CHAPTER 3- CONCRETE STRUCTURES

SECTION 1. CONCRETE TECHNOLOGY

3.1.1 DEFINITION OF CONCRETE. Concrete is a mass of sand, gravel, crushed rock, or other aggregate bonded together by a hardened paste of hydraulic cement and water. When properly proportioned, mixed, and consolidated, these ingredients form a workable mass which can be placed into a form of desired size and shape. The water present reacts with the cement to convert the concrete to a hard and durable product.

3.1.2 COMPONENTS OF CONCRETE

3.1.2.1 Cement. Cement is a kiln-dried and finely pulverized mixture of natural earth materials used as a bonding ingredient in concrete or mortar. Of the five types of cement defined by the American Society for Testing and Materials (ASTM), only Types II and V should be considered for concrete structures that come into contact with seawater. Type V is the recommended product for such structures because of its high resistance to sulfate attack (a form of disintegration occurring in seawater and other high salt environments). The more commonly produced Type II, which has a moderate resistance to sulfate attack, can be used when high cement factors (more than 7-sack) are necessary. This will result in low water/cement ratios.

3.1.2.2 Aggregate. Aggregate is the inert filler material in concrete that permits good physical properties (see 3.1.3) at a low cost. It usually consists of natural sand and gravel, crushed rock, or mixtures of them. Other aggregates, such as blast-furnace slags, manufactured sand, or crushed coral, are used when the more commonly used aggregate is unavailable. The aggregate portion generally constitutes about 75% of the volume of the concrete. Particle size is usually limited to three-fourths the distance between reinforcing bars or one-fifth the minimum dimension, and never more than 3/4 inch. Particles of various sizes should be uniformly distributed throughout the mass and properly graded for dense packing. The quality and gradation of aggregate should conform to ASTM requirements.

3.1.2.3 Water. Water not only changes the concrete mixture to a workable consistency suitable for placing in a mold or forms for a desired size and shape, but it is a necessary ingredient to react with the cement, called hydration, which converts the cement to a hardened mass. The ratio of water to cement (W/C) is largely responsible for determining the strength of the concrete. This ratio, which excludes water absorbed by the aggregate, is expressed as a decimal (on a weight ratio basis) or as gallons of water per standard 94-pound bag of cement. See Table 3-1 for the relationship between these two methods of expressing W/C. The water used in mixing concrete must be clean freshwater. Potable

Table 3-1. Relationship Between Methods of Expressing Water-to-Cement Ratio

Gallons/Bag	Weight Ratio
4	0.36
4.5	0.40
5	0.44
5.5	0.49
6.0	0.53
6.5	0.58
7.0	0.62
7.5	0.66
8.0	0.71
8.5	0.75
9.0	0.80

Weight Ratio	Gallons/Bag
0.35	3.94
0.40	4.50
0.45	5.07
0.50	5.63
0.55	6.20
0.60	6.76
0.65	7.32
0.70	7.88
0.75	8.44
0.80	9.00

water is most commonly used; water with a high mineral or salt content, even though it may be called potable, may not be suitable.

3.1.2.4 Admixtures. Admixtures are materials other than cement, aggregate, or water that are added to the batch of concrete immediately before or during mixing to impart desirable properties to it. Water-reducing admixtures permit the use of less water to give a concrete mix equal consistency that may result in a final product of greater strength, watertightness, and durability. Air-entraining admixtures are used to increase the resistance of hardened concrete to cycles of alternate freezing and thawing and to improve the workability of the concrete mix. For all concrete structures exposed to seawater, the entrained air content should be between 4-1/2 and 6%. Air entrainment will result in decreased strength, but it can normally be counteracted with more cement. Air entrainment in amounts significantly greater than 6% should be tested for strength. Accelerator admixtures are used to increase the early strength of concrete. Some accelerator admixtures contain chloride and should only be used for temporary construction. All admixtures should only be used when necessary.

3.1.3 DESIRABLE PROPERTIES OF CONCRETE

3.1.3.1 Workability. The concrete composition should be such that it is easily mixed, handled, transported, and placed with vibrators without loss of homogeneity.

3.1.3.2 Strength. Much of the strength of concrete is related to the amount of mixing water used (W/C ratio). Thus, the common field practice of adding more water to improve workability at a sacrifice in strength should be avoided. As shown in Figure 3-1, the W/C ratio affects compressive strength much more than tensile and flexural strengths. Compressive strength increases with the age of the concrete. The average portland cement

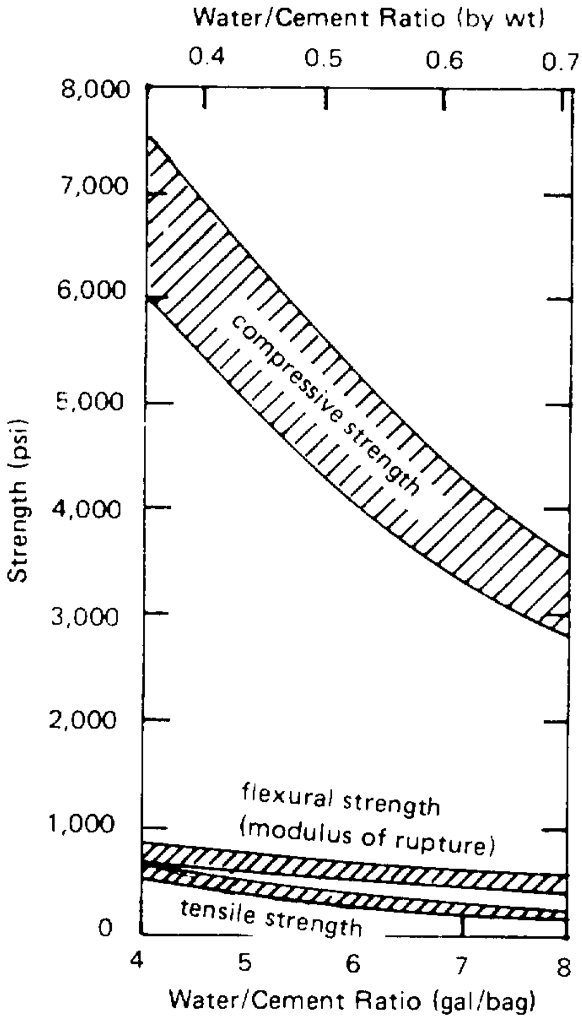

Figure 3-1. Effect of water/cement ratio on 28-day compressive, flexural, and tensile strengths.

concrete develops about 75% of its 28-day compressive strength after 7 days. After 1 year it is about 150% of the 28-day value, and after 5 years, 200% of this value. The hardening process begins at final set and continues indefinitely with favorable curing temperatures. The favorable temperature range extends from 50° to 90°F. The lower the curing temperature within this range, the greater the assurance of proper curing. Too rapid a loss of water at a higher temperature may result in shrinkage cracks. When concrete is poured at temperatures appreciably below 50°F, special heating and/or insulating techniques must be employed to raise the temperature to a more favorable level.

3.1.3.3 Durability. A durable concrete will exhibit resistance to weathering, chemical deterioration, and erosion. Concrete composition is the most important factor related to durability. The cement content should be not less than 8 bags per cubic yard, and the aggregate/cement ratio not less than 2.6 (by weight). The durability of concrete exposed to freezing and thawing is enhanced by use of air-entraining admixtures. Note that newly poured concrete must not be allowed to freeze.

3.1.3.4 Watertightness. Excess water in the concrete mix creates voids or cavities which increase permeability. Thus, a proper W/C ratio is very important as is prolonged, thorough curing for watertightness. However, with an 8-sack mix, one should be able to obtain a proper W/C ratio 0.45 or less.

3.1.4 SPECIAL CONCRETES FOR WATERFRONT STRUCTURES

3.1.4.1 Prestressed Concrete. Prestressed concrete is a special type of reinforced concrete containing stretched tendons of steel (bars, cables, wire ropes). The steel is considered pretensioned if it is stretched before the concrete attains initial set. It is considered post-tensioned if it is stretched after the hardened concrete has obtained a specified strength; the unstretched steel is first encased within ducts to prevent its bonding to the concrete. If the concrete was steam-cured, it will not be equally as durable as a concrete that was simply water-cured for the same period of time.

3.1.4.2 Fiber-Reinforced Concrete. A new approach to reinforcing concrete is the use of steel fibers, about 0.014 inch in diameter and 1.5 inches long, uniformly distributed and randomly directed throughout the concrete mix. Such fibers can be utilized either in ordinary reinforced concrete or prestressed concrete to increase the tensile strength and resistance to cracking.

3.1.4.3 Underwater Concrete. Concrete poured underwater must have good workability and, thus, should meet the following conditions:

(1) The mixture must incorporate the proper proportions of sand and gravel (preferably not crushed material) in a rich paste of portland cement and freshwater.

(2) The mixing water must not exceed 5.5 gallons per bag of cement. (Mixing water includes the water entering the batch in the form of free, surface moisture on the sand and/or gravel; this free water must, therefore, be deducted from the total water to be added.) If the aggregate particles are surface-dry and not saturated, they will absorb some of the gross mixing water; allowance must, therefore, be made for extra mixing water, taking care that the W/C ratio of 5.5 gallons per bag is not exceeded.

(3) The mixture should not contain less than 8 bags and not more than 10 bags of cement per cubic yard of ASTM Type V concrete. (Type II may be used if Type V is unavailable; see Section 3.1.2.1.)

(4) For improved workability, the concrete should incorporate an admixture to provide not less than 3°% and not more than 6% entrained air as determined by standard ASTM methods.

(5) The sand and gravel should be physically sound, and the maximum gravel size should be 3/4 inch The aggregate should be graded as indicated in Table 3-2.

(6) The formwork in which the concrete is poured must be rigid, carefully fitted, and designed so that no underwater currents can pass through it. Provision must be made for the seawater displaced by the concrete to escape from within the form. Timber is generally the most suitable material for construction of the formwork. Joints between the formwork and the intact portion of a structure should be caulked.

(7) Low temperatures during mixing and curing of concrete (i.e., below 50°F) can delay strength development for periods as long as one year and so should be avoided.

(8) An enclosed chute or "trunk" should be specified so that there is no mixing with water during placement.

Table 3-2. Gradation of Aggregates for Tremie Concrete

Aggregrate	U.S. Standard Sieve	Percent Passing (by wt)
Gravel	3/4 in.	90 to 100
	3/8 in.	20 to 55
	No. 4	0 to 10
	No. 8	0 to 5
Sand	3/8 in.	100
	No. 4	95 to 100
	No. 8	80 to 100
	No. 16	50 to 85
	No. 30	25 to 60
	No. 50	10 to 30
	No. 100	2 to 10

3.2.1 CAUSES OF CONCRETE DETERIORATION. In addition to improper mix composition there are several important causes of deterioration to concrete structures in or near seawater.

3.2.1.1 Normal Weathering. Normal, gradual weathering (aging) by sun, wind, and water is usually indicated by slight erosion of the concrete surface (e.g., rounded corners and surface pits). This is normally the result of minor salt, sulfate, or freeze-thaw attack.

3.2.1.2 Accelerated Weathering. Fine cracks are evidence of accelerated weathering by a severe environment or the lack of proper curing, as well as other causes of deterioration.

3.2.1.3 Chemical Attack. Sulfate attack of the concrete by seawater usually results in softening of the concrete and subsequent crumbling. Chemical reaction between the aggregate and the alkalies in the cement usually results in wide (up to 1-1/2 inches) and deep (several inches) cracks.

3.2.1.4 Volume Change. Volume changes can be caused by thermal expansion and contraction, freezing and thawing, changes in moisture content, and chemical reaction between the aggregate and the alkalies in the cement. These create tensile stresses in the concrete that may result in cracking and spalling. The most frequent cause of such damage in reinforced concrete is the corrosion of the embedded steel and resultant stresses caused by the greater volume occupied by the corrosion products than the original steel.

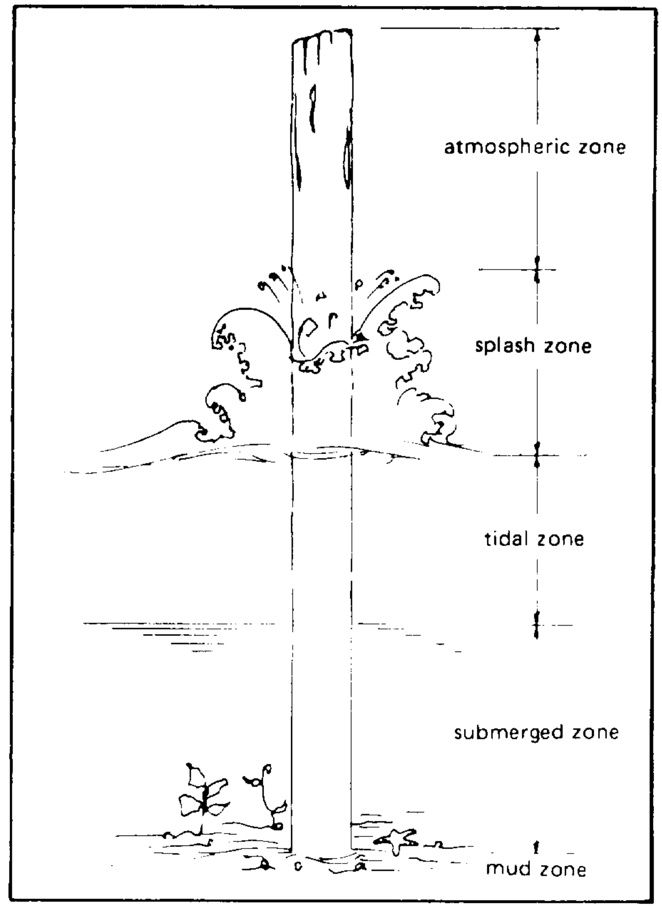

Figure 3-2. Exposure zones.

This type of damage is usually first observed in the splash zone area (see Figure 3-2), but it also occurs above the splash zone and has been found in continuously submerged concrete. Corrosion of steel in reinforced concrete is usually first evidenced by rust stains on the surface of the concrete. The best way to prevent this type of deterioration in piles is to place at least 3 inches of dense concrete (8 sack) over the steel.

Corrosion of the steel has been observed when the chloride-ion content of the concrete is more than 1.0

to 1.3 Ib/cu yd of concrete. Caution must be exercised when using water or aggregates that contain salt. Corrosion of the steel could begin from the day the concrete was cast.

3.2.1.5 Improper Finishing or Curing Practices. Improper finishing or curing practices can cause craze cracking of the concrete.

3.2.1.6 Plastic Shrinkage. Excessively rapid evaporation of water from concrete surfaces can cause plastic shrinkage cracking.

3.2.1.7 Structural Settlement. Structural settlement or unstable subgrade can allow concrete to shift during setting and, thus, cause cracking.

3.2.1.8 Mechanical Damage. Mechanical damage of hardened concrete can be caused by impact or abrasion, such as by floating debris or ice.

3.2.2 TYPES OF CONCRETE DAMAGE

3.2.2.1 Cracks. As indicated in 3.2.1, cracks may be due to many different causes or a combination of them. Cracks resulting from other causes may be aggravated by (1) loads that produce stresses on structural members, (2) restraints to volume changes, (3) thermal stresses, and (4) settlement. The maximum permissible width of cracks before an engineering investigation is initiated is 0.1 inch regardless of the loading and environment. (See Reference 3-1 for a crack repair method.)

3.2.2.2 Spalls. A spall is a thin fragment of concrete that becomes detached from a large mass of concrete by impact, expansion, or weathering. When caused by corrosion of underlying reinforcing steel, it is usually preceded by cracking.

SECTION 3. METHODS OF INSPECTION

3.3.1 VISUAL. All cracking, spalling, chipping, rust staining, and other visual signs of deterioration should be described in written form. The condition of any exposed reinforcing steel should also be noted. The measured location of all damaged areas should be recorded. Areas of inspection and repair should be on a zonal basis. The five zones, as shown in Figure 3-2, are (1) atmospheric; (2) splash zone, which extends about 6 feet above the tidal zone; (3) tidal zone, from low to high water level; (4) submerged zone, which is continuously wet; and (5) mud zone, which can only be inspected after excavation. Visual observations of significant problem areas should be fully documented with photographs and/or video tapes.

Soundness of concrete should be determined by tapping with a hammer, as the actual condition may not be apparent from mere observation. In many instances of shallow spalling, a veneer of damaged concrete is loosely held in place. The only concern for repair of shallow spalls is appearance.

Where deterioration is extensive (Figure 3-3), enough concrete should be removed to indicate the extent of needed repair. The depth of damage can best be determined by chopping away a small section with a

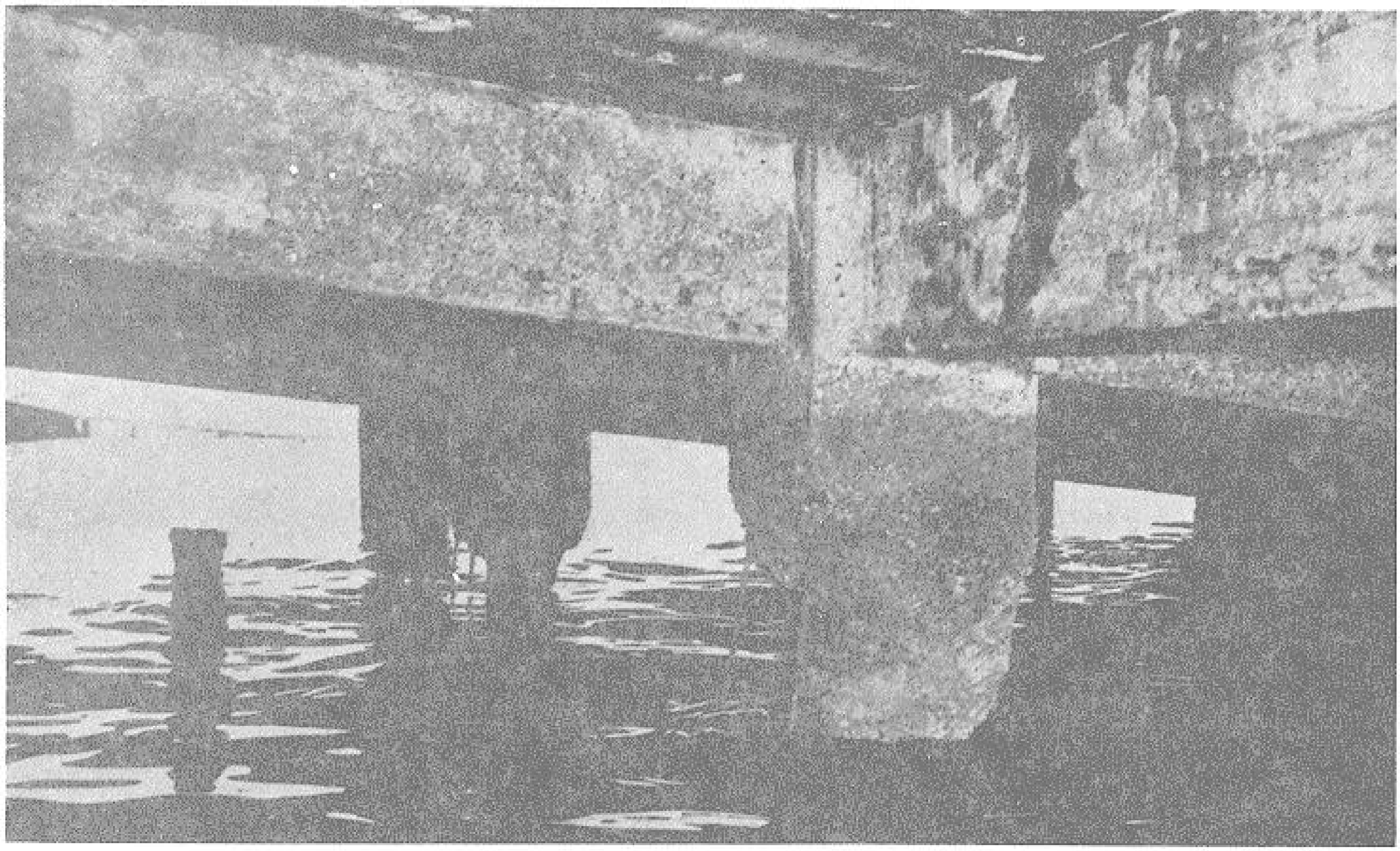

Figure 3-3. Concrete piles in advanced stage of deterioration.

sharp tool, such as a brick mason's or geologist's hammer. A sharp hammer is also useful in determining the soundness of repair work. An unmistakable ring from the blow of a hammer indicates sound material, while a hollow sound indicates loose material. Poorly bonded repair work is identified by a drumming sound. Probing with a gad (sharp pointed tool) can be used to determine the depth of damage.

The atmospheric, splash, and tidal zones of concrete piles can be inspected better from a skiff than from the edge of a deck. The submerged and mud zones (where exposed) should be examined by a diver or, where available and appropriate, an underwater television camera. Both piling and pile caps should be inspected for cracks, spalls (especially in the tidal zone and along edges), disintegration, broken members, exposed reinforcing steel, and rust staining. Decks should be similarly checked, especially along the bottom edges. The general condition of all surfaces, especially wearing surfaces, and expansion joints should be noted. Graving docks should be inspected as described in Appendix B.

3.3.2 MECHANICAL. A reliable method of determining the condition of subsurface concrete is to extract diamond-drilled concrete cores that can be laboratory tested. Such specimens are usually obtained to (1) determine composition or the cause of the problem, (2) determine the depth or extent of deterioration, (3) determine appropriate methods of repair, and (4) establish legal responsibility for the failure.

For structural elements that are not massive (e.g., decks of piers and wharves) and have a sectional thickness of less than 2 feet, the length of a drilled core should be equal to one-half the thickness but not less than 6 inches. The bottom inch of a deck should not be cored because the core could be lost by dropping out of the drill barrel; also, the core hole can be patched more readily. For massive sections (e.g., a seawall), the minimum depth of a drilled core should be 2 feet.

Another mechanical method of inspection uses a concrete test hammer, a portable, manually operated instrument for nondestructive testing of hardened concrete. This instrument measures the hardness or compressive strength of concrete by rebound of a steel plunger in a tubular frame. The hammer should be used only on surfaces where the concrete was cast against a form. Roughfloated or trowel-finished concrete surfaces will produce readings that do not truly indicate the quality of concrete. Readings vary with the age and moisture state of the concrete. Personnel using a test hammer should be well-trained in its proper operation and calibration.

3.3.3 ELECTRONIC. Sonic and ultrasonic methods of inspecting hardened concrete measure the velocities of high frequency waves passing through a structural element. The sonic tester can be used on concrete as thick as 75 feet, while the ultrasonic instrument is limited to thicknesses less than 7 feet. Since sonic pulses do not traverse voids or air-filled cracks, these instruments can be used in detecting and evaluating imperfections and progressive deterioration.

Another method is the use of a standard reference cell and a high-impedance voltmeter. One lead is grounded to the reinforcing steel and the other is connected to the reference cell. The reference cell is touched to numerous locations on the concrete surface. This method can detect corrosion of reinforcing steel when there is no visual evidence of concrete cracking or distress.

Steel can be located by means of magnetic devices, such as a Pachometer.

SECTION 4. REPAIR METHODS

3.4.1 INTRODUCTION. Before planning a repair job it is essential to determine the cause of the problem: the concrete itself, the structural assembly, or both.

For proper repair of concrete structures all defective concrete must be removed, the concrete carefully replaced in accordance with an approved procedure, and effective drainage (where needed) provided.

Concrete that is stressed under loads must be supported properly before the defective portions are cut away. The load on the beams must be removed, and/or the beam relieved of its structural load by shoring to avoid deflection. In the repair of piles that are small in cross section, if the removal of defective concrete could be detrimental to the stability of the structures, an attempt should be made to relieve part of its load.

Where possible, joints should be avoided between low and high tide levels. Patches should not be carried across active cracks or joints. Concrete used in repairs must be protected and cured more carefully than usual. The old concrete could absorb moisture too rapidly from the new concrete, or the temperature of the old concrete could be too low to permit early development of strength of a concrete patch. The volume-change characteristics of the new concrete should correspond to those of the old to avoid differential movements that will weaken the bond.

3.4.2 DRY-PACK MORTAR. The dry-pack method should be used for (1) filling narrow slots that have been cut during the repair of dormant cracks, and (2) filling holes with a cross-sectional area not greater than 36 square inches and a depth equal to or greater than the least surface dimension. The dry-pack method should not be used for filling (1) shallow depressions (less than 1 inch) where lateral restraint cannot be obtained, (2) behind exposed reinforcing bars, or (3) holes that extend through a beam or bulkhead. The saw-tooth bit shown in Figure 3-4 is useful in cutting and undercutting slots and deep holes that are to be dry-packed. Regardless of depth, each hole or slot must be scrupulously clean, free of loose or cracked aggregate, and dry for at least 2 days before filling.

The cleaned interior surface is coated with a stiff bonding grout, immediately followed by the dry-pack mixture. The mix proportions for the bonding grout are 1 part of Type II portland cement to 1 part of fine sand (previously washed and dried), with only enough freshwater to produce a consistency like that of thick cream. The dry pack is a mixture (by dry volume or weight) of 1 part cement to 2-1/2 parts of sand passing a no. 16 standard sieve. The mortar patch is usually darker than the surrounding concrete unless special precautions are taken to match the colors. Where uniform color is important, white cement can be used in sufficient amount (as determined by trial) to produce the desired lighter color.

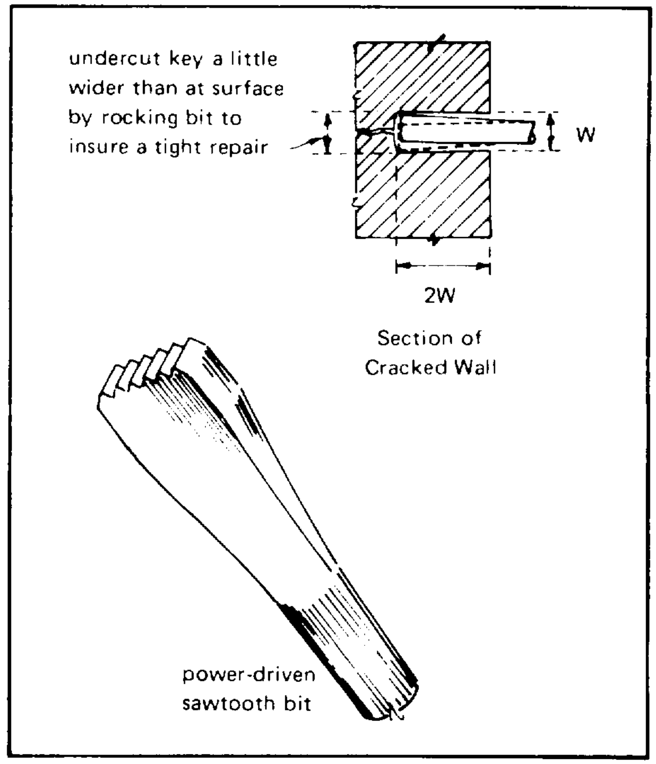

Figure 3-4. Sawtooth bit used to cut a slot for dry-packing.

The dry-pack material should be placed and packed in layers having a compacted thickness of about 3/8 inch; thicker layers cannot be well compacted at the bottom. The surface of each layer should be scratched to facilitate bonding with the next layer. One layer can follow another immediately unless appreciable rubberiness develops, in which event the repair should be delayed 30 to 40 minutes. Alternate layers of wet and dry materials should not be used, and the holes should not be overfilled.

Each layer should be fully compacted over its entire surface by using a hardwood stick and a hammer.

Finishing can usually be completed by laying the flat side of a hardwood piece against the fill and striking it several times with a hammer. A few light strokes with a cloth sometime later may improve the appearance. Neither steel finishing tools nor water should be used to facilitate finishing; otherwise, an ugly patch will result.

3.4.3 CAST-IN-PLACE CONCRETE. The cast-in-place method of restoring concrete should be used when: (1) holes extend through the concrete section, (2) holes in unreinforced concrete are more than 1 square foot in area and over 4 inches deep, and (3) holes in reinforced concrete are more than 1/2 square foot in area and deeper than the reinforcing steel.

All remaining concrete of questionable quality should be removed. Replacement of deteriorated concrete should be delayed several days until the soundness of the excavated surfaces and remaining concrete can be confirmed. Air-driven chipping hammers are most satisfactory for removing the concrete, although good work can be done by hand methods. A gad is better than a chisel because it leaves a rougher, more natural texture for bonding.

The square-cut edges required for many repairs can be sharply and neatly cut with a concrete saw. Small, electrically driven diamond saws with adjustable guide plates are available for depths up to 2-5/8 inches. An experienced operator can cut 20 feet of 1-inch-deep grooves in one hour. Heavier models are available for straight horizontal cuts, with cutting speeds up to 5 feet per minute. A sawed edge is much superior to a chipped edge, and sawing is generally less costly than chipping.

Surfaces within the trimmed holes should be kept continuously wet for several hours, preferably overnight, before placing the new concrete. The saturation of the old concrete will help in proper curing of the new concrete. Immediately before placement of the new concrete, the holes should be cleaned to leave a surface completely free of chipping dust, dried grout, and all other foreign materials that would deter bonding. Final cleaning of the surfaces to which the new concrete is to be bonded should be accomplished by wet sandblasting, followed by washing with an air-water jet for thorough cleaning; drying should be with an air jet. All shiny spots indicating surface moisture should also be eliminated.

Unnecessary tie wires should be removed from exposed reinforcement. Cleaning of the steel, if necessary, should be accomplished by abrasive blasting. All concrete repairs must be thoroughly moist-cured in order to be effective. If a high-strength bond is required and long moist-curing cannot be efficiently provided, either epoxy resin concrete or epoxy resin-bonded concrete can be used (see Section 3.4.8).

The preparations for the cast-in-place method of repair should be as follows:

(1) Holes should have a minimum depth of 6 inches. The minimum cross-sectional area of the opening should be 1/2 square foot in reinforced and 1 square foot in nonreinforced concrete.

(2) Steel reinforcing bars should not be left partially embedded; there should be a clearance of at least 1 inch around each exposed bar.

(3) The top edge of the hole at the face of the structure should be cut to a fairly horizontal line (see

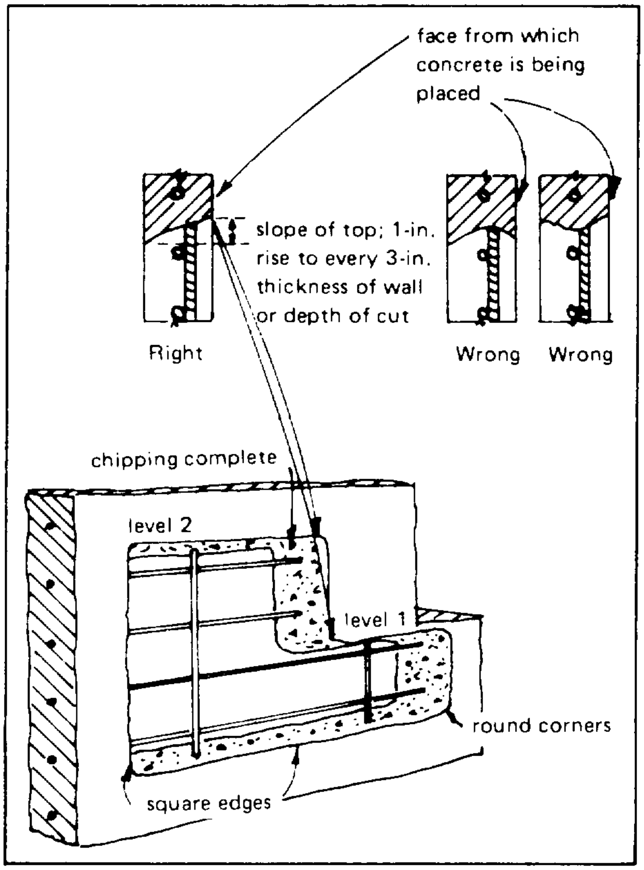

Figure 3-5. Excavation of irregular area of defective concrete where top of hole is cut at two levels.

Figure 3-5). Where a hole passes through a structural element, it may be necessary to fill the hole from both sides. In this case the slope of the top of the cut should be modified accordingly.

(4) The bottom and sides of the hole should be cut sharp and approximately square with the face of the wall. When the hole goes entirely through the concrete section, spalling and featheredges can be avoided by having chippers work from both faces. All interior corners should be rounded to a minimum radius of 1 inch.

The construction and setting of forms are important steps in the procedure for satisfactory concrete replacement where the concrete must be placed from the side of the structure. Form details for walls are shown in Figure 3-6. To obtain a tight, acceptable repair the following requirements must be observed:

(1) Front forms for patches more than 18 inches high should be constructed in horizontal sections so the concrete can be conveniently placed in lifts not more than 12 inches high. The back form can be built in one piece. Sections to be set as concreting progresses should be fitted before concrete placement is started.

(2) For irregularly shaped holes, chimneys may be required at more than one level. In some cases, such as when beam connections are involved, a chimney may be necessary on both sides of the wall or beam. In all cases the chimney should extend the full width of the hole.

(3) Forms should be substantially constructed so that pressure can be applied to the chimney cap at the proper time.

(4) Forms should be mortartight at all joints between adjacent sections, between the forms and concrete, and at the tie-bolt holes to prevent the loss of mortar when pressure is applied to the concrete during the final stages of placement. Twisted or stranded caulking cotton, folded canvas strips, or similar material should be used as the forms are assembled.

Immediately before placing the front section of form for each lift, the surface of the old concrete (at the sides which will be covered by new concrete) should be coated with a 1/8-inch-thick layer of mortar. This mortar should have the same sand and cement content and the

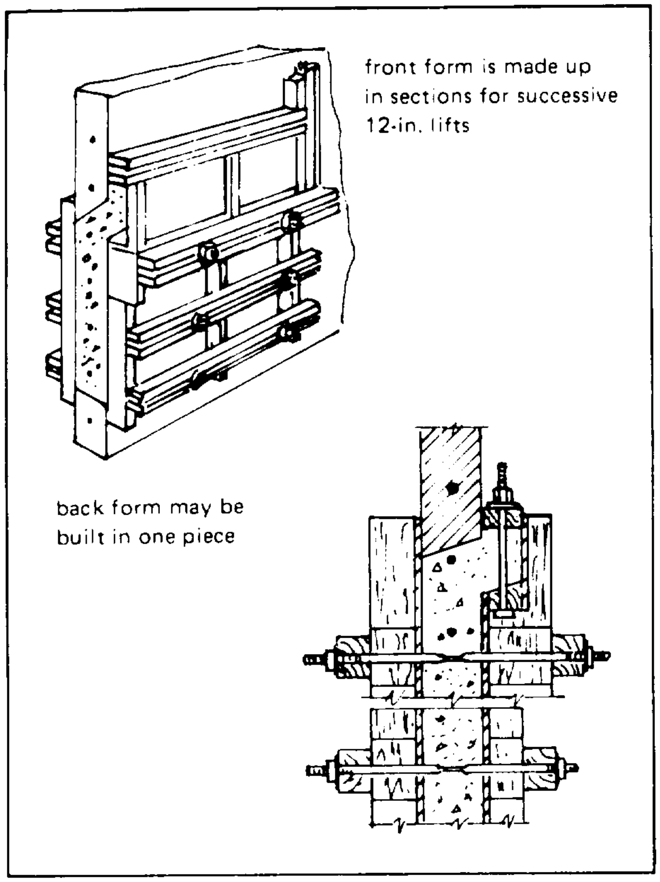

Figure 3-6. Details of forms for concrete replacement in bulkheads.

same W/C ratio as the mortar in the replacement concrete. The surface should be damp, but not wet. The mortar can be applied by means of an air-suction gun, by brushing, or by being rubbed into the surface with the hand encased in a rubber glove. Concrete placement should follow immediately. If the cross-sectional area of the hole is greater than 36 and less than 72 square inches for reinforced concrete repair or 144 square inches for nonreinforced concrete repair, a no-slump concrete should be placed, thoroughly vibrated, and power tamped in 3-inch layers. If practicable, the new concrete should be preshrunk by letting it stand as long as practicable before it is tamped into the hole. The mix proportions and the aggregate gradation should be selected for minimum water content. The W/C weight ratio should be less than 0.40.

Casting concrete in open-top forms, as used for the reconstruction of the top of bulkheads and pier-deck curbs, is a comparatively simple operation. The W/C weight ratio should not exceed 0.45. No special features are required in the forms, but they should be mortartight when vibrated, and should give the new concrete a finish similar to that of the adjacent areas. The slump should be as low as practicable, and the amount of air-entraining agent increased as necessary to ensure the maximum permissible percentage of entrained air, despite the low slump. Top surfaces should be sloped so as to provide rapid drainage. Manipulation in finishing should be held to a minimum, and a wood-float finish is preferable to a steel-trowel finish. Edges and corners should be tooled or chamfered. Water should not be used to aid in finishing.

Forms for repairs involving cast-in-place concrete can usually be removed the day after casting unless form removal would damage the newly placed concrete. The projections left by the chimneys should normally be removed the second day. If the trimming is done earlier, the concrete tends to break back into the repair. These projections should always be removed by working up from the bottom because working down from the top tends to break concrete out of the repair.

3.4.4 SHOTCRETE. Shotcrete is satisfactory for repairing minor damage to concrete piles and framed structures and should be considered whenever there is enough repair work to justify the cost of the equipment. Piers, navigation locks, wooden piling, concrete piling, and steel piling are typical applications for shotcrete where waterfront repairs are necessary.

The advantages of shotcrete, compared with either regular concrete or prepacked concrete, are: (1) ease of placement, (2) minimum need for formwork and plant equipment, and (3) high strength. The comparative disadvantages of shotcrete are: (1) susceptibility to wide structural variation (composition is dependent on the skill of the nozzle man), (2) drying shrinkage rate and coefficient of thermal expansion can be considerably different than those of the original concrete in the structure being repaired, and (3) relatively high porosity.

Repairs and restorations accomplished by the shotcrete method are economical and successful where deterioration is shallow and the repaired area is large and irregular. In regions of severe exposure, periodic protective applications are necessary to seal cracks that allow the entry of water. More information can be found in References 3-2, 3-3, and 3-4.

With shotcrete, only that amount of water necessary for hydration is added to the mixture of aggregate and cement. Thus, shotcrete can be more dense than regular concrete, an important factor in the resistance of concrete to weathering. The ratio of cement to aggregate should never be greater than 1 to 3.5; these proportions will result in a ratio of about 1 to 2.5 (by weight) after gunning the shotcrete in place.

The recommended shotcrete procedure for repairing a deteriorated waterfront structure is: (1) remove all defective concrete, (2) clean all rust off exposed reinforcement, (3) roughen all smooth surfaces and either wire brush or abrasive blast the exposed underlying concrete surfaces, (4) instill wire fabric and ensure that the laps do not project more than 3/4 inch from the surface of the underlying concrete, (5) fix the profiles, (6) fill out with shotcrete to the original face of the structure, and (7) apply not less than 2 inches of shotcrete (the final coat should not be less than 1/2 inch thick).

3.4.5 PREPACKED CONCRETE. Prepacked concrete is used on large repair jobs, particularly underwater placement or where placement of regular concrete would be either difficult or impossible. This method is used also in restoring old concrete and masonry structures. The advantages of either regular concrete or prepacked concrete, compared with shotcrete, are: greater density, greater uniformity, lesser permeability, lower shrinkage, less dependence on personal skills of equipment operators, less dust, less clean-up work, and more economical. The comparative disadvantages of these two methods are that all work on vertical surfaces requires formwork, and for extensive restoration the plant required could be considerably more expensive than that required for shotcrete placement.

Prepacked concrete entails placing coarse aggregate in the form and filling the voids in the aggregate mass with intrusion grout that consists of portland cement, a high grade pozzolan, sand, water and an intrusion aid. The intrusion aid is a chemical admixture that suspends the solid particles in the grout, provides fluidity at low W/C ratios, and undergoes slight expansion before final set. The volume of air entrained in the intrusion grout is about 9%. The amount in the hardened concrete depends on the ratio of grout to coarse aggregate, but usually is about 4%. Bonding strengths of prepacked to regular concrete are between 70% and 100% of that attainable in regular concrete. This makes it possible to restore deteriorated concrete members to near their original strengths or to enlarge existing members to take additional loads.

Weakened material should be removed to expose sound concrete, and the surfaces of sound concrete should be roughened by either chipping or heavy sandblasting before repairing. Space must be provided for the replacement or addition of at least 3 to 4 inches of new prepacked concrete. Forms are then well-anchored to the old concrete, filled with coarse aggregate (of proper gradation for the thickness being placed), and the grout intruded. When the forms are filled, a closing pressure of about 10 psi is held for several minutes to drive out all air and water through a vent at the highest point. The forms are removed one or two days later, and the new concrete is properly cured.

3.4.6 TREMIE CONCRETE. One method of placing concrete underwater, especially at easily accessible locations, involves a tremie (a steel tube having a hopper for filling at its upper end). A plug, consisting of either a rubber ball or a wad of burlap that fits snugly inside the tremie, is inserted below a loading hopper located at the upper end of the tremie. The freshly mixed concrete, introduced at the hopper, forces the plug down and displaces the seawater. The tremie is continually replenished with concrete while the lower end is kept embedded in the newly deposited concrete. Tremie concrete must be quite workable so that it flows readily into place.

It is general practice to use a steel tremie, but a rigid rubber hose could be substituted. An aluminum alloy tremie should never be used because an adverse chemical reaction may occur to produce inferior concrete [3.5]

The size of the tremie depends on the maximum size of gravel and on the quantity of concrete to be emplaced; the usual range in diameter is from 8 to 18 inches. Records of underwater construction show rates of lineal flow between 3/4 and 1 foot per second. The slump of tremie concrete must be maintained between 6 and 7 inches.

3.4.7 PUMPED CONCRETE. Pumping freshly mixed concrete is the most expeditious means of placing concrete in spaces of limited accessibility. The pumping method offers several advantages: (1) High quality concrete is required because the mixture must be workable in order to pass through the pump; (2) Workable mixtures containing relatively small coarse aggregate particles tend to provide a dense concrete; (3) The pump pressure helps to coat the aggregate particles more uniformly and, thus, increase the density of the resultant concrete; (4) Concrete can be transferred from a barge directly into wooden forms at the patching site; and (5) Pumped concrete can be used to fill the forms from the bottom upwards, displacing the seawater as additional concrete is forced in at the bottom.

The pumping method also has some disadvantages: (1) The slump must be carefully controlled to prevent segregation as excessively wet mixtures will sometimes segregate; (2) Coarse aggregate should consist of rounded particles as crushed stone mixtures are comparatively difficult to

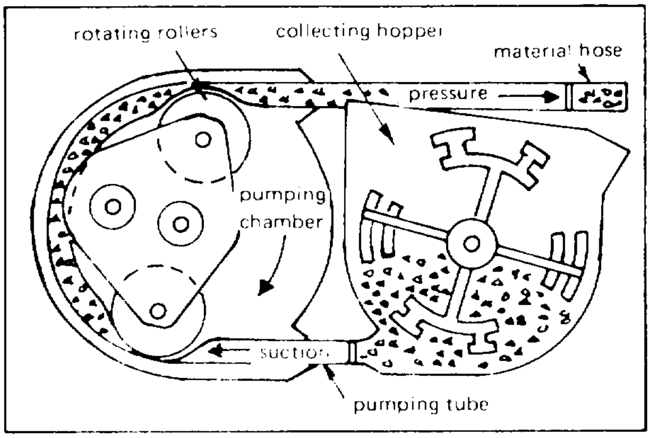

Figure 3-7. Typical squeeze-type concrete pump.

pump because the angular particles tend to interlock; and (3) Porous aggregates (e.g., expanded clay, foamed slag, pumice, and many corallin, materials) should be avoided, if denser aggregates are available.

The squeeze-type pump (Figure 3-7) is preferred for pumping freshly mixed concrete into the form because few of the pump parts contact the concrete. This pump is easy to clean and does not place the concrete under great pressure.

When air-entraining agents are required as described in 3.1.2.4, they are dissolved in the mixing water before it enters the concrete mixer. Quantities needed per bag of cement are specified by the manufacturer and are shown on the containers. Normally about 2 fluid ounces per bag of cement are used.

Water-reducing admixtures will also improve the pumpability of the concrete. If admixtures are used, do not decrease the cement composition; to do so would probably cause blockage in the pipeline. Pumping airentrained concrete will cause little reduction in air content.

The pipeline should be either horizontal or vertical rather than inclined, wherever possible. With an inclined pipeline any water bleeding from the freshly mixed concrete within the pipeline will collect above the concrete and run down the inside of the pipeline.

Delays as long as 1-1/2 hours can generally be tolerated if the mixture is moved several feet at least every 10 minutes (while in the hose or pipeline) until continuous pumping is resumed.

The concrete should be pumped as near to its final underwater position as possible. The diver who has control of the discharge end should not permit lateral flow within the open-top form of more than 2 or 3 feet. The discharge end of the line has to be buried in the mass of fresh concrete; otherwise, segregation will occur at the point where the concrete comes out. Aluminum pipe should not be used because an adverse chemical reaction with the concrete will occur. Rubber hose should only be used for discharge lines or for very short pumping distances. The pipeline should be protected from any excessive heat (solar included).

3.4.8 EPOXY RESIN. Cracks and joints in concrete waterfront structures must be sealed against the adverse effects of a marine environment as a means of prolonging the lives of such facilities. Various formulations of epoxy resin compounds are used for sealing, grouting, patching, and waterproofing cracks and joints in concrete, and as adhesives for bonding freshly mixed concrete or precast concrete to old concrete. No formulation can serve as an all-purpose material for these applications, and so each epoxy formulation should be used only for its intended purpose. Proper methods of treating the surfaces of concrete and reinforcing steel preparatory to applying the epoxy compound, and correct procedures for using epoxy compounds are described in detail in References 3-6 through 3-8.

3.4.9 PROTECTIVE COATINGS. Coating hardened concrete surfaces (e.g., the decks of piers and wharves) with protective water repellents may be a good precautionary measure. A useful guide to coatings for protecting concrete is found in Reference 3-9.