normally lowered to bottom contact, then gradually filled. Discharge is then controlled by raising the pipe only enough to permit discharge at a controllable rate. Where coarse aggregate is being placed through water, it can be discharged directly into the water from bottom-dump barges or self-unloading ships (Davis and Haltenhoff 1956).

Coarse aggregate can also be blown into place around tunnel liners by using 6 in. (150 mm) or larger pipe and large volumes of low-pressure air (Davis, Johnson, and Wendell 1955).

In most placements, there is little to be gained from attempts to consolidate the coarse aggregate in place by rodding or vibration. Rodding or compressed-air lances can be used, however, to achieve placement into heavily reinforced areas and in the construction of overhead repairs.

Around closely spaced piping, reinforcement, and penetrations, such as in some nuclear shielding situations where uniform high density and homogeneity are desired, hand placement in shallow lifts may be required.

7.7.3 *Contamination*—In underwater construction where organic contamination is known or suspected to exist, sample and test the water to estimate the rate of sludge build-up on immersed aggregate and its possible influence on the quality of the concrete.

7.8—Grout mixing and pumping

7.8.1 *Mixers*—Vertical-spindle, paddle-type, and double-tub mixers are commonly used for mixing grout. One tub serves as a mixer while the second, from which grout is being withdrawn, serves as an agitator. Horizontal shaft mixers are used for large-volume work. A separate agitator is used to provide continuous operation.

Pan or turbine mixers are well-suited for mixing grout, although maintenance of a tight seal at the discharge gate can be difficult. Conventional revolving-drum concrete mixers are suitable if the mixing is sufficiently prolonged to ensure thorough mixing. The 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 high-energy input, mixing time should be limited to avoid heating the grout.

7.8.2 *Pumps*—The pump should be a positive-displacement pump such as the piston or progressive cavity type. The pump should be equipped with a bypass line connecting the discharge with the pump inlet or the agitator. On large jobs, providing standby equipment so that continuous discharge can be provided is prudent. A pressure gauge should be installed on the pump line discharge in clear view of the pump operator to indicate incipient line blockage.

7.8.3 *Grout injection*—There are essentially two basic patterns of grout injection: the horizontal layer and advancing slope techniques. With both systems, grout should start from the lowest point within the forms.

In the horizontal layer technique, grout is injected through each insert pipe to raise the grout a short distance at the point of injection, and by sequential injection through adjacent insert pipes, a layer of coarse aggregate is grouted before proceeding to the next horizontal layer above. When injecting through vertical-insert pipes, the injection pipes are withdrawn after each injection, leaving the lower end of the insert pipe embedded a minimum of 1 ft (0.3 m) below the grout surface. When injecting through ports in the forms or horizontal insert pipes, grouting should be continuous through the injection point until grout flows from the next higher point. For the next lift of grout, injection should be into the insert point next above that just completed.

When the horizontal surface procedure is not practical, as when plan dimensions are relatively large compared to the depth, the advancing slope method is used. Intrusion is started at one end of the narrowest dimension of the form and pumping is continued through the first row of insert pipes until the grout appears at the surface. The surface of the grout within the submerged aggregate will assume a generally vertical-to-horizontal slope ranging from 1:5 to 1:10. The slope is advanced by pumping grout through successive rows of insert pipes until the entire slab has been grouted.

Normal injection rates through a given insert pipe 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 voids, and grout fluidity.

7.8.4 *Grout surface determination*—The location of the grout surface within the aggregate mass should be known at all times. When grout is injected horizontally through the side of the formwork, grout location can be readily determined by flow from adjacent grouting points, the location of seepage through the forms, or with the aid of closable inspection holes through the forms. Where grout is injected through vertical-insert pipes, sounding wells should be provided. These sounding wells usually consist of 2 in. (50 mm) diameter thin-wall pipe with 1/2 in. (12 mm) milled (not burned)

slots at frequent intervals. Partially rolled, unwelded tubing providing a continuous slot can also be used. The sounding line is equipped with a 1 in. (25 mm) diameter float weighted to sink in water, yet float on the grout surface, within the slotted pipe. Sounding wells are usually left in place and become a permanent part of the structure.

7.9—Joint construction

7.9.1 *Cold joints*—Cold joints are formed within the mass of preplaced aggregate concrete when pumping is stopped for longer than the grout remains plastic. When this occurs, the insert pipes should be pulled to just above the grout surface before the grout stiffens and rodded clear. To resume pumping, the pipes should be worked back to near contact with the hardened grout surface and pumping resumed, slowly for a few minutes, to create a mound of grout around the end of the pipe.

7.9.2 *Construction joints*—Construction joints can be formed in the same manner as cold joints by stopping the grout rise approximately 12 in. (300 mm) below the aggregate surface. Dirt and debris should be prevented from filtering down to the grout surface.

If construction joints are made by bringing the grout up to the surface of the coarse aggregate, the surface should be green-cut, chipped, or sandblasted to present a clean, rough surface for the new grout in the next lift.

7.10—Finishing

Exercise care when topping out to control the grout injection rate and avoid lifting or dislodging the surface aggregate (Anon. 1954). Coarse aggregate at or near the surface can be held in place by wire screening, which is removed before finishing.

Low-frequency, high-amplitude external vibration of forms at or just below the grout surface will permit grout to cover aggregate-form contacts, thereby providing an excellent, smooth surface appearance. Excessive form vibration will cause bleeding, the usual result being sand streaking from the upward movement of the bleed water. Internal vibration should only be used in short bursts to level the grout between insert pipes for topping out purposes. When a screeded or troweled finish is required, the grout should be brought up to flood the aggregate surface and any diluted surface grout should be removed by brooming. A thin layer of pea gravel is then worked down into the surface by raking followed by tamping. When the surface is sufficiently hardened to permit working, a screeded, floated, or troweled finish is then applied.

7.11—Quality control

Job site control of fresh grout characteristics is maintained by following the appropriate ASTM methods. Compressive strength of PA concrete should be determined in accordance with procedures given in ASTM C 943. The strength of grout alone, when determined in cubes or cylinders, may bear little relation to the strength of PA concrete made with the same grout because these units do not duplicate the weakening effect of excessive bleeding of the grout in place. Properly made PA concrete cylinders, however, bear a close relationship to cores taken from the concrete in place. A typical comparison of lab-made and field-made cylinders with cores taken from a major installation is given in Fig. 7.1.

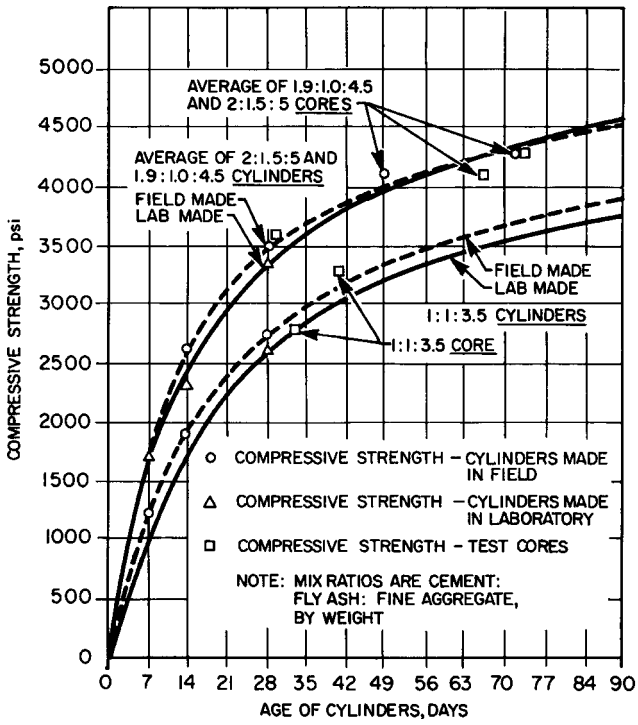

Fig. 7.1—Comparison of results, field- and lab-made cylinders versus cores.

CHAPTER 8—CONCRETE PLACED UNDER WATER

8.1—General considerations

Typical underwater concrete placements include nonstructural elements such as cofferdams or caisson seals, and structural elements such as bridge piers, dry-dock walls and floors, and water intakes. Concrete placed under water has also been used to add weight to sink precast tunnel sections, to join tunnel sections once in place, and to repair erosion or cavitation damage to major hydraulic structures (Gerwick 1964; Gerwick, Holland, and Kommendant 1981).

8.1.1 *Scope*—The recommendations given in this chapter are directed toward relatively large-volume placements of concrete under water, but these recommendations are also generaly applicable to small-volume underwater placements, such as thin overlays or deep confined placements. The reader is cautioned to consider the specific problems associated with these placements and how they differ from typical placements.

8.1.2 *Methods available*—The tremie is currently the most frequently used technique to place concrete under water, but use of direct pumping is increasing. These two methods are similar and are described in this chapter.

8.1.3 *Basic technique*—Successful placement of concrete under water requires preventing flow of water across or through the placement site. Once flow is controlled, either tremie or pump placement consists of the following three steps:

1. The first concrete placed is physically separated from the water by using a go-devil or pig in the pipe, or by having the pipe mouth sealed and the pipe dewatered;

2. Once filled with concrete, the pipe is raised slightly to allow the go-devil to escape or to break the end seal. Concrete will then flow out and develop a mound around the mouth of the pipe. This is termed establishing a seal; and

3. Once the seal is established, fresh concrete is injected into the mass of existing concrete. The exact flow mechanism that takes place is not precisely known, but the majority of the concrete apparently is not exposed to direct contact with the water (Gerwick, Holland, and Kommendant 1981).

8.2—Materials

8.2.1 *General requirements*—Concrete materials should meet all appropriate specifications. In addition, materials should be selected for their contribution toward improved concrete flow characteristics.

8.2.2 *Aggregates*— The maximum size of aggregates used in reinforced placements under water is usually 3/4 in. (19 mm). Larger aggregates (1 in. [25 mm]) can be used depending on availability, reinforcing spacing, and maintenance of the workability of the concrete. The maximum size of aggregates for nonreinforced placements should be 1-1/2 in. (38 mm).

8.2.3 *Admixtures*— Admixtures to improve the characteristics of fresh concrete, especially flowability, are frequently used in concrete placed under water (Williams 1959). For example, an air-entraining admixture can be beneficial because of the increased workability that can be achieved with its use.

Water-reducing or water-reducing and retarding admixtures are particularly beneficial in reducing water content to provide a cohesive yet high-slump concrete. Retarding admixtures are beneficial in a large monolithic placement. Because of the extreme importance of maintaining as high a slump as possible for as long as possible, the use of a high-range water-reducing admixture (HRWR) for massive placements is not recommended, unless slump-loss testing has shown no detrimental results. The use of HRWR for smaller volume placements in which flow distances are not as critical may be acceptable.

Admixtures are also available to prevent washout of cementitious materials and fines from concrete placed under water. These antiwashout admixtures are discussed in Section 8.10.

8.3—Mixture proportioning

8.3.1 *Basic proportions*—Pozzolans (approximately 15% by mass of cementitious materials) are generally used because they improve flow characteristics. Relatively rich mixtures, 600 lb/yd^3 (356 kg/m^3) cementitious materials, or more, or a maximum *w*/*cm* of 0.45 are recommended. Fine aggregate contents of 45 to 55% by volume of total aggregate and air contents of up to approximately 5% are generally used. Refer to 8.8.5 for thermal cracking considerations.

A slump of 6 to 9 in. (150 to 230 mm) is generally necessary, and occasionally a slightly higher range is needed when embedded items obstruct the flow or when relatively long horizontal flow is required.

8.3.2 *Final selection*—If possible, the final selection of a concrete mixture should be based on test placements made under water in a placement box or in a pit that can be dewatered after the placement. Test placements should be examined for concrete surface flatness, amount of laitance present, quality of concrete at the extreme flow distance of the test, and flow around embedded items, if appropriate.

8.4—Concrete production and testing

8.4.1 *Production sampling and testing*—Sampling should be done as near to the tremie hopper as possible to ensure that concrete with the proper characteristics is arriving at the tremies. Once a concrete mixture has been approved, slump, air content, unit weight, and compressive strength testing should be adequate for production control. Because of the importance of the flowability of the concrete to the success of the placement, slump and air content tests should be performed more frequently than is usually done for concrete not placed under water.

Compressive strength specimens should be available for testing at early ages to determine when the concrete has gained enough strength to allow dewatering of the structure.

8.4.2 *Concrete temperature*—The concrete temperature should be kept as low as practical to improve placement and structural qualities. Depending on the volume of the placement and the anticipated thermal conditions within the placement, maximum temperatures in the range of 60 to 90 F (16 to 32 C) are normally specified. While concrete placed under water obviously cannot freeze, a minimum concrete temperature of 40 F (5 C) should be maintained. Because heating either water or aggregates can cause erratic slump-loss behavior, extreme care should be taken when such procedures are used to raise the concrete temperature.

8.5—Tremie equipment and placement procedure

8.5.1 *Tremie pipes*—The tremie should be fabricated of heavy-gage steel pipe to withstand all anticipated handling stresses. In deep placements, buoyancy of the pipe can be a problem if an end plate is used to gain the initial tremie seal. Use of pipe with thicker walls or weighted pipe can overcome buoyancy problems.

Tremie pipes should have a diameter large enough to ensure that aggregate-induced blockages will not occur. Pipes in the range of 8 to 12 in. (200 to 300 mm) diameter are adequate for the range of aggregates recommended herein. For deep placements, the tremie should be fabricated in sections with joints that allow the upper sections to be removed as the placement progresses. Sections can be jointed by flanged, bolted connections, (with gaskets) or screwed together. Whatever joint technique is selected, joints between tremie sections should be watertight and should be tested for watertightness before beginning placement. The tremie pipe should be marked to allow quick determination of the distance from the surface of the water to the mouth of the tremie.

The tremie should have a suitably sized funnel or hopper to facilitate transfer of concrete from the delivery device to the tremie. A stable platform should be provided to support the tremie during placement. Floating platforms are generally not suitable. The platform should be capable of supporting the tremie while sections are being removed from the upper end of the tremie.

8.5.2 *Placement procedures*—All areas in which there is to be bond between steel, wood, or cured concrete and fresh concrete should be thoroughly cleaned immediately before concrete placement.

8.5.2.1 *Pipe spacing*—Pipe spacing should be on the order of one pipe for every 300 ft^2 (28 m^2) of surface area or pipes on approximately 15 ft (4.5 m) centers. These spacings are recommended, but concrete has been placed that flowed as far as 70 ft (21 m) with excellent results. For most large placements, it will not be practical to achieve a pipe spacing as close as 15 ft (5 m) on centers simply because it would be impractical to supply concrete to the number of tremies or pumps involved.

Actual pipe spacing should be established on the basis of the thickness of the placement, congestion due to piles or reinforcing steel, available concrete production capacity, and available capacity to transfer concrete to the tremies. The placement method selected should also be considered.

8.5.2.2 *Starting placements*—Tremies started using the end-plate, dry-pipe technique should be filled with concrete before being raised off the bottom. The tremie should then be raised a maximum of 6 in. (150 mm) to initiate flow. These tremies should not be lifted further until a mound is established around the mouth of the tremie pipe. Initial lifting of the tremie should be done slowly to minimize disturbance of material surrounding the mouth of the tremie.

Tremies started using a go-devil should be lifted a maximum of 6 in. (150 mm) to allow water to escape. Concrete should be added to the tremie slowly to force the go-devil downward. Once the go-devil reaches the mouth of the tremie, the tremie should be lifted enough to allow the go-devil to escape. After that, a tremie should not be lifted again until a sufficient mound is established around the mouth of the tremie.

Tremies should be embedded in the fresh concrete 3 to 5 ft (1.0 to 1.5 m) deep. Exact embedment depths will depend on placement rates and setting time of the concrete. All vertical movements of the tremie pipe should be done slowly and carefully to prevent loss of seal. If loss of seal occurs in a tremie, placement through that tremie should be halted immediately. The tremie should be removed, the end plate should be replaced, and flow should be restarted as described above. To prevent washing of concrete already in place, a go-devil should not be used to restart a tremie after loss of seal.

8.5.2.3 *Placing*—Concrete placement should be as continuous as possible through each tremie. Excessive delays in placement can cause the concrete to stiffen and resist flow when placement resumes.

Placement interruptions of up to approximately 30 min should allow restarting without any special procedures. Interruptions of between 30 min and the initial setting time of the concrete should be treated by removing, resealing, and restarting the tremie. Interruptions of a duration greater than the initial setting time of the concrete should be treated as a construction joint. If a break in placement results in a planned (or unplanned) horizontal construction joint, the concrete surface should be green-cut after it sets. Green-cutting by a diver is difficult but can be accomplished where there is no practical alternative for cleaning. The concrete surface should be water-jetted immediately before resuming concrete placement.

Recommendations on the rate of concrete rise are generally in the range of 1 to 10 ft/h (0.3 to 3 m/h). Calculation of a projected rate is somewhat difficult because the exact flow pattern of the concrete will not be known. The most logical approach is to compare concrete production with the entire area that is being supplied. As with pipe spacing, achieving the recommended values can be difficult. Concrete has been successfully placed under water at rates of approximately 0.5 ft (150 mm) of rise per h (Gerwick, Holland, and Kommendant 1981).

The volume of concrete in place should be monitored throughout the placement. Underruns (using less concrete than anticipated) are indicative of loss of tremie seal, because the washed and segregated aggregates will occupy a greater volume. Overruns (using more concrete than anticipated) are therefore also indicative of loss of concrete from the forms.

Once the placement scheme has been developed, flow distances and rates of rise can be calculated. If flow distances seem excessive or if the rate of concrete rise is too low, make a judgment as to the suitability of the available plant or the necessity for breaking the placement into smaller segments.

Tremie blockages that occur during placement should be cleared extremely carefully to prevent loss of seal. If a blockage occurs, the tremie should be quickly raised 6 in. to 2 ft (150 to 610 mm) and then lowered in an attempt to dislodge the blockage. The depth of pipe embedment should be closely monitored during all such attempts. If the blockage cannot be cleared readily, the tremie should be removed, cleared, resealed, and restarted.

8.5.2.4 *Horizontal distribution of concrete*—The pipe delivering concrete should remain fixed horizontally while concrete is flowing. Horizontal movement of the pipe will damage the surface of the concrete in place, create additional laitance, and lead to loss of seal. Horizontal distribution of the concrete is accomplished by flow of the concrete after exiting the pipe or by halting placement, moving the pipe, reestablishing the seal, and resuming placement.

Two methods are typically used to achieve horizontal concrete distribution in large placements: the layer method or the advancing slope method. In the horizontal layer method, the entire area of the placement is concreted simultaneously using a number of tremies. With the advancing slope method, one portion of the placement is brought to finished grade and then the tremies are moved to bring adjacent low areas to grade. Work normally progresses from one end of a large placement to the other. Concrete slopes from nearly flat to 1:6 (vertical to horizontal) can be expected.

8.5.3 *Postplacement evaluation*—To evaluate the underwater placement, the following techniques can be used:

- Coring in areas of maximum concrete flow or in areas of questionable concrete quality;
- After dewatering, accurately surveying the concrete surface to evaluate the adequacy of the concrete mixture and the placement plan; and
- After removal of forms or sheet piling, inspecting the exterior surface of the concrete with divers for evidence of cracking, voids, or honeycomb.

8.6—Direct pumping

Tremie placement techniques are generally applicable to direct pump placement under water. The following minor differences, however, are worth noting:

- The mechanism causing concrete flow through the pipeline is pump pressure rather than gravity;
- The concrete should be proportioned for flow after leaving the pipe rather than simply for pumping;
- Pipes are typically smaller than those used for tremies. Rigid sections should always be used for the portion actually embedded in the concrete;
- The pump action can cause some lateral movement of the pipe where it is embedded in the fresh concrete; this movement can contribute to laitance formation by drawing fines to the pipe-concrete interface; and
- A relief valve (air vent) can be required near the highest point in the pipeline to prevent development of a vacuum blockage.

8.7—Concrete characteristics

Concrete placed under water can be expected to be of excellent quality. Curing conditions are excellent and drying shrinkage is minimal. Compressive strengths of the rich mixtures used will often be from 4000 to 8000 psi (28 to 55 MPa). There is no evidence that other structural properties differ from those of similar concretes placed in the dry. In-place unit weight, often critical in massive placements to offset hydrostatic uplift, will be close to that measured for the fresh concrete before placement. If laitance is entrapped in the concrete, however, unit weight can be significantly below that of the fresh concrete.

Although there have been recent attempts to ascertain the quality and homogeneity of concrete placed under water using nondestructive techniques (Laine et al. 1980), coring is still the recommended technique for evaluation of questionable areas.

8.8—Precautions

The precautions in this section are applicable to either tremie or pump placement.

8.8.1 *Inspection*—Inspection of concrete placements under water is difficult. The water itself will become increasingly murky as the placement progresses and the surface of the fresh concrete will not support the weight of a diver. Therefore, preplacement inspection becomes extremely important and should concentrate on reviews of the proposed procedures and equipment and the proposed concrete mixture. Inspection during the placement will be limited to observing all phases of the concrete production, transportation, and placement procedures. Because the success of an underwater placement depends largely on the concrete itself, sampling and testing during the placement are critical to ensure compliance with approved mixtures and required concrete characteristics (slump, air content, temperature).

An inspection plan detailing locations and frequency of soundings should be developed. Soundings should be taken over the entire area of the placement on a regular basis, such as every hour or every 200 yd^3 (75 m^3). Locations for taking soundings should be marked on the structure to ensure that all soundings are made at the same location. Additionally, soundings should be required on a more frequent basis adjacent to each tremie to monitor pipe embedment. Data obtained from soundings should be plotted immediately to monitor the progress of the placement.

8.8.2 *Loss of seal*—The most common cause of loss of seal is excessive vertical movement of the pipe to clear a blockage or to remove a pipe section. With either placement method, the loss of seal likely will result in washing and segregation. A related and similar problem is the failure to establish a satisfactory seal at the beginning of a placement.

8.8.3 *Go-devils*—The use of go-devils has traditionally been advocated as a technique for sealing tremies or pump lines. Although the technique is effective, the water that is forced out of the pipe ahead of the go-devil can wash and scour the material underlying the placement area. This condition can be alleviated by the placement of a layer of properly graded rock before the start of concreting.

When a pipe is relocated during a placement, the water forced out of the pipe will wash previously placed concrete, resulting in extreme segregation, laitance formation, and possibly entrapped zones of uncemented aggregates. Therefore, the use of a go-devil at the beginning of a placement is acceptable, but not to restart a tremie or pumping line during a placement.

8.8.4 *Laitance*—Because it is physically impossible to separate the concrete and the water completely, a certain amount of laitance will be formed. If the seal is lost, or if the concrete is disturbed in any way, additional laitance will be formed when starting or restarting pipes. The laitance will flow to and accumulate in any low areas on the surface of the concrete. Such accumulations can prevent sound concrete from filling an area and can become entrapped by subsequent concrete flows. In either case, the zones of laitance will be more permeable and lower in strength. Problems with laitance can be avoided by using pumps or air-lifts during the placement to remove unsuitable material as it accumulates. Another way of reducing laitance problems is to discard several inches of concrete from the form. This can only be done where the top of the form coincides with the top of the placement.

8.8.5 *Cracking*—Problems associated with heat development and subsequent cracking in massive underwater placements have generally not been resolved. The following characteristics, however, of underwater placements should be considered.

8.8.5.1 *Cement content*—Underwater concrete mixtures have traditionally used high cement contents (650 lb/yd^3 [385 kg/m^3] or more) to compensate for cement washout and to provide the necessary flow characteristics to the concrete. Measurements made on one large placement indicated maximum internal concrete temperature in excess of 95 F (35 C) above the placement temperature of 60 F (16 C) (Gerwick, Holland, and Kommendant 1981).

8.8.5.2 *Placement environment*—Tremie concrete is usually placed in locations that act as excellent heat sinks. The temperature of the water surrounding the concrete will normally vary little; thus, the outside of the concrete mass cools quickly, developing steep temperature gradients. In the placement mentioned previously, the concrete temperature varied from 150 F (66 C) to river temperature 55 F (13 C) in only 40 in. (1 m).

8.8.5.3 *Volume*—To eliminate construction joint preparation under water, placements tend to be large monoliths placed over short periods of time.

8.8.5.4 *Restraint*—Underwater placements are frequently made on rock or contain many piles with the concrete acting as a pile cap. In either case, a high degree of restraint can be present.

Of the methods recommended for controlling cracking in mass concrete, modifying the materials or mixture proportions appears to have the greatest potential for application in underwater placements. In particular, use of lower-heat cements, replacement of 15 to 30% of the cement with a suitable pozzolan, and cooled aggregates and water are recommended. It is conceivable, but as yet untried, to provide internal cooling using the water available at the site or to include insulation in the fabrication of forms used in structural placements. The reader is referred to the work of Carlson, Houghton, and Polivka (1979), Gerwick and Holland (1983), and ACI 224R for additional information on cracking.

8.8.6 *Detailing*—Concrete placed under water moves to its final position in the structure by gravity, without vibration and inspection. Therefore, all formwork, reinforcing steel, and precast elements to be filled with concrete should be detailed with underwater placement in mind and incorporate the following:

- Reinforcing steel should be sized and placed to allow the maximum possible openings between bars so that concrete flow will not be impeded;
- Forms should be adequately sealed to prevent loss of concrete or mortar; and
- Forms and reinforcing steel should not trap laitance in areas intended to be filled with concrete.

8.8.7 *Preplacement planning*—Underwater concrete placements are infrequent and cannot be treated as just another concrete operation. Planning for an underwater placement should begin as soon as the decision to do the project has been made. Items that have a long lead time include detailing of reinforcing steel (if any), detailing of forms, consideration of overexcavating the placement area to avoid concrete removal if concrete placed under water is above design grade, and consideration of incorporating members required to support the tremie platforms into the internal bracing scheme of a cofferdam, if appropriate.

Consideration of the above items should result in the development of a placement plan that includes pipe spacings and locations throughout the duration of the placement. The plan should also include the locations to be used for relocating pipes as placement progresses.

8.8.8 *Personnel*—Because underwater placements are infrequent and errors can lead to problems that are extremely difficult and expensive to correct, all underwater placements should be done under the direct supervision of qualified, experienced personnel. An experienced individual should be available to interpret soundings and make necessary decisions concerning relocation of placement pipes and air lifts, and to observe overall placement procedures.

8.9—Special applications

8.9.1 *Fabric forming*—Fabric forming offers some unique advantages for specialized types of underwater concrete placement (Lamberton 1980; Koener and Welsh 1980). Normally, a sand-cement mortar, sometimes with the addition of pea gravel, is pumped into a fabric container tailored to the required shape. The fabric acts as a separator between surrounding water and the concrete as it flows into the container preventing segregation.

A high-strength, water-permeable fabric is preferred. This fabric is usually woven of nylon or polyester yarns of industrial tire cord weight at approximately 20 yarns per in. (780 yarns per m). The use of textured multifilament yarns produces a more stable fabric and is also more effective as a filter, permitting the release of excess mixing water from the concrete and thereby increasing the rate of stiffening and long-term strength and durability (Lamberton 1980).

Fabric forming is used in construction of erosion-control revetments produced by injecting mortar into a double-layer fabric envelope and in the construction of concrete jackets used to rehabilitate deteriorated marine piles. Large fabric containers have been used to cast blocks of concrete weighing up to 15 tons (14 Mg) for construction of breakwaters. Specially designed fabric assemblies have been used to cast saddles and weights for underwater pipelines.

8.9.2 *Diaphragm-wall construction*—In diaphragm- or slurry-wall construction (Xanthakos 1979; Nash 1974; Holland and Turner 1980), concrete is placed under water or under a bentonite slurry in trenches to form walls. These placements can serve as retaining walls for open excavations (when suitably braced or tied back) or as cutoff walls to stop flow through or under existing structures, such as earthfill dams or levees.

Because these walls are confined placements, the rate of concrete rise will be high, necessitating frequent removal of tremie sections to maintain flow.

8.10—Antiwashout admixtures

Chemical admixtures intended for use in concrete placed under water have been developed (Saucier and Neeley 1987; Khayat, Gerwick, and Hester 1990). These antiwashout admixtures make the concrete more cohesive and thus less prone to washout of cement or fines from the concrete during placement.

These admixtures were developed for use in situations where freshly placed concrete, may be exposed to flowing water during or after placement where concrete placement is not thick enough to permit the required tremie pipe embedment, or where the wash-out of cement may cause an environmental problem. A Corps of Engineers test method (CRD-C 61) has been developed to evaluate the effectiveness of these admixtures (Neeley 1988). Because of the thixotropic nature of the concrete treated with these admixtures, they should be used with caution for massive placements in which the concrete is expected to flow for long distances once it exits the tremie pipe. Trial placements should be conducted to verify that the concrete proportioned with the antiwashout admixture can maintain adequate slump life and can flow for the required distance.

Applications of these antiwashout admixtures include underwater paving of a canal (Kepler 1990; Klemens 1991) and underwater repair of a dam (Neeley and Wickersham 1989).

CHAPTER 9—PUMPING CONCRETE

9.1—General considerations

This chapter gives an overview of concrete pumping. For a more detailed discussion, refer to ACI 304.2R.

ACI defines pumped concrete as concrete that is transported through rigid or flexible pipeline by means of a pump. Pumping can be used for most concrete construction, but is especially useful where space for construction equipment is limited. A steady supply of pumpable concrete is necessary for satisfactory pumping. A pumpable concrete, like conventional concrete, requires good quality control: that is, uniform, properly graded aggregate, and uniform batching and thorough mixing of all materials.

Pumped concrete moves as a cylinder riding on a thin lubricant film of grout or mortar on the inside diameter of the pipeline.

Maximum volume output and maximum pressure on the concrete cannot be achieved simultaneously from most concrete pumps because this combination requires too much power. Three to four times more pressure is required per foot of vertical rise than is necessary per foot of horizontal movement.

9.2—Pumping equipment

The most common concrete pumps consist of a receiving hopper, two concrete pumping cylinders, and a valving system to alternately direct the flow of concrete into the pumping cylinders, and from them, to the pipeline. One concrete cylinder receives concrete from the receiving hopper while the other discharges into the pipeline to provide a relatively constant flow of concrete through the pipeline to the placement area. The price of concrete pumps varies greatly with

maximum pumping capacity and maximum pressure that can be applied to the concrete. Pumps should be selected to provide the desired output, volume, and pressure on the concrete in the pipeline.

The most versatile concrete pumps use hydraulically operated concrete valves that have the ability to crush or displace aggregate that becomes trapped in the valve area. Most of these pumps have an outlet port 5 in. (125 mm) or larger in diameter and use reducers to reach smaller pipeline sizes, if necessary.

Other pumps use steel balls and mating seats to control the flow of concrete from the hopper into the pumping cylinder and out of the pumping cylinder into the pipeline. These units are limited to pumping concrete with smaller than 1/2 in. (13 mm) maximum-sized aggregate. ACI 304.2R describes general-purpose, medium-duty, and special-application pumps in detail. These can be trailer- or truck-mounted units. Truck-mounted pumps can also be equipped with placement booms that support a 5 in. (125 mm) diameter pipeline that receives the discharge from a concrete pump and places it in the forms. Most booms have three or more articulating sections and are mounted on a turret that rotates to enable the discharge of the pipeline to be located where needed. Booms are generally rated according to their vertical reach and range in size from about 72 ft to 175 ft (22 to 53 m).

Concrete pumps are powerful machines that use high hydraulic oil pressures, concrete under high pressure, and compressed air for cleanup. Safe operating practices are necessary for the protection of the pump operator, ready-mixed concrete drivers, and the workers placing and finishing the pumped concrete.

9.3—Pipeline and accessories

9.3.1 *General*—Most concrete transported to the placement area by pumping methods is pumped through rigid steel tubing or heavy-duty flexible hose, both of which are called pipeline. The flexibility of the hose allows workers to place concrete exactly where it is needed. For placements on grade, rubber hose is frequently used at the end of a steel tubing pipeline. Large or elevated placements generally are done by placement booms.

Pipeline surface irregularity or roughness, diameter variations, and directional changes disturb the smooth flow of pumped concrete. This results in increased pressure required to push concrete through the pipeline and increased wear rate throughout the pump and pipeline.

All components of the pipeline should be able to handle, with an adequate safety factor, the maximum internal pressure that the concrete pump being used is capable of producing. The safety factor decreases as the pipeline wears due to the abrasiveness of the coarse and fine aggregate used in the concrete. The rate of wear can vary greatly.

Straight sections of pipeline are made of welded or seamless steel tubing, most commonly 10 ft (3 m) in length. The most common diameters are 4 and 5 in. (100 and 125 mm) with most systems in the 5 in. (125 mm) size. Aluminum pipeline should not be used in concrete pumping (Fowler and Holmgren 1971).

9.3.2 *Pipeline components*—Concrete pipeline components can be assembled in virtually any order, then disassembled and reconfigured in a different manner. To achieve this flexibility, each delivery line component requires the use of connecting ends or collars, a coupling, and a gasket. The coupling connections require a gasket sealing ring to hold the required pressure and prevent grout leakage. The most common connecting ends use a raised section profile to make a joint that can withstand pressures in excess of 2000 psi (14 MPa). They can also withstand considerable stress from external bending forces. Grooved-end connections should not be used on pipeline with diameter greater than 3 in. (75 mm).

Concrete pumping hose is divided into two classifications: hose intended for use at the end of a placement line (discharge hose) and hose used on a placement boom (boom hose). A discharge hose has a lower pressure rating. A boom hose typically connects rigid boom sections and should withstand high pressures. Approximately three times more pressure is required to pump concrete through a given length of hose than is needed to pump through the same length of steel line. Pumping pressure can cause a curved or bent hose to straighten. Injuries have resulted from such movement, and sharp bends should be avoided.

To help achieve maximum component life, safe and thorough cleaning of the pipeline is necessary at the end of each placement or at any time a lengthy delay in pumping operation occurs. The pipeline is cleaned by propelling a sponge ball or rubber go-devil through the line with air or water pressure. Arrangements for disposal of this residual concrete should be made before pumping begins.

9.4—Proportioning pumpable concrete

9.4.1 *Basic considerations*—Concrete pumping is so established in most areas that most ready-mixed concrete producers can supply a concrete mixture that will pump readily if they are informed of the concrete pump volume and pressure capability, pipeline diameter, and horizontal and vertical distance to be pumped.

The shape of the coarse aggregate, whether angular or rounded, has an influence on the required mixture proportions, although both shapes can be pumped satisfactorily. The angular pieces have a greater surface area per unit volume as compared with rounded pieces and thus require more mortar to coat the surface for pumpability.

9.4.2 *Coarse aggregate*—The maximum size of angular or crushed coarse aggregate is limited to 1/3 of the smallest inside diameter of the pump or pipeline. For well-rounded aggregate, the maximum size should be limited to 2/5 of these diameters. The principles of proportioning are covered in ACI 211.1 and ACI 211.2.

Whereas the grading of sizes of coarse aggregate should meet the requirements of ASTM C 33, it is important to recognize that the range between the upper and lower limits of this standard is broader than ACI Committee 304 recommends to produce a pumpable concrete.

9.4.3 *Fine aggregate*—The properties of the fine aggregate have a much more prominent role in the proportioning of pumpable mixtures than do those of the coarse aggregate. Together with the cement and water, the fine aggregate provides the mortar or fluid that conveys the coarse aggregates in suspension, thus rendering a mixture pumpable.

Particular attention should be given to those portions passing the finer screen sizes (Anderson 1977). At least 15 to 30% should pass the No. 50 (300 μm) screen and 5 to 10% should pass the No. 100 (150 μm) screen. ACI 211.1 states that for more workable concrete, which is sometimes re-

quired when placement is by pump, it may be desirable to reduce the estimated coarse aggregate content by up to 10%. Exercise caution to ensure that the resulting slump, *w*/*cm*, and strength properties of the concrete meet applicable project specification requirements.

9.4.4 *Combined normalweight aggregates*—The combined coarse and fine aggregates occupy about 67 to 77% of the mixture volume. For gradation purposes, the fine and coarse aggregates should be considered as one even though they are usually proportioned separately.

ACI 304.2R includes an analysis worksheet for evaluating the pumpability of a concrete mixture by combining the fine and coarse aggregate with nominal maximum-sized aggregate from 3/4 to 1-1/2 in. (19 to 38 mm). The worksheet makes provision for additional coarse and fine aggregate that can be added to a mixture to improve the overall gradation and recognizes possible overlap of some coarse and fine aggregate components. If a mixture is known to be pumpable is evaluated and graphed first, the curve representing its proportions provides a useful reference for determining the pumpability of a questionable mixture. If that mixture has a curve running in a zigzag fashion, or has one or more values falling below the boundary line, the mixture is questionable for pumping and may not be pumpable by all types of concrete pumps. Those pumps with powered valves, higher pressure on the concrete, and the most gradual and smallest reduction from concrete tube diameter can pump the most difficult mixtures.

Concrete containing lightweight fine and coarse aggregate can be pumped if the aggregate is properly saturated. Refer to ACI 304.2R for more detailed information and procedures.

9.4.5 *Water*—Water requirements and slump control for pumpable normalweight concrete mixtures are interrelated and extremely important considerations. The amount of water used in a mixture will influence the strength and durability (for a given amount of cement) and will also affect the slump or workability.

Mixing water requirements vary for different maximum sizes of aggregate as well as for different slumps.

To establish the optimum slump resulting from water content for a pump mixture and to maintain control of that particular slump through the course of a job are both extremely important factors. Slumps from 2 to 6 in. (50 to 150 mm) are most suitable for pumping. In mixtures with higher slump, the coarse aggregate can separate from the mortar and paste and can cause pipeline blockage. Slumps obtained through the use of superplasticizers, however, are usually pumped without difficulty.

There are several reasons why the slump of concrete can change between initial mixing and final placement. If the slump at the end of the discharge hose can be maintained within specification limitations, it may be satisfactory for the concrete to enter the pump at a higher slump to compensate for slump loss, if the change is due simply to aggregate absorption.

9.4.6 *Cementitious materials*—The determination of the cementitious materials content follows the same basic principles used for any concrete.

In establishing the cement content, remember the need for overstrength proportioning in the laboratory to allow for field variations.

The use of extra quantities of cementitious materials as the only means to correct pumping difficulties is shortsighted and uneconomical. Correcting any deficiencies in the aggregate gradation is more important.

9.4.7 *Admixtures*—Any admixture that increases workability in both normalweight and lightweight concretes will usually improve pumpability. Admixtures used to improve pumpability include regular and high-range, water-reducing admixtures, air-entraining admixtures, and finely divided mineral admixtures.

Increased awareness of the need to incorporate entrained air in concrete to minimize freezing and thawing damage to structures has coincided with increased use of concrete pumps, as well as the development of longer placement booms. This has resulted in considerable research and testing, which has established that the effectiveness of the air-entraining agent (AEA) in producing a beneficial air-void system depends on many factors. The more important factors are:

- The compatibility of the AEA and other admixtures as well as the order in which they are introduced into the batch;
- The mixture proportions and aggregate gradation;
- Mixing equipment and procedures;
- Mixture temperatures; and
- Slump.

AEA effectiveness and the resulting dosage of AEA also depend on the cement fineness, cement factor, and water content, and the chemistry of cement and water, as well as that of other chemical and mineral admixtures used in the concrete. Refer to ACI 304.2R for more detailed information on air content and admixtures.

9.5—Field practice

Preplanning for concrete pumping is essential for successful placements, with increasing detail and coordination required as the size of the placement and the project increases. This planning should provide for the correct amount and type of concrete for the pump being used, provision for necessary pipeline, and agreement as to which personnel will provide the labor necessary to the complete placement operation.

Any trailer- or truck-mounted concrete pump can be used for pipeline concrete placement. The limiting factor in this method is the ability to spread the concrete as needed at the end of the pipeline. Generally, this is done by laborers using a rubber hose at the end of a rigid placement line.

The discharge of powered placement booms can be positioned at almost any point within the radius of the boom and at elevations achieved with the boom from near vertical (up or down) to horizontal. Their use generally reduces the manpower required for a given placement.

9.6—Field Control

Pumped concrete does not require any compromise in quality. A high level of quality control, however, should be maintained to ensure concrete uniformity.

Concrete has been pumped successfully during both hot and cold weather. Precautions may be necessary to provide adequate protection during extreme conditions. Refer to ACI 305R and ACI 306R for guidance.

CHAPTER 10—CONVEYING CONCRETE

10.1—General considerations

This chapter gives an overview of conveying concrete. For a more detailed discussion, refer to ACI 304.4R.

Belt conveyors for handling concrete are unique in that they transport plastic concrete that is approximately 48% heavier than aggregate or other commonly conveyed materials. They transport plastic concrete from a supply source, such as a truck mixer or a batching and mixing plant, to the point of placement or to other equipment that is used to place the concrete. Maximum success for conveyor placement requires a constant supply of properly mixed concrete for charging the belt conveyor and a provision for moving the discharge point during placement so that the plastic concrete is deposited over the entire placement area without the need for rehandling or excessive vibration. Concrete belt conveyors are classified into three types: 1) portable or self-contained; 2) feeder or series; and 3) spreader-radial or side-discharge.

All concrete conveyors require charge and discharge hoppers, belt wipers, and proper combinations of belt support idlers and belt speed to prevent segregation of the concrete. Any normalweight or lightweight aggregate concrete that can be discharged by a truck mixer can be placed by a concrete belt conveyor.

10.2—Conveyor operation

Concrete conveyors running at the correct belt speed and with properly functioning charging hoppers, transfer devices, and belt wipers have only a minor effect on the strength, slump, or air content of the concrete that they carry.

The characteristics of the ribbon of concrete on a conveyor belt are determined by the angle of surcharge of the concrete, the required minimum edge distance, and the load cross section. The angle of surcharge is the angle to the horizontal that the surface of the same concrete assumes while it is being carried on a moving (horizontal) belt conveyor. The angle of surcharge for most concrete falls in a range from 0 to 10 degrees (Anon. 1979). The angle of surcharge determines the cross section of the concrete ribbon that can be efficiently carried on the belt and the maximum slope (ascending or descending) at which concrete can be handled by a belt conveyor.

Concrete cannot be carried across the entire face of a belt. The ribbon of concrete should be centered on the belt with equal widths of clear belt or edge distance between it and each edge of the belt. Failure to observe the minimum edge distance requirement will result in excessive spilling and loss of large aggregate off the edges of the belt.

All concrete belt conveyors use idlers that trough or cup the belt, enabling it to carry a deeper ribbon of concrete than would be possible on a flat belt. As the angle of the belt (ascending or descending) is increased, the ribbon of concrete on the belt becomes shallower. As concrete is loaded on a belt conveyor, any difference between its velocity in the direction of belt travel and the speed of the belt will be equalized by acceleration or deceleration of the concrete, which results in turbulence. Properly designed charging hoppers use this turbulence to produce a remixing of the concrete as it flows onto the belt. A concrete belt conveyor should be equipped with a charging hopper that levels out surges of concrete flow and delivers a uniform ribbon of concrete onto the belt with proper edge distance.

Plastic concrete is traveling at the same speed as the belt when it is discharged from a belt conveyor. The plastic concrete generally leaves the belt as a cohesive mass except that some of the larger pieces of coarse aggregate can segregate from the stream and some mortar clings to the belt. Using properly designed discharge hoppers, chutes, drop-chutes, or elephant trunks will eliminate concrete segregation problems. Equipping every end-discharge conveyor belt with a belt wiper or scraper will limit mortar loss.

10.3—Conveyor design

Concrete conveyor belts are quite flexible because they operate at high speeds over relatively small-diameter head and tail pulleys. Almost all conveyor belting is made in long lengths and is cut to fit the conveyor on which it is installed. The ends of the belt are spliced to make the belt continuous.

Most concrete belt conveyors are moved frequently and it is impossible to ensure that the supporting structure and belt idlers will always be level in the plane at a right angle to the center line of the belt. Whenever a belt conveyor is not level, gravity will cause the belt to drift to the low side. This problem is usually solved with specially designed belt-support idlers or with guide rollers that are in contact with the belt edge.

The single most important factor in determining load cross section is belt width. A relatively small increase in conveyor belt width greatly increases capacity. For example, increasing belt width from 16 to 24 in. (400 to 600 mm) more than doubles the capacity of the conveyor system at the same belt speed.

A convenient method of estimating concrete belt-conveyor capacity is to use conveyor capacity tables published by the conveyor manufacturer. These tables usually assume continuous horizontal operating conditions, average angle of surcharge, and a conventional three-roll idler configuration. These tables are intended to cover average conditions and are usually accurate enough for most purposes. There is a direct relationship between capacity and belt speed so that capacities can be interpolated for belt speeds not shown.

Keeping the weight of concrete on the belt to a minimum will allow the belt conveyor to run at optimum belt speed. Generally, this speed is in the range of 300 to 750 ft/min (90 to 230 m/min) depending on the type of concrete belt conveyor involved, the angle of surcharge of the concrete, and the angle of the conveyor.

The proper combination of idler spacing and belt tension allows concrete belt conveyors to stop and hold concrete on the belt without spillage. Increasing idler spacing decreases the overall weight of the concrete conveyor but increases the belt tension required for successful operation.

Operating conditions for concrete belt conveyors require the use of watertight or waterproof electrical components, sealed bearings, and closed hydraulic circuits. Consequently, there is no equipment-related reason to protect the conveyors from weather and environmental conditions. There is rarely a need to enclose or protect the concrete on portable conveyors or on other types of conveyors up to 200 to 300 ft (60 to 90 m) long. The concrete is conveyed at high speed and is exposed to ambient conditions for only a short time.

If extreme ambient conditions are anticipated when using longer conveyor systems, some form of enclosure may be necessary to maintain the workability of the concrete or to protect it from freezing. Whether such an enclosure will be required should be determined on a project-by-project basis.

All structural concrete can be handled satisfactorily by a concrete belt conveyor. Extremes of slump, either below 1 in. (25 mm) or above 7 in. (180 mm), reduce the placement capacity of a belt conveyor significantly.

Saucier (1974) reported that in tests of concrete conveyed over 3000 ft (900 m), cement hydration, water evaporation, or

aggregate absorption resulted in loss of slump for concrete conveyed these long distances. Strength tests indicated a definite increase in strength corresponding to the decrease in slump. The loss of entrained air was less than 0.5% for concrete originally containing approximately 5% air.

No single factor of conveyor design is of such overriding importance that it alone will produce satisfactory or unsatisfactory operation.

10.4—Types of concrete conveyors

Different project requirements have resulted in the development of portable, feeder, and spreading conveyors for concrete placement. Each type can be used alone or combined with others to form a conveyor system.

10.4.1 *Portable conveyors*—Short-lift or short-reach concrete-placement applications require the use of a portable belt conveyor. The most important characteristic is that each unit is self-contained and can be readily moved about the project. Belt widths of 16 or 18 in. (400 or 460 mm) are most common. The weight and mobility trade-off of the portable belt conveyor restricts its overall length to approximately 60 ft (18 m). This, in turn, establishes the maximum discharge height at approximately 35 ft (11 m).

Portable belt conveyors are generally powered with diesel or gasoline engines and use hydraulic drive systems to power the load-carrying belt. A self-propelled conveyor with an overall belt length of 56 ft (17 m), a 30 hp (22 MW) engine, and power steering can place at a rate as high as 100 yd^3/h (76 m^3/h).

10.4.2 *Feeder conveyors*—Long-reach concrete-placement applications require the use of transporting or feeder-type belt conveyors that operate in series with end-discharge transfer points.

Feeder-belt conveyors are normally powered with alternating current electric motors so that the load-carrying belt speed will be controlled by the power supply. Controls and cables should meet the normal electrical code requirements and be safe for use in a wet environment. The motors should be protected against both overload conditions and low-voltages. It is important that the conveyors automatically start in sequence and that the system ensure that each flight or unit of the system is operating at the proper belt speed before concrete is discharged onto the belt.

Feeder-belt conveyors can be operated over a rail or track that allows the feeder train to be extended or retracted without interrupting concrete placement. On large projects, relatively permanent feeder-belt conveyors can be installed. Under these conditions, much longer conveyor units can be used.

Spreading of the concrete at the discharge end of the train requires particular attention because feeder-belt conveyors move such a large volume of concrete. Usually, feeder conveyors discharge into equipment especially designed for spreading concrete.

10.4.3 *Spreading conveyors*

10.4.3.1 *Radial spreaders*—Radial spreaders are mounted on the placement conveyor or on a cantilevered support that swings the discharge end through an arc. They also have provision for extending and retracting the placement conveyor a substantial distance. Cantilevered radial spreaders normally rely on outrigger legs supported by the forms or the base on which the concrete is being cast to resist the overturning moment created by the loaded belt. Radial spreaders are also supported by rigid posts mounted in or near the placement area.

The limitations of reach and weight of radial spreading units have been largely overcome through the use of two- or three-section telescoping conveyors mounted on tracks or the telescoping boom of a hydraulic crane. Radial spreaders have the advantages of relatively quick setup time and the capability of reaching past obstructions. They also cause a minimum obstruction or congestion in the placement area itself.

For wide placements, the most efficient method of equipment use and the best placement pattern for finishing with mechanical equipment are achieved by side-discharge conveyors or straight-line spreaders (Cope 1972).

10.4.3.2 *Side-discharge conveyors*—Side-discharge conveyors span completely across the placement area. By discharging concrete over the side of the belt with a traveling plow or diverter, they place a straight ribbon of concrete that is ideal for mechanical finishing. Side- discharge conveyors normally operate horizontally, so the belt can be loaded heavily. Those equipped with 16 in. (400 mm) wide belts have a capacity of approximately 100 yd^3/h (75 m^3/h), 20 in. (500 mm) wide belt capacity is 200 yd^3 (153 m^3) per h, and 24 in. (600 mm) wide belt capacity is approximately 300 yd^3 (230 m^3) per h.

A crane using a bucket to bring concrete to the relatively stationary and usually visible hopper of a side-discharge conveyor is significantly more efficient than the same crane swinging blind to place concrete for an elevated slab. Side-discharge conveyors have made pumps more practical for wide slabs or decks by eliminating the labor needed to constantly move the discharge end of the pipeline back and forth in front of the commonly used straight-line finishing equipment.

The diverter that removes concrete from the belt and discharges it over the side of the conveyor uses a wiper blade to remove the concrete from the belt. The operation and adjustment of the wiper blade is critical on an end-discharge conveyor. Provisions should be made for adjusting the belt wiper or scraper on side-discharge conveyors while concrete is being placed. Some wear on the wiping strip is normal, and a small amount of grout can be carried past the diverter.

10.4.3.3 *Conveyor combinations*—Each type of conveyor has some limited ability to reach, lift, carry, or spread. On complex or large projects, economics will normally favor using each type of machine for the function it performs best. As long as belt speeds and widths are compatible, it is practical to combine various types of equipment.

10.5—Field practice

It is generally not practical to custom design belt conveyors for each project or application. Normal practice is to select standard, commercially available equipment that has adequate capacity and reach, and to organize and plan its use to meet the general construction sequences required to properly perform the work.

The actual field placement rate of a concrete conveyor will rarely equal the theoretical capacity from charts. This is primarily attributable to the inevitable delays that occur in batching, mixing, and transporting concrete to the belt conveyor at the placement area. Other delays involve consolidation and finishing of the concrete and moving of the conveyor. There is no way that a belt conveyor can place a surge of concrete in excess of design capacity because

excess concrete placed on the belt will usually be spilled off the sides.

Hourly production on an efficient project will usually average about 70% of the capacity of the belt conveyor. This adjustment of the theoretical capacity provides the safety factor that most jobs require for successful completion within scheduled times.

As the placement progresses, fresh concrete should always be discharged onto or against concrete of plastic consistency that is already in place so there will be some blending of concrete through vibration and there will be no opportunity for objectionable rock pockets to be formed. Vibration at the delivery point and immediately behind the advancing edge of the concrete will cause the concrete to surround reinforcing steel without significant segregation.

Some conveyor maintenance can be necessary during concrete placement on large-volume projects because conveyor belting will stretch to some degree during concrete placing. Concrete conveyors should have provision for increasing belt tension.

Any spilled concrete should be cleaned off the conveyor before it can harden.

Concrete belt conveyors are an open system where almost all of the concrete being placed can be visually inspected. The ribbon of concrete on the conveyor belt should be observed at the start and frequently through the placement. The main emphasis of inspection should be on the proper discharging of concrete from the conveyors and consolidation of the concrete. Concrete discharged from a conveyor should not free-fall far enough to cause segregation.

Concrete belt conveyor systems should be tested under job conditions before any significant placement is attempted if there is any doubt about the ability of the system to successfully place the concrete. Fortunately, handling of only a few cubic yards of concrete over any belt conveyor system will validate the conveyor design and identify problem areas.

Tests of the plastic concrete and samples for strength determination taken at the discharge from the mixing or transporting equipment and at the concrete belt conveyor discharge point should provide adequate assurance of satisfactory operation. The quality of concrete being placed in the structure can be measured only at the point of placement in the structure. Once a satisfactory correlation between samples taken at the point of placement and the point of discharge of the mixer has been established, sampling at the more convenient point should be satisfactory, provided placement conditions remain unchanged.

CHAPTER 11—HEAVYWEIGHT AND RADIATION-SHIELDING CONCRETE

11.1—General considerations

The procedures for measuring, mixing, transporting, and placing heavyweight and radiation- shielding concrete are similar to those used in conventional concrete construction. Special expertise and thorough planning are necessary for the successful completion of this type of concrete work (Pihlajayaara 1972). For a detailed discussion on heavyweight and radiation-shielding concrete, refer to ACI 304.3R.

Normalweight concrete is generally specified for radiation shielding when space is available. When space is limited, however, the thickness of these shields can be reduced by using both natural and synthetic heavyweight aggregates. Natural mineral aggregates and synthetic aggregate can produce concrete having a typical density as high as 240 lb/ft^3 (3840 kg/m^3) and 340 lb/ft^3 (5450 kg/m^3), respectively. Heavyweight concrete not only has a higher density, but also more desirable attenuation properties.

When heavyweight concrete is used to absorb gamma rays, the density is of prime importance (Pihlajayaara 1972). When the concrete is to attenuate neutrons, material of light atomic weight containing hydrogen should be included in the concrete mixture (Davis 1972a). Some aggregates are used because of their ability to retain chemically bound water at elevated temperatures (above 185 F [85 C]), which ensures a source of hydrogen.

Colemanite, a mineral containing boron, and manufactured boron additives, such as boron frit, ferroboron, and boron carbide have been used in conjunction with normalweight and heavyweight concrete. Their use enhances absorption of thermal neutrons, limits hard gamma radiation, and limits buildup of long-lived activity. Caution should be exercised because of the possibility of retardation due to the presence of soluble borates (Volkman 1994).

11.2—Materials

11.2.1 *General*—Cements, admixtures, and water used in heavyweight concrete should conform to the standards generally required for normalweight concrete, only the aggregate is different and may require special consideration during handling, batching, mixing, transporting and placing.

11.2.2 *Aggregate*—Thorough examination and evaluation of heavyweight aggregate sources are necessary to obtain material suitable for the type of shielding required (Browne and Blundell 1972).

Composition of aggregates for use in radiation-shielding concrete is described in ASTM C 638, and aggregates should meet requirements of ASTM C 637. Some typical properties for shielding aggregates are shown in Table 11.1.

Some aggregates (ferrophosphorous and barite) and some iron ores are brittle and highly crystalline in structure and tend to break up into smaller pieces while being handled. These factors should not preclude the use of the material, provided it is demonstrated that the concrete manufactured has properties meeting the specification requirements.

Fine metallic aggregate should consist of commercial chilled-iron, steel shot, or ground iron meeting the specifications of the Society of Automotive Engineers (1993).

Heavyweight PA concrete usually precludes the use of aggregate larger than 1-1/2 in. (40 mm) due to form configuration and embedment limitations. Coarse aggregate should be uniformly graded from 1/2 to 1-1/2 in. (10 to 40 mm) and conform to Grading 1 in Table 7.1 (Chapter 7). Fine aggregate grading should be within the limits shown in Table 7.1 so that the smaller particles show less tendency to segregate.

Aggregate should be shipped, handled, and stored in a manner that will ensure little loss of fines, no contamination by foreign material, or significant aggregate breakage or segregation.

11.2.3 *Proprietary premixed mortar*—Heavyweight iron mortar and lightweight organic and inorganic mortar concretes produced commercially by manufacturers for biological shielding should be tested before use for radiation-shielding properties. Inspection at the point of manufacture should be as stringent as for natural and synthetic heavyweight aggregates and shielding concretes.

Table 11.1—Typical radiation-shielding aggregates*

Natural mineral					Synthetic mineral			
			Percent by weight				Percent by weight	
Aggregate	Source‡	Specific gravity†	Iron	Fixed water	Aggregate	Specific gravity‡	Iron	Fixed water
Hydrous ore					Crushed aggregate			
Bauxite	—	1.8 to 2.3	0	15 to 25	Heavy slags	5.0	0	0
Geothite	Utah, Michigan	3.4 to 3.8	0	8 to 12	Ferrophosphorous§	5.8 to 6.3	0	0
Limonite	Utah, Michigan	3.4 to 3.8	55	8 to 12	Ferrosilicon	6.5 to 7.0	70	0
Heavy ore					Metallic iron products			
Barite	Nevada, Tennessee	4.0 to 4.4	1 to 10	0	Sheared reinforcing bars	7.7 to 7.8	99	0
Magnetite	Nevada, Wyoming, Montana	4.2 to 4.8	60	1.0 to 2.5	Steel punchings	7.7 to 7.8	99	0
Ilmentite	Quebec	4.2 to 4.8	40	0	Iron and steel shot	7.5 to 7.6	99	0
Hematite	South America, Africa	4.2 to 4.8	70	—	Boron Products			
Boron additives					Boron frit	2.4 to 2.6	0	0
Boro calcite	Turkey	2.3 to 2.4	0	0	Ferroboron	5.0	85	0
Colemanite	California	2.3 to 2.4	0	0	Borated Diatomaceous earth	1.0	0	0
					Boron carbine	2.5 to 2.6	0	0

*Source: Society of Automotive Engineers (1993), Davis (1967), and Anon (1955).
†Material water-saturated with its surface dry.
‡Other sources may be available.
§Ferrophosphorous when used in portland cement will generate flammable and possible toxic gases that can develop high pressure if confined.

11.3—Concrete characteristics

11.3.1 *Physical properties*—High modulus of elasticity, low coefficient of thermal expansion, and low elastic and creep deformation are ideal properties for heavyweight concrete. High compressive strengths may be required if heavyweight concrete is to be subjected to high stresses. Heavyweight concrete with a high cement content and a low *w*/*cm* can exhibit increased creep and shrinkage, and in a massive concrete placement could generate high temperatures at early ages, causing undesirable localized cracking from the thermally induced stresses. When structural considerations require this cracking potential to be eliminated, it is necessary to use appropriate temperature control measures, which could include precooling or postcooling the concrete, or both, as described in ACI 207.2R and ACI 224R.

11.3.2 *Mixture proportioning*—Procedures outlined in ACI 211.1 should be used for concrete proportioning. Conventionally placed heavyweight concrete should be proportioned to provide the desired compressive strength and density as well as adequate workability. Also, the chemical constituents and fixed water content of the resulting mixture should provide satisfactory shielding properties (Davis 1972b). Typical proportions for heavyweight, conventionally placed concrete, PA concrete, and grout mixtures are shown in Table 11.2.

11.4—Mixing equipment

Standard mixing equipment is generally used to mix heavyweight concrete, but care should be taken not to overload the equipment. In general, the amount of heavyweight concrete mixed should be equivalent to the mixture weight of normalweight concrete rather than the volume capacity of the mixing equipment. Heavyweight concrete should be agitated when transported from the mixing plant to the point of placement to prevent segregation, consolidation, and packing.

11.5—Formwork

Formwork should follow the practices set forth in ACI 347R. Formwork for conventionally placed heavyweight concrete needs to be stronger than comparable formwork for ordinary concrete because of the increased concrete density.

Typical radiation-shielding structures require a complex shape, and they can contain many penetrations through the formwork. The strutting and bracing system should be carefully designed to avoid unintentionally placing a load on penetrating members and to ensure precise alignment of external fixtures corresponding to these penetrations. Consider the use of permanent steel forms.

Steel penetrations are often precisely machined and fabricated assemblies that can be subject to delays in delivery. It is prudent to allow for such delays by providing for blockouts to receive these penetrations. Blockouts should be provided with normal bends or a stepped configuration to reduce the possibility of radiation streaming or leakage. The basic structure then can be completed around the blockouts. After the items to be embedded are placed, the blockouts are filled with heavyweight grout. Precautions should be taken to ensure that penetrations and blockouts are tightly grouted with a nonshrink grout of appropriate density.

11.6—Placement

11.6.1 *Conventional method*—Placement of conventionally mixed heavyweight concrete is subject to the same considerations of quality control as normalweight concrete, except that it is far more susceptible to variations in quality due to segregation caused by improper handling.

The placement of heavyweight concrete dictates the strictest observance of good placement practice. Regular concrete placement techniques can be used, including pumping. Heavyweight concrete should be placed as close as possible to

Table 11.2—Typical proportions for radiation-shielding concrete conventionally mixed and placed

Fine aggregate			Coarse aggregate				Slump		Wet density	
Mixture no.	*W/R**	Material	*W/R**	Material	Admixture	*W/CM*	in.	mm	lb/ft^3	kg/m^3
A	3.40	Ilmenite	—	—	Specify	0.43	0	0	190	3040
B	3.35	Magnetite	—	—	Specify	0.47	0	0	190	3040
C	2.39	Serpentine	5.07	Magnetite	Specify	0.62	2	50	190	3040
D	4.46	Barite	5.44	Barite	Specify	0.60	2	50	220	3520
E	3.66	Ilmenite	4.62	Ilmenite	Specify	0.45	3	75	225	3630
F	3.61	Magnetite	4.58	Magnetite	Specify	0.49	2	50	225	3630
Q	2.95	Ferrophosphorous	2.95	Ferrophosphorous	Specify	0.54	2	50	260	4170
	1.48	Barite	2.11	Barite	Specify	0.54	2	50	260	4170
H	3.01	Magnetite	1.76	Magnetite	Specify	0.49	2	50	270	4330
	—	—	2.69	S330/390 iron shot	—	—	—	—	—	—
	—	—	2.65	S1110/1320 iron shot	—	—	—	—	—	—
I	2.98	Magnetite	2.60	S330/390 iron shot	Specify	0.51	2	50	300	4800
	—	—	5.76	S1110/1320 iron shot	—	—	—	—	—	—
J	3.21	Ilmenite	2.60	S330/390 iron shot	Specify	0.49	2	50	300	4800
	—	—	5.54	S1110/1320 iron shot	—	—	—	—	—	—
K	3.82	Ferrophosphorous	7.10	Ferrophosphorous	Specify	0.53	2	50	300	4800
L	1.00	Magnetite	5.96	S330/390 iron shot	Specify	0.46	2	50	330	5290
	—	—	5.89	S1110/1320 iron shot	—	—	—	—	—	—
Preplaced-aggregate grout										
M	1.15	Serpentine	—	—	—	0.50	—	—	128	2050
N	1.00	Conventional	—	—	—	0.42	—	—	129	2060
O	1.28	Limonite	—	—	—	0.55	—	—	146	2390
P	1.49	Barite	—	—	—	0.54	—	—	155	2480
Q	2.12	Magnetite	—	—	—	0.55	—	—	170	2720
Preplaced-aggregate concrete										
Mixture no.	Grout no.	Material	*W/R**	Material	Admixture	*W/CM*	in.	mm	lb/ft^3	kg/m^3
R	O	Limonite	1.23	Limonite	Specify	0.55	—	—	215	3440
		—	5.37	Magnetite	—	—	—	—	—	—
S	Q	Magnetite	10.29	Magnetite	Specify	0.55	—	—	240	3850
T	M	Serpentine	2.46	Serpentine	Specify	0.50	—	—	240	3850
—	—	—	7.44	Steel punchings	—	—	—	—	—	—
U	Q	Magnetite	6.16	Magnetite	Specify	0.55	—	—	260	4170
		—	3.38	Steel punchings	—	—	—	—	—	—
V	O	Limonite	2.70	Limonite	Specify	0.55	—	—	260	4170
		—	6.31	Steel punchings	—	—	—	—	—	—
W	Q	Magnetite	8.08	Steel punchings	Specify	0.55	—	—	300	4810
X	Q	Magnetite	13.11	Steel punchings	Specify	0.55	—	—	340	5450

**W/R* = weight ratio aggregate/cement.

its final position in the forms with a minimum of vibration to prevent segregation. The use of long, rigid chutes or drop pipes should be avoided. Where concrete is placed in narrow forms or through restricted areas, a short, flexible-type drop chute that tends to collapse and restrict the fall should be employed. Lifts should be limited to a maximum 12 in. (300 mm) thickness.

Consolidation procedures should conform to ACI 309R. In heavyweight concrete, vibrators have a smaller effective area or radius of action; therefore, greater care should be exercised to ensure that the concrete is properly consolidated.

Vibration and revibration for removing entrapped air and to establish aggregate-to-aggregate contact can cause an excessive amount of grout to collect on the top of lift surfaces (Davis 1972c). This grout should be removed from the lift surface while the concrete is still in a fresh state.

11.6.2 *Preplaced-aggregate method*—Precautions for placement of heavyweight PA concretes are given in Chapter 7. Placement of grout for heavyweight PA concrete requires extreme care because of a greater tendency for segregation and line blockages. Therefore, ample preparations should be made for rapid clearing of grout hoses and pipes. Standby equipment should be provided, and a trial run is recommended before operation.

11.7—Quality control

11.7.1 *Samples and testing*—Heavyweight and radiation-shielding concrete materials should be sampled and tested before and during construction to ensure conformance with

applicable standards and specifications. Guidance presented in ACI standards and reports, as well as previous experience with the same materials, will determine the required frequency of testing.

The complexity of structures in which heavyweight concrete is placed usually precludes the possibility of taking test cores. It is, therefore, of the utmost importance that a thorough quality control program be established before the start of construction and maintained throughout construction.

11.7.2 *Control tests*—The quality of the concrete produced and of its constituent materials should be controlled by an established program of sampling and testing in accordance with appropriate ASTM test methods. The limits of rejection for heavyweight concrete should be established in the construction specifications and conform to the design parameters of the structures involved. Prior to wasting expensive heavyweight concrete, the engineer should be notified so that the severity of any nonconformance can be evaluated.

Heavyweight PA concrete is adaptable to the use of sophisticated and exacting quality control tests. The extent of control exercised depends on the complexity and importance of the project.

Tests of materials, grouts, and compressive strength of heavyweight PA concrete should be the same as those discussed in Chapter 7.

11.7.3 *Inspection*—The inspection of heavyweight concrete should be in accordance with applicable standards and project specifications.

Other than special modifications discussed in this chapter, those inspection items emphasized as important in ACI 311.4R should be followed for heavyweight concrete as well.

CHAPTER 12—LIGHTWEIGHT STRUCTURAL CONCRETE

12.1—General considerations

This chapter gives an overview of lightweight structural concrete. For a more detailed discussion, refer to ACI 304.5R.

Procedures for measuring, mixing, transporting, and placing lightweight concrete are similar in many respects to comparable procedures for normalweight concrete. There are certain differences, however, especially in proportioning and batching procedures, that should be considered to produce a finished product of comparable quality. The weight and absorptive properties of lightweight aggregates are different and should be considered. This chapter deals primarily with batching methods for coarse lightweight aggregates to correct for changes in weight and moisture content to ensure proper yield (Tobin 1971). It also covers batching of lightweight fine aggregates using a modification of the method used for coarse lightweight aggregates (Expanded Shale, Clay and Slate Institute 1958a, Portland Cement Association 1988).

These proportioning and batching methods have been coordinated with the basic principles set forth in ACI 211.2 and ACI 304.5R. It is necessary for the user to refer to those documents for detailed discussions of the methods available for batching lightweight aggregate, as that material is not duplicated herein.

12.2—Measuring and batching

12.2.1 *Free water and absorbed water*—One of the first considerations in batching lightweight concrete mixtures is a proper understanding of the water used in the mixture (Tobin 1967). The total water used per unit volume is divided into two components. One part is the water absorbed by the aggregates, whereas the other is similar to that in normalweight aggregate concrete and is classified as free water. Free water controls the slump, and when mixed with a given quantity of cement, establishes the strength of the paste, as for any concrete mixture. The amount and weight of absorbed water will vary with different lightweight materials, presoaking, and mixing times (Reilly 1972; Shideler 1957). Absorbed water does not change the volume of the aggregates or the concrete because it is inside the aggregate. Most important, absorbed water does not affect the *w*/*cm* or the slump of the concrete.

12.2.2 *Unit-weight variations*—The unit weight of lightweight aggregate varies depending on the raw materials used and the size of the aggregate. Smaller particles usually have higher unit weights than larger particles. Unit weights also vary due to changes in absorption or moisture content. If the lightweight aggregates are batched by weight without adjusting for these variations in unit weight, problems of over- or under yield of the concrete can result.

The dry, loose unit weight of aggregate depends primarily on its specific gravity and on the grading and shape of the particles. Angular crushed aggregates have more voids or unfilled spaces between the aggregate particles than rounded or spherically shaped pieces (Tobin 1978; Wills 1974). Poorly graded aggregate (that is, all one size) generally has more voids than a uniformly graded material that has enough smaller pieces to fit into the voids between the larger particles.

Numerous routine tests of both natural and lightweight aggregates show an amazingly close correlation of the void content for specific products being produced by a given plant over a long period.* Each production facility has its own characteristic void content values for each size of aggregate being produced and this information can usually be obtained from the source.

The absolute volume of a specific lightweight coarse aggregate is the volume of material remaining after the volume of voids has been subtracted. The absolute volume or the displaced volume in the concrete for a given lightweight material remains the same even though its density or its moisture content changes.

The proper usage of these basic principles makes it possible to batch and deliver lightweight concrete at the proper slump and yield for any job.

12.2.3 *Volume-weight batching of coarse aggregate*—To avoid problems with yield of concrete, it is necessary to maintain the same absolute volumes of lightweight aggregates in each batch of concrete by adjusting the batch weights to compensate for changes in unit weights. Standard unit weight tests on the lightweight aggregates, made frequently during batching operations can be used to adjust batch weights to reflect any changes that can occur in unit weights. This practice is rather time-consuming in a busy production facility, and a volume-weight batching system has been developed and used in some areas as an alternate method. Either method produces satisfactory results. The principal difference between the systems reported herein and that reported in ACI 211.2 is that the volume-weight method provides automatic yield adjustments for each batch of

*Unpublished data provided by committee member Robert E. Tobin.

lightweight concrete without the need for determining specific gravity factors of structural lightweight aggregate.

12.2.3.1 *Calibrating the weighing hopper*—The volume-weight system can be set up for virtually any batching system that employs a hopper or bin for weighing materials. The first operation is to determine the volume of this weighing hopper.

When the discharge gate in the overhead bin containing the lightweight coarse aggregate is opened, the material will flow into the weighing hopper until it builds up to the level of the discharge gate. Some plants may be slightly different than others but suitable modifications can be made in the overhead bins, the weighing hopper, or both to allow the weighing hopper to be filled to a prescribed level each time.

The volume of lightweight aggregate in this filled weighing hopper can be calibrated for most batching plants in the following manner. The total weight of the material (either dry or containing absorbed water) in the filled hopper can be read directly from the scales. The hopper is then discharged into a dump truck and the unit weight of three or four samples of loose material is determined in a suitable container. The total hopper weight divided by the average unit weight will give the total volume of the material in the weighing hopper in ft^3 or in m^3. For example, if the net weight of the filled hopper is 4650 lb (2100 kg) and the average unit weight of the material in it is 48.2 lb/ft^3 (772 kg/m^3), the volume is simply 4650/48.2 = 96.5 ft^3 (2210/772 = 2.73 m^3). This calibration procedure should be performed about three times to ensure valid measurements. A new calibration can be necessary if the source of lightweight aggregate is changed, because the new material can have a different angle of repose that could alter the overall volume in the weighing hopper. If no major changes occur in the lightweight aggregates, one calibration will suffice for several months or until the materials are changed significantly.

The calibrated weighing hopper can be used as a container to determine the unit weight of the lightweight coarse aggregate for each batch of concrete. A batching chart can be prepared for any specified mixture proportions based on a full range of unit weights of aggregate as measured in the weighing hopper. This procedure is explained in detail in ACI 304.5R.

12.2.4 *Batching lightweight fine aggregate*—It is not practical to batch the lightweight fine aggregate by volumetric methods because their volume changes due to variable bulking with different amounts of surface water (Portland Cement Association 1944). For this reason, the lightweight fines are batched by mass in much the same manner as natural sand with allowances made for total moisture content.

Because the moisture in lightweight fines can be partly absorbed water as well as surface or free water, the moisture meters used in batch plant storage bins for natural sand are not satisfactory for lightweight sand. Satisfactory batching results have been achieved by drying a small sample [approximately 1 lb (500 g)] of the lightweight sand being used in a suitable container to a constant weight at the temperature of 212 to 230 F (100 to 110 C). The total moisture (absorbed plus free moisture) is calculated by comparing the moist weight of the sample with its dry weight. Moisture tests should be conducted at least once per day or whenever a fresh supply of lightweight sand is introduced.

To adjust for the proper amount of lightweight fines, the oven-dry unit weight of the material being used is determined as indicated previously. If this dry unit weight differs from that shown on the laboratory mixture proportion, then the dry batch weight is changed by multiplying the loose volume by the new dry unit weight just determined. This dry batch weight is increased by the moisture content as determined previously to give the actual scale weight to be used.

12.3—Mixing

The absorptive properties of lightweight aggregates require consideration during mixing. The time rate of absorption as well as the maximum total absorption have to be properly integrated into the mixing cycle to control consistency properly (Expanded Shale, Clay and Slate Institute 1958b; Tobin 1971).

12.3.1 *Charging mixers*—The sequence of introducing the ingredients for lightweight concrete into a mixer can vary from one plant to another. Once acceptable procedures for both wetting and batching have been established, it is important to repeat these as closely as possible at all times to produce uniformity. Weather conditions, such as ambient temperature and humidity, can exert significant influences on lightweight concrete production and should be properly considered.

12.3.1.1 *Stationary mixers*—Stationary plant mixers are commonly used in precasting or prestressing operations and occasionally on building sites where concrete is not moved a great distance. They can also be used at a ready-mixed concrete production plant.

Coarse aggregates should be placed in the mixer first, followed by the fine aggregates. Then add in sequence the required water, cement, and any specified additives.

After all of the ingredients have been fed into the plant mixer, it should be operated at mixing speed to produce a complete mixture that will meet the evaluation tests as described in ASTM C 94. When stationary mixers are used for the purpose of partial or shrink mixing, they are only required to blend the materials together as mixing is completed in the truck mixer. If the lightweight aggregate has not reached its full saturation, further absorption during and after mixing can cause the mixture to stiffen.

12.3.1.2 *Truck mixers*—Charging or loading a truck mixer follows the same general practice used with stationary mixers. Larger volumes of lightweight concrete can sometimes be hauled in truck mixers without exceeding the legal weight or axle load limits. The volume of concrete in the drum should not exceed 63% of the drum volume when used as a mixer or 80% of the drum volume when used as an agitator (Gaynor and Mullarky 1975).

12.3.2 *Mixer operation*—Delivery time has an important role in slump control and can require changes in the amount of water needed to produce the desired slump. Construction jobs at different distances from the batch plant require longer or shorter haul periods, and it is not uncommon to have a delay in unloading. These factors make it difficult to determine the total time that a mixture will be in the drum for any particular load. Most lightweight aggregates continue to absorb water with time, even though they are prewetted. Prewetting slows the rate of absorption but does not necessarily eliminate absorption. It can be desirable to hold back 2 or 3 $gal./yd^3$ (10 to 15 L/m^3) of water to make certain

that the batch is not too wet upon arrival. It is often necessary and permissible to add water to a lightweight concrete mixture on the job to replace free water that has been absorbed by the lightweight aggregate to bring the concrete back to the desired slump. Mixing is done as described in Section 4.5.2.

12.4—Job controls

Field control of the yield of lightweight concrete is most important. Overyield produces a larger volume of concrete than intended, whereas underyield produces less. Overyield is nearly always associated with a loss in strength due to a reduction in the net cement content. Underyield results in less concrete being delivered than was expected or ordered. ASTM C 127, C 138, C 173, and C 231 give methods of establishing field control.

The unit weight of the fresh concrete is used to measure the yield of a mixture. The total weight of all the ingredients that are placed in a mixer drum as given on the delivery ticket is computed, or the entire truck can be weighed before and after discharging. The weight of all of the ingredients divided by the unit weight of the concrete will give the total volume of concrete in the mixer drum. When the calculated volume is more than 2% above or below the volume shown on the delivery ticket, an adjustment is required.

If the change in yield is due to entrained air content, then an adjustment in the amount of air-entraining admixture can correct this condition.

If the unit weight measured in the field is greater than the wet unit weight shown for the mixture proportioning, this indicates an underyield; conversely, if the weight is less, an overyield can occur. When there have been no appreciable changes in the weights of the lightweight aggregates themselves, in all probability, the differences in yield can be attributed to an incorrect amount or an incorrect absolute volume of lightweight aggregates. In this case, steps should be taken at the batch plant to correct the absolute volume of lightweight aggregates used in the concrete as it is being batched.

CHAPTER 13—VOLUMETRIC-MEASURING AND CONTINUOUS-MIXING CONCRETE EQUIPMENT

13.1—General Considerations

This chapter gives an overview of volumetric-measuring and continuous-mixing concrete equipment (VMCM). For a more detailed discussion, refer to ACI 304.6R.

When aggregates or cementitious materials are batched by volume, the method of batching is considered volumetric. It is normally a continuous operation coupled with continuous mixing. Accurate volumetric batching is achieved by passing material through a calibrated rotary vane feeder, conveying material through a calibrated gate opening, or by any other method that would provide a known volume in a calibrated unit time.

Volumetric batching is suitable for the production of most concrete, provided the equipment is operated in accordance with ASTM C 685 and with the same attention to detail as that required for weigh batching. The available equipment is highly mobile, requires little or no setup time, and often serves as its own material transport.

VMCM units carry enough materials to produce 6 to 10 yd^3 (5 to 8 m^3) of concrete (Fig. 13.1). This limitation is based on axle loading limitations. Production of larger volumes of concrete or high rates of production will require special provisions for recharging the material storage compartments.

The portability of the equipment makes it practical to bring the VMCM unit to the point of use, which can be an advantage in many applications. Having the unit at the placement site also allows close control of concrete quality at the site.

VMCM equipment lends itself to many different applications. Many of these applications involve relatively low-volume production of concrete, but large jobs have also been done with this equipment. In addition to producing conventional concrete, VMCM equipment is well suited for a variety of special applications, such as:

- Mixtures with short working times;
- Low-slump mixtures;
- Long unloading times;
- Concrete at remote sites;
- Making small deliveries;
- Precast operations;
- Hot weather concreting;
- Mining applications;
- Grouting and pile filling;
- Colored concretes;
- Emergency applications;
- Variable slumps within same load; and
- Flowable-fill mixtures.

13.2—Operations

Quality control—The production of concrete by volumetric measurement and continuous mixing is subject to the same rules of quality control as any other concrete production method.

Calibration—To ensure production of quality concrete, calibrate each volumetric-measuring unit for each respective concrete ingredient, following the manufacturer's recommendations and ASTM C 685.

Operational precautions—The VMCM should be in good condition. All shields and covers should be in place. All controls should operate smoothly and be connected according to the manufacturer's recommendations. All material-feed operations should start and stop simultaneously. The cement-measuring device should be inspected and cleaned regularly. Indicating meters and dials should be checked for proper

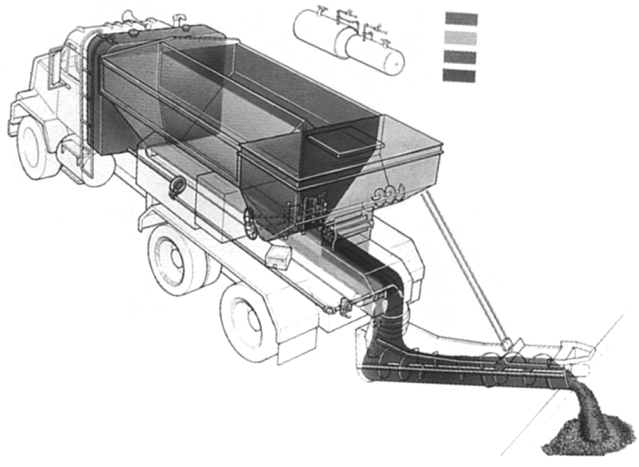

Fig. 13.1—Typical system.

flow and operation. All filters should be clean and allow full flow of water. Aggregate feed systems should be free of any blockage. Checks of the various feeding systems should be carried out according to the manufacturer's recommendations and as job experience indicates.

13.3—Fresh concrete properties

Fresh concrete produced by VMCM behaves slightly differently than ready-mixed concrete. Elapsed hydration time at discharge is measured in seconds rather than in minutes. This means that, although the actual setting time (from start of hydration) is the same, the apparent setting time (from time in place) can seem longer. Finally, the apparent slump at discharge is often higher than the measured slump 3 to 5 min after discharge. Finishers and inspectors should be made aware of these differences.

CHAPTER 14—REFERENCES

14.1—Referenced standards and reports

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

American Concrete Institute

116R Cement and Concrete Terminology
207.1R Mass Concrete
207.2R Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete
207.5R Roller Compacted Mass Concrete
211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete
212.3R Chemical Admixtures for Concrete
221R Guide for Use of Normalweight and Heavyweight Aggregates in Concrete
223 Standard Practice for the Use of Shrinkage Compensating Concrete
224R Control of Cracking in Concrete Structures
302.1R Guide for Concrete Floor and Slab Construction
304.1R Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications
304.2R Placing Concrete by Pumping Methods
304.3R Heavyweight Concrete: Measuring, Mixing, Transporting and Placing
304.4R Placing Concrete with Belt Conveyors
304.5R Batching, Mixing, and Job Control of Lightweight Concrete
304.6R Guide for the Use of Volumetric-Measuring and Continuous Mixing Concrete Equipment
305R Hot Weather Concreting
306R Cold Weather Concreting
308 Standard Practice for Curing Concrete
309R Guide for Consolidation of Concrete
311.1R ACI Manual of Concrete Inspection (SP-2)
311.4R Guide for Concrete Inspection
318 Building Code Requirements for Structural Concrete
325.9R Guide for Construction of Concrete Pavements and Concrete Bases
347R Guide to Formwork for Concrete
506R Guide for Shotcrete
544.3R Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber-Reinforced Concrete

ASTM

C 33 Specification for Concrete Aggregates
C 94 Specification for Ready-Mixed Concrete
C 127 Test Method for Specific Gravity and Absorption of Coarse Aggregate
C 138 Test Method for Unit Weight, Yield and Air Content (Gravimetric) of Concrete
C 150 Specification for Portland Cement
C 172 Practice for Sampling Freshly Mixed Concrete
C 173 Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
C 231 Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C 595M Specification for Blended Hydraulic Cements (Metric)
C 618 Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
C 637 Specification for Aggregates for Radiation-Shielding Concrete
C 638 Descriptive Nomenclature of Constituents of Aggregates for Radiation-Shielding Concrete
C 685 Specification for Concrete Made by Volumetric Batching and Continuous Mixing
C 845 Specification for Expansive Hydraulic Cement
C 938 Practice for Proportioning Grout Mixtures for Preplaced-Aggregate Concrete
C 939 Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method)
C 943 Practice for Making Test Cylinders and Prisms for Determining Strength and Density of Preplaced-Aggregate Concrete in the Laboratory
C 953 Test Method for Time of Setting of Grouts for Preplaced-Aggregate Concrete in the Laboratory
D 75 Practice for Sampling Aggregates
D 2419 Test Method for Sand Equivalent Value of Soils and Fine Aggregate

U.S. Army Corps of Engineers

CRD-C 55 Test Method for Within-Batch Uniformity of Freshly Mixed Concrete
CRD-C 61 Test Method for Determining the Resistance of Freshly Mixed Concrete toWashing Out in Water

The above publications may be obtained from the following organizations:

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

ASTM
100 Barr Harbor Drive
West Conshohocken, Pa., 19428

U. S. Army Corps of Engineers Waterways
Experiment Station
3909 Halls Ferry Road
Vicksburg, Miss., 39180

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