Quality Control of Portland Cement Concrete[1]

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Concrete control is a vast subject involving many materials and construction procedures and it can be covered only in general terms in the space allotted to this paper. The ACI Manual of Concrete Inspection and the Concrete Manual of the Bureau of Reclamation have been written to assist the engineer and inspector in obtaining good, economical concrete construction. Also, a number of very good committee reports have been published by the American Concrete Institute dealing with specific phases of concrete construction such as the Recommended Practice for Winter Concreting, the Recommended Practice for Hot Weather Concreting, and the Recommended Practice for Measuring, Mixing and Placing Concrete.

Materials used in concrete construction; i.e., cement, pozzolan, water, air-entraining agents, aggregates, reinforcement, joint sealers, and mats, paper and sealing compounds for curing, are covered by available AASHO, ASTM and Federal Specifications. Methods of making construction control tests have been standardized by AASHO and ASTM and are available to the inspector. Excellent publications on almost every phase of concrete construction are available from the Portland Cement Association.

Much has been learned about the behavior and limitations of portland cement concrete since portland cement was invented about 150 years ago, and what must be done to secure an economical serviceable concrete structure is well known. Although the procedures that should be followed to obtain strong, durable concrete are well known, we are not always willing to exercise control over the many operations required to secure a top notch structure. Effective concrete control can be attained only when its importance and objectives are recognized throughout all segments of the organization, from top management, through the design, specifications writing, construction stages, and

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into operation and maintenance. The esprit d'corps of any organization starts at the top and so does the support required to do a top job in concrete construction.

Many organizations spend much time and effort in carefully designing their structures in every detail, yet seem to be unconcerned about the many details which must be looked after during the construction phases. The best of us are apt to slough over exacting requirements unless someone is assigned to see that good practices are followed in every necessary detail.

It is generally accepted practice in specifications to avoid specifying how the work shall be done, and instead, to concentrate on the results to be obtained, leaving the methods of accomplishment to the contractor's ingenuity. The contractor, being in a highly competitive business, however, cannot be expected to perform beyond the requirements of the specifications. The designer and specification writer, therefore, should give careful attention to quality and uniformity of materials, mixing and placing procedures, location of construction joints, thickness of sections, concentration of reinforcement as it may affect placement of concrete, finishes desired, tolerances in line and grade, type and length of curing, winter protection, and hot weather precautions. New and improved equipment and methods are constantly being developed and specifications should be written to take advantage of these developments. Once a contract has been executed, it becomes a legal document which can be changed only by negotiations. The construction engineer should see that it is enforced and should not permit changes without consulting with designers and specification writers.

CONTRACTOR-INSPECTOR RELATIONS

The inspector should be completely familiar with the requirements of the specifications and should have an understanding with his supervisor on all points which need interpretation. Each phase of the work should be discussed with the contractor's foreman prior to its start as it is much easier to settle differences the day before concrete placing starts than while it is in progress. The inspector should not take over the foreman's responsibility by giving instructions to the workmen, and all dealings should be with the foreman.

State, Federal and other agencies that have a number of projects under construction at one time should conduct an annual training school for field engineers and inspectors. They should be instructed in methods of making control tests, and the standards of control desired should be made clear to them so that each job is administered with the same degree of exactness.

The contractor is in business to make a profit, and when he does, everyone benefits. Therefore, he should not be requested to do more than the specifications require nor should unnecessary demands be made on him. The spirit of cooperation between representatives of the agency and contractor should prevail throughout the job. The objectives of both should be the same, that is, to accomplish the intent of the plans and specifications in the most effective manner and at the least cost. It is frequently possible for a good inspector to point the way whereby a contractor can save money and at the same time secure a better structure for the agency. Similarly, a contractor's foreman can make the inspector's job more pleasant by providing appropriate inspection facilities, by maintaining good "housekeeping," by considerate scheduling of operations and by exhibiting a genuine desire to follow the specifications.

RESEARCH AND TESTING

Any endeavor that is as large and involved as concrete construction will always offer an opportunity for improvement of designs, materials and methods. For this reason large organizations that have the responsibility for designing and supervising concrete construction should have capable laboratories on which they can call to have new ideas in design developed and new materials and methods tested. The Bureau of Reclamation has found through 30 years of experience that it is very profitable to maintain a well equipped and staffed laboratory at Denver, Colorado, to work on the many problems which develop in the planning, design, construction and maintenance of irrigation projects in the 18 Western States. There are many excellent private and college laboratories available in every part of the country to help smaller organizations. Construction contractors have also found that these laboratories can be helpful in working out problems that develop during construction.

Control laboratories used for making control tests during the progress of the job should be staffed by competent, experienced men who have been trained in the importance of accurately following the prescribed test procedures. Even well managed laboratories, unbeknowing to the operators, have sometimes used equipment and procedures that did not meet standards, and it is recommended that the equipment and procedures be checked each year by the Cement and Concrete Reference Laboratory. The Cement and Concrete Reference

Laboratory is under the sponsorship of the American Society for Testing Materials and can be contacted by addressing the Cement and Concrete Reference Laboratory, National Bureau of Standards, Washington 25, D. C.

CEMENT

There are five types of portland cement covered by AASHO and ASTM Specifications. These can also be purchased with interground additives for the purposeful entrainment of air in the concrete. Portland blast-furnace slag cement, covered by AASHO and ASTM Specifications, is available in many parts of the country. In addition, pozzolans and natural cements are economically available in some sections of the country for blending with portland cement, and, where available, should be considered in selecting the cementing material for the job.

Type I cement is the general all-purpose cement used in most construction. Type II cement is used where mild exposure to sulfate soils or water is indicated and/or where some control is desired over the heat of hydration of the cement. Type V is specified when the concrete will be exposed to sea water and high concentrations of sulfates in the soil or water. Type IV, a low-heat-developing cement, is used in massive structures where the dissipation of heat of hydration of the cement is a consideration. Type III cement is a high early strength-developing cement.

In the western part of the United States where high concentrations of sodium and magnesium sulfates are encountered in soil and water, some structures made with Type I cement have failed in as little as one year due to sulfate attack (Fig. 1). Concrete made with Type V cement is much more resistant to this attack and it should be used where concentrations of sulfate are encountered. The Concrete Manual of the Bureau of Reclamation contains information on sulfate concentrations when Type II and Type V cement should be used. Certain siliceous constituents when present in aggregates will react with the alkalies in the cement (K_20 and Na_20) to produce disruptive expansion of the concrete. Usually when these alkalies in the cement are less than 0.60 per cent expressed as sodium oxide equivalent, harmful expansion does not occur. Tests of the aggregates will show whether the alkali content of the cement should be limited. Hot cement and false-setting cement have given trouble on some jobs and it may be desirable to limit the temperature of the cement as delivered to a maximum of 170° F, as suggested in ACI Recommended Practice for Hot Weather Concreting, and to limit the false-setting tendencies of the cement.

Fig. 1. Barrack floor failure a few years after construction from sulfate attack.

AGGREGATES

In many areas the concrete-making properties of available aggregates are well known through years of experience in their use. When aggregates from a new source are being considered, they should be tested to determine what processing will be necessary to meet grading requirements and whether they are suitable for making strong, durable, wear resistant concrete. In addition to the usual tests for soundness, hardness and deleterious substances, the aggregate should be examined for constituents which may react with the alkalies in the cement to cause disruptive expansion and for particles which may cause unsightly pop-outs at the surface when the concrete is frozen (Fig. 2).

The strength of concretes made with aggregates from different sources may vary greatly and their strength-producing properties should be determined particularly when it is intended to base mix proportions on a specified cement content. Large differences in compressive strength of concrete having the same cement content have been found on Bureau of Reclamation projects with aggregates from different sources. With the same amount of cement, aggregates used in the construction of Canyon Ferry Dam produced concrete having a strength about 1,000 psi greater than aggregates used for construct-

Fig. 2. Pop-outs in three- by six-in. cylinders after 30 cycles of freezing and thawing in water. Concrete contained aggregate graded up to ¾-in. maximum size w/c 0.51 by weight of cement, 4.2 per cent entrained air. Specimens were fog cured for 14 days followed by 76 days of storage at 50 per cent relative humidity before starting freezing and thawing tests. Pop-outs resulted from soft calcareous siltstones, calcareous cherts, shaly limestones, and ferruginous concretions.

ing Hungry Horse Dam. This was the more surprising since Canyon Ferry aggregates were considered actually to be of poorer quality than the Hungry Horse aggregates by the usual standard aggregate tests.

A number of years ago it was noted that high strengths were being obtained on one project with below the average amount of cement and on another similar project, above the average amount of cement was being used to meet the minimum water-cement ratio and strength requirements. Samples of these two aggregates, which were both from natural river-worn deposits and which were similar in physical characteristics, were brought into our Denver Concrete Laboratory for examination and test. They were graded identically up to 1½-in. maximum size and mixed with cement from the same source to the same consistency. It was found that concrete containing one aggregate required 100 pounds more water per cubic yard of concrete than concrete containing the other aggregate when brought to the same slump. The concrete made with the high water-requiring aggregate required approximately one sack more cement per cubic yard of concrete than the other to produce a strength of 4,000 psi. Because of the large differences found in the concrete-making properties of aggregates and cements the Bureau of Reclamation requires that, except for manufactured items such as pipe, the portland cement be furnished by the contractor under a separate bid item. Under such an arrangement the contractor is paid for the cement actually used and adjustments can be made in the concrete mix during the progress of the job to obtain the strength and quality desired at minimum cement content. Also, there is no incentive for the contractor to skimp on cement under this procedure.

ADMIXTURES

Admixtures are widely used to entrain air in concrete, to reduce the amount of mixing water required to produce a given slump, and/or to accelerate the early strength development of the concrete. There is wide agreement that the purposefully entrained air is an economical means of improving the workability of fresh concrete and the frost resistance of the hardened concrete (Fig. 3). However, this agreement does not extend to water-reducing agents and the common accelerator, calcium chloride. Water-reducing agents usually will improve the quality of concrete but their benefits must be balanced against their cost. Calcium chloride, which accelerates early strength development, is widely used for this purpose. The Bureau of Reclamation requires that 1 per cent calcium chloride by weight of the cement shall be used in concrete placed in freezing weather as its use permits the reduction of the time required to protect the concrete from freezing. The use of calcium chloride permits earlier form removal and results in economies through accelerating the number of units which can be cast in a given time. The quality of the concrete apparently is not reduced by the use of calcium chloride in small percentages during cold weather. Alkali-aggregate expansion is increased and the resistance of the concrete to sulfate attack is reduced by the use of calcium chloride at higher temperatures. There are indications that calcium chloride contributes to the

Fig. 3. Superior resistance of air-entrained concrete pavement to heavy and frequent applications of salt is demonstrated by the concrete on the left compared to the concrete at the right which was built similarly in all respects except that the pavement on the right contained no entrained air.

corrosion of highly stressed steel used in prestressed concrete and to the corrosion of left-in-place galvanized forms. There has been no report of damaging corrosion of ordinary reinforcement resulting from the use of calcium chloride.

MIX PROPORTIONS

Concrete is generally benefited by lowering the amount of mixing water required to produce the consistency required for placing. For a given set of materials, the amount of mixing water can be reduced by mixing to the lowest slump which will permit efficient placing of the concrete, by using the lowest percentage of sand required for good workability and by using the largest usable maximum size of aggregate. Trial mixes should always be made to determine the concrete-making properties of untried materials and their strength-developing characteristics. ASTM Designation C31-57 states that the cylindrical specimens used for compressive strength tests should have a diameter at least three times the maximum normal size of aggregates, and it is the writer's opinion that the diameter should be at least four times the maximum size of aggregate for determining representative strengths.

In Table 4 of ACI Recommended Practice for Selecting Proportions for Concrete there are listed recommended maximum water-cement ratios for different types of structures and degrees of exposure. The net water-cement ratio of concrete which will be exposed to freezing and thawing should not exceed six gallons of water per bag of cement. The water-cement ratio of thin sections which will be exposed to freezing and thawing such as railings, curbs, sills, parapets and tops of walls should not exceed 5.5 gallons of water per bag of cement. Purposefully entrained air in the amounts listed in Table 3 of the Recommended Practice for Selecting Proportions for Concrete greatly improves the resistance of concrete to freezing and thawing and to scaling resulting from salts used for de-icing, and air should be entrained in all concrete which will be exposed to freezing weather. Entrained air greatly improves the workability of concrete, and its addition to concrete will usually be advantageous from this standpoint alone.

Overwet concrete should always be avoided as it is difficult to transport and place without segregation and is almost certain to be weak and lacking in durability. With proper transportation and placing equipment a maximum slump of two inches should be adequate for slabs and lightly reinforced large sections. A maximum slump of four inches should be adequate for walls and heavily reinforced sections.

BATCHING AND MIXING

On any job it is desirable to have uniformly good concrete produced batch after batch. To accomplish this, the coarse aggregates must be separated into their component sizes and reach the batcher in a cleanly separated condition. The grading of the sand must be kept within narrow limits. On Bureau of Reclamation projects involving more than 10,000 cubic yards of concrete, it is customary to require that the coarse aggregate be finish screened just before batching to remove excessive oversize or undersize material which may have accumulated in the size fractions during the handling processes (Fig. 4). There is no need to specify finished screening if the grading requirements can be rigidly enforced otherwise. It is usually difficult, however, to reject aggregates that are delivered to the batching plant which are heavy in undersize and oversize, because such rejection may involve the installation of new screens and reprocessing the stockpiles with considerable delay in the progress of the work. The gradings specified are more positively assured and the enforcement of the

Fig. 4. This stockpile of processed aggregate was built in layers by trucking over each layer. The trucks caused breakage and contamination. Amount of undersize varied, sometimes running as high as 30 per cent.

specifications are made less difficult by requiring that the aggregates be finished screened.

The sand should be well drained so it approaches a stable moisture content. A one per cent change in surface moisture in the sand will change the slump of the concrete about 1½ inches.

Automatic batching plants are superior to manually operated plants, because they eliminate the personal error and they are highly recommended for central plants (Fig. 5). Automatic plants get out of adjustment and must be checked periodically to determine that they are working as intended. During the construction of a large concrete dam in the western part of the country, the automatic cement batcher went out of adjustment on the swing shift, and it was necessary to control the batching of the cement by hand. When the night crew took over, this fact was not made known to them, and a number of batches of aggregate, water, and air entraining agent were mixed and placed in the dam before it was discovered that the cement batcher was broken and no cement was entering the mix. The air content of concrete will increase as the cement content is decreased, and at night it was difficult to see that there was no cement in the mix because the workability was satisfactory due to the increased air content. The removal of the aggregates from the structure was a costly operation.

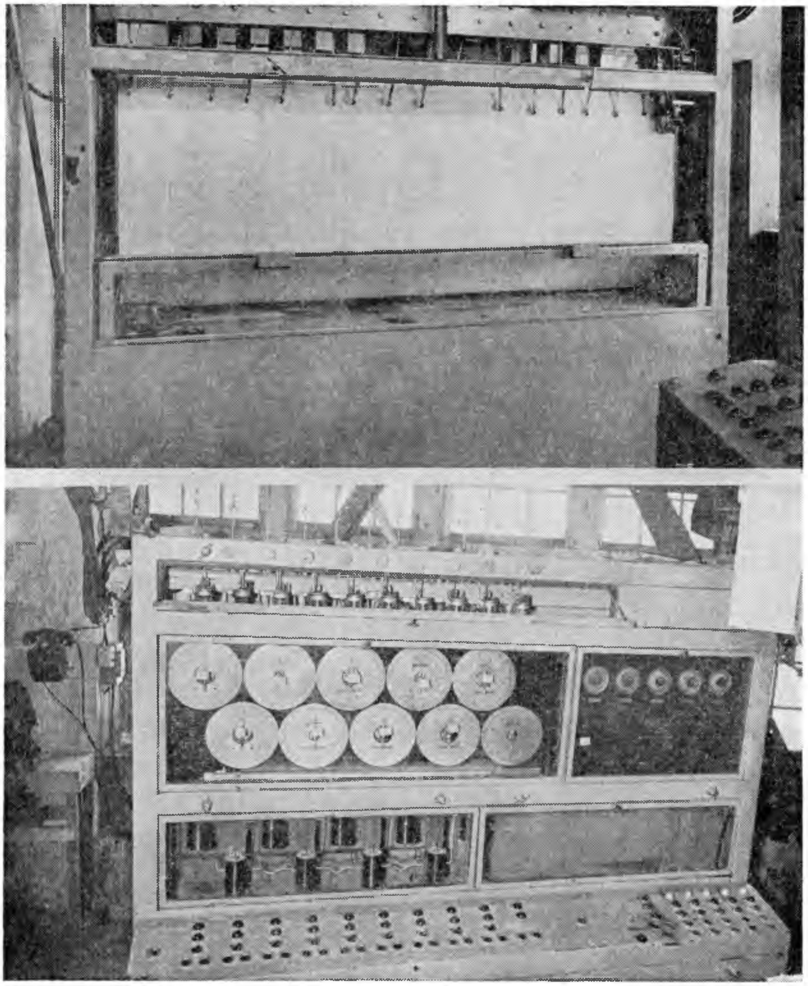

Fig. 5. Automatic batching control cabinet at bottom and recorder cabinet at top of picture used in construction of Hungry Horse Dam. Modern plants will automatically select, batch, and mix the proper proportions of as many as ten liquid, solid, powdered, or granular materials.

Recently very low strengths were reported for about 90 cu. yards of concrete in the base of a high bridge abutment on a Bureau of Reclamation project. Examination of the concrete showed high air content and low cement content. Further checking showed that at the time this concrete was placed, the automatic batcher was batching only about half the specified amount of cement. This resulted in an increased amount of air being entrained in the concrete with the same amount of air entraining agent. It was necessary to remove this weak concrete (strength averaged 950 psi. at 28 days) at considerable expense to the contractor. On one other Bureau job where pozzolan was being used, pozzolan was erroneously placed in the cement bin, and for a while no cement was included in the concrete. Inspectors and plant operators should be constantly alert for such possibilities.

For Bureau of Reclamation work it is specified that the concrete shall be mixed for not less than a specified time (1½ minutes for a 2 cu. yard capacity mixer and 2½ minutes for a 4 cu. yard capacity mixer) with a provision that this time can be reduced if it is demonstrated by mixer efficiency tests that the concrete can be uniformly mixed throughout the batch in less time. The specified time is usually ample and generally it is found that the concrete can be adequately mixed in less time. If the contractor does not maintain the mixer properly and replace worn blades as needed to mix efficiently, he can be required to mix the full specified time, and longer, if necessary. Some of the mixing can be done during the batching of the materials, and it has been found that the mixing time for large mixers can be reduced by introducing the ingredients (cement, pozzolan, fine and coarse aggregate) into the mixer simultaneously and in such a manner that the period of flow of each is about the same. About 5 to 10 per cent of the water should precede, and a like quantity should follow, the introduction of the other materials. The remainder of the water should be added uniformly with the other materials. During cold weather, when very hot water is used in mixing, it may be desirable to bring the cold aggregates and hot water together first to reduce the possibility of "flash set" by contact of the hot water with the cement.

Because of long haul distances and poor communications, more attention and effort are required to obtain uniform, well mixed concrete from the truck mixers than from central plants, pavers or other portable mixers served at the forms by batch trucks. Some truck mixers have difficulty discharging low slump concrete and the concrete is more apt to segregate as it is discharged from these mixers.

TRANSPORTATION AND PLACING

Even though concrete is carefully designed and properly mixed, its quality may be seriously impaired by use of improper or careless methods of transportation and placing. Concrete may be transported by buckets, railroad cars, trucks, chutes, belt conveyors, pneumatic guns, and pumps (Fig. 6).

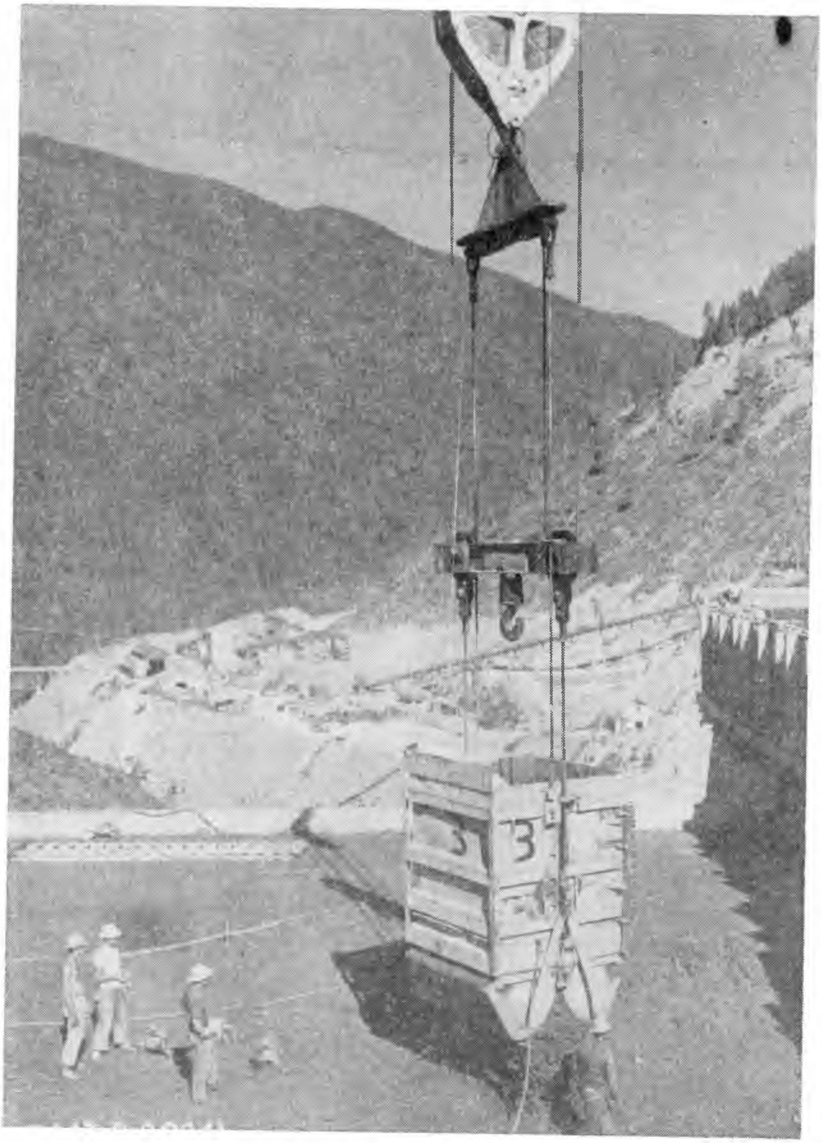

Fig. 6. An eight-cubic-yard bucket being emptied in block of Hungry Horse Dam. Transportation by highline and bucket usually causes little segregation. The eight-cubic-yard pile of concrete requires considerable work with large vibrators to consolidate into horizontal layers of not more than 20 in. deep.

The prime objective of all methods is to get the concrete to the forms in the least time without causing segregation and without undue exposure to the elements. The safe length of haul without agitation is dependent on the properties of the concrete and the amount of vibration received during transportation.

The concrete pump and pneumatic gun are commonly used to transport concrete to tunnel linings. The pump is superior to the gun because of difficulty of controlling the velocity of the concrete at the discharge end of the gun. When a gun is used, the discharge end should be kept buried in the concrete to minimize segregation.

The slump of the concrete should be governed by what is required to consolidate the concrete in the forms under adequate mechanical vibration and not by the degree of wetness which may be required to cause the concrete to run down a gently sloping chute or to flow from a particular bucket or mixer (Fig. 7). The transportation

Fig. 7. Concrete at about one-in. slump containing aggregate graded up to six-in. in size is compacted in layers in Canyon Ferry Dam by heavy two-man internal vibrators. Concrete contained two sacks of portland cement and one sack of fly ash.

equipment should be able to transport the concrete at a slump which will permit it to be placed and consolidated in the forms with reasonable effort.

Concrete should be deposited as nearly as practicable directly in its final position and should not be caused to flow in such a way that the lateral movement will permit or cause segregation of the coarse aggregate, mortar, or water from the concrete mass. Unless the concrete is wetter than necessary, it is seldom that it is vibrated and/or spaded sufficiently to cause the concrete to segregate. Tests show that once air is entrained into concrete in recommended amounts by an approved agent, it is difficult to vibrate out the beneficial small bubbles which protect the concrete from frost damage. Concrete can be revibrated up to the time of initial set without damage. When overvibration is indicated, the slump is usually too high and should be reduced. The bond of reinforcing steel is improved by vibration of the steel up to the time of initial set of the concrete.

CURING

Many engineers require concrete be kept moist for at least 14 days immediately following placement or until covered with fresh concrete. The concrete may be kept damp by covering with earth, sand, burlap, cotton mats, or straw, which are kept moist by sprinkling with water. In all cases, the water spraying should be frequent enough to prevent damaging the young concrete by intermittent wetting and drying. Plastic sheets, paper and membrane sealing compounds which seal the mixing water in the concrete are also used for curing. On Bureau of Reclamation jobs, that in many cases are located at considerable distance from a source of water, it has been found that white membrane sealing compounds give the most positive and economical curing. Once the compound is applied at the specified coverage to form a continuous, uniform membrane over the surface of the concrete, no further inspection is required except to see that the coating is protected from damage. The ordinary sealing compounds cannot be used on construction joints or on areas that will be painted because they inhibit bond.

FORMS AND FINISHES

The appearance of the finished structure is governed to a large extent by the forms used for casting the concrete. For this reason, specifications should stipulate the type of finish desired with information on the form material which will be acceptable for each finish required. Concrete properly placed in well-built forms requires little or no sacking, stoning, and rubbing to make it presentable. Revibration and spading along the forms will permit many of the large air bubbles which form objectionable "bug holes" in the surface to rise and escape (Figs. 8, 8a). Early form removal facilitates needed repairs and treatment of surface and permits earlier curing of the concrete. For these reasons, forms should be removed as soon as the concrete has hardened sufficiently to prevent damage by careful form removal. Of course, beams and floors must remain supported until they are strong enough to carry their own weight and any load they may be supporting.

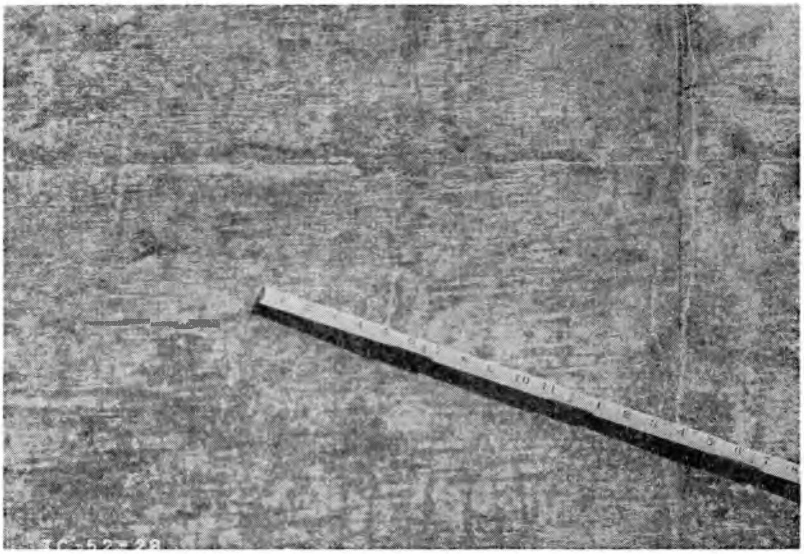

Fig. 8. Some of bug holes shown in Fig. 8a were removed by extra vibration as shown in this picture.

Unformed concrete surfaces should be worked as little as possible to obtain the desired finish as excessive working brings water and fines to the surface which reduces its wearing qualities. In some cases, it may be found necessary to adjust the mix or alter the grading of the aggregate to obtain a satisfactory finish. Because of a deficiency in fines, mortar made with some sands will "chatter" under the trowel making it impossible to obtain a wave free surface. In concrete placed by the slip-form method, commonly used in constructing canal linings, the pea gravel is reduced to about five per cent to prevent rolling of this size under the slip-form as it is pulled over the fresh concrete (Fig. 9). It is usually necessary to increase the amount of sand in the mix above that used for structural concrete to give the mix the required smoothness for slip-form type finish required in canal linings (Fig. 10).

COLD AND HOT WEATHER PROTECTION

In general, Bureau of Reclamation specifications follow the ACI Recommended Practice for Winter Concreting. The Bureau encourages the use of insulation to protect the concrete from freezing and for maintaining temperatures above 50 F for the first three days after placing. Artificial heat, with the exception of steam, drys the concrete and contributes to carbonation of the surface. Heaters are

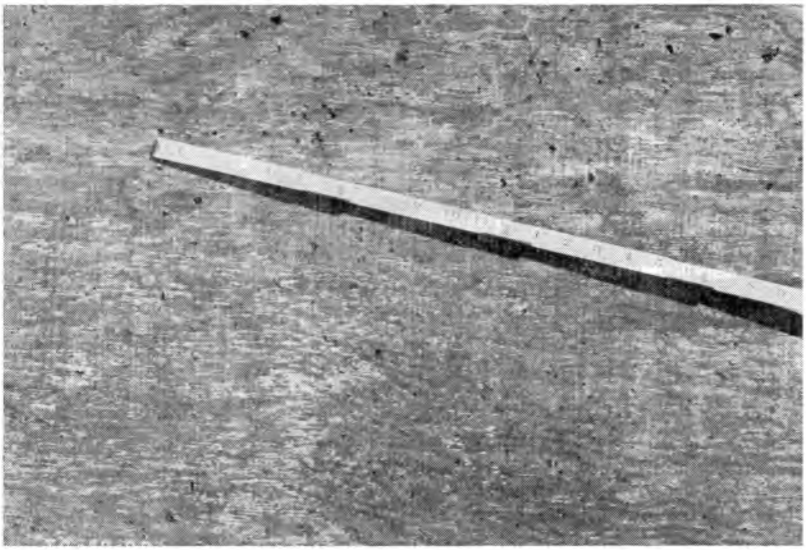

Fig. 8a. Bug holes which were removed by vibration as in Fig. 8.

fire hazards and many structures have been damaged by fires resulting from the forms being ignited by them (Fig. 11). It has already been mentioned that the Bureau requires that one per cent calcium chloride by weight of the cement be added to concrete placed during cold weather. The calcium chloride contributes to early strength development and reduces the time required to protect concrete from freezing temperatures. Air entraining agents should be used in all concrete which will later be subjected to freezing.

The ACI Recommended Practice for Hot Weather Concreting is an excellent discussion of procedures which should be followed during hot weather. Usually specifications stipulate the temperature of the concrete when placed shall be not more than 90 F. Other things being equal, concrete of best quality is produced at temperatures between 40 and 60 F. High temperatures accelerate setting, increase mixing water requirements, reduce ultimate strength, contribute to

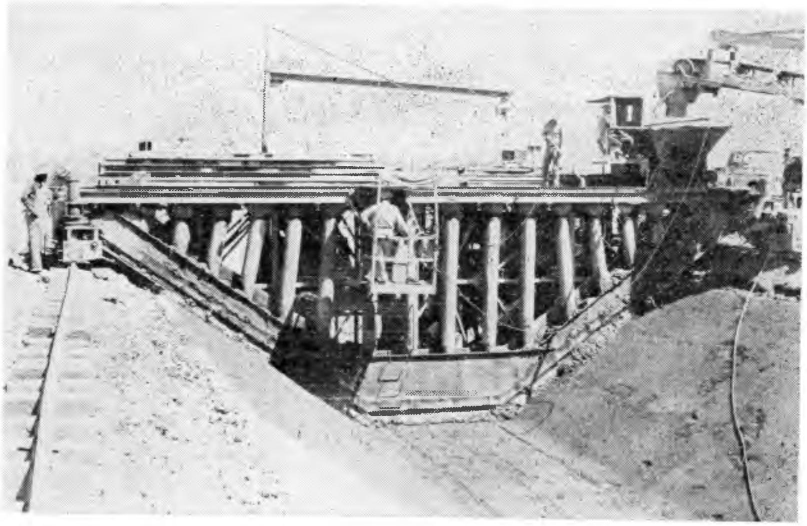

Fig. 9. Slip-form used in placing three-in. thick concrete lining of large canal. Concrete must be on dry side to prevent sloughing on side slopes.

Fig. 10. Finished lining is cured with sealing compound immediately after finishing.

Fig. 11. Culvert destroyed by fire resulting from burning of wooden forms which were ignited by heater used to protect concrete from freezing.

cracking, make protection from drying more difficult, and may make handling, placing and finishing of the concrete more difficult because of accelerated setting. The Recommended Practice for Hot Weather Concreting lists a number of procedures for lowering the temperature of the concrete; among these the use of cold mixing water and the use of ice as part of the mixing water are mentioned as being the simplest and most effective method for reducing the temperature. On one Bureau bridge built in the southwest during the hot summer months, the contractor found that cooling the concrete by using ice during mixing facilitated placing and finishing sufficiently to more than pay for the cost of the ice.

STRENGTH TESTS OF CONCRETE

The working stresses listed in the ACI Building Code are based on the compressive strength of six- by 12-in. cylinders that are made, cured and tested in a very precise, prescribed manner. The Code states that the samples of concrete from which the specimens are cast shall be secured in accordance with ASTM Designation C-172, Method of Sampling Fresh Concrete, that the specimens be made and laboratory cured in accordance with Method of Making and Curing Concrete Compression and Flexure Test Specimens in the Field (ASTM Designation C31) and that the specimen shall be tested for strength in accordance with Method of Test for Compressive Strength of Molded Concrete Cylinders (Fig. 12). Specimens cured at uncontrolled temperatures near the structure are useful for indicating when

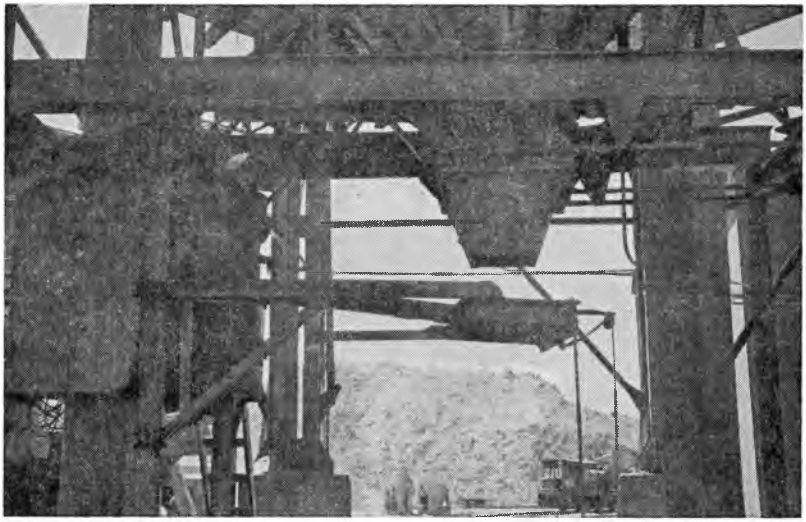

Fig. 12. Sampling tray which is swung under concrete hopper to obtain two cubic feet of concrete for tests.

the concrete is strong enough to remove forms or support traffic but are not suitable for measuring the strengths on which designs are based and concrete specifications written. It is true that the cylinder which is moist cured in the laboratory at the prescribed constant temperature may not be representative of the concrete in the structure which is subjected to different curing conditions, but neither will a cylinder or beam cured near the structure accurately indicate the strength of the concrete in the structure. Apart from the variations which occur in the concrete, the strength of a concrete specimen is influenced by compaction effort used in casting, temperature of concrete at time of casting, curing temperature, moisture available during curing, moisture content at time of testing, type of cap, and rate of loading. As an example, the strength of a cylinder tested with a soft cap may be as much as 50 per cent less than one tested with a hard cap, other things being equal. The strength indicated with the soft cap may be more nearly representative of unrestrained concrete strength at the surface of the structure than a value obtained with a hard cap because the soft cap releases the lateral restraining forces of the testing head. European and Russian engineers base their designs on strengths indicated by six- by six-in. and eight- by eight-in. cubes which give indicated strengths that are 15 to 20 per cent higher than that indicated by six- by 12-in. cylinders made from the same concrete. Because of the lower height-to-width ratio of the cubes as compared to the six- by 12-in. cylinder their indicated strength is probably influenced more by the restraining forces of the testing heads. Cores four by eight inches, six by 12 in., and 10 by 20 in. in size drilled from the same block of concrete containing 1½-in. maximum size aggregate, in the Concrete Laboratory of the Bureau of Reclamation, indicated higher strengths as the size of the core increased. The indicated strength as measured by the 10-in. diameter core was about 25 per cent higher than that measured by the four-in. diameter core, showing that size of specimen may have a pronounced effect on the indicated strength of concrete.

In spite of the fact that the strengths of test specimens do not accurately indicate the strengths of the concrete in the structure, they are very good yardsticks of the uniformity of control being obtained on a job when made and testing in the prescribed manner.

Under any controlled manufacturing procedure the product will vary about an average value in accordance with a normal frequency distribution and usually there will be as many values on the high as on the low side of the average (Fig. 13). Under good control, the values are all near the average; and under poor control, they spread out on both sides. There is a tendency in sampling concrete to select those batches that have the right slump and avoid the wet and dry mixes. Under such selection, better control may be indicated than is being obtained. When the time comes to take a sample it should be taken of the concrete being placed at that time. Also, the results of all test specimens should be reported. The only time a result can be discarded is when it is noted beforehand that the cylinder has been dropped, contained honeycomb areas, or was otherwise obviously below standard.

This paper has discussed in general terms some of the factors involved in the control of concrete construction. The reader is referred to the following references for more detailed information on this subject:

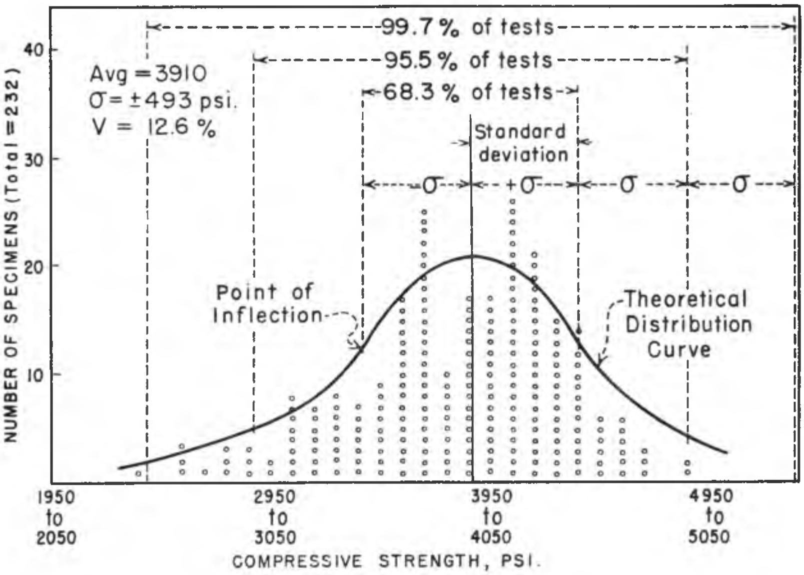

Fig. 13. Typical frequency distribution of compressive strength of six- by 12-in. control cylinders (Angostura Dam, 1948 season).

REFERENCES

1. *Concrete Manual,* 6th ed., Bureau of Reclamation.
2. *ACI Manual of Concrete Inspection.*
3. *Concrete Pavement Inspector's Manual,* Portland Cement Association.
4. *Concrete Pavement Manual,* Portland Cement Association.
5. *ASTM Standards on Cement, Specifications, Chemical Analysis and Physical Tests,* a special publication.
6. *ASTM Standards on Mineral Aggregate and Concrete, Specifications, Methods of Testing, and Definitions,* a special publication.
7. *Standard Specifications for Highway Materials and Methods of Sampling and Testing of the American Association of State Highway Officials.*
8. *Standard Specifications for Road and Bridge Construction and Maintenance,* State Highway Department of Indiana.

9. *ACI Specifications for Concrete Pavements and Concrete Bases.*

10. *ACI Recommended Practice for Evaluation of Compressive Test Results of Field Concrete.*

11. *ACI Recommended Practice for Winter Concreting.*

12. *ACI Recommended Practice for Hot Weather Concreting.*

13. *ACI Recommended Practice for Selecting Proportions for Concrete.*

14. *ACI Recommended Practice for Measuring, Mixing and Placing Concrete.*

15. "Factors Influencing Concrete Strength," by Walter H. Price, *ACI Proceedings,* Vol. 47.

16. "Significance of Tests and Properties of Concrete and Concrete Aggregates," *ASTM Special Technical Publication No. 169.*

17. "Grading of Mineral Aggregates for Portland Cement Concrete and Mortars," by Walter H. Price, *ASTM Special Technical Publication No. 83.*

18. "Precision Indices for Compression Tests of Companion Concrete Cylinders," by S. P. Wing, Walter H. Price and Clemeunt T. Douglass, *ASTM Proceedings,* Vol. 44.